# A Physics Guide for Car Enthusiasts

## Why Cars Accelerate, Corner, Brake, Grip, Drag, Heat Up, and Go Fast

Dr. Yves J. Hilpisch[1]

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[1] Get in touch: `https://linktr.ee/dyjh`. Web page `https://hilpisch.com`. Research, structuring, drafting, and visualizations were assisted by different LLMs as a co-writing tool under human direction.

# Preface — The Car as a Physics Laboratory

A car is an extraordinary concentration of physics packed into one familiar machine. Translation and rotation, forces and acceleration, momentum, energy conversion, friction, heat, fluid dynamics, oscillation, electricity and magnetism, feedback and control—all of it is at work every time you drive, hidden in plain sight behind the steering wheel.

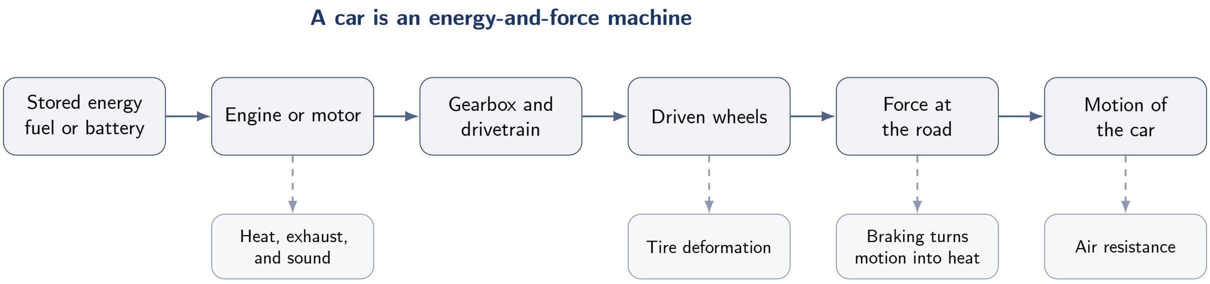
Consider what already happens during a short, unremarkable drive:

1. chemical or electrical energy sits stored on board;
2. an engine or motor converts it into mechanical power;
3. a drivetrain carries torque to the driven wheels;
4. the tires push against the road—and the road pushes back;
5. a large mass accelerates;
6. the air resists, quietly at first, then with authority;
7. the tires deform and dissipate energy as they roll;
8. steering inputs bend the trajectory into corners;
9. springs and dampers absorb the road's imperfections;
10. brakes turn hard-won kinetic energy back into heat.

Every chapter of this book picks one thread of that tapestry and follows it until a familiar automotive phenomenon becomes physically obvious. The promise is this:

> *By the end of this book, horsepower figures, braking distances, gear ratios, drag coefficients, tire grip, downforce, regenerative braking, and suspension damping will no longer be isolated automotive terms. They will be pieces of one coherent physical picture.*

The map below is the whole book on one page: a car is an energy-and-force machine, and every chapter studies one part of the flow—the main chain from stored energy to motion, or one of the many side exits where energy leaves as heat, sound, deformed rubber, or displaced air.



**How to Read This Book**

Read it cover to cover as a guided tour, or open it at *Horsepower*, *Braking*, *Aerodynamics*, or *Suspension* and enjoy that chapter on its own. Figures lead and formulas follow: every important relationship is shown before it is written, and equations appear only when they compress an idea you already understand. Colored boxes carry the recurring devices—*Garage Physics* (a quick calculation with plausible numbers), *What You Feel* (physics as sensation), *Speed Changes Everything* (the nonlinear surprises), *Myth vs. Physics* (one popular oversimplification corrected), *Track-Side Note*, *Try It Mentally*, and *One Equation Worth Remembering*.

## The Reference Fleet

A few generic archetypes appear throughout the book whenever a comparison helps. Their numbers are deliberately round and *illustrative*—they describe no specific production vehicle:

**Car A — lightweight sports car.** About 1,200 kg and 150 kW (200 hp); rear-wheel drive, small frontal area.

**Car B — performance sedan.** About 1,800 kg and 330 kW (450 hp); all-wheel drive.

**Car C — performance EV.** About 2,200 kg and 450 kW (600 hp); strong wheel torque at low speed, regenerative braking.

Whether the energy arrives from fuel or a battery—internal-combustion engine (ICE), electric vehicle (EV), or hybrid—the physics is the same physics. That is rather the point.

## Who This Book Is For

This book is written for car enthusiasts with no formal physics background; for drivers who love performance cars, sports cars, EVs, or motorsport and want to know *why* things work; and for technically curious readers who suspect that a car might be a better physics teacher than a block sliding down an inclined plane. It assumes only basic arithmetic, comfort with percentages, very elementary algebra, and a willingness to look at a simple equation when the equation genuinely clarifies something. It does not assume calculus. Readers with an engineering background, and students looking for an intuitive companion to introductory mechanics, are equally welcome.

## Style and Approach

Three habits govern every chapter. *Cars first, physics second*: each chapter opens with a question a driver might actually ask, never with a law. *Intuition before formula*: the idea is explained in words and pictures before it is compressed into symbols. *Light-hearted but correct*: the tone is relaxed, the physics is not. Where a simple model is only a first approximation—and tire friction is the prime example—the book says so. The technically inclined reader will find the full mathematical development of everything used here in the companion volume *Newtonian Physics — A Self-Contained Introduction with Mathematical Foundations*; this book reuses that physics but speaks the language of cars. When a popular belief collides with the facts, we side with the facts—cheerfully, and without pedantry.

# Notation and Conventions

The formal base of this book is the International System of Units (SI): metres, seconds, kilograms, newtons, joules, and watts. But this is a car book, so every quantity that matters is routinely translated into the units drivers actually use: kilometres per hour, kilowatts, horsepower, newton-metres, and kilowatt-hours. The conversions below are used constantly; Appendix B collects them with more detail.

**Speed: km/h and m/s**

Physics works in metres per second; speedometers work in kilometres per hour. The bridge is the exact rule

$$\mathrm{km/h} \div 3.6 = \mathrm{m/s} \qquad \text{and} \qquad \mathrm{m/s} \times 3.6 = \mathrm{km/h}.$$

Three anchors cover most of the interesting range: $100 \approx 27.8$, $200 \approx 55.6$, and $300 \approx 83.3\,\mathrm{m/s}$.

**Power, Energy, and Torque**

- Power: $1\,\mathrm{kW} = 1{,}000\,\mathrm{W}$; $1\,\mathrm{hp} \approx 0.746\,\mathrm{kW}$ (mechanical horsepower); the metric $1\,\mathrm{PS} \approx 0.735\,\mathrm{kW}$ is close but not identical—this book uses kW with hp in parentheses.
- Energy: the joule (J), with $1\,\mathrm{kWh} = 3.6\,\mathrm{MJ}$ as a practical unit for batteries.
- Torque: newton-metres (Nm); rotational speed in revolutions per minute (rpm), converted via $\omega = 2\pi\,\mathrm{rpm}/60$ when radians per second are needed.
- Acceleration: metres per second squared, often compared with $1\,g \approx 9.81\,\mathrm{m/s^2}$.

**Symbols at a Glance**

The recurring cast, in order of appearance: $t$ time; $x$ position; $v$ velocity; $a$ acceleration; $m$ mass; $F$ force; $p$ momentum; $K$ kinetic energy; $P$ power; $\tau$ torque; $\omega$ angular speed; $N$ normal force; $\mu$ friction coefficient; $r$ radius or tire radius; $h$ height (e.g., of the center of mass); $L$ wheelbase; $\rho$ air density; $C_D$ drag coefficient; $A$ frontal area; $C_{rr}$ rolling-resistance coefficient; $k$ spring stiffness; $I$ moment of inertia; $U$ potential energy. Scalars are italic; the rare vector appears in bold, e.g. $\boldsymbol{v}$.

**The Reference Fleet**

Where a comparison helps, the book uses three generic archetypes introduced in the preface: Car A (lightweight sports car, $\sim$ 1,200 kg, $\sim$ 150 kW), Car B (performance sedan, $\sim$ 1,800 kg, $\sim$ 330 kW), and Car C (performance EV, $\sim$ 2,200 kg, $\sim$ 450 kW). All numbers are illustrative, rounded, and belong to no specific production vehicle.

# Acknowledgments

With gratitude, I acknowledge the artificial intelligence research community for advancing the modern generation of AI systems. Their work has made projects like this book both feasible and joyful. It is a privilege to witness—and to contribute during—this period of rapid progress.

I am not an automotive engineer by formal training, but I have been fascinated by cars and by physics for as long as I can remember. Modern AI systems let me write—and learn from—books I wish already existed. The style and presentation reflect my preferences and experience: cars first, figures first, clear prose, and just enough formalism to sharpen intuition.

I would be grateful for feedback on any of my AI-powered projects. You can find ways to get in touch at `https://linktr.ee/dyjh`.

**Disclaimer.** This book is intended solely for educational and illustrative purposes. It has not been formally peer-reviewed or vetted as a textbook, and it may contain inaccuracies or omissions. It is shared in the hope that readers may benefit from a different way of presenting these topics to a broader audience, but it should not be regarded as an authoritative reference. Readers are encouraged to cross-check important results and interpretations with standard engineering texts or qualified instructors.

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# Motion: What the Car Is Actually Doing

### Part I Overview

Before anything can be explained, it must be described. Chapter 1 separates the two quantities that everyday language loves to confuse—speed and acceleration—and shows why a calm cruise and a hard launch feel so different. Chapter 2 then asks what actually pushes a car forward and introduces the partnership between force and mass. Chapter 3 gives the fast, heavy car its two calling cards: momentum and kinetic energy, similar-sounding ideas with very different consequences.

# Chapter 1

# Speed Is Not Acceleration

Cruising at 200 km/h on an empty, straight motorway can feel strangely calm. The engine hums, the scenery glides past, the coffee in the cup holder sits undisturbed. Yet a traffic-light launch from 0 to 100 km/h in four seconds—half that speed—presses you into the seat and makes your passenger reach for the grab handle. If speed alone were the drama, the cruise should win easily. It does not. Something else is at work, and that something is the subject of this chapter.

**The Question**

Why can 100 km/h feel completely calm while *going from* 0 *to* 100 km/h can feel dramatic?

**Symbols at a Glance**

$t$ time [s]; $x$ position [m]; $\Delta x$ distance covered [m]; $\Delta t$ time elapsed [s]; $v$ velocity [m/s or km/h]; $a$ acceleration [m/s$^2$]; $g \approx 9.81\,\mathrm{m/s^2}$, the acceleration of gravity, used as a handy measuring stick.

**At a Glance**

Speed tells you how fast you are moving. Acceleration tells you how rapidly your velocity is changing—in magnitude *or* in direction. Your body reports acceleration, never speed. Cruising, launching, braking, and cornering feel different because they are different acceleration stories, not different speed stories.

## 1.1 The Calm of Constant Speed

Picture a long, straight, well-surfaced motorway and a car settled at a steady 200 km/h. The speedometer needle is parked. Apart from wind noise and the distant ticket you are mentally negotiating, nothing dramatic is happening—and physics agrees. The car covers ground at a constant rate, and that rate is all the word *speed* means:

$$v = \frac{\Delta x}{\Delta t},$$

the distance covered divided by the time it took. At 200 km/h the car eats 200 kilometres every hour, or—in the units physics prefers—about 55.6 metres every second.

Why two units for the same idea? Speedometers speak kilometres per hour because drivers think in journeys; physics speaks metres per second because forces, energies, and powers all click together cleanly in the International System of Units (SI). The translation is one exact division, summarized in Figure 1.1: kilometres per hour divided by 3.6 gives metres per second.

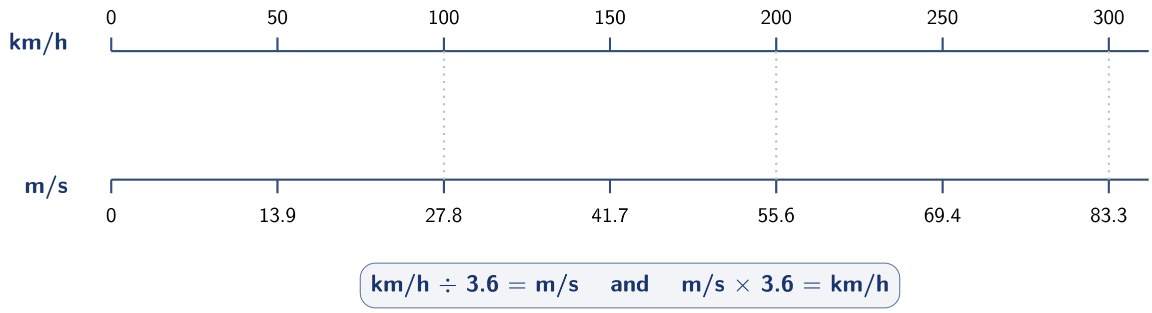



Figure 1.1: The same physical speed on two scales. The conversion rule is exact: $1\,\mathrm{km/h} = 1/3.6\,\mathrm{m/s}$. Three anchors are worth memorizing: $100 \approx 27.8$, $200 \approx 55.6$, and $300 \approx 83.3\,\mathrm{m/s}$.

**Garage Physics**

The three conversions most worth memorizing, because they recur throughout the book:

- $100\,\mathrm{km/h} \approx 27.8\,\mathrm{m/s}$;
- $200\,\mathrm{km/h} \approx 55.6\,\mathrm{m/s}$;
- $300\,\mathrm{km/h} \approx 83.3\,\mathrm{m/s}$.

At $200\,\mathrm{km/h}$ you cover nearly 56 metres per second—more than the length of an Olympic swimming pool, every single second. Yet inside a well-built car you feel almost nothing. Your senses cannot detect constant speed at all; they only register noise, vibration, and the view. A passenger in a whisper-quiet train at $300\,\mathrm{km/h}$ with the curtains drawn would have no idea the train was moving.

So the calm cruise is not an illusion of a soft suspension or good seats. Constant velocity genuinely is a non-event for your body. The interesting question is what happens when velocity *changes*.

## 1.2 Acceleration: The Change You Actually Feel

The light turns green and the driver floors it. Now the speedometer needle sweeps instead of sitting still, and you are pressed firmly into the seat. The quantity that changed the mood is acceleration: the rate at which velocity changes,

$$a = \frac{\Delta v}{\Delta t}.$$

A car that reaches $100\,\mathrm{km/h}$—that is $27.8\,\mathrm{m/s}$—four seconds after launch has accelerated, on average, at

$$a_{\text{avg}} = \frac{27.8\,\mathrm{m/s}}{4\,\mathrm{s}} \approx 6.9\,\mathrm{m/s^2} \approx 0.7\,g.$$

That last comparison is worth pausing on. We measure everyday accelerations against $g$, the acceleration gravity would give you in free fall, because our bodies know $1\,g$ intimately. A brisk family car doing 0–100 km/h in ten seconds averages about $0.28\,g$; a serious sports car launching in four seconds averages $0.7\,g$; the quickest machines on sale exceed $1\,g$ for a moment. The seat pushing your back is the physical signature of this number.

Two subtleties hide inside the phrase "on average." First, 0–100 km/h in four seconds is an *average* acceleration: it compares two velocities and the stopwatch, and ignores everything in between. Second, the *instantaneous* acceleration during a real launch is anything but constant. It peaks early—when the tires, the gearing, and the power delivery are all working at their best—and fades as speed builds. Figure 1.2 shows the shape of a hard launch: the velocity curve rises steeply and then begins to level, while the acceleration curve starts high and decays. The dashed secant in the left panel is the average; the curve itself is the truth.

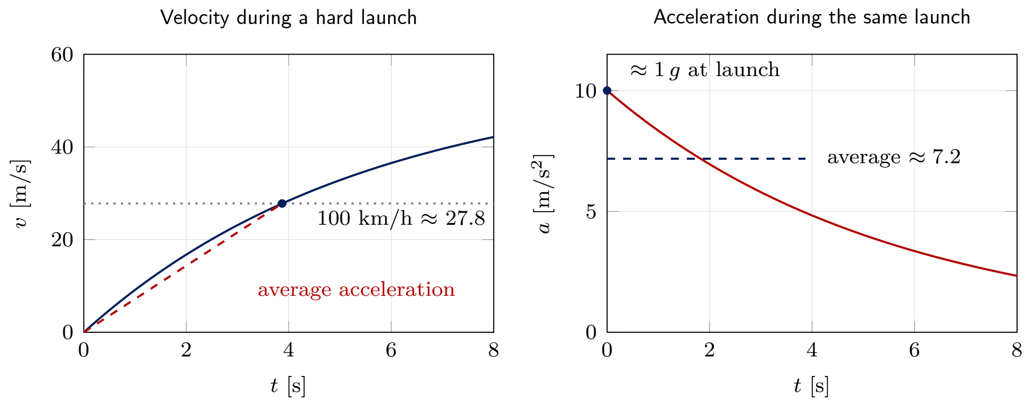



Figure 1.2: A hard launch (illustrative curve). Left: velocity rises quickly at first, then levels off; the dashed secant shows the *average* acceleration over the 0–100 km/h sprint. Right: the instantaneous acceleration is highest at the start and fades as speed builds—one reason why 0–100 km/h times and 100–200 km/h times tell different stories.

**What You Feel**

During a launch it feels as if a mysterious force were pushing you backward into the seat. Nothing of the sort exists. Your body simply tends to keep doing what it was doing—sitting still relative to the road—while the seat, bolted to an accelerating car, pushes *you* forward. The pressure you feel on your back is the seat doing its job: accelerating your body along with the car. Chapter 2 turns this sensation into a law.

**Try It Mentally**

A night train glides along a perfectly straight, perfectly smooth track at a constant 300 km/h. Are you accelerating? And a moment later, when the driver brakes gently from 300 to 280 km/h, are you accelerating then? (Answers: no, and yes—read on if that surprises you.)

## 1.3 Slowing Down and Turning Are Acceleration Too

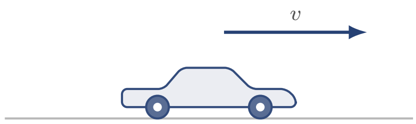
Here is the point where everyday language and physics part company. In the showroom, "acceleration" means speeding up. In physics, acceleration is *any* change of velocity—and velocity has both a magnitude (the speed) and a direction. Three familiar situations therefore all count as acceleration, and Figure 1.3 puts them side by side:

- **Braking.** Velocity shrinks while pointing the same way, so the acceleration vector points *backward*, opposite to the motion. Engineers sometimes say "deceleration"; physicists just say the acceleration is negative. A firm emergency stop runs at roughly 0.8–1.0 $g$—harder than most cars can accelerate.

- **Cornering.** A car sweeping through a bend at a constant 80 km/h has a constant speed but a changing velocity, because the direction keeps rotating. The acceleration points toward the inside of the bend, and Chapter 10 will show that it grows with the *square* of the cornering speed—one of the most consequential squares in this book.

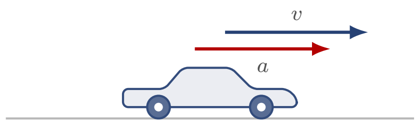
- **Launching.** The intuitive case: speed and acceleration point the same way, and the speedometer climbs.

Only the fourth scene in Figure 1.3—steady speed on a straight road—has no acceleration at all. Note what this means: of cruising, launching, braking, and cornering, the *calm* one is cruising, regardless of whether the cruise happens at 50 or at 250 km/h.



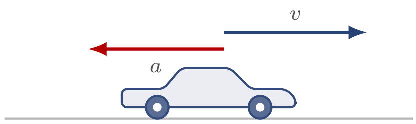

**(a) constant speed, straight road**

velocity constant: $a = 0$



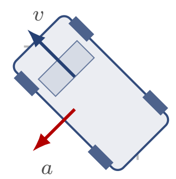

**(b) accelerating hard**

velocity grows: $a$ points forward




**(c) braking hard**

velocity shrinks: $a$ points backward




**(d) constant speed through a bend**

direction changing: $a \neq 0$

Figure 1.3: Four everyday driving scenes. (a) Cruising at constant speed: the velocity $v$ is high, but the acceleration $a$ is zero. (b) Launching: $a$ points forward, in the direction of motion. (c) Braking: $a$ points opposite to the motion. (d) Cornering at constant speed: the direction of $v$ changes, so the car accelerates toward the inside of the bend even though the speedometer needle does not move.

**Myth vs. Physics**

**Myth:** "High speed means high acceleration." **Physics:** A car or train can move very fast with essentially zero acceleration—that is what a steady cruise is. Conversely, a car creeping at walking pace can be accelerating violently: every hard launch begins at $v = 0$. Speed describes where the needle is; acceleration describes what the needle is *doing*. The two are independent, and confusing them is the most common category error in car talk.

## 1.4 What It Means for Cars

Why do manufacturers quote 0–100 km/h times at all? Because a single number—seconds from rest to 100 km/h—is an average-acceleration figure that every driver can picture. It is honest as far as it goes, but it compresses the whole story of Figure 1.2 into one data point. Two cars with identical 0–100 times can deliver them completely differently: one brutal at the start and breathless later, the other building steadily. Later chapters will decode that shape—traction and gearing in Chapters 5 and 7, the fading pull at high speed in Chapter 13, and the reason electric cars feel so violent from rest in Chapter 6.

For now, hold on to the measuring stick: an acceleration of about 7 m/s$^2$ is what "0–100 km/h in about four seconds" means physically, and your body, not your speedometer, is the instrument that notices.

**One Equation Worth Remembering**

$$a = \frac{\Delta v}{\Delta t}$$

Acceleration is how quickly velocity changes. If velocity is not changing—no speeding up, no slowing down, no turning—there is nothing to feel, no matter how fast the trip.

## 1.5 In One Minute

The chapter in five bullets:

- Speed is distance per time, $v = \Delta x/\Delta t$; convert with km/h $\div 3.6 =$ m/s.
- Acceleration is the change of velocity per time, $a = \Delta v/\Delta t$—speeding up, slowing down, *or* turning.
- Constant speed, however high, produces no acceleration and no drama; your body cannot detect it.
- A "0–100 km/h in 4 s" figure is an average acceleration of about $6.9\,\mathrm{m/s^2} \approx 0.7\,g$; real launches start harder and fade.
- Speed tells you how fast you are moving; acceleration tells you how rapidly your velocity is changing.

So acceleration is what you feel. But feeling is not a mechanism: something must physically produce that acceleration, and it is not the engine pushing the car through the air. The next chapter asks what actually pushes a car forward—and the honest answer is hiding where the tires meet the road.

# Chapter 2

# Mass, Force, and the Push in Your Back

Your engine cannot pull on the road. Your tires can. Open the hood and admire the machinery all you like: between that machinery and the asphalt sit four patches of rubber, each about the size of your hand, and everything the car ever does—every launch, every stop, every corner—is negotiated through them. This chapter asks where the force that accelerates a car actually comes from, and why the answer involves the road pushing *you*.

**The Question**

What actually makes a car accelerate?

**Symbols at a Glance**

$m$ mass [kg]; $F$ force [N]; $F_{\text{net}}$ net (total) force [N]; $a$ acceleration [m/s$^2$]; $N$ normal force, the perpendicular push between road and tire [N]; $g \approx 9.81\,\text{m/s}^2$.

**At a Glance**

Acceleration needs a net force, and mass resists acceleration: $F_{\text{net}} = ma$. The forward force does not come from the engine pushing against the air; it enters through the tires, from the road, by Newton's third law.

## 2.1 Inertia: Why Nothing Changes by Itself

Chapter 1 ended with a calm observation: a car cruising at constant velocity has zero acceleration. Newton's first law is the reason such a state is natural rather than miraculous. A body keeps doing what it is doing—standing still, or moving in a straight line at constant speed—unless a *net external force* acts on it. Parked cars do not wander off; cruising cars do not spontaneously speed up or slow down. (A real cruising car *would* slow down, because drag and rolling resistance tug at it; the engine's job at steady speed is merely to cancel those losses. Chapter 17 adds up that bill.)

The property that resists every change of motion is *inertia*, and its quantitative measure is *mass*. A heavier car is harder to start, harder to stop, and harder to turn—not because of some mystical sluggishness, but because its mass is larger. That single fact shapes automotive engineering more than any styling fashion: every kilogram added to a car taxes every launch, every stop, and every corner.

## 2.2 Force and Mass: $F = ma$

Newton's second law compresses the whole story into three symbols:

$$F_{\text{net}} = ma.$$

In words: the acceleration of a car equals the *net* force acting on it divided by its mass. Double the force and you double the acceleration; double the mass and you halve it. Force is measured in newtons (N): one newton is the force needed to accelerate one kilogram at one metre per second squared. A small apple pulled by gravity presses on your hand with about one newton, so 6,000 N is roughly the gravitational pull on six thousand apples—or, less picturesquely, on about 610 kg of adult humanity.

**Garage Physics**

Take a net tractive force of 6,000 N—a plausible figure for a brisk car at low speed—and apply it to two different vehicles, as shown in Figure 2.1:

- **Light sports car,** $m = 1{,}200\,\text{kg}$**:** $a = F/m = 6{,}000/1{,}200 = 5.0\,\text{m/s}^2 \approx 0.51\,g$. If that force could be sustained, 0–100 km/h would take $27.8/5.0 \approx 5.6$ seconds.
- **Heavy SUV,** $m = 2{,}400\,\text{kg}$**:** $a = 6{,}000/2{,}400 = 2.5\,\text{m/s}^2 \approx 0.25\,g$, and 0–100 km/h would take about 11.1 seconds.

Same force, double the mass, exactly half the acceleration. Real cars cannot hold peak force all the way to 100 km/h—gearing, power limits, and drag see to that, as Chapters 5 and 13 will show—but the comparison makes the law tangible.

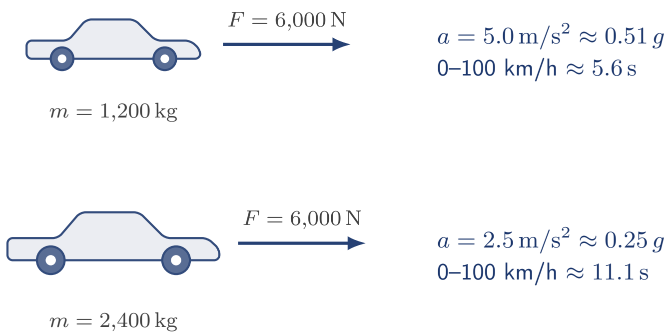



Figure 2.1: The same 6,000 N net force—same arrow length—applied to two different cars. Halving the mass doubles the acceleration: $F = ma$ in its most practical form. (The 0–100 km/h times assume the force could be held constant; Chapters 5 and 13 explain why real drivetrains cannot quite do that.)

**What You Feel**

During a $0.7\,g$ launch, what does the seat actually do to you? It pushes your body forward with $F = ma$. An 80 kg driver at $0.7\,g$ needs about 550 N from the seat—the weight of a full-grown pig, delivered through foam and upholstery. That is the push in your back: not a mystical backward force, but the seat accelerating you along with the car, exactly as Newton's second law demands.

## 2.3 Where the Forward Force Really Comes From

Here is the subtlest point of the chapter, and the most liberating once seen. The engine or motor spins a shaft; the gearbox and differential pass that rotation to the driven wheels; the wheels spin. None of this, by itself, moves the car one millimetre. The car moves because of what happens where tire meets road, illustrated in Figure 2.2: the spinning tire pushes *backward* on the road surface, and—Newton's third law—the road pushes *forward* on the tire with an equal and opposite force. That forward push from the road is the external force in $F_{\text{net}} = ma$.

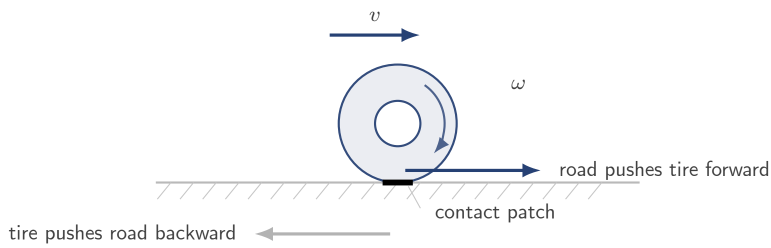



Figure 2.2: Newton's third law at the driven wheel. The spinning tire pushes *backward* on the road; the road pushes *forward* on the tire. That forward push—not the engine—is the external force that accelerates the car, and it enters through a contact patch not much larger than the palm of your hand.

The distinction is not pedantry. On a patch of perfect, frictionless ice, the engine can roar and the wheels can spin furiously—and the car stays put, because the road can no longer push back. No grip, no force, no acceleration. The drivetrain *enables* the push; the road *delivers* it. Chapter 7 is entirely about the limits of that delivery.

**Myth vs. Physics**

**Myth:** "The engine pushes the car forward." **Physics:** The engine pushes only on parts of the car itself—pistons, shafts, gears. Internal pushes cannot accelerate the car any more than pulling on your own bootstraps can lift you off the ground. The external force that accelerates the car comes from the road, acting on the driven tires. The engine's true job is to make the wheels push backward on the road so that the road will push forward on the car.

Figure 2.3 assembles the complete force picture of an accelerating car. Vertically, nothing exciting happens: the road's normal forces at the four wheels add up to the weight $mg$, and the car neither levitates nor sinks. Horizontally, the story of this book begins: when the traction force at the driven wheels exceeds the aerodynamic drag (and the small rolling losses), the net force points forward and the car accelerates. When they balance, the car cruises—fast or slow, the physics of Chapter 1 does not care. When drag exceeds traction, or the brakes bite, the net force points backward and the car slows.

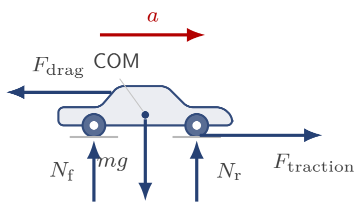



Figure 2.3: The forces on an accelerating car. Vertically, the normal forces at the wheels together balance the weight $mg$. Horizontally, the car accelerates while the traction force at the driven wheels exceeds aerodynamic drag. Note where each force acts: traction enters at road level—a detail that becomes important in Chapter 8.

**Try It Mentally**

Imagine your car on a vast, perfectly frictionless sheet of ice. You press the accelerator fully. What happens? And what does your answer tell you about where the accelerating force comes from? (The wheels spin; the tachometer flies; the speedometer stays at zero. Force needs something to push *against*.)

## 2.4 What It Means for Cars

The law $F = ma$ quietly explains several things every enthusiast already knows. It explains why manufacturers chase low mass so obsessively: every 100 kg removed is a free acceleration upgrade, everywhere, all the time. It explains why a modest-powered but light car—our Car A archetype—can feel livelier than a heavier car with a bigger engine: what reaches your back is force *per kilogram*. And it explains the eternal escalation of power figures: once cars grow heavier, keeping the same acceleration requires proportionally more force, which requires more torque, more power, bigger brakes, and stronger tires—which add mass. The industry's favourite virtuous circle, viewed from the other side, is a spiral.

It also sets up the two questions that organize the rest of Part II. If force is what matters, what does the engine's *torque* figure actually tell you, and what does *power* have to do with it? Those are the next two chapters.

**One Equation Worth Remembering**

$$F_{\text{net}} = ma$$

The acceleration of a car is the net force on it divided by its mass. Everything that makes cars quick—engines, motors, gears, tires, light materials—is ultimately a way to raise the left side or lower the right.

## 2.5 In One Minute

The chapter in five bullets:

- A car keeps its velocity unless a net force acts; mass is the measure of its reluctance to change.
- $F_{\text{net}} = ma$: twice the force, twice the acceleration; twice the mass, half the acceleration.
- The engine cannot push the car through the air; the road pushes the driven tires forward, by Newton's third law.
- No grip, no force: on frictionless ice, full throttle produces noise, not motion.

- The seat pushing your back is $F = ma$ applied to your own body.

Force tells you how acceleration happens in the moment. But a fast, heavy car also *carries* something with it—something that becomes painfully relevant when you need to stop or swerve. The next chapter gives that something its two names: momentum and kinetic energy.

# Chapter 3

# Momentum and Energy: Similar-Sounding, Very Different Ideas

Two identical cars roll toward an obstacle, one at 50 km/h, one at 100 km/h. Ask anyone which impact is worse and they will say the faster car. Ask *how much* worse and most will say: twice. Physics disagrees, and the size of the disagreement—a factor of four—is one of the most consequential numbers in all of driving. To see where it comes from, we need to give a precise meaning to what a moving car "carries." It turns out there are two different answers, and confusing them is the source of endless pub debates.

**The Question**

What does a moving car carry with it—and why does everything get so much worse so quickly as speed rises?

**Symbols at a Glance**

$p$ momentum [kg m/s]; $E_{\text{kin}}$ kinetic energy [J]; $m$ mass [kg]; $v$ speed [m/s]; $F$ force [N]; $\Delta t$ time interval [s]; $d$ distance [m]. One joule (J) is the energy needed to accelerate 1 kg by 1 m/s$^2$ over 1 m; energies of moving cars are conveniently measured in megajoules (MJ).

**At a Glance**

A moving car carries momentum $p = mv$, which grows in proportion to speed and governs *collisions and impulses* (force times time). It also carries kinetic energy $E_{\text{kin}} = \frac{1}{2}mv^2$, which grows with the *square* of speed and governs *braking distances, fuel, and destruction* (force times distance). Double the speed: double the momentum, quadruple the energy.

## 3.1 Two Ways to Measure "Motion"

A heavy truck crawling through a parking lot and a motorcycle flashing past on the motorway are both "moving," but intuitively they carry very different amounts of *oomph*. Physics sharpens this intuition into not one but two quantities, because two different practical questions need answering:

- **"How hard is it to change this motion in a given *time*?"**—the question that matters in collisions, where a force acts for a brief moment.
- **"How much *work* must be done to create or destroy this motion?"**—the question that matters for acceleration runs, braking distances, and fuel tanks.

The first question is answered by *momentum*; the second by *kinetic energy*. Both involve mass and speed, but in different combinations—and that difference, summarized in Figure 3.1, drives everything in this chapter.

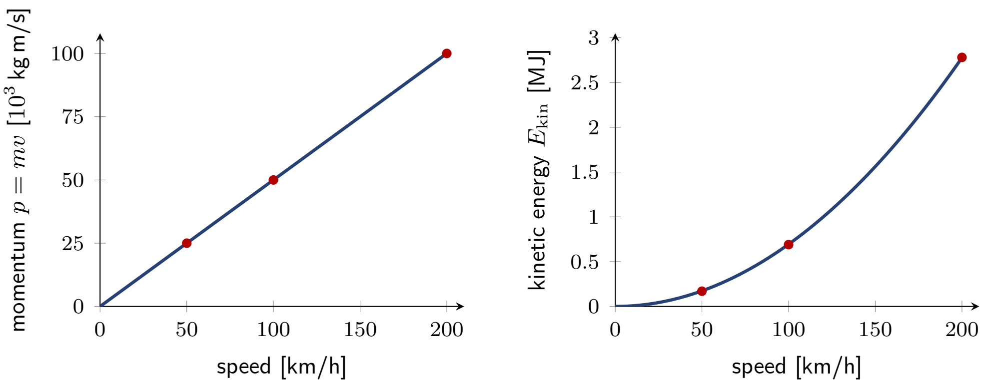



Figure 3.1: Momentum and kinetic energy of an 1,800 kg car (Car B) as functions of speed. Momentum grows in direct proportion to speed; kinetic energy grows with its *square*. Going from 50 to 200 km/h multiplies the momentum by four but the energy by sixteen. The red dots mark 50, 100, and 200 km/h.

## 3.2 Momentum: The Quantity of Motion

Momentum is simply mass times velocity:

$$p = mv.$$

It is a *vector*: it has the direction of the motion, not just a size. Our reference sedan, Car B (1,800 kg), carries

$$p = 1{,}800 \times 13.9 \approx 25{,}000 \text{ kg m/s}$$

at 50 km/h, exactly twice that (50,000) at 100 km/h, and four times that (100,000) at 200 km/h. Momentum grows in lockstep with speed: nothing surprising yet.

Momentum earns its keep through the *impulse* law, which is just Newton's second law reread: to change a car's momentum by $\Delta p$, you need a force acting over time,

$$\Delta p = F\,\Delta t.$$

This is the law of collisions. In any crash, the momentum change is fixed by the speeds involved; the violence of the event depends on how *quickly* that change happens. Stop a car's momentum in 0.1 s (hitting a wall) and the forces are enormous; stretch the same momentum change over 1 s (hitting a crash cushion) and they drop tenfold. Crumple zones, airbags, and deformable barriers are all impulse-management devices: they buy time. We will return to this when discussing what happens when things go wrong; for now, hold on to "momentum equals force times time."

Because momentum is a vector, *turning* also changes it. A car cornering at constant speed keeps its $mv$ but rotates its direction—a momentum change that must be paid for with tire force, continuously. Chapter 10 collects that bill.

## 3.3 Kinetic Energy: The Price Tag of Speed

Kinetic energy is the second measure of motion:

$$E_{\text{kin}} = \tfrac{1}{2}mv^2.$$

No direction here—energy is a plain number—but a decisive new feature: the *square*. Car B at 50 km/h carries about 0.17 MJ; at 100 km/h already 0.69 MJ; at 200 km/h a full 2.78 MJ, as Figure 3.2 shows. Each doubling of speed *quadruples* the energy.

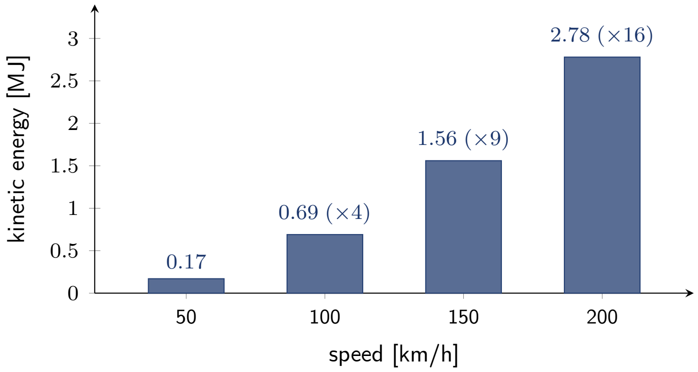



Figure 3.2: Kinetic energy of Car B (1,800 kg) at four speeds, with the multiple relative to 50 km/h in parentheses. Equal steps on the speedometer buy ever-larger steps in energy. This quadratic growth is why high speed is disproportionately expensive to reach, to brake away, and—in a crash—to survive.

Why should you care about the square? Because energy is the currency in which three practical things are paid: accelerating (the engine or battery must supply $E_{\text{kin}}$), braking (the brakes must absorb and dissipate exactly the same amount as heat), and crashing (the structure must absorb it in whatever time and distance the crumple zone offers). Speed is not bought linearly; it is bought quadratically.

### Speed Changes Everything

The square in $E_{\text{kin}} = \frac{1}{2}mv^2$ is the single most important "unfair" rule in car physics. Going from 50 to 100 km/h does not double the energy you must brake away—it quadruples it: 0.17 to 0.69 MJ. Even in the city it bites: 50 km/h versus 30 km/h means $(50/30)^2 \approx 2.8$ times the kinetic energy. "Just 20 km/h more" is, energetically, almost three times the car to get rid of.

### Garage Physics

How big is 0.69 MJ—Car B's kinetic energy at 100 km/h? Two comparisons make it tangible:

- **As height:** the same energy as potential energy $mgh$ would lift the car to $h = E/(mg) = 694{,}000/(1{,}800 \times 9.81) \approx 39\,\text{m}$—the height of a thirteen-story building. Braking from 100 km/h to zero is, energetically, like driving off a thirteen-story roof and landing gently.
- **As electricity:** $0.69\,\text{MJ} \approx 0.19\,\text{kWh}$. An EV like Car C with a 75 kWh battery could, in principle, launch to 100 km/h almost 400 times—which is why a single acceleration run barely dents the range, but also why repeated hard runs heat everything up (Chapter 17).

What You Feel

You cannot feel energy directly, but you can feel its bill. Braking hard from 100 km/h with the same deceleration as from 50 km/h does not take twice as long—it takes twice as long *and* covers four times the distance: roughly 12 m from 50 km/h versus 49 m from 100 km/h at 0.8 $g$ (Chapter 9 does the arithmetic). The pedal does not feel four times as heavy; the stop simply goes on and on. That endless glide is $v^2$, felt through the seat of your pants.

Myth vs. Physics

**Myth:** "Momentum and kinetic energy are two names for the same thing." **Physics:** They measure motion differently and obey different rules. Momentum is a vector and its total is *conserved* in every collision of an isolated system—it can only be passed around, never destroyed. Kinetic energy is a scalar and is *not* conserved in real crashes: it converts into heat, sound, and bent metal. A collision can destroy most of the kinetic energy while conserving every last unit of momentum—which is exactly what crumple zones are for.

Try It Mentally

Two identical cars brake with identical maximum force—one from 50 km/h, one from 100 km/h. The slower car stops in 12 m. Roughly how far does the faster one need? (Removing energy means doing work $F \times d$; the faster car has four times the energy and the same force, so it needs four times the distance: about 48 m.)

## 3.4 What It Means for Cars

The two quantities sort the engineering world into two camps. *Momentum thinking* governs crashes, impacts, and the sideways shove of cornering: anything where force acts over time. *Energy thinking* governs performance and efficiency: acceleration runs, braking distances, brake temperatures, fuel consumption, and range—anything where force acts over distance. Brake engineers live in the energy camp: a braking system is a heat engine in reverse, and its size is dictated by $\frac{1}{2}mv^2$ at top speed, not by anything linear. Regenerative braking in EVs is energy thinking par excellence: instead of converting the kinetic energy into heat, the motor runs backward as a generator and pumps most of it back into the battery (Chapters 9 and 17).

And the quadratic law quietly sets the stakes for everything sporty. The reason a 200 km/h car needs vastly bigger brakes than a 100 km/h car, the reason fuel consumption explodes with speed (Chapter 12), and the reason crash tests at 64 km/h already look so violent—all of it is that little exponent 2.

One Equation Worth Remembering

$$E_{\text{kin}} = \tfrac{1}{2}mv^2$$

The energy a car carries grows with the square of its speed. Doubling speed quadruples what the engine must supply, the brakes must absorb, and the crash structure must survive.

## 3.5 In One Minute

The chapter in five bullets:

- A moving car carries two distinct quantities: momentum $p = mv$ and kinetic energy $E_{\text{kin}} = \frac{1}{2}mv^2$.
- Momentum (force times time) governs collisions; crumple zones and airbags stretch the stopping time to shrink the force.
- Kinetic energy (force times distance) governs braking distances, brake heat, and fuel bills.
- The square is the story: twice the speed means four times the energy; even 30 versus 50 km/h differs by a factor of 2.8.
- Total momentum is conserved for an isolated system during a collision; kinetic energy is not—it becomes heat, noise, and deformation.

We now know what acceleration costs and what a moving car carries. What we have not yet settled is the enthusiast's oldest pub argument: is it *torque* or *power* that makes a car fast? The next chapter ends that argument with physics.

# Part II

# Making the Car Go

### Part II Overview

This part follows the power from the engine or motor to the road. Chapter 4 settles the great pub argument between torque and horsepower. Chapter 5 shows how a gearbox trades rotational speed for wheel force without creating a single extra watt. Chapter 6 steps back and views the internal-combustion engine, the electric motor, and the hybrid as three answers to the same question: how to turn stored energy into force at the road.

# Chapter 4

# Torque, Horsepower, and the Great Pub Argument

It is the oldest argument in the enthusiast world. One side taps the spec sheet: "Horsepower sells cars, but torque wins races." The other side shakes its head: "Torque is meaningless without rpm—only power matters." Both sides quote racing drivers, both sides feel vindicated by their last overtaking maneuver, and both are half right. Physics ends the argument, and the verdict is more interesting than either camp expects.

**The Question**

Torque or power—which one actually makes a car fast?

**Symbols at a Glance**

$\tau$ torque [N m]; $r$ lever arm [m]; $\omega$ angular speed [rad/s]; $n$ rotational speed [rpm]; $P$ power [W, kW]; $F$ force [N]; $v$ speed [m/s]. Conversions: $\omega = 2\pi n/60$; $1\,\text{hp} = 0.746\,\text{kW}$; $1\,\text{PS} = 0.735\,\text{kW}$; $1\,\text{kW} \approx 1.36\,\text{PS}$.

**At a Glance**

Torque is a *twist*: force times lever arm, $\tau = F \cdot r$. Power is the *rate of doing work*: $P = \tau\omega = F \cdot v$. What accelerates a car at any given speed is the force at its driven wheels—and with gears chosen freely, that force is set by engine *power* divided by road speed. Power settles the argument; the torque curve decides how the power feels.

## 4.1 Torque: The Twist

Everyone who has fought a stuck wheel bolt knows torque intuitively. The bolt does not care how hard you push; it cares how hard you push *times how far from the center* you push. That product is torque:

$$\tau = F \cdot r,$$

shown in Figure 4.1. Push with 100 N at the end of a 0.25 m wrench and the bolt feels 25 N m; double the wrench length and the same effort delivers 50 N m. (Wheel bolts, by the way, are typically tightened to about 110 N m—a number your arms already know.)

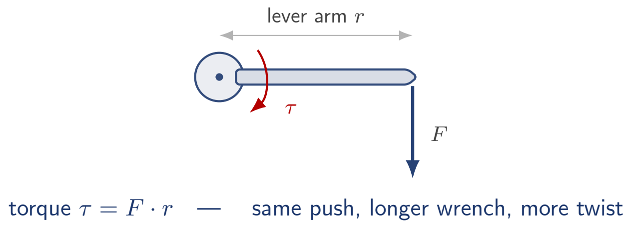



Figure 4.1: Torque is force times lever arm: $\tau = F \cdot r$. The same push produces twice the twist on a wheel bolt when the wrench is twice as long. An engine's torque figure is exactly this: the twist its crankshaft delivers, measured in newton-metres (N m).

An engine's torque figure is precisely this twist, measured at the crankshaft. A modern turbocharged engine might deliver 360 N m: if you bolted a one-metre bar to the crankshaft, it would press on a bathroom scale with the weight of about 37 kg. Torque is what the engine *produces*; what the *wheels* receive depends on the gearbox, which trades rpm for torque at will—that arbitrage is Chapter 5. So torque alone, quoted at the crankshaft, cannot tell you how hard the car will pull. Something is missing, and the missing something is *how fast the twist is spinning.*

## 4.2 Power: The Rate of Doing Work

Chapter 3 established that speed is bought with energy: $E_{\text{kin}} = \frac{1}{2}mv^2$. Power is simply the *rate* at which energy is delivered—energy per second, measured in watts (or kilowatts, or horsepower). Two equivalent formulas matter for cars:

$$P = \tau\,\omega \qquad \text{and} \qquad P = F \cdot v.$$

The first belongs to spinning things (crankshafts, motors): torque times angular speed. The second belongs to moving things (cars): driving force times road speed. They are the same law seen from the two ends of the drivetrain.

Here comes the insight that ends the pub argument. At full throttle, an engine delivers roughly its rated power. The force pushing the car is then

$$F = \frac{P}{v},$$

which means: *at a given road speed, the acceleration a car can muster is set by its power*—not by its torque figure. Torque without rpm is half a product; power is the whole product.

**Garage Physics**

Car B (1,800 kg, 330 kW) at full throttle, and for the moment ignore drag and losses (Chapters 12 and 17 will restore them). At 100 km/h = 27.8 m/s, the available driving force is

$$F = \frac{P}{v} = \frac{330{,}000}{27.8} \approx 11{,}900\,\text{N} \quad \Rightarrow \quad a = \frac{F}{m} \approx 6.6\,\text{m/s}^2 \approx 0.67\,g.$$

The same power at 50 km/h would allow twice the force, 23,800 N—except that the tires cannot transmit it: 1,800 kg on tires with friction coefficient near 1.0 support at most about 17,700 N (Chapter 7). At low speed the *tires* are the bottleneck; at high speed the *power* is. Somewhere in between lies the crossover, and much of performance driving lives around it.

Notice what $F = P/v$ implies for the shape of acceleration: once the car is power-limited—once traction, gearing, and torque ceilings no longer bind—the available force falls off as $1/v$, so acceleration fades as speed rises, before drag even enters the picture. (At very low speed the formula would promise infinite force; reality's limits, tires first among them, intervene.) The kick in your back is strongest at the start of the on-ramp and softest at its end, and now you know why.

**What You Feel**

The "shove" you feel in a given gear follows the engine's torque curve: it swells toward the torque peak, then fades toward redline. But the shove available *across* gears at a given road speed follows power: at 100 km/h it matters little which gear you are in, as long as the engine spins where its power peaks. That is why a downshift before overtaking works: the gearbox spins the engine faster, into a region where more *power* is available—the engine's torque usually changes with rpm too, but it is the new torque-times-rpm product, multiplied afresh by the shorter gear, that delivers the extra wheel force.

## 4.3 The Curves

Real engines do not deliver constant torque or constant power; they deliver *curves*, as Figure 4.2 shows for a typical modern turbocharged unit in Car A's output class. Torque climbs early, plateaus through the midrange (360 N m at 3,800 rpm here), and sags toward redline as the engine struggles to breathe. Power, being torque times rpm, keeps rising past the torque peak and tops out later—about 159 kW near 4,500 rpm in this example—before falling off as the torque sag wins over the rpm gain.

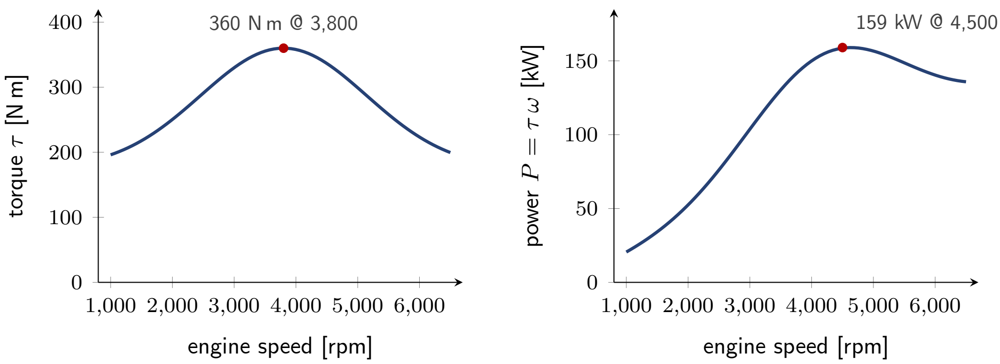



Figure 4.2: Torque and power of a typical modern turbocharged engine, in the output class of Car A's 150 kW unit. Torque peaks early—here 360 N m at 3,800 rpm. Power, being torque times rotational speed, peaks later: about 159 kW near 4,500 rpm. Both fall toward the redline—one reason upshifting before redline is often fastest (Chapter 5).

Engine characters live in these curves. A naturally aspirated sports engine holds its torque high and breathes best near redline: peaky, thrilling, demanding to drive fast. A turbo engine flattens its torque early: effortless, muscular, relaxed. An electric motor rewrites the shape entirely—full torque from zero rpm, no gears needed (Chapter 6). Same physics, different personalities.

**Track-Side Note**

Where is the right moment to upshift? The physics gives a precise rule: for maximum acceleration, stay in the current gear until the wheel force available *after* the shift—at the lower rpm the next gear drops to—would exceed the wheel force available *before* it. Because the next gear multiplies torque by a smaller ratio, that crossing usually happens somewhere past the power peak, but gear spacing and the shape of the power curve decide case by case: peak power is an important reference point, not a universal shift point. The redline, meanwhile, is simply where the engineers stopped trusting the hardware.

**Myth vs. Physics**

**Myth:** "Horsepower sells cars, torque wins races." **Physics:** Take two engines. Engine one: 350 N m at 3,800 rpm, hence $350 \times 3{,}800 \times 2\pi/60 \approx 139$ kW. Engine two: only 250 N m, but at 7,000 rpm, hence $\approx 183$ kW. Bolted to the right gears, the "low-torque" engine out-accelerates the "high-torque" one at every road speed, because its torque arrives with 84% more rpm attached. Torque tells you the size of each shove; power—torque times how often the shoves come—tells you how fast the car goes. Races are won by power, delivered well.

**Try It Mentally**

Two cars have identical peak power, but one engine makes twice the torque at half the rpm. Which car is quicker? (Neither, given appropriate gearing: the gearbox converts low-rpm-plus-big-torque into high-rpm-plus-smaller-torque at the wheels, and $P = \tau\omega$ is the same on both sides. What differs is feel, gearing, and where in the rev range the shove lives.)

## 4.4 What It Means for Cars

You can now read a spec sheet like an engineer. *Peak power* sets the ceiling on acceleration at speed and, together with drag, the top speed (Chapter 13). *The rpm of the power peak* tells you the engine's character and how hard you must rev it. *The torque plateau* tells you how elastic the car feels in daily driving—how rarely you need a downshift. And the quickest single-number proxy for pace is *power-to-weight*: Car A's 150 kW moving 1,200 kg is 125 kW per tonne; Car B's 330 kW per 1,800 kg is 183 kW/t; Car C's 450 kW per 2,200 kg is 205 kW/t. One glance, one division, and the hierarchy of our little fleet is obvious.

**One Equation Worth Remembering**

$$P = \tau\,\omega = F \cdot v$$

Power is torque times revs at the engine, and force times speed at the wheels. Once traction and gearing no longer bind, acceleration at a given road speed is limited by available power—so power, not torque, is the number that wins the argument.

## 4.5 In One Minute

The chapter in five bullets:

- Torque is a twist: $\tau = F \cdot r$, measured in newton-metres—your arms know it from wheel bolts.

- Power is the rate of doing work: $P = \tau\,\omega$ at the crankshaft, $P = F \cdot v$ at the wheels.
- Once power-limited, the ideal acceleration ceiling is $a = P/(mv)$; drag reduces the actual acceleration further. The torque curve shapes the feel.
- Upshift when the next gear offers more wheel force after the rpm drop—near the power peak, but the curves and gear spacing decide.
- Power-to-weight (kW per tonne) is the fastest honest proxy for a car's pace.

One hero of this chapter has so far worked silently in the background: the gearbox, which converts crankshaft torque-and-rpm into wheel torque-and-rpm as needed. It deserves its own chapter—and it explains why first gear pins you to the seat while fifth never will.

# Chapter 5

# Gears: Trading Force for Speed

First gear pins you to the seat. Fifth gear, at the same throttle, barely nudges you. Same engine, same car, same right foot—wildly different shove. The device responsible does no work of its own and adds no energy; it merely *trades*. The gearbox is the great currency exchange of the drivetrain, and its exchange rate is the subject of this chapter.

**The Question**

How does a gearbox turn one engine into a hard shove at low speed and effortless speed at low force—and why does a car need several gears at all?

**Symbols at a Glance**

$i$ gear ratio (dimensionless); $\tau_{\text{eng}}$, $\tau_{\text{wheel}}$ torque at crankshaft and wheels [N m]; $n$ rotational speed [rpm]; $r_{\text{wheel}}$ wheel radius [m]; $F_{\text{wheel}}$ driving force at the contact patches [N].

**At a Glance**

A gear pair multiplies torque and divides rotational speed by the same factor, keeping power essentially unchanged. Wheel force equals engine torque times the *total* ratio (gearbox times final drive), divided by the wheel radius. Low gears are long levers: huge force, modest speed. High gears are short levers: modest force, high speed.

## 5.1 The Gearbox as a Lever for Rotation

Chapter 4 opened with a wrench: a longer lever turns the same push into more twist. A gear pair does exactly this for continuous rotation, as Figure 5.1 shows. A small gear driving a gear twice its size halves the rotational speed and doubles the torque—the teeth are just a lever arm that never runs out. Power is conserved in the bargain:

$$\tau_{\text{in}}\,\omega_{\text{in}} = \tau_{\text{out}}\,\omega_{\text{out}} \qquad \text{(minus a few per cent of friction losses).}$$

The *gear ratio* $i$ states the trade: $i = 3.6$ means the input spins 3.6 times for each output turn, and the output torque is 3.6 times the input torque.

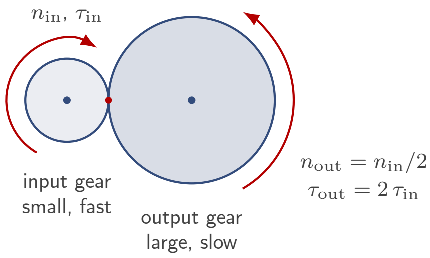



Figure 5.1: A gear pair is a lever for rotation. The small input gear turns twice while the large output gear turns once; the output twist is doubled (minus small losses). Power—torque times rotational speed—stays the same on both sides. A gearbox chains such pairs; the final drive adds one more fixed reduction.

A complete drivetrain chains two such reductions: the selectable one in the gearbox (first through sixth, say) and a fixed one at the driven axle, the *final drive*. The total ratio is their product—and that product is what your back feels.

## 5.2 From Crankshaft to Contact Patch

The force that actually accelerates the car falls out of a short chain of multiplications:

$$F_{\text{wheel}} = \frac{\tau_{\text{eng}} \times i_{\text{gear}} \times i_{\text{final}}}{r_{\text{wheel}}}.$$

**Garage Physics**

Take the engine of Figure 4.2 (360 N m at its peak) in a car like Car A, with first gear 3.6:1, final drive 3.4:1, and wheels of radius 0.32 m:

$$F_{\text{wheel}} = \frac{360 \times 3.6 \times 3.4}{0.32} \approx 13{,}800\,\text{N}$$

—more than the car's entire weight of $1{,}200 \times 9.81 \approx 11{,}800\,\text{N}$! The rear tires of a rear-wheel-drive car cannot transmit that: carrying roughly 60% of the weight at launch (Chapter 8 explains the shift), they support at most $0.6 \times 11{,}800 \times 1.0 \approx 7{,}000\,\text{N}$ before spinning. First gear is therefore *grip-limited*, not engine-limited. Now third gear, 1.55:1: the wheel force becomes $360 \times 1.55 \times 3.4/0.32 \approx 5{,}900\,\text{N}$, an honest $a \approx 5{,}900/1{,}200 \approx 4.9\,\text{m/s}^2 \approx 0.5\,g$. Same engine, same torque—a third of the shove. That is the gearbox, trading.

**What You Feel**

This is why the launch feels violent and the mid-race upshift feels gentle. In first gear the engine's torque arrives at the wheels multiplied more than twelvefold; by fifth gear the multiplier is barely three. The seat only reports $F = ma$, and $F$ is set by the lever length you have selected with the gear lever. Choosing a lower gear *is* choosing a longer wrench.

## 5.3 The Staircase

Why not one gear, or two? Because an engine delivers its best power in a narrow band of rpm (Figure 4.2), while the car must pull from walking pace to top speed—a factor of thirty or more.

The solution is a staircase of ratios, and Figure 5.2 draws it: for each gear, the wheel force available at every road speed, traced from the engine's own torque curve.

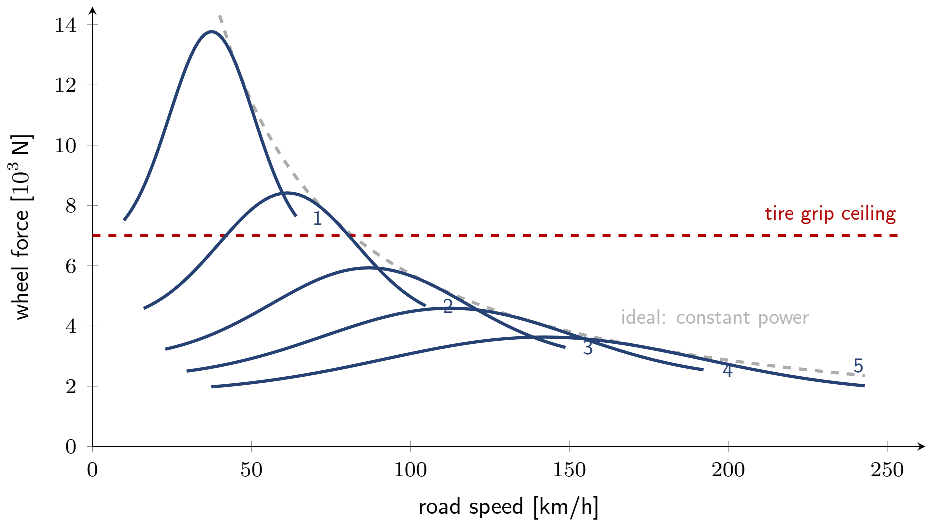



Figure 5.2: The tractive-effort staircase: wheel force versus road speed for the engine of Figure 4.2 in gears 1–5 (with a 3.4:1 final drive and 0.32 m wheels). Each gear lifts the engine's torque curve to a different height and stretches it over a different speed range. The dashed gray hyperbola is the constant-power ideal $F = P/v$ that a perfect stepless transmission would follow; the dashed red line is the tire grip ceiling, which makes the tallest part of first gear unusable on dry asphalt—and much more on a wet one.

Read the figure slowly; it repays attention. Each curve is the same engine seen through a different lever. First gear towers over the others but ends at 64 km/h; fifth reaches 243 km/h but offers a gentle nudge. The peaks of the curves just touch the dashed gray hyperbola $F = P/v$—the signature of constant power from Chapter 4. A hypothetical ideal transmission (a CVT driven perfectly) would hold the engine at its power peak continuously and trace that hyperbola exactly. Real gearboxes approximate it in steps, which is why more, closer ratios keep the engine nearer its best more of the time.

The dashed red line is the chapter's quiet hero: the *tire grip ceiling* from our garage calculation. Everything above it is fantasy—the tires spin before the force arrives. First gear's tall left flank is usable only in part, which is why launching a powerful car is an exercise in restraint, and why rear-wheel-drive sports cars spin their wheels rather than posting the acceleration their engines could theoretically deliver.

**Track-Side Note**

On a wet track, grip halves, and the ceiling in Figure 5.2 drops to half its height. Experienced drivers respond by *short-shifting*—upshifting early into a taller gear. Taller gear, shorter lever, less wheel torque: the curve slides under the lowered ceiling. The same physics, run in reverse, is why a gentle right foot in first gear on snow beats a brave one.

**Myth vs. Physics**

**Myth:** "More gears make a car faster." **Physics:** More ratios let the engine *stay* near its power peak more of the time, which helps—but each upshift costs a fraction of a second of interrupted drive, and beyond seven or eight well-chosen ratios the gains shrink toward the CVT ideal they approximate. An eight-speed is not automatically quicker than a good six-speed; and a single-speed EV, whose motor makes its torque everywhere, needs no staircase at all (Chapter 6).

**Try It Mentally**

Why can't you pull away from a standstill in fifth gear? (Fifth multiplies engine torque only by about 3.2 overall—roughly a quarter of first gear's leverage. The wheel force would be a few hundred newtons at clutch-engagement rpm, and the engine, dragged below its idle speed, stalls. First gear exists because engines cannot breathe at near-zero rpm; electric motors can, which is why EVs skip the question.)

## 5.4 What It Means for Cars

You can now decode a spec sheet's ratio table: widely spaced ratios mean relaxed cruising but larger drops in wheel force between gears; close ratios keep the shove coming at the cost of more shifting. You also know why top speed is sometimes reached in fourth rather than fifth: if fifth is geared so long that the engine cannot reach its power peak against drag, the shorter gear wins (Chapter 13 settles top speed properly). And you have the conceptual tool for the next chapter's question: ICE, EV, or hybrid—where does the torque actually come from, and why do their drivetrains look so different?

**One Equation Worth Remembering**

$$F_{\text{wheel}} = \frac{\tau_{\text{eng}} \times i_{\text{gear}} \times i_{\text{final}}}{r_{\text{wheel}}}$$

Wheel force is engine torque multiplied by every ratio along the way and divided by the wheel radius. Gears trade rpm for torque; power is the currency that passes through unchanged.

## 5.5 In One Minute

The chapter in five bullets:

- A gear pair is a rotating lever: torque up, rpm down, power conserved.
- Wheel force = engine torque × total ratio ÷ wheel radius; first gear multiplies by 12 or more, top gear by about 3.
- The tractive-effort staircase shows each gear's force over its speed range; peaks touch the constant-power hyperbola $F = P/v$.
- The tire grip ceiling caps usable force: powerful cars are grip-limited in first gear and short-shifted in the wet.
- More gears approximate the ideal better, but with diminishing returns; EVs sidestep the staircase entirely.

So far the engine has been a black box that emits torque curves. Time to open it: combustion, electricity, and the hybrid marriage—and why each produces its characteristic shape of shove.

# Chapter 6

# Where the Power Comes From: ICE, EV, and Hybrid

Every force figure in the previous chapters had to be produced somewhere. The "somewhere" differs profoundly between a combustion engine, an electric motor, and the arranged marriage of the two—yet all three feed the same physics downstream: torque at wheels, force at contact patches, acceleration of mass. This chapter opens the black box, comparing how each powertrain stores energy, converts it, and delivers its characteristic shape of shove.

**The Question**

ICE, EV, or hybrid: where does the power actually come from, and why do the drivetrains feel so different?

**Symbols at a Glance**

$E$ stored energy [MJ or kWh; 1 kWh = 3.6 MJ]; $\eta$ (eta) efficiency, the fraction of input energy that arrives at the wheels; $P$ power [kW]; $\tau$ torque [N m].

**At a Glance**

Fuel is an astoundingly dense energy carrier and batteries are not—but the combustion engine wastes most of its advantage as heat, while the electric drivetrain delivers nearly everything it stores. And their torque personalities differ fundamentally: the engine needs revs and gears; the motor delivers maximum twist from the first revolution.

## 6.1 Two Ways to Carry Energy

A litre of gasoline stores about 34 MJ—roughly 9.4 kWh. Per kilogram, fuel carries some 12 kWh/kg; a modern battery pack manages perhaps 0.15–0.20 kWh/kg. That is a factor of about sixty against the battery, and it is why range anxiety is an EV topic while a 50-litre tank quietly holds 470 kWh of chemistry.

Garage Physics

Energy on board, and energy that matters. A 50 l tank: $50 \times 9.4 \approx 470$ kWh of chemical energy. Car C's battery: 75 kWh—six times less. But apply the efficiency chains of Figure 6.2: the tank delivers $470 \times 0.28 \approx 132$ kWh to the wheels, the battery $75 \times 0.88 \approx 66$ kWh. At the wheels, where physics keeps its accounts, the ratio is only two to one. Refueling speed, though, remains chemistry's trump card: 40 litres in about a minute is an energy transfer above 20 MW—no charger comes close (a fast one manages 0.25–0.35 MW).

## 6.2 The Combustion Engine: A Heater with Ambitions

A gasoline engine is a rapid sequence of controlled combustion events, each releasing hot, expanding gases that push on a piston; each piston's shove reaches the crankshaft through a connecting rod, and the sum of the shoves is the torque curve of Figure 4.2. Two consequences shape every ICE car. First, the engine only works in a narrow rpm band—it cannot operate usefully down to zero rpm, and its safe upper speed is limited—hence clutch and gearbox (Chapter 5). Second, most of the fuel's energy never becomes motion: it leaves as hot exhaust and radiator heat. Peak thermal efficiency of a good modern engine approaches 40% at its sweet spot; averaged over real driving, tank-to-wheel lands near 25–30%—a representative order of magnitude for the comparison, as Figure 6.2 shows; the exact figure moves with operating point, drive cycle, temperature, and accessory load.

## 6.3 The Electric Motor: Torque from Revolution Zero

An electric motor's torque is born from magnetic fields pulling on the rotor—fields that work perfectly well at a standstill. The result is the torque shape of Figure 6.1: full torque from zero rpm, a flat plateau until the battery voltage runs out of headroom, then a gentle constant-power decline—all the way to 15,000 rpm or beyond. No idle, no clutch, usually a single fixed gear (Chapter 5 explained why the staircase becomes unnecessary). And the drivetrain is a miser: battery-to-wheel efficiency around 85–90% in representative conditions—the same order-of-magnitude caveat applies—with the motor doubling as a generator on the way back down: regenerative braking (Chapter 9).

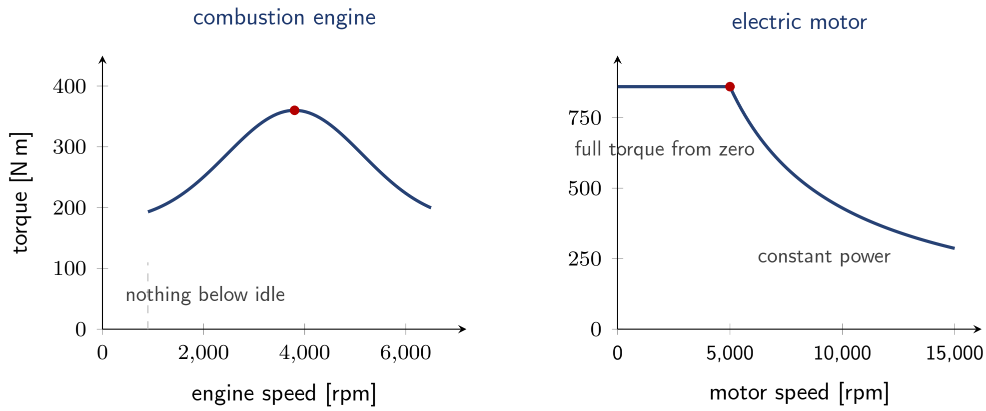



Figure 6.1: Two torque personalities, drawn to the same idea but different scales. Left: the combustion engine of Figure 4.2—silent below idle, peaky, finished by 6,500 rpm. Right: a performance EV motor (Car C's class)—maximum torque from the very first revolution, then a constant-power decline, still pulling at 15,000 rpm. The right-hand shape is why an EV needs no clutch and, usually, no gearbox.

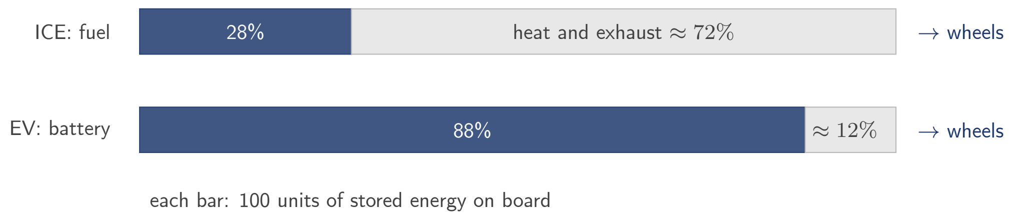



Figure 6.2: Of every 100 units of stored energy, a combustion drivetrain delivers roughly 25–30 to the wheels; an electric drivetrain roughly 85–90. The combustion engine is, first of all, a heater with a side business in propulsion—Chapter 17 follows the heat. (Indicative modern fleet values; individual cars vary.)

**What You Feel**

This is the physical root of the "EV shove" that surprises first-time drivers. An ICE car at 30 km/h in a high gear is waiting for revs; the EV is already at its maximum torque. The response gap you feel between pressing the pedal in a combustion car—downshift, revs build, torque swells—collapses in an EV to the speed of an inverter switching current. Instant torque is not a tuning trick; it is the shape of the curve.

**Myth vs. Physics**

**Myth:** "Electric cars are only quick in the city; real speed needs an engine." **Physics:** Acceleration at any speed is $P/(mv)$ (Chapter 4), and Car C carries 450 kW—the electric shove does not fade early. What *is* true: with a single fixed gear, the motor's rpm eventually caps the top speed, and aerodynamic drag (Chapter 12) taxes range brutally at high speed. EVs trade some top-end for instant response everywhere else; that is a design choice, not a physics limit.

## 6.4 The Hybrid: An Arranged Marriage That Works

A hybrid bolts both machines together and lets a computer arbitrate. The combustion engine is kept near its efficient sweet spot while the motor fills its torque gaps, launches the car, recovers braking energy, and smooths the shifts. The physics win is real: the engine stops idling at lights (zero rpm is fine for a motor), stops lugging inefficiently in traffic, and stops wasting its output as brake heat. In city driving—the ICE's worst habitat and the motor's best—a hybrid's advantage is largest, which is why the technology conquered taxis before sports cars. Performance hybrids add another twist: the motor's instant torque covers the turbo's lag, so the combustion engine can be tuned for peak power while the drivetrain still feels immediate.

**Try It Mentally**

Why doesn't an EV stall at a traffic light, and why would an ICE car? (Stalling is torque demand exceeding what the engine can produce at near-zero rpm. The motor's torque at zero rpm is at its *maximum*, so there is nothing to stall; the combustion engine below idle produces nothing at all.)

## 6.5 What It Means for Cars

Reading a modern spec sheet now takes seconds. ICE: look for the torque plateau and the power peak—they describe character and pace. EV: peak power, and whether it is sustainable (many EVs quote a short-burst figure); torque is almost always "enough, from zero." Hybrid: system power is rarely the sum of both machines, because their peaks arrive under different conditions—now you know why. And whichever powertrain you prefer, Part II's conclusion stands: stored energy becomes wheel force, wheel force becomes acceleration, and everything—every last newton—must pass through four palm-sized patches of rubber. That is where Part III goes next.

**One Equation Worth Remembering**

$$E_{\text{wheels}} = \eta \times E_{\text{stored}}$$

Efficiency is the fraction of stored energy that reaches the wheels: $\eta \approx 0.25$–$0.30$ for combustion, $\approx 0.85$–$0.90$ for electric. It converts the battery's sixty-fold energy-density deficit into a practical two-fold one.

## 6.6 In One Minute

The chapter in five bullets:

- Fuel stores ~12 kWh/kg; batteries ~0.2 kWh/kg—but efficiency reclaims most of the gap: 2×, not 60×, at the wheels.
- The combustion engine wastes 70%+ of its energy as heat and only works in a narrow rpm band: hence clutch and gearbox.
- The electric motor delivers maximum torque from zero rpm to a wide band: no stall, no clutch, usually one gear.
- Hybrids win by letting each machine avoid its worst operating region.
- Refueling at 20 MW-equivalent remains chemistry's unbeatable trick.

# Part III

# The Four Small Patches That Run the Show

### Part III Overview

Everything a car does—accelerate, brake, corner—is negotiated through four contact patches not much larger than your hands. Chapter 7 introduces friction and the traction limit that no horsepower figure can overrule. Chapter 8 explains why hard acceleration loads the rear tires and braking loads the front ones, even though the car's weight has not changed. Chapter 9 follows the kinetic energy into the brake discs and asks where all that speed actually goes.

# Chapter 7

# Tires, Grip, and Friction

Everything this book has discussed—engine power, gearing, momentum, energy—must pass through one final gate before it becomes motion: four patches of rubber, each about the size of your palm, carrying the entire negotiation between car and road. Engines are powerful and brakes are strong; tires decide how much of either you may use. This chapter is about the rules of that negotiation.

**The Question**

Why can a car accelerate, brake, or corner only so hard—and what sets the limit?

**Symbols at a Glance**

$N$ normal force pressing tire and road together [N]; $\mu$ (mu) friction coefficient, dimensionless; $F_x$, $F_y$ longitudinal and lateral tire forces [N]; slip: the small speed difference between tire surface and road, in %.

**At a Glance**

The contact patch can deliver at most $F_{\max} = \mu N$ of force, in any direction—acceleration, braking, cornering, or any combination, shared according to the friction circle. Maximum grip needs a few per cent of slip; beyond the peak, the tire slides and grip falls. On dry asphalt $\mu \approx 0.9$; on ice $\approx 0.15$.

## 7.1 The Patch

Lift any corner of a car and look at the tire: only a hand-sized area actually touches the road, deformed flat against the asphalt by the car's weight. Four such patches—call it an A4 sheet of paper in total—transmit every force the car will ever use. The engine's 450 kW, the brakes' megajoules per second, the cornering shove of Chapter 10: all of it flows through those four patches. It is no exaggeration to call tires the most important performance component on the car.

## 7.2 Friction's Simple Law

The classic model of friction is beautifully simple. The maximum force a contact can transmit before sliding is proportional to how hard the two surfaces are pressed together:

$$F_{\max} = \mu N,$$

where $N$ is the normal force—for a car on level ground, its weight $mg$—and $\mu$ is the friction coefficient, a property of the two surfaces meeting. Figure 7.1 gives the numbers that govern a driver's life.

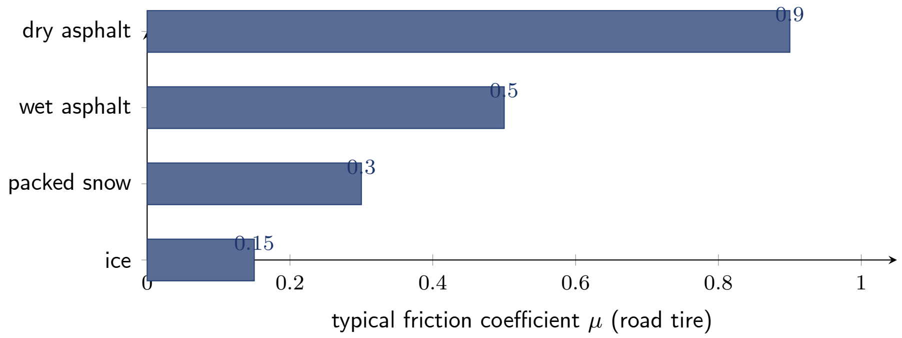



Figure 7.1: Typical peak friction coefficients between a road tire and four surfaces. The rule $F_{\max} = \mu N$ turns each bar directly into a performance limit: on dry asphalt a car can accelerate, brake, or corner at about $0.9\,g$; on ice, barely $0.15\,g$. Racing slicks on dry asphalt exceed $\mu \approx 1.2$–1.5, because soft compounds do more than Coulomb friction—they interlock and adhere.

A stunningly useful identity follows. Maximum acceleration of any kind is $a_{\max} = F_{\max}/m = \mu mg/m = \mu g$: *a car's performance ceiling in g's is just the friction coefficient.* Dry asphalt, $\mu \approx 0.9$: up to $0.9\,g$ of anything. Ice, $\mu \approx 0.15$: $0.15\,g$, which is why everything on ice happens in slow motion.

**Garage Physics**

How fast can physics possibly launch a car to 100 km/h? Car B (1,800 kg, all-wheel drive, dry asphalt, $\mu = 0.9$) can use its whole weight for traction: $F_{\max} = 0.9 \times 1{,}800 \times 9.81 \approx 15{,}900\,\mathrm{N}$, so $a_{\max} \approx 8.8\,\mathrm{m/s^2}$ and

$$t_{0-100} \geq \frac{27.8}{8.8} \approx 3.2 \text{ s}.$$

No engine upgrade can beat that number—only more $\mu$ (slicks) or more clever load distribution can. A rear-wheel-drive car uses only the rear axle's share of the weight, so its launch ceiling sits lower—exactly why powerful cars love all-wheel drive off the line.

## 7.3 The Friction Circle: One Budget for Everything

Here is the rule that governs every lively moment of driving. The patch does not have separate budgets for braking and cornering; it has *one* budget, $\mu N$, spendable in any direction:

$$F_x^2 + F_y^2 \leq (\mu N)^2.$$

Figure 7.2 draws the budget as a circle. Brake at the limit, and nothing is left for steering; corner at the limit, and nothing is left for braking. Combining the two—trail-braking into a corner—means sliding along the circle's edge, spending exactly 100%. This is why braking in a fast corner unsettles a car, why the smooth driver finishes braking before turning in, and why the very best drivers deliberately blend the two. Chapter 11 returns to what happens when the front and rear budgets disagree.

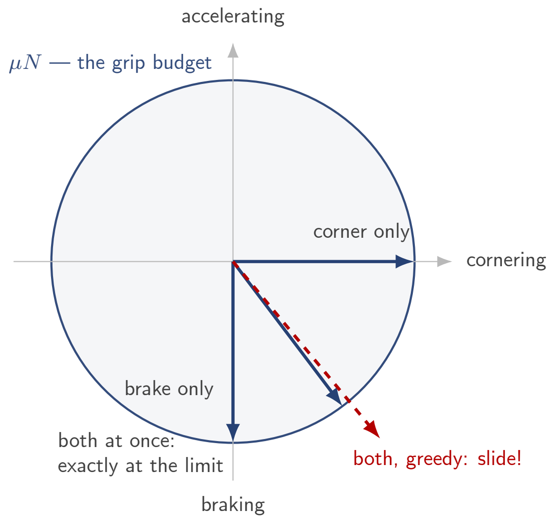



Figure 7.2: The contact patch can deliver at most $\mu N$ of force, in *any* direction: $F_x^2 + F_y^2 \leq (\mu N)^2$. Braking alone or cornering alone can each spend the whole budget; doing both at once means sharing it. Asking for more than the budget—the dashed arrow—is not a request the tire can decline politely: it slides.

**What You Feel**

You feel the circle when a mid-corner pothole or a stab of brakes suddenly asks the front tires for more than they have: the steering goes light and the car plows straight on. That lightness is not vagueness—it is the friction budget hitting zero in the steering direction. Lift gently, return some budget to the front, and the steering wakes up again.

## 7.4 Slip: Rubber's Little Secret

Coulomb's law has a twist when the surfaces include rubber. A tire gripping at its best is not rolling perfectly; it is *creeping*—the rubber in the patch is being sheared a little, a few per cent of difference between wheel speed and road speed. Grip rises steeply with this slip, peaks around 5–10%, then falls off as the patch begins to genuinely slide, as Figure 7.3 shows. A locked, skidding wheel sits far down the right-hand slope: less braking force *and* no steering authority. That is the entire reason ABS exists—not to stop you shorter by magic, but to keep each wheel pulsing near the red dot where grip is greatest and steering still works. Traction control does the same job in the accelerating direction.

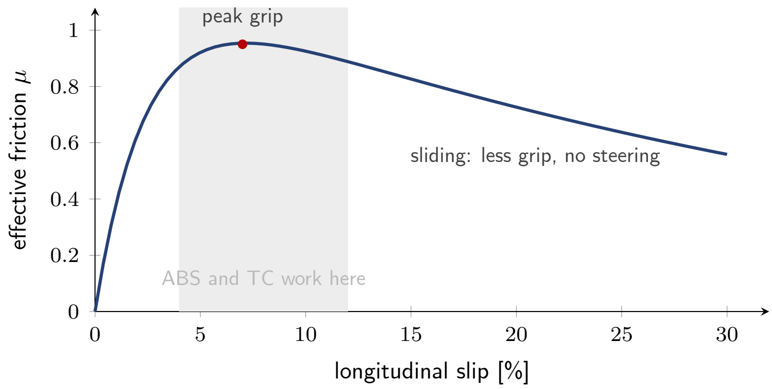



Figure 7.3: Rubber's secret: maximum grip needs a little slip—a few per cent of difference between wheel speed and road speed. Beyond the peak, the tire slides and grip *falls*; a locked wheel both brakes worse and cannot steer. ABS and traction control exist to keep the tire dancing near the red dot.

**Track-Side Note**

Racing drivers talk about tires "coming in"—grip rising as rubber reaches its working temperature—and about pressure changing the patch's shape. Both are real physics beyond the simple $\mu N$ model: compound temperature changes adhesion, and inflation pressure changes how the load spreads over the patch. The model in this chapter is the reliable first approximation; the paddock arts are the second-order corrections.

**Myth vs. Physics**

**Myth:** "Wider tires always grip more because there's more rubber on the road." **Physics:** In the simple law $F_{\max} = \mu N$, area does not appear at all—double the width at half the pressure per square centimetre, same force. Real tires are kinder to the wide: a wider patch runs cooler, can use softer compound, and suffers less from rubber's *load sensitivity* (grip growing slightly slower than load). So wider often does grip more—but through material physics, not because area itself buys grip.

**Try It Mentally**

You are braking at the absolute limit in a straight line, ABS humming. An obstacle appears slightly to the left. How much steering can you add without exceeding the front tires' budget? (Very little, if the tire is genuinely using its full combined-force capacity. To ask for more lateral force, some longitudinal demand has to be surrendered—which is precisely why ABS manages slip around its optimum rather than allowing a locked wheel, preserving steering authority even during hard braking.)

## 7.5 What It Means for Cars

Tire thinking explains spec-sheet mysteries and driveway decisions alike. Why do supercars wear enormous rear tires? Because power is useless beyond $\mu N$ at the driven axle. Why do winter tires transform a car? Because compound and tread raise $\mu$ on cold, wet, and snowy surfaces—the single biggest performance upgrade available at any price. And why does every serious lap time start with tires? Because everything else in this book—engine, brakes, downforce, suspension—is ultimately a way of asking the patches for force, and the patches answer only within their budget.

**One Equation Worth Remembering**

$$F_x^2 + F_y^2 \leq (\mu N)^2$$

The contact patch has one force budget, usable in any direction or combination. Every driving limit—launch, braking, cornering—is this circle with different numbers plugged in.

## 7.6 In One Minute

The chapter in five bullets:

- All forces between car and road pass through four palm-sized patches of rubber.
- The patch's budget is $\mu N$: about 0.9× weight on dry asphalt, 0.15× on ice; a car's ceiling in g's equals $\mu$.
- Braking and cornering share one budget—the friction circle; using both at once means trading them off.
- Peak grip needs a few per cent of slip; ABS and TC exist to hold the tire at that peak.
- Tires are the cheapest big performance upgrade: they set the value of $\mu$, and $\mu$ sets everything.

One subtlety was quietly assumed away: the load $N$ on each wheel was treated as a fixed share of the weight. It is not—acceleration, braking, and cornering all *move* load between the wheels, and with it the size of each tire's budget. That motion of load is the next chapter.

# Chapter 8

# Acceleration, Weight Transfer, and Why Cars Squat

Launch a powerful car hard and it rears up like a speedboat: the nose lifts, the tail settles. Brake hard and the opposite happens—the nose dives. The car is not gaining or losing weight; nothing is moving inside it but a few millimetres of suspension travel. And yet the loads on the axles change dramatically. This quiet reshuffling—*load transfer*—decides which tires may work hard and which may not, every time the car speeds up, slows down, or turns.

**The Question**

Why does acceleration unload the front axle and load the rear—and why does it matter for grip?

**Symbols at a Glance**

$h$ height of the center of mass (COM) above the road [m]; $L$ wheelbase, the distance between front and rear axles [m]; $\Delta N$ transferred load [N]; $a$ acceleration [m/s$^2$]; $N_\mathrm{f}$, $N_\mathrm{r}$ front and rear axle loads [N].

**At a Glance**

Driving force acts at road level; the car's inertia acts at COM height. The offset $h$ between them forms a pitching couple, shifting load between the axles by $\Delta N = mah/L$. Because each tire's grip budget is $\mu N$ (Chapter 7), load transfer moves *grip*—toward the rear under acceleration, toward the front under braking.

## 8.1 The Couple

Push a filing cabinet at floor level and it slides; push it at chest height and it tips. The difference is not the force but the *height*. A car lives the same physics in miniature: the road's forward push enters at the contact patches, at road level, while the car's mass—its reluctance to accelerate, from Chapter 2—acts at the center of mass, roughly knee-to-hip height. Figure 8.1 shows the geometry: forward force at the bottom, inertia at the top, and between them a *couple* that tries to rotate the car nose-up.

The car does not flip, of course. Instead the couple is answered by the axles: the front wheels press the road a little less, the rear wheels a little more, until the torques balance. That rebalancing *is* the load transfer. The body squat you see—nose up, tail down—is just the suspension springs complying with the new loads; it is the visible symptom, not the cause.

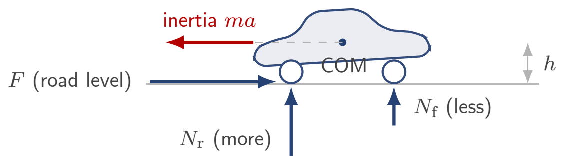



Figure 8.1: Why a car squats under acceleration. The road pushes the car forward at ground level; the car's inertia resists at the height $h$ of the center of mass. The offset between the two creates a pitching couple that unloads the front axle and loads the rear by $\Delta N = mah/L$ each. Stiffer springs reduce the visible pitch, not the transfer itself.

## 8.2 The Formula

Torque balance around the wheels gives the transferred load directly:

$$\Delta N = \frac{m\,a\,h}{L}.$$

Four levers: heavier car, harder acceleration, higher COM, shorter wheelbase—each increases the transfer. (The same formula with lateral acceleration and *track width* describes cornering; Chapter 11 picks that up.)

**Garage Physics**

Car B: $m = 1{,}800\,\mathrm{kg}$, $h = 0.55\,\mathrm{m}$, $L = 2.8\,\mathrm{m}$, so each axle statically carries half the weight, 8.8 kN.

- **Braking at** $0.9\,g$**:** $\Delta N = 1{,}800 \times 8.8 \times 0.55/2.8 \approx 3.1\,\mathrm{kN}$ moves *forward*: the front axle carries $8.8 + 3.1 = 11.9\,\mathrm{kN}$ (68% of the car), the rear just 5.7 kN.
- **Accelerating at** $0.8\,g$**:** $\Delta N \approx 2.8\,\mathrm{kN}$ moves *rearward*: the rear axle carries 11.6 kN, the front only 6.1 kN.

Figure 8.2 draws all three states side by side.

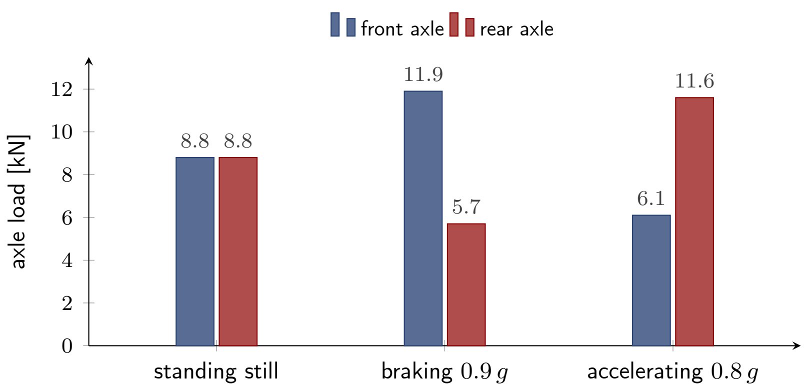



Figure 8.2: Axle loads of Car B (1,800 kg, wheelbase 2.8 m, COM height 0.55 m): at rest, braking at $0.9\,g$, and accelerating at $0.8\,g$. Hard braking shifts over 3 kN onto the front axle—which is why front brakes and front tires do most of the stopping. Acceleration does the reverse—which is why rear-wheel drive launches so well.

Now connect this to Chapter 7: each axle's grip budget is $\mu$ times *its own* load. Under hard braking the front axle's budget grows to $\mu \times 11.9\,\mathrm{kN}$ while the rear's shrinks to $\mu \times 5.7\,\mathrm{kN}$.

This is why front brake discs are bigger, part of why front tires often wear faster (steering and, in front-drive cars, propulsion add their share), and why a locked rear axle under braking is treacherous: the rear has little load left, so it reaches its small budget early—and a sliding rear end wants to come around (Chapter 11).

## 8.3 Why the Body Moves (and Why That Is Not the Point)

The body pitches because the springs compress under the new loads. It is tempting to conclude that stiffening the suspension would "reduce weight transfer"—and here lies one of the paddock's most persistent confusions.

**Myth vs. Physics**

**Myth:** "Stiffer suspension reduces weight transfer." **Physics:** Look at the formula: $\Delta N = mah/L$ contains mass, acceleration, COM height, and wheelbase—no spring rate anywhere. At steady acceleration the axle loads are fixed by these alone; stiffer springs merely reduce how far the body *rotates* while reaching the same loads. Stiffness changes the *motion*, not the *transfer*. (Springs do change how *quickly* the transfer happens and how it is shared front-to-rear in corners—Chapters 11 and 15 go there.)

Engineers do play geometry games with the suspension links—*anti-squat* and *anti-dive*—which route the driving force through the suspension arms so that the force itself, not the springs, holds the body level. The load transfer still happens (physics insists); the body simply stops nodding about it.

## 8.4 What It Means for Cars

Load transfer explains a row of automotive facts you already knew but perhaps never connected. *Rear-wheel drive* launches hard because acceleration loads the driven axle exactly when it needs grip—the couple helps. *Dragsters* wheelie because $h$ is large and $a$ enormous: when $\Delta N$ exceeds the entire front axle load, the front wheels genuinely leave the ground—the formula's dramatic limit case. *Front brakes* dominate because braking shifts load forward. *Low, long* cars transfer less: sports cars sit low partly for this reason, and SUVs lean and dive more because their $h$ is large. And since tire grip grows slightly *slower* than load (load sensitivity, Chapter 7), shifting load always costs a little total grip—a loss Chapter 11 will turn into the whole story of understeer and oversteer.

**What You Feel**

The nose-dip when you squeeze the brakes, the squat when you pull away, the gentle body roll in a roundabout: all three are the same formula, read in different directions. Once you feel them as *load moving between budgets*, you start driving with the transfer instead of against it—braking firmly first, then blending in steering as the front tires' budget frees up.

**Try It Mentally**

A car brakes at the absolute front-axle limit. Is the rear axle also at its limit? (Not necessarily. Because the rear's normal load has fallen, the rear axle can accept less braking force before locking—which is exactly why brake-force distribution is biased toward the front and must move further forward as deceleration rises, a job electronic brake-force distribution automates.)

**One Equation Worth Remembering**

$$\Delta N = \frac{m\,a\,h}{L}$$

Load transferred between the axles: mass times acceleration times COM height, divided by wheelbase. High, heavy, short cars transfer the most; grip follows the load.

## 8.5 In One Minute

The chapter in five bullets:

- Force enters at road level; inertia acts at COM height; the offset pitches the car and shifts axle loads.
- $\Delta N = mah/L$: at $0.9\,g$ braking, Car B's front axle load grows from 50% to 68% of the car's weight.
- Grip budgets ride along: loaded axle, bigger $\mu N$; unloaded axle, smaller.
- Stiff springs change the body's motion, not the steady-state transfer.
- The formula explains RWD launches, big front brakes, wheelies, and why low and long is good.

Braking deserves its own chapter: it is the mirror of acceleration, the fastest thing most cars can do, and—through the energy lens of Chapter 3—a story about megajoules becoming heat.

# Chapter 9

# Braking: Turning Speed into Heat

Here is a fact that recalibrates every spec-sheet argument: your brakes are stronger than your engine. Not a little stronger—much stronger. Car B's engine, through first gear, can push the wheels with at most about 14 kN; its brakes, acting through all four contact patches, can pull 16 kN the instant the pedal bites. Acceleration builds speed slowly and lovingly; braking can erase it in three seconds. This chapter is the physics of that erasure—where the force comes from, where the energy goes, and why brakes glow.

**The Question**

What happens physically when you brake hard—and why do the brakes heat up?

**Symbols at a Glance**

$a_\mathrm{b}$ braking deceleration [m/s$^2$]; $d$ stopping distance [m]; $E_\mathrm{kin}$ kinetic energy [J]; $P_\mathrm{brake}$ braking power [W]; $\Delta T$ temperature rise [°C].

**At a Glance**

Braking removes kinetic energy with tire-limited force: $d = v^2/(2a_\mathrm{b})$. The brake discs convert that energy to heat—a single stop from 100 km/h can heat a set of discs by more than 150 °C. EVs route most of the energy back into the battery instead.

## 9.1 The Physics of Stopping

Braking force obeys the same budget as every other tire force: $F \le \mu N$ (Chapter 7). With all four wheels braking, $N$ totals the car's weight, so the achievable deceleration is again just $a_\mathrm{b} \approx \mu g$—about $0.9\,g$ on dry asphalt with good tires. Chapter 8 added the refinement: braking shifts load forward, so the front brakes do most of the work—hence their bigger discs.

The distance follows from energy, not force: removing $E_\mathrm{kin} = \frac{1}{2}mv^2$ with a constant force $F = ma_\mathrm{b}$ needs a distance

$$d = \frac{v^2}{2a_\mathrm{b}}.$$

Figure 9.1 plots it: the parabola from Chapter 3, now with consequences. From 50 km/h, a committed stop takes 12 m; from 100, four times that; from 200, sixteen times—nearly 200 m, two football pitches. The dashed line adds half a second of reaction time: at 100 km/h that is another 14 m traveled before the brakes even engage.

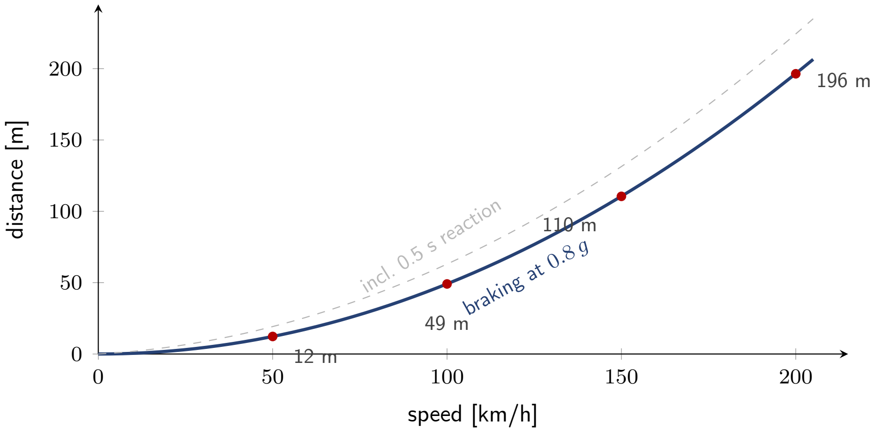



Figure 9.1: Braking distance versus speed at a constant 0.8 $g$—already a committed, dry-asphalt stop. The parabola is $v^2$ made visible (Chapter 3): twice the speed, four times the distance. The dashed line adds a 0.5 s reaction time, which grows only linearly—yet dominates the difference at city speeds.

**What You Feel**

A full ABS stop feels violent because it is: 0.9 $g$ means your 80 kg torso presses the belt with its own weight. The pulsing pedal is Figure 7.3 in action—the system releasing and re-applying each wheel many times per second, holding the tires at the grip peak where a locked wheel would be slower *and* unsteerable.

## 9.2 Where the Energy Goes: Heat

The friction force is only the tire half of the story. Between brake pad and disc, the kinetic energy does not vanish—it becomes *heat*. And the amounts are brutal, as Figure 9.2 shows: Car B arriving at 100 km/h carries 0.69 MJ; stopping means dumping all of it into four discs of steel.

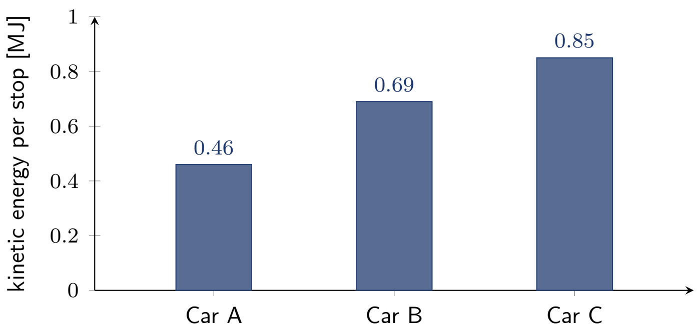



Figure 9.2: What one stop from 100 km/h dumps into the brakes of each fleet car. Mass is the multiplier: Car C's battery weight costs its brakes nearly twice Car A's burden. In an EV, the motor-generator can recover a substantial share of this energy during moderate braking instead—that is regenerative braking.

Garage Physics

How hot does one stop make the brakes? Car B from 100 km/h: 694 kJ into roughly 8 kg of disc steel (specific heat ≈ 500 J/(kg °C)):

$$\Delta T = \frac{694{,}000}{8 \times 500} \approx 174\,^{\circ}\mathrm{C}$$

—in about 3.5 seconds, an average heating *power* of 694/3.5 ≈ 200 kW. From 200 km/h it is four times the energy: nearly 700 °C if the discs had to swallow it alone. (Airflow carries much of it away—that is what brake ducts are for.) Do this repeatedly and the pads, fluid, and rubber seals reach their limits: the pedal goes long and soft. That is *brake fade*—not a force problem (the tires still have grip) but a temperature problem.

Track-Side Note

Track driving is brake-thermal management. Drivers learn to brake *once*, hard and late, rather than dragging the brakes—the same energy in less time, with more airflow at speed to remove it. Brake ducts, ventilated discs, and heat-resistant fluid all exist to raise the thermal ceiling. When commentators say a car "eats its brakes," they mean this chapter's arithmetic.

## 9.3 The EV Exception: Banking the Energy

An electric motor runs happily backward: as a generator it converts motion back into battery charge. This is *regenerative braking*, and it changes the chapter's conclusion for EVs—in moderate braking, the motor-generator can recover a substantial share of the 0.85 MJ in Figure 9.2 instead of heating discs (Chapter 17 totals the savings). The friction brakes remain essential for hard stops—regen power is limited by what motor, inverter, and battery will accept at that moment, so in a full-force 100–0 stop the discs still do most of the work—and for creeping maneuvers, which is why EV discs can look rusty from disuse. One-pedal driving—lifting off to decelerate firmly—is simply regen mapped to the accelerator.

Myth vs. Physics

**Myth:** "Bigger brakes stop you shorter." **Physics:** Stopping distance is set by the *tires*: $d = v^2/(2\mu g)$—the brake hardware does not appear. Bigger discs and calipers buy *thermal capacity and repeatability*: the same short stop, twenty times in a row, without fade. The first stop is the tires'; the twentieth belongs to the brakes.

Try It Mentally

A truck and a sports car brake side by side from 100 km/h, both with good tires. Who stops shorter? (About equal: $d = v^2/(2\mu g)$ contains no mass. What differs is the heat: the truck's brakes must absorb far more energy—which is why trucks suffer brake fade on long descents and use engine braking.)

## 9.4 What It Means for Cars

You can now read brake hardware like an engineer: disc diameter and ventilation speak to *heat*, not stopping distance; tire width and compound speak to *distance*; brake bias forward speaks to Chapter 8. And you carry the chapter's one survival-grade number: stopping distance grows with the *square*. Every "just 20 faster" is a parabola, not a line.

**One Equation Worth Remembering**

$$d = \frac{v^2}{2\,a_\mathrm{b}} \approx \frac{v^2}{2\mu g}$$

Stopping distance grows with the square of speed and shrinks only with tire grip. Mass does not appear—it cancels between the energy to remove and the friction that removes it.

## 9.5 In One Minute

The chapter in five bullets:

- Brakes out-pull engines: all four patches against $\mu N$ beats one drivetrain through gears.
- Distance is $v^2/(2\mu g)$: twice the speed, four times the road; reaction time adds linearly on top.
- Braking is heat: one 100–0 stop in Car B raises the discs ∼174 °C at an average of 200 kW.
- Fade is thermal, not frictional—big brakes buy repeatability; tires buy distance.
- EVs bank the energy: in moderate braking, regen recovers a substantial share, sparing discs and extending range.

So far every force has pointed along the road. The next part turns the wheel—literally: why does a car need *force* just to go around a corner, even at perfectly constant speed?

# Part IV

# Cornering: Speed Without a Straight Line

**Part IV Overview**

A car at constant speed through a bend is accelerating every second. Chapter 10 explains why turning requires a continuous inward force and why the required force grows with the square of speed. Chapter 11 then looks at rotation: why a car sometimes runs wide, sometimes steps out, and why grip placement matters as much as grip size.

# Chapter 10

# Why a Car Needs Force Just to Turn

The speedometer says nothing is happening: a steady 80 km/h all through the long motorway sweeper. Yet your body slides gently against the seat bolster, and loose change creeps across the dashboard. The speedometer lies by omission—it reports *speed*, and cornering at constant speed is still acceleration. Chapter 1 made the distinction; this chapter collects the bill.

**The Question**

Why does a car need force just to go around a corner—and how much?

**Symbols at a Glance**

$r$ corner radius [m]; $v$ speed [m/s]; $a_c$ centripetal (center-seeking) acceleration [m/s$^2$]; $F_c$ centripetal force [N].

**At a Glance**

A car on a circular path accelerates toward the center at $a_c = v^2/r$, even at constant speed. The tires must supply $F_c = mv^2/r$ sideways—out of the same friction budget as braking and accelerating. The fastest possible cornering speed is $v_{max} = \sqrt{\mu g r}$.

## 10.1 Turning Is Accelerating

Velocity is a vector: it has a direction as well as a size. Change the direction—bend the path—and the velocity changes even if the speed does not, and every change of velocity is an acceleration. For steady circular motion the result is one of the prettiest formulas in mechanics: the acceleration points at the circle's center and has magnitude

$$a_c = \frac{v^2}{r}.$$

Figure 10.1 shows the geometry from above: velocity tangent to the path, force toward the middle. The force is real and must come from somewhere physical—the tires, deforming against the road. On glare ice ($\mu \to 0$) no sideways force exists, and the car obeys Newton's first law with heartbreaking fidelity: it goes straight.

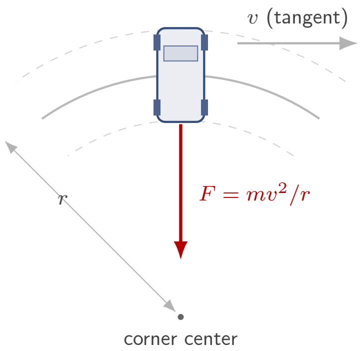



Figure 10.1: A car in a steady corner moves along a circle of radius $r$ at constant speed—yet it accelerates, because its *direction* changes. The acceleration points toward the corner's center, and the tires must supply the corresponding force $F = mv^2/r$ sideways. No force, no turn: on glare ice the car simply continues straight.

**Garage Physics**

Car B through an $r = 50\,\text{m}$ roundabout at $60\,\text{km/h}$ ($16.7\,\text{m/s}$):

$$a_c = \frac{16.7^2}{50} = 5.6\,\text{m/s}^2 \approx 0.57\,g, \qquad F_c = 1{,}800 \times 5.6 \approx 10{,}000\,\text{N}$$

—the weight of a small car, applied sideways through the four patches. And the ceiling? With $\mu = 0.9$, the fastest possible lap of that roundabout is $v_{\max} = \sqrt{0.9 \times 9.81 \times 50} = 21\,\text{m/s} \approx 76\,\text{km/h}$. The roundabout does not care what engine you have.

## 10.2 The Cornering Budget

Notice what the formula demands: sideways force grows with the *square* of speed and falls only inversely with radius. That has three practical consequences.

First, *speed is the expensive variable.* Take the corner at 80 instead of 60 km/h and the tire force rises by $(80/60)^2 = 1.78$—not by a third, but by nearly double. This is the second appearance of the $v^2$ law from Chapter 3, and not the last: aerodynamics (Chapter 12) is next.

**Speed Changes Everything**

Every driver has felt a corner "suddenly" go from easy to impossible within a small speed increase. That cliff edge is $v^2$ meeting the friction circle: at 90% of the limit you use $0.9^2 = 81\%$ of the budget and feel relaxed; at 110% you need 121%—and no talent, technology, or prayer supplies the missing fifth. The last few km/h before the limit are where all the safety margin lives.

Second, *radius is the cheap variable*: force falls only as $1/r$, so opening the radius helps modestly. This is the entire physical basis of the racing line: starting wide, clipping the inside, exiting wide turns one tight arc into one much larger arc—a bigger effective $r$, hence more speed for the same tire force.

Third, *grip divides by $\sqrt{2}$-style penalties*: Figure 10.2 compares dry and wet. Halving $\mu$ does not halve the cornering speed—it multiplies it by $\sqrt{0.5} \approx 0.71$—but it halves the *margin*, and the margin is what mistakes consume.

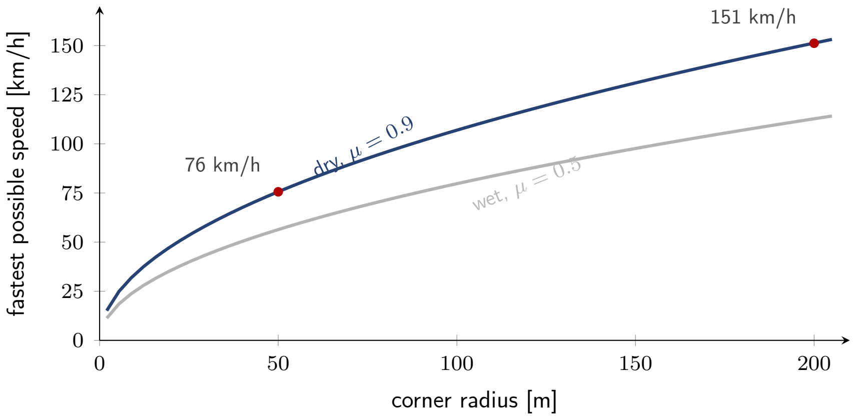



Figure 10.2: The fastest possible speed through a corner, $v_{\max} = \sqrt{\mu g r}$, for dry and wet asphalt. Two lessons: speed grows only with the *square root* of radius—doubling the radius buys only 41% more speed—and rain costs about 30% everywhere, because halving $\mu$ divides speed by $\sqrt{2}$.

**What You Feel**

At $0.9\,g$ of cornering, your body presses sideways against the seat with nearly its full weight. Your arms load the steering wheel, your head drifts toward the window, and anything not bolted down migrates. None of that is an outward force—it is your body's inertia continuing straight (Chapter 2) while the car accelerates inward around you. You feel the *seat* pushing you toward the center, just as you felt it push you forward under acceleration.

**Myth vs. Physics**

**Myth:** "A heavy car corners worse because its weight overwhelms the tires." **Physics:** In the ideal model, mass cancels exactly: $F_c = mv^2/r$ against $F_{\max} = \mu m g$ leaves $v_{\max} = \sqrt{\mu g r}$—no $m$ anywhere. A truck and a sports car share the same theoretical cornering speed on the same tires. Real heavy cars do corner worse, but through the side doors: tires are load-*sensitive* (grip grows slower than load, Chapter 7), taller vehicles transfer more load (Chapter 8), and brakes and suspensions suffer. Mass matters—just not through the headline formula.

**Try It Mentally**

You are a passenger in a car cornering left at the grip limit. In which direction does the door press you, and what pushes you "outward"? (The door presses you *inward*—toward the corner's center—providing your centripetal force. Nothing pushes you outward; your inertia simply keeps trying to go straight, which relative to the turning car feels like being thrown out.)

## 10.3 What It Means for Cars

Steady cornering speed is a property of *tires, radius, and surface*—not of engine or, ideally, mass. That reframes a lot of marketing: cornering g-figures are tire tests; skidpad numbers measure $\mu$ more than the car. What *is* the car? The balance—which end runs out of budget first, and whether it does so gently or spitefully. That balance has names you know: understeer and oversteer. Next chapter.

**One Equation Worth Remembering**

$$a_c = \frac{v^2}{r}, \qquad v_{max} = \sqrt{\mu g r}$$

Cornering is acceleration toward the center. The fastest possible speed grows only with the square root of radius and grip—there are no bargains.

## 10.4 In One Minute

The chapter in five bullets:

- Constant-speed cornering is still acceleration: $a_c = v^2/r$ toward the center.
- The tires pay for it from the same friction budget as braking and acceleration (Chapter 7).
- Force grows with $v^2$: the last 10% of speed before the limit eats a fifth of the budget.
- Bigger radius helps only as $1/r$—hence the racing line.
- Mass cancels in the ideal limit: cornering ceilings are made of rubber, not horsepower.

# Chapter 11

# Understeer, Oversteer, and Yaw

Every car at the grip limit does one of two things: it plows toward the outside of the corner no matter how much you steer (understeer), or its tail steps out and it tries to spin (oversteer). Same tires, same road, same driver—opposite failures. The difference is not magic or brand character; it is the answer to a precise question: *which axle exhausts its friction budget first?* This chapter builds that answer from the slip angle up.

**The Question**

What decides whether a car plows wide or spins—and why is one of them so much scarier?

**Symbols at a Glance**

$\alpha$ slip angle [°]; $F_{\text{lat}}$ lateral tire force [N]; $a_{\text{lat}}$ lateral acceleration [m/s$^2$]; $t$ track width (distance between left and right wheels) [m]; yaw: rotation around the car's vertical axis.

**At a Glance**

A cornering tire works at a slip angle and saturates beyond 8–12°. Cornering transfers load sideways ($\Delta N = ma_{\text{lat}}h/t$), and because tire grip grows slower than load, the end of the car that carries more transfer loses grip faster. Front end first: understeer (stable). Rear end first: oversteer (unstable). ESC exists to manage the resulting yaw.

## 11.1 How a Tire Corners: The Slip Angle

Look at a rolling, cornering tire from above and you find something odd: it does not roll exactly where it points. The wheel plane aims slightly *outward*; the actual velocity lies a few degrees *inward*. The difference is the *slip angle* $\alpha$, shown in Figure 11.1. Inside the contact patch, tread blocks are laid down straight, dragged sideways by the road's grip, and snap back as they lift—their elastic shearing, summed over the patch, is the lateral force. It is the longitudinal slip of Figure 7.3 turned ninety degrees, and it behaves similarly: force rises steeply with angle, peaks, then saturates, as Figure 11.2 shows. Steering precision lives in the linear part; the limit of cornering lives at the plateau.

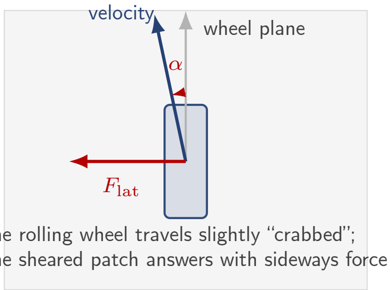



Figure 11.1: How a rolling tire corners: the wheel plane points one way, the actual velocity lies a few degrees inward—the *slip angle* $\alpha$. The contact patch is continually sheared sideways, and its elastic resistance is the lateral force. No slip angle, no cornering force.

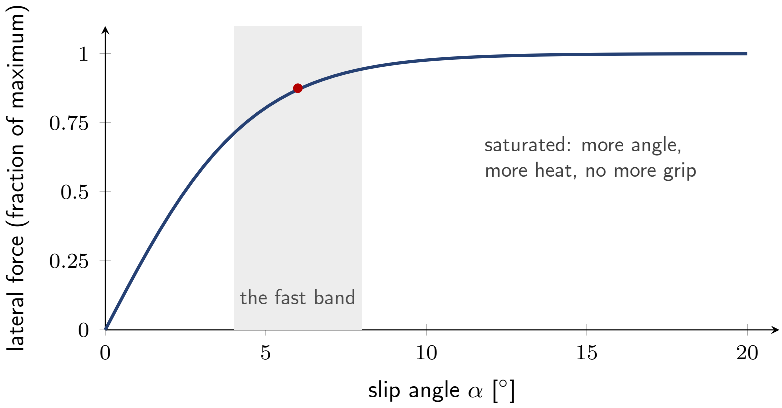



Figure 11.2: Lateral force versus slip angle (schematic, force normalized to its maximum). Nearly linear at first—which is why steering feels precise—then saturating around 8–12°. Skilled drivers hold the tire in the shaded band; beyond it, the tire slides more and grips no harder.

## 11.2 Load Transfer, Now Sideways

Chapter 8 moved load between front and rear; cornering moves it between left and right, by the same kind of formula with track width in place of wheelbase:

$$\Delta N = \frac{m\, a_{\text{lat}}\, h}{t}.$$

**Garage Physics**

Car B cornering at $0.8\,g$ ($h = 0.55\,\text{m}$, $t = 1.6\,\text{m}$):

$$\Delta N = \frac{1{,}800 \times 7.85 \times 0.55}{1.6} \approx 4{,}900\,\text{N}$$

—more than a quarter of the car's weight moves to the outside wheels, which now carry 13,700 N while the inside pair keeps 3,900 N. If the inside pair reaches zero, the car is on the verge of rolling over; the static threshold is $a_{\text{lat}} = g\,t/(2h)$, about $1.46\,g$ for Car B but barely $1.1\,g$ for a tall SUV with $h = 0.75\,\text{m}$—one reason SUVs carry electronic stability control so eagerly. (Tall, narrow vehicles roll over; low, wide ones slide first. Physics prefers the slide.)

Now the crucial subtlety from Chapter 7: tire grip grows *slower* than load (load sensitivity). Split an axle's load evenly and it generates maximum total grip; shift load to one side and the axle's total *falls*—the loaded tire gains less than the unloaded tire loses. Cornering therefore spends grip twice: once on the centripetal force, once on the imbalance. One precision matters here: $\Delta N = m a_{\mathrm{lat}} h/t$ gives the vehicle's *total* lateral transfer across the track; suspension geometry and the front/rear split of roll stiffness determine how much of it each axle carries. And because front and rear rarely share the transfer equally (different springs, bars, tire sizes), one end runs out first.

## 11.3 The Balance: Which End Gives Up First

Figure 11.3 draws both failures. *Understeer*: the front axle saturates first. The car follows a wider arc than the steering demands—"plowing." It feels safe because it is safe: the yaw damps itself, speed washes off, the required force drops. Manufacturers tune road cars to understeer at the limit for exactly this reason. *Oversteer*: the rear axle saturates first. The tail slides out, the car yaws *beyond* the steering input—and here is the vicious part: more yaw means a bigger rear slip angle, which past the peak means even less rear grip. The situation feeds itself. Catching it requires countersteering (steering into the slide) faster than the yaw builds.

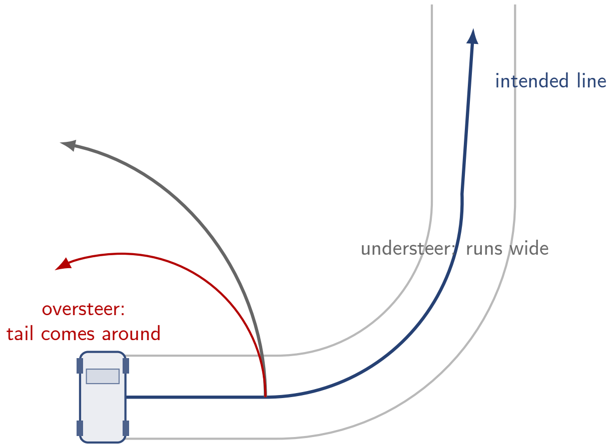



Figure 11.3: Three ways through the same left-hand corner. On the intended line the car follows the driver's arc. With understeer the front tires saturate first: the arc widens no matter how much more you steer. With oversteer the rear tires saturate first: the tail steps out and the car yaws beyond the steering—caught early it is a slide, caught late it is a spin.

Two everyday triggers deserve mention. *Power oversteer*: in a rear-wheel-drive car, throttle spends part of the rear tires' friction-circle budget on propulsion (Chapter 7), leaving less for cornering—squeeze the pedal mid-corner and the rear end steps out. *Lift-off oversteer*: lifting abruptly mid-corner shifts load forward (Chapter 8), shrinking the rear budget exactly when it was fully spent. Both are this book's earlier chapters arriving at once.

**Track-Side Note**

Trail braking—carrying a little brake into the corner—deliberately plays the budget trade: front tires share braking and steering, the rear stays light and mobile, and the car rotates. It is the friction circle and load transfer, choreographed. ESC does the same thing with a computer's hands: braking individual wheels to create yaw moments that veto a developing spin, roughly ten times faster than any driver.

Myth vs. Physics

**Myth:** "Oversteer is a rear-wheel-drive disease." **Physics:** Drive wheels decide *where throttle spends budget*, nothing more. A front-wheel-drive car lifted abruptly mid-corner transfers load off its rear axle and can step out just as eagerly; a well-set-up RWD car understeers gently at the limit. Balance is set by loads, tires, springs, and bars at each end—the driven axle only writes one line of that ledger.

Try It Mentally

You are cornering briskly at a steady throttle, front and rear budgets both near 100%. What happens if you squeeze on more power in a rear-drive car—and why does the *front* stay planted? (The rear's combined force $F_x^2 + F_y^2$ would exceed $\mu N_\mathrm{r}$; the front's budget is untouched by throttle. The rear slides first: power oversteer.)

## 11.4 What It Means for Cars

You now speak the language of handling reviews. "Safe, predictable understeer" is a setup choice, not a law of nature; "rotation on corner entry" is managed oversteer; "snap oversteer" is a rear axle whose grip falls off a cliff past the slip-angle peak. And the spec-sheet entries that shape balance—weight distribution, tire widths front versus rear, anti-roll bars—are all ways of deciding *which end runs out first, and how politely.* With cornering understood, Part V turns to the force that grows fastest of all: the air itself.

One Equation Worth Remembering

$$\Delta N = \frac{m\, a_\mathrm{lat}\, h}{t}$$

Lateral load transfer: mass times cornering acceleration times COM height, divided by track width. It unloads the inside wheels, and—through load sensitivity—spends grip on imbalance. Which end runs out first is the car's character.

## 11.5 In One Minute

The chapter in five bullets:

- Tires corner via the slip angle; lateral force saturates beyond 8–12°.
- Cornering shifts load outward: $\Delta N = m a_\mathrm{lat} h/t$; load-sensitive tires lose total grip when load is uneven.
- Front saturates first: understeer—wider arc, self-stabilizing, the manufacturers' choice.
- Rear saturates first: oversteer—yaw feeds itself; countersteer or spin.
- Throttle and lift both move the balance, through the friction circle and load transfer respectively.

# Part V

# Speed Changes Everything

## Part V Overview

At high speed the main opponent is no longer the car's mass but the air itself. Chapter 12 introduces aerodynamic drag and its unforgiving speed-squared growth. Chapter 13 raises the stakes once more: the power needed to push air aside grows with the cube of speed, which is why top speed eats horsepower. Chapter 14 shows how wings and spoilers turn the same airflow into extra grip—for a price.

# Chapter 12

# Air Resistance: The Invisible Wall

Hold your hand out of the window at 100 km/h and the air pushes it back with a force you clearly feel—and that is just a hand, maybe $0.01\,\mathrm{m}^2$. The car presents two hundred times that area. Air feels like nothing at walking pace and like a wall at speed; understanding that transformation—and its ruthless mathematics—explains why cars are shaped like teardrops, why fuel gauges fall so much faster on the motorway, and why top speed is the most expensive number on a spec sheet.

**The Question**

Why does air resistance grow so savagely with speed?

**Symbols at a Glance**

$\rho$ (rho) air density [$\mathrm{kg/m^3}$, about 1.2 at sea level]; $c_d$ drag coefficient, dimensionless; $A$ frontal area [$\mathrm{m}^2$]; $F_D$ aerodynamic drag [N]; $f_{rr}$ rolling-resistance coefficient, dimensionless ($\approx 0.01$ for car tires).

**At a Glance**

Air drag obeys $F_D = \frac{1}{2}\rho c_d A v^2$: force grows with the *square* of speed, so the power to overcome it grows with the *cube*. Rolling resistance, roughly constant at $f_{rr}\,mg$, dominates below ~80 km/h; above that, the air rules.

## 12.1 The Air Has Mass

Air is not nothing: a cubic metre of it weighs about 1.2 kg. A moving car must continually push air aside—impart momentum and kinetic energy to a river of air—and Newton's third law pushes back. The result is captured in the drag equation:

$$F_D = \tfrac{1}{2}\rho\, c_d\, A\, v^2.$$

Why the square? Because speed hits twice: a faster car meets *more air per second*, and it must push *each* parcel of air *harder*. More air, pushed harder: $v \times v$. (You met this square in kinetic energy, Chapter 3; it is the same physics wearing a different coat.)

Two car-dependent factors sit in the middle. The *frontal area* $A$ is the shadow the car casts head-on—about $2.2\,\mathrm{m}^2$ for a sedan. The *drag coefficient* $c_d$ measures how gracefully the shape slips through: a brick scores near 1; boxy classics 0.4–0.5; modern sedans 0.25–0.30; the sleekest EVs about 0.20. Their product $c_d A$—"drag area"—is the number that matters.

## 12.2 Two Road Loads, One Crossover

Air is not the only resistance. Tires flex as they roll, and that flexing eats a roughly constant force, $F_{rr} = f_{rr}\,mg$—about 177 N for Car B. Figure 12.1 plots both loads: the flat rolling line and the climbing parabola of drag, crossing near 80 km/h. City driving is mostly a fight against the tires; motorway driving is a fight against the air.

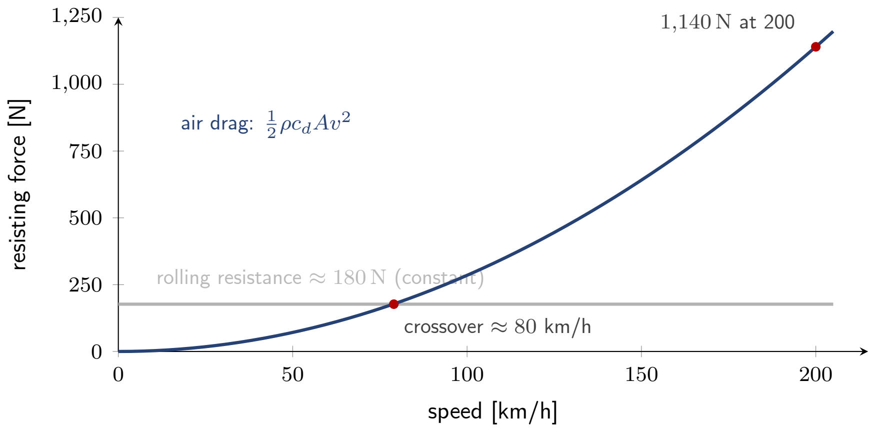



Figure 12.1: The two road loads of Car B. Rolling resistance is nearly constant; aerodynamic drag grows with $v^2$ and overtakes it around 80 km/h. Below that speed the tires' rolling losses dominate the fuel bill; above it, the air takes over completely.

**Garage Physics**

Car B ($c_d = 0.28$, $A = 2.2\,\mathrm{m}^2$, so $c_d A \approx 0.616\,\mathrm{m}^2$):

- At 50 km/h: $F_D = \frac{1}{2} \times 1.2 \times 0.616 \times 13.9^2 \approx 71$ N—less than half the rolling resistance. Barely matters.
- At 100 km/h: ≈ 285 N—already 60% more than rolling.
- At 200 km/h: ≈ 1,140 N—over six times the rolling resistance. The invisible wall.

## 12.3 The Cube: Why Speed Eats Power

Force is only half the story. The *power* needed to sustain a speed is force times speed (Chapter 4), so the aerodynamic power bill grows as $v^2 \times v = v^3$. Figure 12.2 draws the total for Car B: 13 kW suffices at 100 km/h, but 200 km/h needs 73 kW and 300 km/h needs 229 kW. *Half again the speed, more than three times the power.* This cubic wall is the single most important curve in high-speed driving.

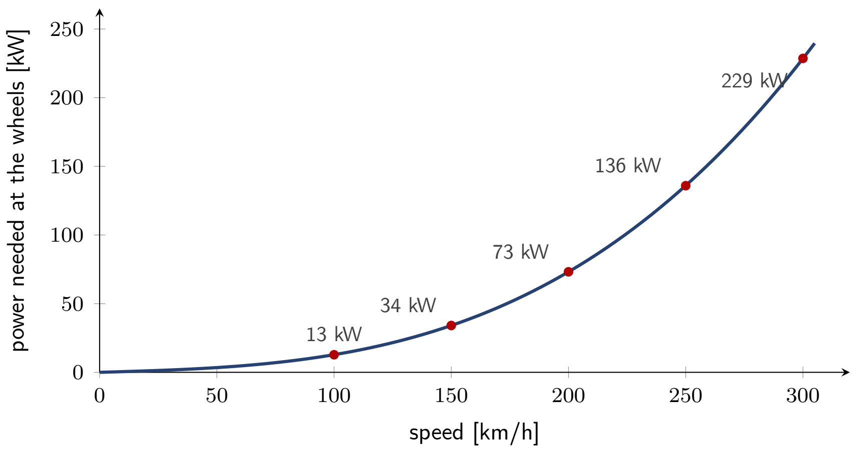



Figure 12.2: Power needed to push Car B through the air and along the road, at the wheels. Because drag grows with $v^2$ and power is force times speed, the requirement grows with $v^3$: 200 km/h asks for 73 kW, but 300 km/h asks for 229 kW—50% more speed, more than three times the power. Where this curve crosses an engine's available power lies the top speed: Chapter 13.

**Speed Changes Everything**

The cube punishes optimism everywhere. Want to cruise 10% faster? Pay $1.1^3 = 33\%$ more power—and, per kilometre, about 20% more fuel. This is why the difference between 130 and 160 km/h is so visible at the fuel pump, why EV range collapses at autobahn pace, and why "just 20 km/h more" at the top of the speed range costs dozens of kilowatts.

## 12.4 Shape: The Art of Leaving the Air Alone

The $c_d$ of a shape is mostly about its *wake*. Air that follows a smooth contour and rejoins gently behind the car leaves little disturbance; air that separates and tumbles into a large turbulent wake drags hard. Hence the teardrop ideal (round front, long tapering tail), the Kamm tail (chop the taper where the air has nearly finished its job), flush glass, smooth underbodies, active grille shutters, and camera pods instead of mirrors. Racing cars complicate the picture by *using* the air for downforce—at the price of drag; Chapter 14 settles that trade.

**What You Feel**

You feel the quadratic wall most honestly in bad weather: a stiff headwind at 120 km/h road speed makes the aerodynamic speed 150, and the engine note, the fuel gauge, and the faint buffet at the A-pillars all report the difference. A tailwind the same strength does the opposite. The car lives in the *air's* frame; the speedometer lives in the road's.

**Myth vs. Physics**

**Myth:** "Aerodynamics only matters above 200 km/h." **Physics:** The crossover is near 80 km/h. At 130 km/h cruise, drag already costs Car B about 30 kW—the majority of its total road load. Every motorway kilometre is paid mostly to the air; $c_dA$ is a fuel-economy number long before it is a top-speed number.

**Try It Mentally**

Why do racing drivers "draft" bumper-to-bumper on the straights—and why does the car in front also gain a little? (The leading car's wake is already moving air: the trailing car meets air at lower relative speed and its drag drops sharply. And the trailer's presence fills the leader's wake, shrinking the low-pressure zone behind it. Both win; the trailer wins more.)

## 12.5 What It Means for Cars

Drag thinking reads the industry: EVs chase $c_d$ obsessively because their energy is precious (Chapter 6); SUVs pay a permanent toll for their frontal area; and every "top speed" brag is secretly a power-versus-$v^3$ story. That story deserves its own chapter—the next one—where we put engine power and the cubic wall on the same axes and watch them fight.

**One Equation Worth Remembering**

$$F_D = \tfrac{1}{2}\rho\, c_d\, A\, v^2 \qquad \Rightarrow \qquad P_D = \tfrac{1}{2}\rho\, c_d\, A\, v^3$$

Drag force grows with the square of speed; the power to beat it grows with the cube. Aerodynamics is cheap downtown and brutal on the autobahn.

## 12.6 In One Minute

The chapter in five bullets:

- Air has mass; pushing it aside costs $F_D = \frac{1}{2}\rho c_d A v^2$.
- Speed hits twice—more air per second, each parcel pushed harder: hence $v^2$.
- Rolling resistance ($\approx$0.01$\times$ weight) dominates below $\sim$80 km/h; drag dominates above.
- Power against drag is cubic: 300 km/h needs three times the power of 200.
- Low $c_d$ is mostly wake management: smooth attachment, small turbulent trail.

# Chapter 13

# Why Top Speed Eats Horsepower

"How fast does it go?" is the question non-enthusiasts ask first and engineers answer last. Top speed is not a feature a car *has*; it is the residue of a tug of war between everything pushing and everything resisting, fought out at the top of Chapter 12's cubic wall. This chapter watches that fight—and explains why the result eats horsepower disproportionately.

**The Question**

What actually sets a car's top speed?

**Symbols at a Glance**

$v_{\max}$ top speed [m/s, km/h]; $P_{\text{avail}}$ power available at the wheels [kW]; $c_d A$ drag area [m$^2$]; $f_{rr}$ rolling-resistance coefficient.

**At a Glance**

Top speed is where the power *required*—$\frac{1}{2}\rho c_d A v^3 + f_{rr} m g v$—equals the power *available* at the wheels. Because the requirement is cubic in $v$, doubling speed costs eight times the power; and because gearing must deliver the engine's power peak at that speed, the transmission can lower $v_{\max}$ even when physics would allow more.

## 13.1 The Tug of War

Accelerate gently and the force balance of Chapter 2 does its work. But as speed builds, drag's $v^2$ keeps doubling while the drivetrain's available force, $F = P/v$ (Chapter 4), keeps *falling*. The end comes where the two meet:

$$\underbrace{\tfrac{1}{2}\rho c_d A\, v^3 + f_{rr}\, m g\, v}_{\text{required power}} \;=\; \underbrace{P_{\text{avail}}}_{\text{wheel power}} \, .$$

Figure 13.1 draws the fight for all three fleet cars. Requirement curves climb cubically; available power (peak engine power minus roughly 12% drivetrain loss—10% for the EV) sits flat. The crossing is the top speed.

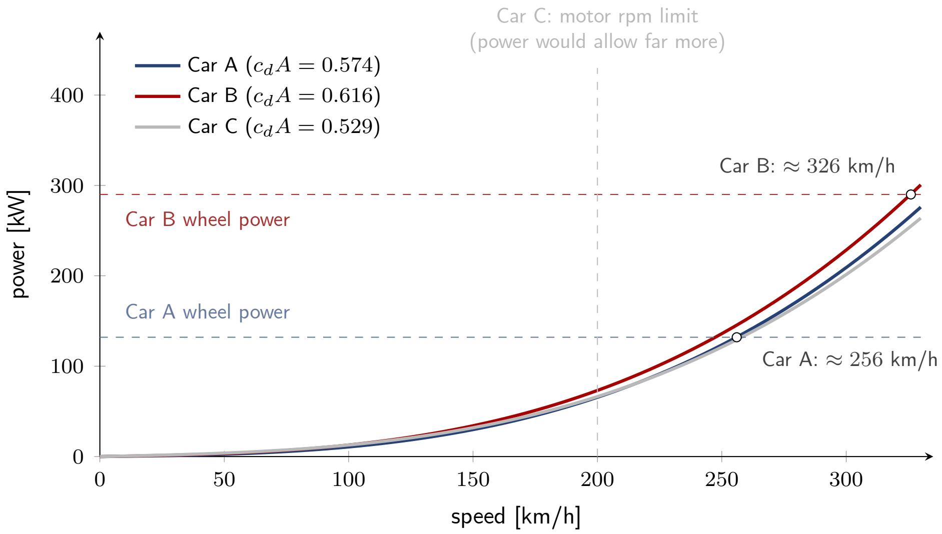



Figure 13.1: Top speed is a crossing. The solid curves give the power each fleet car needs at the wheels (Chapter 12); the dashed lines give what the drivetrain delivers (peak power minus losses). Where they meet, acceleration ends. Car C shows the electric twist: its single gear runs out of rpm around 200 km/h, far below what its 450 kW could push through the air.

**Garage Physics**

Reading the crossings: Car A (150 kW, $c_dA = 0.574\,\text{m}^2$) balances at about 256 km/h; Car B (330 kW, $c_dA = 0.616\,\text{m}^2$) at about 326 km/h. Note the sting: Car B has 120% more power than Car A and goes only 27% faster. Cube roots are like that: $v_{\text{max}} \propto P^{1/3}$. To go *twice* as fast you need roughly *eight* times the power—aerodynamics permitting.

## 13.2 Why the Last Kilometres Cost the Most

The cube concentrates its cruelty at the top. Figure 13.2 shows Car B's requirement at three speeds: 73 kW at 200, 136 kW at 250, 251 kW at 310 km/h. Each additional km/h at high speed costs several kilowatts; marketing's favorite number is bought by the kilowatt, at a rising price. This is why 300-plus cars exist mostly as engineering statements—and why removing a limiter or adding 10 kW changes nothing you would notice.

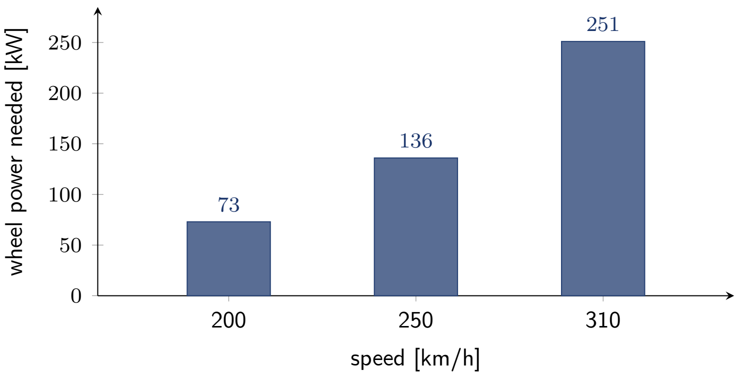



Figure 13.2: Car B's wheel-power requirement at 200, 250, and 310 km/h. The step from 250 to 310—a 24% speed gain—costs an 85% power gain. This is why "how fast does it go?" is the most expensive line on the spec sheet.

**What You Feel**

Drive a car toward its top speed and the arrival slows to a crawl: 250 comes willingly, 270 takes a straight, 285 needs patience and a gentle downhill. You are feeling the force curves converge—the available force $P/v$ sagging toward the drag parabola until only centimetres of daylight remain between them. Acceleration does not stop; it evaporates.

## 13.3 Gearing: The Gatekeeper

The physics balance is necessary but not sufficient—the *gears* must deliver. Top speed can only be reached if some gear places the engine's power peak at $v_{\max}$ (Chapter 5); a long "economy" top gear can intersect the drag curve before the engine ever reaches its best, and the car tops out early. Many cars are fastest in their *second*-highest gear for exactly this reason. Electronic limiters add another layer (250 km/h is a famous voluntary ceiling). And Car C illustrates the electric version of the gatekeeper: with a single fixed ratio, its motor hits maximum rpm near 200 km/h—as Figure 13.1 shows, its 450 kW would suffice for far more, but no gear remains. (This is why a few EVs carry two-speed transmissions.)

**Myth vs. Physics**

**Myth:** "Top speed is all about horsepower." **Physics:** Required power is $\frac{1}{2}\rho c_d A v^3$: cut the drag area $c_d A$ by 10% and the same engine reaches about 3.4% more speed—equivalent to finding 10% more power, but permanent, free of fuel cost, and effective at every speed. Le Mans prototypes and solar cars are shaped by this identity: power buys speed at a cubic tariff; streamlining buys it wholesale.

**Try It Mentally**

Two cars have the same engine. One is a sleek coupe ($c_d A = 0.60\,\mathrm{m}^2$), one a boxy SUV ($c_d A = 0.90\,\mathrm{m}^2$). Roughly how much faster is the coupe at the top end? (Requirement scales with $c_d A$, so $v_{\max}$ scales as $(c_d A)^{-1/3}$: the coupe gains $(0.90/0.60)^{1/3} \approx 1.14$—about 14%. If the SUV touches 230 km/h, the coupe reaches $\approx 263$.)

**Track-Side Note**

At Le Mans, teams trim wings down to slash drag for the long straights, accepting less downforce in the corners; at Monaco they bolt on everything. Same cars, opposite choices—because the drag–downforce trade (Chapter 14) has no free lunch, only the right lunch for each circuit.

## 13.4 What It Means for Cars

Top speed is the meeting of four characters: power (Part II), gearing (Chapter 5), drag area (Chapter 12), and—for EVs—motor rpm limits (Chapter 6). Read a spec sheet accordingly: power tells you the *potential*, $c_d$ and frontal area tell you the *price*, and the ratio table tells you whether the car can *collect*. Next, the air's other job: not resisting the car, but pressing it into the road.

**One Equation Worth Remembering**

$$\tfrac{1}{2}\rho c_d A\, v_{\max}^3 + f_{rr} m g\, v_{\max} = P_{\text{avail}}$$

Top speed is the root of this equation: cubic aerodynamics plus rolling equals wheel power. More power helps like a cube root; less drag helps the same way and saves fuel doing it.

## 13.5 In One Minute

The chapter in five bullets:

- $v_{\max}$ is where required power (cubic in $v$) meets available wheel power.
- Twice the top speed needs roughly eight times the power; $250 \to 310$ km/h costs Car B +85%.
- Gearing must place the power peak at $v_{\max}$; economy gears and limiters can lower it.
- Single-gear EVs are often rpm-limited far below their aerodynamic potential.
- Drag reduction is as good as power for top speed—and better everywhere else.

# Chapter 14

# Downforce, Lift, and High-Speed Stability

Put your hand out of the window at highway speed, palm flat, and tilt it slightly. Your hand is shoved backward—and, depending on the tilt, pressed up or down. Your hand just became a wing, and the force you felt is the same physics that pins a race car to the road. A wing is nothing more than a deliberate, refined version of that tilted hand—and it can give a car more grip without adding a single kilogram on the scales, provided the car is moving.

**The Question**

Why do wings help in corners but hurt on straights?

**Symbols at a Glance**

$F_L$ aerodynamic lift/downforce [N]; $c_L$ lift coefficient (sign set by convention); $A$ reference area [$\mathrm{m}^2$]; $\rho$ air density [$\mathrm{kg/m}^3$]; $v$ speed [m/s].

**At a Glance**

A wing deflects air downward and receives an equal, opposite push onto the car: downforce. It obeys $F_L = \frac{1}{2}\rho c_L A v^2$—zero at a standstill, serious only at speed. Downforce raises the normal load on the tires, which raises their grip limit, so cornering speeds climb. But deflecting air costs energy: extra drag is the invoice, and on the straights that invoice comes due.

## 14.1 Pushing Air Down

Wings are usually explained with curved surfaces and faster-moving air. That picture is not wrong, but it hides the essence. The essence is momentum (Chapter 3): a wing takes air that was moving horizontally and sends it away with a downward component. Air that leaves moving down was pushed down—so, by Newton's third law, the air pushes back on the wing, up for an aircraft, down for a car's inverted wing. Figure 14.1 shows the exchange.

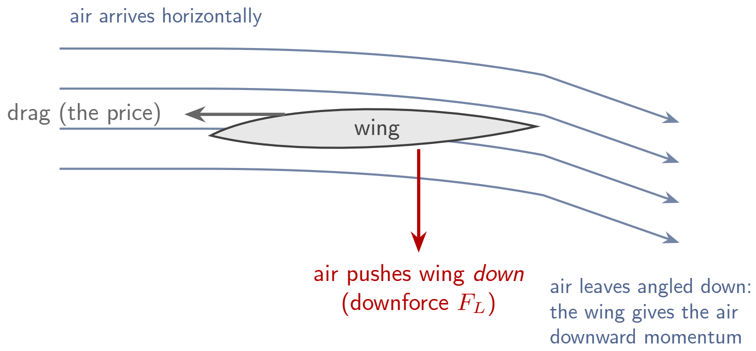



Figure 14.1: Downforce is momentum exchange, inverted. A wing deflects the passing airflow downward—the air leaves with downward momentum it did not have. By Newton's third law (Chapter 2), the air pushes the wing the opposite way: down onto the car. Deflecting air also costs energy, which the car feels as extra drag—downforce is bought, not free.

This is why downforce feels like cheating: it is a contact-free force. No weight was added; nothing on the scales changed; yet the tires are pressed harder into the road. And it is also why downforce is *not* free. Giving all that air a downward shove, continuously, takes energy, and the car pays for it as drag. Every racing wing lives on a budget line between grip bought and speed surrendered.

## 14.2 Growing with the Square

Downforce obeys the same $v^2$ law as drag (Chapter 12):

$$F_L = \tfrac{1}{2}\rho\, c_L A\, v^2.$$

Everything from Chapter 12 about the square applies here, with one inversion: drag is the enemy that grows with $v^2$, downforce is the ally that grows with $v^2$. At 50 km/h even a big wing produces a rounding error; at 200 km/h it produces sixteen times as much. Figure 14.2 shows three aerodynamic packages: a road sports car with a discreet spoiler, a GT racer, and a formula car.

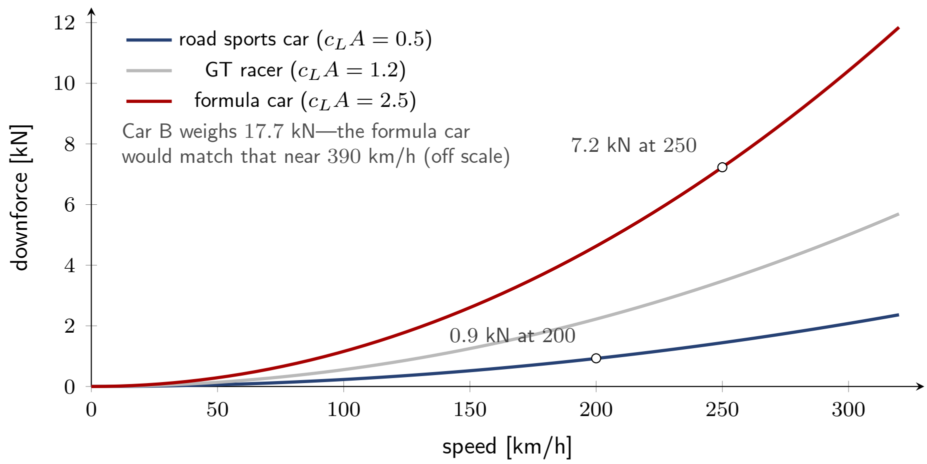



Figure 14.2: Downforce against speed for three aerodynamic packages. Like drag, downforce obeys $F_L = \frac{1}{2}\rho c_L A v^2$: at rest there is none, at city speed it is a rounding error, and only beyond about 150 km/h does it become a force worth engineering around. At 250 km/h the formula car's wings press it down with roughly 7 kN—like parking a small car on its roof.

Two consequences follow. First, wings are *irrelevant* at the speeds where most road driving happens—a spoiler on a city car is jewelry, not engineering. Second, aerodynamic grip arrives exactly where ordinary grip is most missed: the fast corners, where $v^2/r$ demands the most from the tires (Chapter 10). The physics hands you help precisely when the stakes are highest—if you are going fast enough to afford it.

## 14.3 Turning Load into Corner Speed

Grip scales with load (Chapter 7): a tire pressed into the road with force $N$ can deliver up to $\mu N$ sideways. Downforce raises $N$ *without* raising the mass $m$ that the corner's $mv^2/r$ demand is proportional to—and that asymmetry is the whole game. The cornering limit of Chapter 10 becomes

$$v_{\max} = \sqrt{\mu\, r \left(g + \frac{F_L}{m}\right)}.$$

One modeling note: treat $F_L$ here as the downforce available *at the speed under consideration.* A full aerodynamic calculation substitutes $F_L(v) = \frac{1}{2}\rho c_L A v^2$, putting $v$ on both sides and making the corner-speed equation self-consistent rather than one-step—the qualitative conclusion is unchanged. Figure 14.3 applies it to Car B in the familiar 50 m corner: with no downforce the limit is 76 km/h; with 5 kN pressing down—what a serious wing makes at such speeds—it rises to 86 km/h; with 10 kN, to 95 km/h.

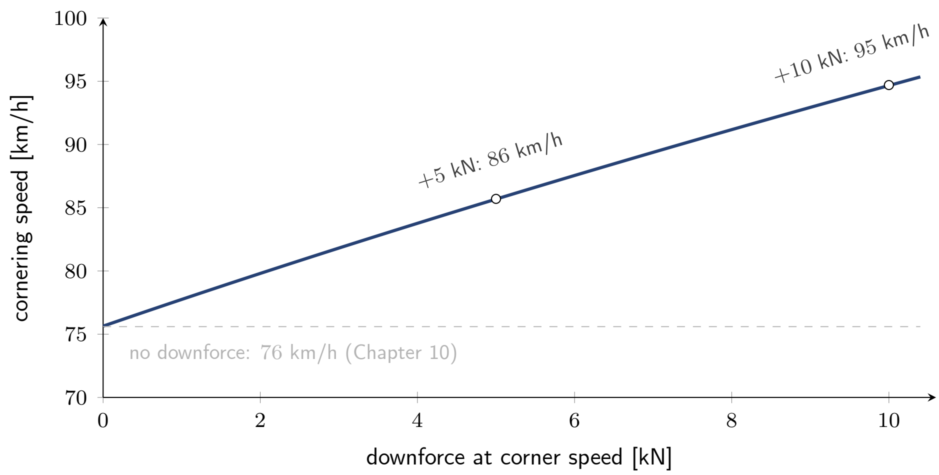



Figure 14.3: Cornering speed of Car B through the familiar 50 m corner of Chapter 10, as a function of aerodynamic downforce pressing on the tires. Grip scales with the load on the tire, and downforce adds load without adding mass to accelerate: $v_{\max} = \sqrt{\mu r\,(g + F_L/m)}$. Real wings make $F_L$ grow with $v^2$, so the true gains compound with speed—which is why aero matters most in fast corners.

**Garage Physics**

Bolt a GT package ($c_L A = 1.2$) onto Car B and run the numbers at 250 km/h: $F_L = \frac{1}{2} \times 1.2 \times 1.2 \times 69.4^2 \approx 3{,}470\,\mathrm{N}$ of downforce. In the 50 m corner, if the aero holds even 2 kN at corner speed: $v = \sqrt{0.9 \times 50 \times (9.81 + 2000/1800)} \approx 80\,\mathrm{km/h}$ instead of 76. Four km/h sounds small—until you remember that corner exit speed is amplified down the entire following straight.

One honest caveat: real tires are *load-sensitive*. Double the load and the grip grows, but not quite double—the coefficient $\mu$ sags a little as the tire is worked harder. Downforce still wins clearly (the mass term is untouched), but the last few percent of theoretical gain evaporate in the contact patch. This is one reason race engineers measure rather than assume.

## 14.4 Balance: Where the Force Lands Matters

A single downforce number is not enough; *where* it lands decides the car's manners. Downforce acts at the aerodynamic *center of pressure*, and its position relative to the center of mass sets the *aero balance*—the share of total downforce carried by the front axle versus the rear. Move the balance forward and the front tires gain grip relative to the rears: the car turns in more eagerly, tending toward oversteer (Chapter 11). Move it rearward and the car plants its tail, tending toward understeer. Race teams tune wings, splitters, and diffusers to place this balance a few percent behind the static weight distribution—close enough to stay neutral, biased just enough to stay stable.

Lift is the same physics with the sign flipped, and ordinary road cars make plenty of it: a typical sedan body generates a few hundred newtons of *lift* at highway speed. That is why an unmodified car can feel light and nervous in fast sweepers—the tires are literally being unloaded—and why even modest spoilers, which often just cancel lift rather than create true downforce, transform high-speed stability.

**What You Feel**

In a car with real aero, the steering wheel gives you the square law directly. The same corner that feels edgy at 120 feels glued at 180—weightier steering, calmer chassis, grip that seems to arrive from nowhere. You are feeling the tires' normal load doubling while the car's mass stays exactly the same.

## 14.5 The Price on the Straight

Nothing in Chapter 13's tug of war was repealed. A wing that makes 5 kN of downforce with a lift-to-drag ratio of 3 adds about 1.7 kN of drag; at 250 km/h that drag burns roughly 115 kW of engine power—a third of Car B's output, spent holding the wing's end of the bargain. The cornering gain is bought with top speed, every time. Hence the visible compromise of motor racing: skinny wings where the straights are long, barn doors where the corners are tight. Active aerodynamics—wings that flatten on the straight and deploy for the corner—are simply an attempt to change the deal mid-lap.

**Myth vs. Physics**

**Myth:** "Downforce is free grip." **Physics:** Downforce is *taxed* grip. The wing pays for its downforce with induced and profile drag, the engine pays the drag with power, and Chapter 13's cube law collects. How steep the tax is varies enormously with the device and its operating point—wing aspect ratio, ground effect, diffuser contribution—so good aero design is the art of producing useful load for as little drag as possible. The correct statement is better than the myth, though: downforce is grip bought with power—and in corners, grip is usually worth more than power.

**Try It Mentally**

Your sedan ($m = 1{,}500\,\mathrm{kg}$, corner $r = 80\,\mathrm{m}$, $\mu = 0.9$) gains a wing producing 1 kN of downforce at corner speed. How much does the limit move? (From $\sqrt{0.9 \times 80 \times 9.81} \approx 95\,\mathrm{km/h}$ to $\sqrt{0.9 \times 80 \times (9.81 + 1000/1500)} \approx 98\,\mathrm{km/h}$. Three km/h for free—except for the drag invoice on the straights.)

**Track-Side Note**

The famous claim that a formula car "could drive upside down through a tunnel" is just Figure 14.2 read literally, with the right car plugged in: a modern formula car weighs only about 7.9 kN ($m \approx 800$ kg), and with the ground-effect floor counted, its total $c_L A$ reaches roughly 4—so downforce matches weight near 200 km/h, and comfortably exceeds it beyond. (The figure's red curve, wings alone against Car B's 17.7 kN, would need $\approx$ 390 km/h; the race car's lower weight and floor close most of that gap.) It has never been attempted—tunnels with ceilings engineered for race-car loads are rare—but the arithmetic is sound, and it is the cleanest illustration in motorsport that downforce is a real force, not a metaphor.

## 14.6 What It Means for Cars

Road-car aerodynamics is mostly *lift management*: flat floors, careful underbody airflow, small spoilers, and active grille work aim to keep the tires' load from evaporating at speed, at the lowest possible drag cost. The next time a spec sheet boasts about downforce, ask the two physical questions: *at what speed* (the square law makes big numbers cheap to claim) and *at what drag* (the trade is universal). Up next: the hardware that keeps the tires pressed to the road when the road itself fights back—springs and dampers.

**One Equation Worth Remembering**

$$F_L = \tfrac{1}{2}\rho\, c_L A\, v^2$$

Downforce is the drag equation turned to good purpose: air deflected downward presses the car into the road, raising tire load and cornering grip, while its sibling term in Chapter 12 raises the price on every straight.

## 14.7 In One Minute

The chapter in five bullets:

- A wing deflects air downward; Newton's third law presses the car down in return.
- Downforce grows with $v^2$: negligible in town, decisive on fast corners.
- It raises tire *load* without raising *mass*, so the cornering limit rises—minus a small load-sensitivity tax.
- Aero balance (front versus rear) tunes understeer and oversteer at speed.
- Downforce is bought with drag; the exchange rate varies with the device—good aero maximizes load per unit of drag.

# Part VI

# Making the Car Behave

## Part VI Overview

Between the road and the driver sits a machine that must absorb bumps, control body motion, and keep the tires in contact with the ground. Chapter 15 explains why a car needs both springs and dampers, and why stiffer is not automatically better. Chapter 16 looks at mass that spins—wheels, tires, brakes—and asks whether a kilogram at the rim is really the same as a kilogram in the seat.

# Chapter 15

# Suspension: Springs, Dampers, and the Art of Not Bouncing Forever

Drop a steel ball on the floor and it bounces. Drop it into a jar of honey and it stops dead. A car's suspension is the deliberate pairing of those two behaviors: a spring that bounces, and a damper that stops the bouncing. A spring without a damper would make every speed bump memorable for far too long; a damper without a spring would be a rigid cart with extra steps.

**The Question**

Why does a car need both a spring and a damper?

**Symbols at a Glance**

$F$ spring force [N]; $k$ spring rate [N/m]; $x$ displacement [m]; $f_n$ natural frequency [Hz]; $\zeta$ damping ratio [–].

**At a Glance**

The spring carries the car's weight and absorbs bumps, storing energy as it compresses ($F = -kx$). The damper removes that energy as heat, so stored motion dies quickly instead of echoing. Together they pursue two goals that constantly conflict: keep the tires pressed to the road (grip) and keep the body calm (comfort). Stiffness and damping are the dials, and every car is a setting.

## 15.1 What the Spring Does

Strip one corner of a car to its physics and you get Figure 15.1: a heavy *sprung* mass (the body) resting on a spring, a light *unsprung* mass (wheel, brake, hub) riding against the road, and a damper strapped across the pair.

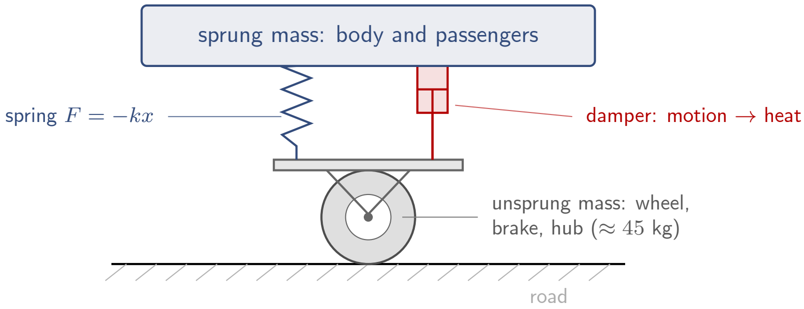



Figure 15.1: One corner of a car, reduced to its physics: the *sprung* mass (body and passengers, ≈ 1,620 kg of Car B's 1,800) rides on a spring, the *unsprung* mass (wheel and brake, ≈ 45 kg per corner) follows the road, and the damper sits in parallel with the spring. The spring decides how hard the body is pushed when the wheel moves; the damper decides how long the resulting motion lasts.

The spring obeys Hooke's law:

$$F = -k\,x,$$

pushing back proportionally to how far it is compressed. Its two jobs are to hold the body up—Car B's corner springs each carry about 4 kN just standing still—and to let the wheel move without moving the body: when the wheel hits a bump, the spring compresses instead of launching the cabin. But compression stores energy ($\frac{1}{2}kx^2$), and stored energy must go somewhere (Chapter 3). Released, it throws the body back up; the body overshoots, the spring stretches, pulls it down again—and the car is bouncing.

## 15.2 Why the Damper Exists

A bouncing car is a physics demonstration, not a vehicle: while the body oscillates, the load on the tires oscillates too, and grip (Chapter 7) rises and falls with every cycle. The damper's job is to make the stored energy disappear—into heat. Inside, a piston forces oil through small holes; the faster the suspension moves, the harder the damper resists. It converts ordered motion into warm oil, one jolt at a time. Shock absorbers on a hard-driven car get genuinely hot; that heat is your bumps, retired.

## 15.3 The Damping Dial

Figure 15.2 shows one bump answered three ways. Too little damping (worn shocks are the classic case) and the body keeps swinging for seconds. Too much and the suspension barely moves at all—the body creeps back so slowly that the next bump arrives before the recovery, and every small ripple is transmitted rigidly. Between them lies the target: one clean motion, no echo.

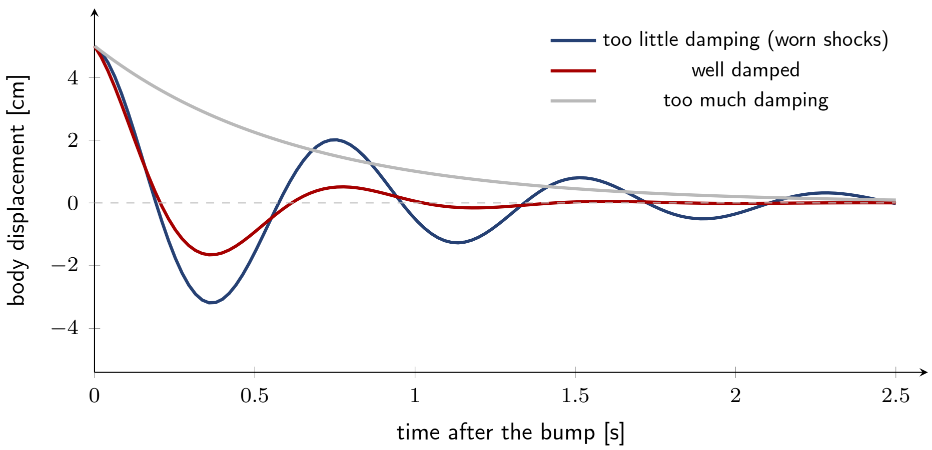



Figure 15.2: One bump, three cars. With too little damping the body keeps bouncing for seconds—the spring's energy sloshes back and forth because nothing removes it. With good damping the motion dies in a single smooth return. With too much, the body creeps back slowly and the suspension feels harsh over every small ripple. The spring sets *how far*; the damper sets *how long*.

**Garage Physics**

Each corner of Car B carries 405 kg of sprung mass on a spring of about $k = 30\,\mathrm{kN/m}$. The natural frequency is

$$f_n = \frac{1}{2\pi}\sqrt{\frac{k}{m}} = \frac{1}{2\pi}\sqrt{\frac{30\,000}{405}} \approx 1.4\,\mathrm{Hz},$$

roughly one-and-a-half bounces per second—deliberately close to the rhythm of a walking human, the frequency our bodies find least objectionable. A 5 cm compression stores $\frac{1}{2} \times 30\,000 \times 0.05^2 \approx 38\,\mathrm{J}$ per corner; after a hard bump, the dampers must quietly turn all four corners' worth into heat, several times a second.

**What You Feel**

You can diagnose damping with your diaphragm. A car that keeps nodding twice after a dip—*boing, boing*—is underdamped. A car that thuds once and is done feels disciplined. And a car that jitters constantly on rough asphalt without ever settling has too much of a good thing: dampers so stiff the springs barely get a turn.

## 15.4 Resonance: The Wrong Rhythm

Suspensions have a natural frequency, and roads sometimes sing at it. When bumps arrive rhythmically near $f_n$—washboard gravel, evenly spaced concrete joints—each push lands in step with the motion, and the swing builds (Figure 15.3). With light damping the amplification multiplies several-fold; with strong damping the peak collapses. This is why a car can feel fine at 60 km/h and terrifying at 80 on the same corrugated road: you tuned the road to the suspension by changing speed. It is also why dampers, not stiffer springs, are the cure—stiffening merely retunes the resonance to a new speed.

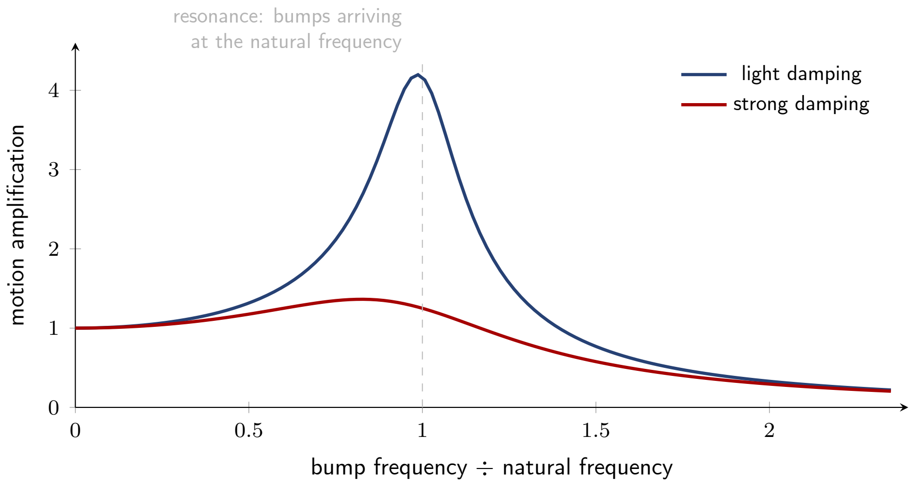



Figure 15.3: How much a suspension amplifies rhythmic bumps, against bump frequency divided by the suspension's natural frequency. Near 1—washboard gravel, concrete joints at just the wrong speed—even small bumps build into large motion, and weak damping lets the peak grow many-fold. Strong damping flattens the peak: this, not stiffness, is what tames resonance.

## 15.5 Sprung and Unsprung

The wheel cannot wait for the body. Between the road and the spring sits the unsprung mass—wheel, tire, brake, hub—and it must track every ripple instantly, or the contact patch leaves the road. Physics explains why racers obsess over light wheels: a heavy wheel, flung upward by a bump, carries momentum $mv$ that the spring can only absorb slowly; a light wheel follows the surface like a fingertip. Every kilogram saved below the spring is worth more than a kilogram saved above it—which sets up Chapter 16.

## 15.6 The Stiffness Trade

Why not simply fit rock-hard springs and be done with body roll? Because the spring is also the tire's manager. On smooth pavement, greater stiffness can improve platform and geometry control—the body stays flat, camber holds, tires work evenly. But even there it is a tuning trade, not a law: stiffness also steers how load transfer is distributed and how hard the tires are worked. And on any real road, overly stiff springs make the *body* do the bouncing the wheel should have done—a tire whose load jitters delivers less average grip than one pressed steadily. Softer springs keep the contact patch faithful to the tarmac at the price of lean and dive. Comfort and rough-road grip, it turns out, want the same thing; only smooth-road pose wants stiffness.

**Myth vs. Physics**

**Myth:** "Hard suspension means better handling." **Physics:** Harder suspension means *flatter* handling—less roll, quicker response—which feels like grip on smooth tarmac. But grip comes from the contact patch (Chapter 7), and on imperfect roads an unyielding suspension unloads the tires thousands of times per minute. Rally cars, the fastest machines on the worst surfaces, run long, supple suspension for exactly this reason. Stiffness controls the body; compliance feeds the tires; the damper referees.

**Try It Mentally**

Two otherwise identical cars cross the same washboard track: one at 40 km/h where the corrugation frequency sits well below $f_n$, one at the speed where bump rhythm matches 1.4 Hz. Which loses grip first, and why? (The second. Near resonance the wheel motion amplifies (Figure 15.3), tire load oscillates, and average grip falls. Slowing down is not just prudence—it detunes the road.)

**Track-Side Note**

A formula car's suspension looks impossibly stiff because it is: at 250 km/h, Chapter 14's wings press several extra tonnes onto the springs, and only very high spring rates keep the floor's critical ride height within millimetres. The compliance comes from the only spring left—the tire sidewall. Watch slow-motion footage: the body barely moves while the sidewalls do all the traveling. Same physics, opposite end of the dial.

## 15.7 What It Means for Cars

Every ride review is a damping report in disguise: "floaty" means underdamped, "busy" means over-sprung, "composed" means the two are balanced. And the unsprung budget—wheels, brakes—decides how faithfully the tires can follow a bad road. Next, we weigh a kilogram where it matters most: spinning at the corner of the car.

**One Equation Worth Remembering**

$$F = -k\,x$$

The spring pushes back in proportion to compression, storing energy with every bump; the damper spends that energy as heat. Springs set how far the body moves—dampers, how long.

## 15.8 In One Minute

The chapter in five bullets:

- The spring carries the load and absorbs bumps ($F = -kx$); it stores energy, it does not remove it.
- The damper turns bounce energy into heat; without it, every bump echoes for seconds.
- Good damping is a dial setting: too little wallows, too much jitters, just right returns once.
- Rhythmic bumps near the natural frequency ($\approx 1.4$ Hz) resonate—damping, not stiffness, tames them.
- Light unsprung mass keeps tires on the road; stiff springs serve smooth roads, supple ones serve real ones.

# Chapter 16

# Rotating Mass, Wheels, and Why Location Matters

Ask a forum what a set of lightweight wheels is worth and you will hear a confidently wrong answer: "one kilogram at the wheel equals four at the seat." The truth is more interesting than the slogan. Mass that spins carries a second kinetic energy, mass below the springs rides the bumps unsheltered, and mass spun through the gearbox gets squared by the ratio. Location and rotation both matter—just not by a magic factor of four.

**The Question**

Is one kilogram at the wheel the same as one kilogram in the seat?

**Symbols at a Glance**

$K_{\text{rot}}$ rotational kinetic energy [J]; $I$ moment of inertia [kg m$^2$]; $\omega$ angular velocity [rad/s]; $R$ wheel radius [m]; $i$ overall gear ratio [–].

**At a Glance**

A rolling wheel moves *and* spins, so it stores $\frac{1}{2}mv^2 + \frac{1}{2}I\omega^2$: it acts like about 1.5–1.7 kilograms per real kilogram when accelerating. Parts spun through the gears act like $I(i/R)^2$—hundreds of kilograms in first gear, a handful in top. And unsprung mass has a separate, suspension-level cost (Chapter 15). Three different penalties, one lazy myth.

## 16.1 The Rolling Wheel Does Two Jobs at Once

Look at a rolling wheel as a physicist does (Figure 16.1): the center translates at $v$, the rim spins around it at $v = \omega R$, the top races along at $2v$, and the contact patch—the only part doing useful work—is instantaneously at rest. Every kilogram of that wheel is therefore paying two energy taxes at once: $\frac{1}{2}mv^2$ because it travels with the car, and $\frac{1}{2}I\omega^2$ because it spins.

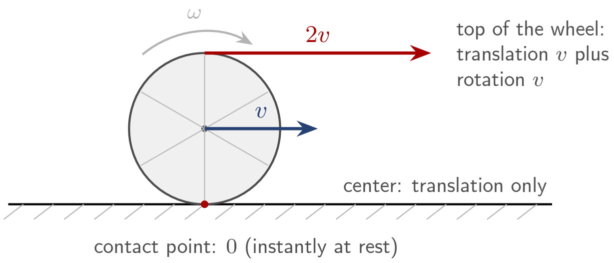



Figure 16.1: Ideal rolling combines translation and rotation: every point of the wheel moves with the car at $v$, *and* spins around the center with rim speed $v = \omega R$. The two add at the top ($2v$), cancel at the contact patch (instantaneously at rest—which is why a tire can grip without sliding), and leave the center moving at $v$. A wheel therefore carries two kinetic energies at once: $\frac{1}{2}mv^2$ for moving, $\frac{1}{2}I\omega^2$ for spinning.

For a wheel-and-tire of mass $m_w$ and radius $R$, the moment of inertia is roughly $I \approx 0.7\, m_w R^2$ (between a hoop's $mR^2$ and a disc's $\frac{1}{2}mR^2$). Since $\omega = v/R$, the rotational energy works out to $\frac{1}{2}(0.7m_w)v^2$: spinning adds about 70% to each wheel-kilogram's energy appetite. So the honest slogan is: *a kilogram at the wheel costs about* 1.7 *when accelerating*—not four.

## 16.2 Counting the Real Cost

**Garage Physics**

Car B's four wheels at 20 kg each: translation bills them at 80 kg, rotation adds $0.7 \times 80 = 56$, so the wheels accelerate like 136 kg of mass. Against 1,800 kg of car, that is a 7.5% tax on every acceleration—and shaving 2 kg per wheel returns about 13.6 kg of it. Real, worthwhile, and a long way from the forum's factor of four (which would have promised 32).

The myth probably grew by confusion with a different, larger effect: parts that spin *through the gearbox*.

## 16.3 The Gearing Multiplier

Engine, flywheel, clutch, and gearbox shafts do not spin at wheel speed—they spin $i$ times faster, where $i$ is the overall ratio (Chapter 5). Energy goes as $\omega^2$, so their *reflected* mass scales with $i^2$:

$$m_{\text{reflected}} = I\,\frac{i^2}{R^2}.$$

Figure 16.2 runs Car B's numbers: with $I \approx 0.15\,\text{kg}\,\text{m}^2$ for the engine's rotating core, first gear ($i = 12.2$) makes it feel like 219 kg of extra car; fifth gear, like 15. The wheels' steady 56 kg rides along regardless of gear.

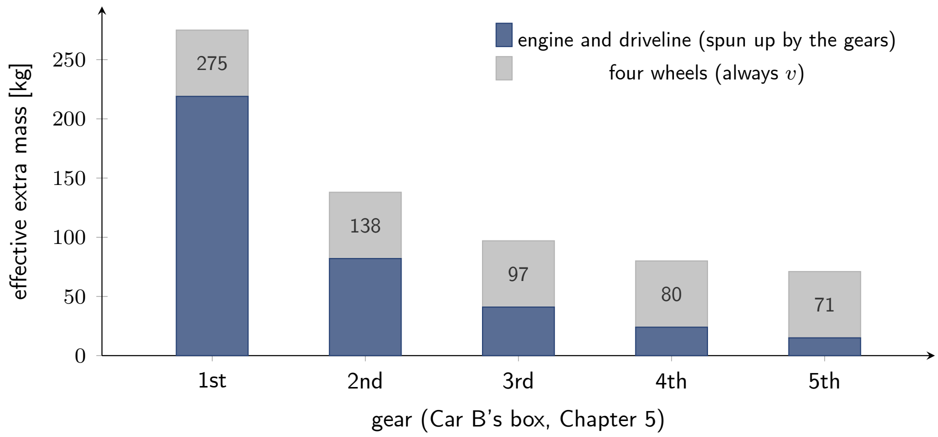



Figure 16.2: Mass that must spin up acts like extra mass to accelerate, and the gear ratio decides how much. The four wheels always roll at road speed: about 56 kg of effective mass, whatever the gear. Engine and driveline parts spin $i$ times faster than the wheels, so their reflected mass scales with $i^2$: over 200 kg in first gear, a small fraction of that in fifth. First gear still wins the car's acceleration contest, because its torque multiplication (Chapter 5) overwhelms the extra inertia—but the spinning tax is real, and it is paid hardest exactly where the revs climb fastest.

Two everyday observations fall out of this. Blipping the throttle in neutral is the engine moving its *own* reflected mass—nothing—which is why revs fly up so eagerly. And the first-gear launch pays the spinning tax hardest, exactly when you are asking for maximum acceleration. (First gear still wins; its 12× force multiplication dwarfs its 219 kg inertia.)

**What You Feel**

Drive the same car with heavy aftermarket wheels and then with light forged ones, and the difference is not in your imagination or the scale's: slightly keener response off the line, slightly calmer ride over sharp edges, slightly shorter stops. Each effect is a few percent—but they stack, and they all trace back to the same two ledger lines: $\frac{1}{2}mv^2$ and $\frac{1}{2}I\omega^2$.

## 16.4 Unsprung Is a Separate Crime

Do not conflate the spinning tax with the bump tax. Wheel mass is also *unsprung* (Chapter 15): it must follow every ripple instantly, and a heavy wheel's momentum makes it sluggish to start and stubborn to stop, letting the contact patch unload over rough tarmac. That penalty has nothing to do with rotation—a non-rotating heavy wheel would pay it in full—and everything to do with how faithfully the tire tracks the road. Lightweight wheels pay off twice: once in the energy ledger, once in the contact patch.

Brakes close the loop: every joule stored in a spinning wheel is a joule the brakes must later absorb (Chapter 9). Rotating mass is borrowed three times—accelerating, bump-following, and stopping.

**Myth vs. Physics**

**Myth:** "One kilogram of wheel weight equals four kilograms of body weight." **Physics:** For the wheel itself, the factor is about 1.7—set by geometry ($I \approx 0.7mR^2$), not marketing. Larger factors appear only for parts spun through deep gearing, and they shrink with the square of the ratio as you shift up. The kernel of truth: wheel mass also counts double in the *suspension's* ledger, where no simple factor captures it. Real physics beats round numbers.

**Try It Mentally**

Two identical cars accelerate to 100 km/h; one carries 40 kg of sand in the trunk, the other 10 kg of extra wheel mass per corner. Which is slower? (The wheel car: the sand costs 40 kg-equivalent, the wheels cost $4 \times 1.7 \times 10 = 68$ kg-equivalent. Bonus question: on a washboard road, which also loses grip? The wheel car again—the sand is sprung.)

**Track-Side Note**

Racing's obsession with light flywheels is Figure 16.2 taken personally: with first-gear ratios around 12, every 0.1 kg m$^2$ trimmed from the flywheel sheds $\approx 15$ kg of reflected mass during the launch. The price is drivability—less stored rotational energy means easier stalls and lumpier low-rpm running. Race cars accept it; your commute would not.

## 16.5 What It Means for Cars

Spec sheets never list moments of inertia, yet they shape how a car feels: wheel and tire weight (energy plus unsprung), flywheel mass (response versus smoothness), even brake disc size (both ledgers at once). Read "lightweight wheels" as a small, real, triple dividend—and the "factor of four" as a reminder that geometry, gearing, and springs each demand their own accounting. Next: where all this energy *goes* once the car is up to speed.

**One Equation Worth Remembering**

$$K_{\text{rot}} = \tfrac{1}{2} I \omega^2$$

Spinning mass stores energy just as moving mass does. For rolling parts $\omega = v/R$ adds a fixed surcharge; for geared parts $\omega = i\,v/R$ multiplies it by $i^2$. Where mass sits—and how fast it must spin—matters as much as the number on the scale.

## 16.6 In One Minute

The chapter in five bullets:

- A rolling wheel moves *and* spins: the contact patch rests while the top does $2v$.
- Wheel mass costs about $1.7\times$ when accelerating ($I \approx 0.7mR^2$)—not $4\times$.
- Geared rotating parts reflect as $Ii^2/R^2$: $\approx 219$ kg in Car B's first gear, 15 in fifth.
- Unsprung mass is a separate penalty: it governs how faithfully tires follow bumps.
- Everything spun up must later be stopped: rotating mass taxes acceleration, ride, and brakes alike.

# Part VII

# Energy, Efficiency, and Range

**Part VII Overview**

The final part zooms out to the complete energy balance. Chapter 17 asks why cruising at constant speed still consumes energy and follows the losses through air, tires, drivetrain, and hills. Chapter 18 closes the book by reading a specification sheet the way a physicist would, connecting horsepower, torque, acceleration times, braking distances, and drag coefficients into one coherent picture.

# Chapter 17

# Where the Energy Goes

Here is a puzzle. A car cruising at a steady 120 km/h is not accelerating, so by Chapter 2 the net force on it is zero. No net force, no net work—and yet the fuel gauge slides downward and the battery percentage ticks away. Where is the energy going? The answer is this book's recurring lesson seen from the other end: the car is a machine for *losing* energy gracefully, and cruising speed is the rate at which the leaks must be refilled.

**The Question**

Why does maintaining speed require energy if the car is no longer accelerating?

**Symbols at a Glance**

$P$ power [kW]; $F_{\text{drive}}$, $F_{\text{resistance}}$ tractive and resistive forces [N]; $C_{rr}$ rolling-resistance coefficient [–]; $\Delta U = mgh$ gravitational potential energy [J]; $\eta$ efficiency [–].

**At a Glance**

Steady speed means force balance, not energy balance: $F_{\text{drive}} = F_{\text{resistance}}$, and the engine must supply $P = Fv$ continuously because drag, rolling resistance, and accessories drain energy every second. Upstream of those leaks sit the drivetrain and the engine itself—each with its own tax. Hills add a reversible account: climbing banks $mgh$, descending spends it, and only the EV gets most of the deposit back.

## 17.1 The Leaks Never Stop

At constant speed the force ledger of Chapter 13 closes: drive force equals the sum of air drag (Chapter 12), rolling resistance $F_{rr} \approx C_{rr}mg$ (Chapter 7), and the small change of bearings and accessories. But zero *net* force does not mean zero *energy* flow—each resistive force acts through the distance traveled, draining $P = Fv$ every second. The engine's job in cruise is not to accelerate the car but to feed the leaks. And upstream of the wheels, two more taxes apply: the gearbox and differential take their few percent, and the engine itself—the biggest leak of all in a combustion car—turns most of the fuel's energy straight into heat (Chapter 6).

Figure 17.1 draws the complete picture for Cars B and C at 120 km/h, using the representative efficiencies of Chapter 6 (33% engine, 88% drivetrain-and-motor chain—illustrative values, moving with operating point, temperature, and accessories). The contrast is stark: the combustion car throws away two units in the engine for every unit that reaches the road; the electric car, under the same assumptions, throws away barely one in ten. Note also what survives in both: at cruise, the *road-side* losses are dominated by aerodynamics—the $v^2$ force that Part V spent three chapters on.

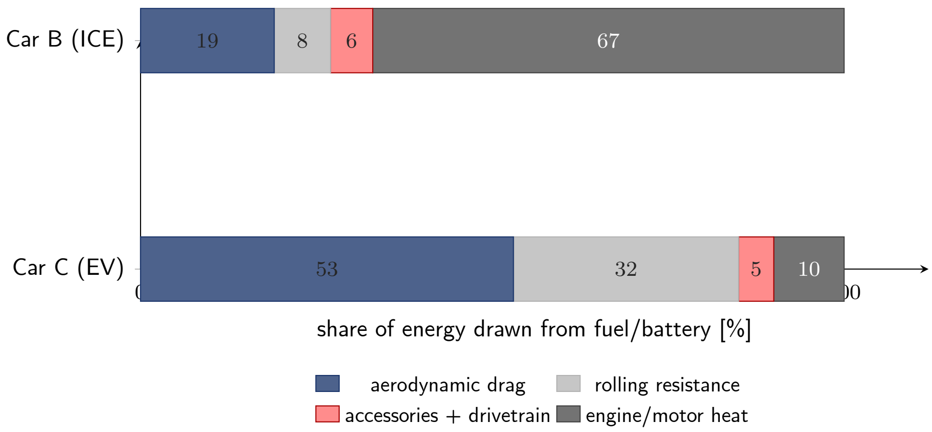



Figure 17.1: One hundred units of energy drawn at a steady 120 km/h, apportioned under representative efficiency assumptions (Chapter 6). In the combustion car, two-thirds leaves as engine heat before reaching the wheels at all; the useful third is split between pushing air and flexing tires. The electric car inverts the picture: nearly nine-tenths reaches the road, and—because its slick shape meets the same $v^2$ air—aerodynamics is the dominant destination. Physics, not preference, sets both pies.

**Garage Physics**

Car B at 120 km/h: drag $= \frac{1}{2} \times 1.2 \times 0.616 \times 33.3^2 \approx 411$ N, rolling $\approx 177$ N, so the wheels need $(411 + 177) \times 33.3 \approx 19.6$ kW. Add 1 kW of accessories, divide by a 0.88 drivetrain: the engine must make $\approx 23$ kW. At a realistic cruise efficiency of 33%, the fuel burns at $\approx 71$ kW—a household's worth of heaters—to keep a sedan at highway speed. Car C needs only $\approx 22$ kW from its battery for the same job.

## 17.2 Hills: The Reversible Account

Gravity is the one leak that returns deposits. Climbing stores $\Delta U = mgh$ as potential energy—real, banked, recoverable. Figure 17.2 puts Car B on a 500 m pass: 8.8 MJ, about 2.5 kWh, added to the climb's fuel bill on top of everything the road and air were already charging.

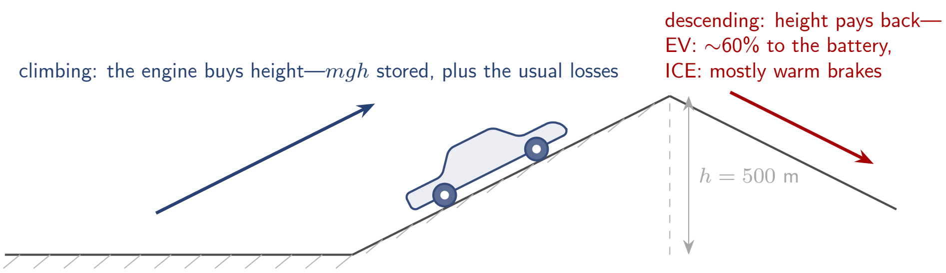



Figure 17.2: A hill is an energy account. Car B climbing 500 m banks $mgh \approx 8.8$ MJ $\approx 2.5$ kWh of gravitational potential—on top of every joule the road and air were already charging. The descent returns the deposit, but the collector differs: an EV's regenerative braking routes most of it back to the battery, while a combustion car hands it to the brake discs (Chapter 9) and the air. Mountain roads are where this accounting becomes impossible to ignore.

The descent is where the powertrain philosophies part ways (Chapter 6). The combustion car can only throttle the fall: engine braking pushes air through the cylinders, and the brakes turn the remainder into heat (Chapter 9). The EV runs its motor backward as a generator and returns the majority of the deposit—typically around 60% after motor, inverter, and battery round-trip losses—to the battery. Same hill, same $mgh$, different accountant.

**What You Feel**

Drive an EV through mountains with the consumption display on and the physics becomes visceral: the kilowatt-hours flood out on the way up—double or triple the flat-road rate—and stream back on the way down, the range estimate recovering as if by magic. It is not magic; it is $mgh$, the only line in the whole energy ledger that runs in both directions.

## 17.3 Reading the Flow Backward

The flow diagram also explains two familiar observations. City driving punishes the combustion car twice: the engine idles and crawls far from its efficient sweet spot, while every braking event (Chapter 9) burns the kinetic energy that the EV would have recovered. And at autobahn speeds the roles compress: drag's $v^3$ appetite (Chapter 13) dwarfs every efficiency trick, and even the EV's clean drivetrain cannot dodge the physics of pushing air. Efficiency moves the constants; the exponents belong to nature.

**Myth vs. Physics**

**Myth:** "A steady cruise barely uses energy—only acceleration does." **Physics:** Acceleration is a one-time purchase of kinetic energy; cruising is a subscription. At 120 km/h Car B's leaks total $\approx$ 20 kW at the wheels—the entire kinetic energy of a 0–100 km/h sprint (0.69 MJ, Chapter 3) drains away every 35 seconds of cruising. The sprint feels dramatic; the subscription is what the fuel tank actually pays for.

**Try It Mentally**

Car C's battery holds 75 kWh. Cruising at 120 km/h needs $\approx$ 22 kW. How far can it go, and why does the real number shrink in winter? ($75/22 \times 120 \approx 410$ km in the idealized ledger. Winter adds cabin heating—several kW of pure accessory load—and cold batteries both accept and deliver less. The leaks get leakier.)

**Track-Side Note**

Endurance racing is this chapter with a stopwatch: the Le Mans rulebook limits *energy per stint*, not just fuel, so engineers obsess over every arrow in Figure 17.1—engine thermal efficiency past 40%, hybrid systems recovering both braking energy *and* exhaust energy, and bodywork that pays less drag tax per lap. Winners are decided by whose leaks are smallest.

## 17.4 What It Means for Cars

Every efficiency feature on a modern car is a patch on one of these leaks: tall gearing and cylinder deactivation address the engine's thirst at low load; sleek mirrors and underbody panels address the air; low-rolling-resistance tires address the contact patch; regenerative braking and heat pumps address the city and the cold. You now own the complete map—which means we can finally read a spec sheet the way an engineer does. That is the last chapter's job.

**One Equation Worth Remembering**

$$F_{\text{drive}} = F_{\text{resistance}}, \qquad P = F\,v$$

Cruising is equilibrium of forces, not of energies: the drive force holds the leaks at bay while the engine pays $Fv$ forever. Speed is free in Newton's universe; in ours, it is metered.

## 17.5 In One Minute

The chapter in five bullets:

- Steady speed means $F_{\text{drive}} = F_{\text{resistance}}$—and a constant power bill $P = Fv$ to feed the leaks.
- At 120 km/h, with representative efficiency assumptions, two-thirds of Car B's fuel energy leaves as engine heat; nearly 90% of Car C's battery energy reaches the road.
- At cruise, aerodynamics is the biggest road-side leak; in town, rolling and accessories dominate.
- Hills bank $mgh$ on the way up; EVs recover most of it descending, combustion cars brake it away.
- Acceleration is a one-time purchase; cruising is a subscription—the tank pays for the subscription.

# Chapter 18

# The Physics Behind the Numbers

Every car argument ever held in a pub was fought with spec-sheet numbers: horsepower, torque, 0–100, top speed, lateral $g$. After seventeen chapters, those numbers are no longer trivia—each is a compressed answer to a physics question you can now ask deliberately. This closing chapter decodes them: what each number measures, which physics it reports on, and exactly where it stops telling the truth.

**The Question**

What do the familiar car-spec numbers actually tell you—and what do they hide?

**Symbols at a Glance**

$P$ power [kW]; $\tau$ torque [N m]; $m$ mass [kg]; $c_d A$ drag area [m$^2$]; $\mu$ friction coefficient [–]; $E$ stored energy [kWh].

**At a Glance**

No single specification tells the whole story, because each lives in a different physical regime: acceleration numbers mix traction, gearing, and power; top speed mixes power, drag area, and gearing; braking and lateral $g$ report on tires more than on hardware. Specifications become meaningful only when you know the physics connecting them.

## 18.1 One Sprint, Two Stories

Start with the most quoted number of all: 0–100 km/h. Figure 18.1 shows why, in a sufficiently powerful car, it is two measurements disguised as one. Below roughly 60–70 km/h, Car B accelerates on the *grip ceiling*: tires (Chapter 7), driven axles, and launch control decide, and the engine is deliberately underused. Above that, the *power ceiling* $a = P/(mv)$ takes over (Chapter 4). Where the crossover sits depends on the car: a 100 kW hatchback may be power-limited almost from the outset, while a 700 kW AWD electric can ride its traction limit far up the speed range. For powerful cars, then, 0–100 is heavily shaped by traction, driven wheels, gearing, and launch control, while 100–200 is much more strongly a power-to-weight and aerodynamic test. A car can win one and lose the other—and the spec sheet will only show you the first.

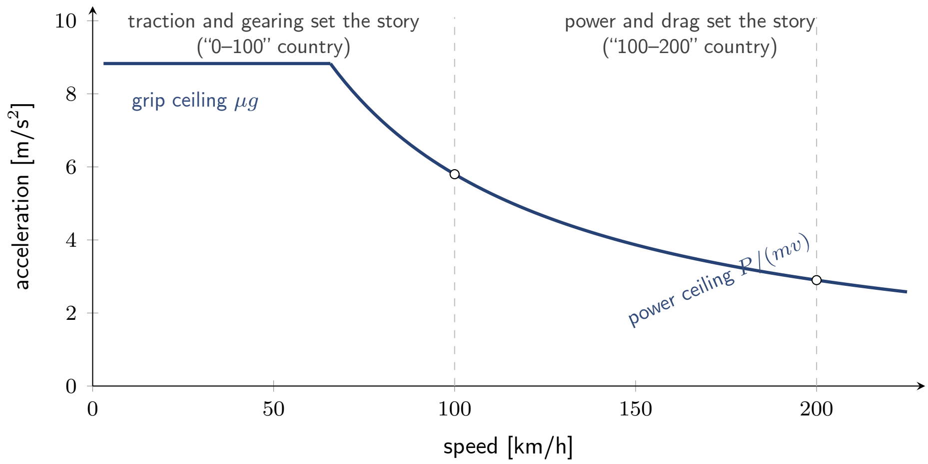



Figure 18.1: Car B's acceleration against speed, idealized. Below about 66 km/h the tires and the gearing decide: the engine has more to give than the contact patch can transmit, so acceleration sits on the grip ceiling. Above it, power is the binding constraint and acceleration falls as $P/(mv)$. This is why "0–100" and "100–200" are different physics questions wearing the same units—and why spec sheets that quote only the first hide the second.

## 18.2 The Map That Lies Politely

Or take the two numbers marketing loves together: power-to-weight and top speed. Figure 18.2 plots our fleet. Power-to-weight ranks them A, B, C; top speed ranks them B, A, C. Neither is lying—they simply answer different questions. Top speed obeys the cube law in $P/(\rho c_d A)$ (Chapter 13), so drag area and gearing gate it, and Car C's single-speed drivetrain caps it outright. The lesson generalizes: *every spec number is a projection* of the car onto one axis, and projections hide dimensions.

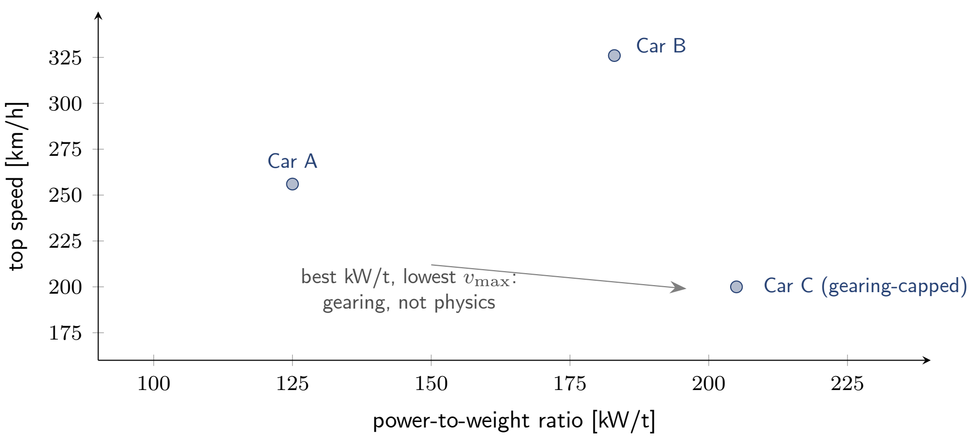



Figure 18.2: The fleet on the two axes spec sheets love most. Power-to-weight orders the cars A, B, C—yet top speed orders them B, A, C. The cube law of Chapter 13 spreads the combustion pair out (256 versus 326 km/h for a 46% power-to-weight gain), while Car C's single gear caps it at 200 km/h despite the best ratio on the chart. Two honest numbers, three different stories.

## 18.3 The Decoder Table

Table 18.1 collects the decoding for the usual suspects. Read it as a pocket version of the book: the middle column is the physics, the last column is the fine print.

Table 18.1: The spec sheet, decoded. Each number is a window onto one piece of physics—and a wall around everything else.

| **Number** | **Physics behind it** | **What it does not tell you** |
|---|---|---|
| Power [kW] | $P = \tau\omega = Fv$: the energy rate available for acceleration and top speed (Chapter 4) | Where in the rev range it lives; drivetrain losses; whether gearing can deliver it |
| Torque [N m] | Force at the crank; multiplied by gears into wheel force (Chapter 5) | Anything without the rpm and ratios attached—torque is leverage, not speed |
| 0–100 [s] | Traction, launch, gearing, then power (Figure 18.1) | Overtaking pace at speed (100–200); shift quality; surface dependence |
| Power-to-weight [kW/t] | The power ceiling's slope, $a = P/(mv)$ | Drag area, gearing, traction; where the power band sits |
| Top speed [km/h] | $P_{\text{avail}} = \frac{1}{2}\rho c_d A v^3 + f_{rr} mgv$ (Chapter 13) | How quickly it reaches 90% of that speed; whether gearing or limiters capped it |
| Braking 100–0 [m] | $v^2/(2a)$ with $a \approx \mu g$: mostly tires and ABS (Chapter 9) | Fade resistance on the fifth stop; feel; wet behavior |
| Lateral $g$ | $\mu$ on a skidpad, at one radius and speed (Chapter 10) | Balance (understeer vs. oversteer, Chapter 11); transient response |
| $c_d$ | Shape efficiency of the airflow (Chapter 12) | Anything alone—only $c_d A$ sets the force |
| Mass [kg] | Inertia in every equation of this book | Where it sits: center of gravity height (Chapter 8), rotation (Chapter 16) |
| Tire size | Contact patch, gearing effective radius, sidewall spring (Chapter 7) | Compound and construction—the chemistry that sets $\mu$ |
| Battery [kWh] | Stored energy; range $\approx E/(P/v)$ (Chapter 17) | Usable versus gross capacity; charge rate; cold-weather loss |
| Efficiency [kWh/100 km] | The sum of all leaks: air, rolling, drivetrain, accessories | At which speed and temperature it was measured |
| Downforce claims | $F_L = \frac{1}{2}\rho c_L A v^2$ (Chapter 14) | The speed of the claim, and the drag invoice attached |

### Garage Physics

Decode Car B's line: "330 kW, 580 N m, 0–100 in 4.5 s, $v_{\max} = 250$ km/h (limited)." Power and mass say the power ceiling allows $a = 290/1.8/27.8 \approx 5.8\,\text{m/s}^2$ at 100 km/h. Torque 580 N m× first-gear $12.24 \div 0.32\,\text{m} \approx 22\,\text{kN}$ at the wheels—beyond the 15.9 kN the tires can transmit ($\mu mg$), so the launch is grip-limited, exactly as Figure 18.1 predicts. And "(limited)" tells you the physics would allow $\approx 326$ (Chapter 13)—the number on the sheet is a lawyer's, not an engineer's.

### Myth vs. Physics

**Myth:** "More power always means a faster car." **Physics:** Faster *where*? More power raises the power ceiling, so it buys high-speed acceleration and top speed (at the cube's tariff). At the grip ceiling it buys nothing—no extra cornering, no extra braking, and no extra launch *once the launch is traction-limited* (below that limit, more power genuinely shortens the sprint). The complete sentence is: more power makes a car faster exactly where power is the binding constraint, and nowhere else.

**Try It Mentally**

Two cars post identical 0–100 times. One is a 300 kW all-wheel-drive sedan; one is a 180 kW rear-drive lightweight. Which would you pick for a rolling 100–200 km/h pull, and which for a tight autocross? (The sedan for the pull—the power ceiling rules there. The lightweight for the autocross—low speeds live on the grip ceiling, and less mass means less $mv^2/r$ for the tires to supply at every corner.)

**Track-Side Note**

Racing series know this chapter by heart: Balance of Performance regulations tune power, mass, and sometimes wing angle to compress the field—because no single number controls lap time, the regulators adjust several physics dials at once. When a car wins despite worse specs, look for the axis nobody published: tire warm-up, drag, or how deep into the race the brakes still work.

## 18.4 What It Means for Cars

You can now read a spec sheet the way its authors secretly do: as a set of clues about forces, energies, and constraints, each with an expiration date. Power is potential, torque is leverage, 0–100 is a traction story, top speed is an aero-gearing story, and every "$g$" number is a tire review in disguise. The numbers never lied; they just never claimed to tell the whole story. That required the physics—which you now have.

**One Equation Worth Remembering**

$$P = F\,v$$

The spec sheet's master key: power is force times speed, so every performance number is this identity viewed from a different angle—traction at low $v$, cube-law drag at high $v$, gearing in between.

## 18.5 In One Minute

The chapter in five bullets:

- 0–100 and 100–200 are different physics in powerful cars: traction and gearing at the bottom, power and drag at the top—the crossover moves with the car.
- Power-to-weight ranks sprint pace; top speed ranks power against drag area; neither ranks the other.
- Braking and lateral-$g$ numbers are tire measurements wearing a car's name.
- Torque without rpm and ratios is leverage without a fulcrum—$P = Fv$ is the key that connects them.
- Read every spec as a projection: one axis of a high-dimensional machine.

# Epilogue — The Next Drive Will Feel Different

Take an ordinary drive: out of the driveway, down the street, onto the main road, a roundabout, a hill, a motorway stretch. Nothing special—except that you now watch it with different eyes.

The launch from the driveway is no longer just motion; it is the road pushing the tires forward, a mass resisting, a seat accelerating your body. The brake pedal before the roundabout is an energy device, turning the speedometer's excitement into heat in iron discs. Mid-corner, you feel the load migrate and the tires negotiate their small patches of rubber with the tarmac. On the motorway, the car leans against an invisible wall of air whose resistance grows with the square of your speed while the required power grows with its cube. Over the crest of the hill, springs store what the dampers then patiently bleed away. Underneath it all, the powertrain—fuel or battery, it hardly matters—is quietly converting stored energy into force at the road and paying its tax to heat at every step.

That is the real content of every specification sheet and every pub argument: not isolated numbers, but one coherent balance of force, energy, momentum, rotation, heat, airflow, and control.

> *A car is not merely an object moving down a road. It is a constantly changing balance of force, energy, momentum, rotation, heat, airflow, and control. Once you see that, even a routine drive becomes a small physics experiment.*

Enjoy the experiment. And keep both hands on the wheel while you think about it.

# Part VIII

# Reference Appendices

### Appendix Overview

Compact quick references for everything the main text uses.

- **Appendix A** collects the fifteen equations a car enthusiast should know, each with symbols, a one-sentence meaning, and a car application.
- **Appendix B** makes units painless: km/h and m/s, kW, hp and PS, Nm, joules and kWh, g, and rpm.
- **Appendix C** walks through ten back-of-the-envelope car calculations, step by step.
- **Appendix D** is an alphabetical index of the myths and oversimplifications corrected throughout the book.

# Appendix A

# The 15 Equations a Car Enthusiast Should Know

Fifteen equations carry the whole book. Each entry gives the relation, its symbols, a one-sentence meaning, and where it earns its keep in a car.

1. **Average speed.** $v = d/t$.
   *Symbols:* $v$ speed [m/s], $d$ distance [m], $t$ time [s].
   *Meaning:* speed is distance covered per unit time.
   *Car:* every speedometer, lap time, and range estimate starts here (Chapter 1).

2. **Acceleration.** $a = \Delta v/\Delta t$.
   *Symbols:* $a$ acceleration [m/s$^2$], $\Delta v$ speed change [m/s], $\Delta t$ time [s].
   *Meaning:* acceleration is how quickly speed itself changes—not the speed you have.
   *Car:* the 0–100 km/h sprint is this equation with a stopwatch (Chapter 1).

3. **Newton's second law.** $F = ma$.
   *Symbols:* $F$ net force [N], $m$ mass [kg], $a$ acceleration [m/s$^2$].
   *Meaning:* acceleration is bought with force, and mass sets the price.
   *Car:* the push in your back, weight transfer, braking—everywhere (Chapter 2).

4. **Momentum.** $p = mv$.
   *Symbols:* $p$ momentum [kg m/s].
   *Meaning:* motion has a quantity; changing it requires impulse, force over time.
   *Car:* crash forces, and why mass and speed together decide how hard stopping is (Chapter 3).

5. **Kinetic energy.** $K = \frac{1}{2}mv^2$.
   *Symbols:* $K$ kinetic energy [J].
   *Meaning:* the energy of motion grows with the *square* of speed.
   *Car:* braking distances, crash severity, EV battery accounting (Chapter 3).

6. **Power as force times speed.** $P = Fv$.
   *Symbols:* $P$ power [W].
   *Meaning:* delivering force at speed costs power in proportion to both.
   *Car:* why acceleration fades as speed rises and why cruise has a power bill (Chapters 4 and 17).

7. **Power from rotation.** $P = \tau\,\omega$.
   *Symbols:* $\tau$ torque [N m], $\omega$ angular velocity [rad/s].

*Meaning:* spinning leverage times spin rate is power.
*Car:* the honest reading of any engine's torque and power curves (Chapter 4).

8. **Friction limit.** $F_{\max} \approx \mu N$.
   *Symbols:* $\mu$ friction coefficient [–], $N$ normal load [N].
   *Meaning:* grip is capped by what presses the surfaces together.
   *Car:* every acceleration, cornering, and braking limit lives under this ceiling (Chapter 7).

9. **Cornering acceleration.** $a_{\text{lat}} = v^2/r$.
   *Symbols:* $r$ corner radius [m].
   *Meaning:* turning *is* acceleration, and it grows with speed squared.
   *Car:* why the same corner is calm at 50 and impossible at 100 (Chapter 10).

10. **Aerodynamic drag.** $F_D = \frac{1}{2}\rho\, c_d A\, v^2$.
    *Symbols:* $\rho$ air density [kg/m$^3$], $c_d A$ drag area [m$^2$].
    *Meaning:* air pushes back with the square of speed.
    *Car:* highway fuel economy and the shape of every body panel (Chapter 12).

11. **Aerodynamic power.** $P_{\text{aero}} = F_D\, v = \frac{1}{2}\rho\, c_d A\, v^3$.
    *Meaning:* the *power* the air demands grows with the cube of speed.
    *Car:* top speed, and why the last kilometres per hour cost the most (Chapter 13).

12. **Hooke's law.** $F = -k\, x$.
    *Symbols:* $k$ spring rate [N/m], $x$ displacement [m].
    *Meaning:* a spring pushes back in proportion to how far it is compressed—and stores the energy meanwhile.
    *Car:* ride, body control, and why dampers exist (Chapter 15).

13. **Rotational kinetic energy.** $K_{\text{rot}} = \frac{1}{2}I\omega^2$.
    *Symbols:* $I$ moment of inertia [kg m$^2$].
    *Meaning:* spinning mass stores energy just as moving mass does.
    *Car:* wheels, flywheels, and why rotating location matters (Chapter 16).

14. **Rolling condition.** $v = \omega R$.
    *Symbols:* $R$ wheel radius [m].
    *Meaning:* a rolling wheel ties spin rate directly to road speed.
    *Car:* gearing math, speedometer calibration, tire sizes (Chapter 16).

15. **Gravitational potential energy.** $\Delta U = mgh$.
    *Symbols:* $h$ height [m].
    *Meaning:* climbing banks energy; descending pays it back.
    *Car:* mountain passes, and why EVs love the way down (Chapter 17).

# Appendix B

# Units Without Pain

Car conversations mix unit systems without apology: kW here, horsepower there, km/h on the dial, g in the review. This appendix is the phrasebook. Physics itself speaks one language—metres, kilograms, seconds—so every rule below is a translation into or out of it.

## B.1 Speed: km/h and m/s

The one conversion worth memorizing:

$$\mathrm{km/h} \div 3.6 = \mathrm{m/s}, \qquad \mathrm{m/s} \times 3.6 = \mathrm{km/h}.$$

Anchors: 36 km/h = 10 m/s; 100 km/h ≈ 27.8 m/s; 200 km/h ≈ 55.6 m/s. Every kinetic-energy or drag calculation in this book first converts to m/s—because $v$ appears squared or cubed, doing it in km/h would be off by factors of thousands.

## B.2 Power: kW, hp, and PS

The watt is the SI unit: 1 kW = 1 000 J/s. Two horsepowers roam the wild and they are *not* the same animal:

- Mechanical (imperial) horsepower: 1 hp ≈ 0.746 kW.
- Metric horsepower (PS, *Pferdestärke*, cv, pk): 1 PS ≈ 0.735 kW.

Quick rules: PS ≈ kW × 1.36; kW ≈ PS ÷ 1.36. A "450 hp" car and a "450 PS" car differ by about 5 kW—small, but the distinction matters when comparing American and European spec sheets. This book quotes kW throughout: 150 kW ≈ 204 PS ≈ 201 hp.

## B.3 Torque: N m

Torque is force times lever arm: 1 N m is one newton pulling on a one-metre wrench (Chapter 4). Some sheets quote pound-feet: 1 lb ft ≈ 1.356 N m. Remember that torque never acts alone—it becomes wheel force only through a gear ratio and a wheel radius.

## B.4 Energy: J, MJ, and kWh

One joule is one newton pushed through one metre—small. Cars deal in millions of them:

$$1\,\mathrm{kWh} = 3.6\,\mathrm{MJ}, \qquad 1\,\mathrm{MJ} \approx 0.278\,\mathrm{kWh}.$$

The bridge between the combustion and electric worlds: Car B at 100 km/h carries 0.69 MJ ≈ 0.19 kWh of kinetic energy, and a 75 kWh battery holds 270 MJ—about the chemical energy in 8 litres of petrol, which is simultaneously a compliment to batteries and a tribute to fuel (Chapter 17).

## B.5 Acceleration: g

One $g$ is Earth's own acceleration: $1\,g \approx 9.81\,\mathrm{m/s^2}$. It is the natural unit for anything the tires do, because their grip ceiling is $a \approx \mu g$ (Chapter 7): a "$0.9\,g$ corner" means the tires are working at 90% of the car's weight in sideways force. And it is felt directly: your body is the accelerometer.

## B.6 Rotation: rpm and rad/s

Physics counts angles in radians: $\omega$ in rad/s. Engines count revolutions per minute:

$$\omega = \frac{2\pi}{60}\,n \approx \frac{n}{9.55}, \qquad n \approx 9.55\,\omega.$$

Anchor: $6\,000\,\mathrm{rpm} \approx 628\,\mathrm{rad/s}$. The conversion hides inside $P = \tau\omega$: a quick mental check is $P[\mathrm{kW}] \approx \tau[\mathrm{N\,m}] \times n[\mathrm{rpm}]/9\,549$ (Chapter 4).

## B.7 Tire Pressures: bar and psi

Tire placards mix bar and psi: $1\,\mathrm{bar} = 10^5\,\mathrm{Pa} \approx 14.5\,\mathrm{psi}$. A typical $2.4\,\mathrm{bar}$ is $\approx 35\,\mathrm{psi}$. Pressure matters here because it shapes the contact patch—the four handprints through which every equation in this book must pass (Chapter 7).

# Appendix C

# Ten Back-of-the-Envelope Car Calculations

Ten calculations you can do on a napkin, each one a worked example of a chapter's core equation. All use the fleet: Car B is the 1,800 kg sedan ($c_d A = 0.616\,\mathrm{m}^2$), Car C the 2,200 kg EV with a 75 kWh battery.

## 1. Average acceleration of a 0–100 run

$a = \Delta v/\Delta t$. Converting: $100\,\mathrm{km/h} = 27.8\,\mathrm{m/s}$. For a 4 s sprint: $a = 27.8/4 \approx 6.9\,\mathrm{m/s^2} \approx 0.7\,g$. Feel check: two-thirds of what gravity does to you in free fall, horizontally. (Chapter 1)

## 2. Wheel force from torque and gearing

$F = \tau \cdot i/R$. With 360 N m of engine torque, first gear's overall ratio $i = 12.24$ (Chapter 5), and wheel radius 0.32 m: $F = 360 \times 12.24/0.32 \approx 13.8\,\mathrm{kN}$. Compare the grip ceiling $\mu mg = 0.9 \times 1\,800 \times 9.81 \approx 15.9\,\mathrm{kN}$: one strong first gear nearly spends the entire friction budget. (Chapters 5 and 7)

## 3. Kinetic energy at 200 km/h

$K = \frac{1}{2}mv^2$ with $v = 55.6\,\mathrm{m/s}$: $K = 0.5 \times 1\,800 \times 55.6^2 \approx 2.78\,\mathrm{MJ} \approx 0.77\,\mathrm{kWh}$. Dropping from 200 to 100 sheds three quarters of it—speed squared is not a slogan, it is arithmetic. (Chapter 3)

## 4. Braking-distance scaling

$s = v^2/(2\mu g)$. At $0.8\,g$: $100\,\mathrm{km/h} \to 49\,\mathrm{m}$; doubling to 200 quadruples it: 196 m. The same factor-of-four applies to *energy*—the brakes barely care which you count. (Chapter 9)

## 5. Lateral g in a corner

$a_{\mathrm{lat}} = v^2/r$. Through a 50 m corner at 76 km/h (21.1 m/s): $a = 21.1^2/50 \approx 8.9\,\mathrm{m/s^2} \approx 0.91\,g$. Which is exactly Car B's dry-grip ceiling—the corner and the speed were chosen for each other (Figure 14.3 shows what downforce adds). (Chapter 10)

## 6. Drag force at 200 km/h

$F_D = \frac{1}{2}\rho c_d A v^2 = 0.5 \times 1.2 \times 0.616 \times 55.6^2 \approx 1\,140\,\mathrm{N}$—over six times the rolling resistance (177 N). The air has become the main opponent. (Chapter 12)

## 7. Aerodynamic power at 250 km/h

$P = F_D v$ with $v = 69.4\,\mathrm{m/s}$: $F_D = 0.3696 \times 69.4^2 \approx 1\,780\,\mathrm{N}$, so $P \approx 124\,\mathrm{kW}$ for the air alone—136 kW including rolling. At 125 km/h the same car needs an eighth of the aero power: the cube at work. (Chapter 13)

## 8. Energy cost of a mountain pass

$\Delta U = mgh = 1\,800 \times 9.81 \times 500 \approx 8.8\,\mathrm{MJ} \approx 2.5\,\mathrm{kWh}$, on top of the road and air costs. For Car C that is $\approx 3.3\%$ of its battery in height alone—before a single metre of road is paid for. (Chapter 17)

## 9. Rotational energy of the wheels

$K_{\mathrm{rot}} = \frac{1}{2} I\omega^2$ per wheel with $I \approx 1.43\,\mathrm{kg\,m^2}$, $\omega = v/R = 86.8\,\mathrm{rad/s}$ at 100 km/h: $\approx 5.4\,\mathrm{kJ}$ each, $\approx 22\,\mathrm{kJ}$ for four—about 3% of the car's 690 kJ translational energy at that speed. Small, real, and the reason lightweight wheels are felt rather than measured. (Chapter 16)

## 10. What an EV recovers on the descent

The 500 m pass returns 8.8 MJ; at a realistic $\sim 60\%$ round-trip through motor, inverter, and battery, Car C banks $\approx 5.3\,\mathrm{MJ} \approx 1.5\,\mathrm{kWh}$—roughly 7 km of range handed back by gravity. The combustion car's share of the same hill: warm brakes. (Chapters 9 and 17)

# Appendix D

# Myth Index

An alphabetical lookup of the claims this book corrects, each with the short answer and the chapter with the long one.

**"AWD gives more grip."**
AWD *spends* grip better: it splits the traction budget across four tires instead of two, so acceleration uses less of each patch. The budget itself, $\mu N$, is unchanged—AWD corners and brakes no better on the same tires. (Chapter 7)

**"Bigger brakes mean shorter stops."**
Once the brakes can lock the wheels (or trigger ABS), the tire—not the caliper—sets the limit. Bigger brakes buy *repeatability*: thermal capacity against fade on the fifth stop, not a shorter first one. (Chapter 9)

**"A car's centrifugal force throws you outward in a corner."**
There is no outward force on the car: the only horizontal force is the tires pushing *inward*, supplying $mv^2/r$. What you feel is your body trying to continue straight while the car turns around it. (Chapters 2 and 10)

**"Downforce is free grip."**
It is taxed grip: wings pay for every newton of downforce with drag, and the engine repays that at the cube-law tariff on the straights. Grip bought with power—usually a good trade in corners. (Chapter 14)

**"EVs have instant torque, so torque explains their speed."**
Instant *response* is real, but what sustains acceleration is power, $P = Fv$—and EVs are often power- and rpm-limited early, with single gears capping top speed. Torque curves open the story; they do not close it. (Chapters 6 and 13)

**"Heavier cars are safer because they are heavier."**
Heavier cars carry more kinetic energy ($\frac{1}{2}mv^2$) and more momentum into every stop and crash. Mass wins a two-car collision for its occupants and loses it for the other car's—while braking and cornering limits ($F \approx \mu mg$) are mass-blind to first order. Safety lives in structure and systems, not the scale. (Chapters 3 and 9)

**"High torque means a fast car."**
Torque is leverage; without rpm it says nothing about speed. $P = \tau\omega$ converts the pair into the number that accelerates cars—and gears deliver it to the road. A diesel with 500 N m can be slower than a gasoline engine with 350. (Chapter 4)

**"Low-profile tires always handle better."**
They sharpen response (less sidewall flex) but shrink the compliance that keeps the patch

planted on real roads—and often ride on stiffer suspension that makes it worse. Profile is a trade, not an upgrade. (Chapters 7 and 15)

**"More power always means a faster car."**
Only where power binds: above the grip ceiling and against the drag cube. It buys nothing in corners or under braking, and nothing at launch once the launch is traction-limited—those are tire territories. (Chapter 18)

**"One kilogram at the wheel equals four in the seat."**
About 1.7, from $I \approx 0.7\,mR^2$—geometry, not marketing. The bigger factor belongs to parts spun through deep gearing, and the separate unsprung-mass penalty is a suspension matter entirely. (Chapter 16)

**"A spoiler equals downforce."**
Only if it moves air down: most road-car spoilers merely cancel *lift*, and many are jewelry. Downforce obeys $\frac{1}{2}\rho c_L A v^2$—zero at city speeds whatever the brochure says. (Chapter 14)

**"Stiff suspension means better handling."**
Stiffer means *flatter*, which feels like grip on smooth tarmac. On real roads, excessive stiffness unloads the tires thousands of times per minute and costs grip. Damping, not stiffness, tames resonance. (Chapter 15)

**"Top speed is all about horsepower."**
Required power is $\frac{1}{2}\rho c_d A v^3$: 10% less drag area buys as much top speed as 10% more power—permanently, and with fuel savings attached. Gearing and limiters can cap it below either. (Chapter 13)

**"Wider tires automatically give more friction."**
Coulomb's $\mu N$ has no area term; width helps by managing heat, pressure distribution, and wear, not by multiplying grip. Compound chemistry sets $\mu$; width arranges the logistics. (Chapter 7)

# Glossary

Short, alphabetized definitions for quick lookup. Cross-links point to the chapters where a concept features prominently. (This glossary grows together with the manuscript.)

**Acceleration** Rate of change of velocity, $a = \Delta v/\Delta t$; includes braking and turning, not only speeding up; see Chapter 1.

**Air density** Mass per volume of air, $\rho \approx 1.2\,\mathrm{kg/m^3}$ at sea level; scales aerodynamic forces; see Chapter 12.

**All-wheel drive (AWD)** Drivetrain that can drive all four wheels; distributes driving force but does not create extra friction; see Chapter 7.

**Braking distance** Distance covered while slowing under braking; grows with the square of speed; see Chapter 9.

**Center of mass (COM)** The mass-averaged position of the car; its height drives load transfer; see Chapter 8.

**Coefficient of friction** Dimensionless ratio $\mu$ in the first model $F_{\max} \approx \mu N$; a useful approximation, not a complete tire model; see Chapter 7.

**Contact patch** The small area where each tire actually touches the road; the only place where driving, braking, and cornering forces enter the car; see Chapter 7.

**Damper** Suspension element ("shock absorber") that resists motion and converts bounce energy into heat; controls how long oscillations last; see Chapter 15.

**Downforce** Aerodynamic force pressing the moving car toward the road; grows with speed squared and usually costs drag; see Chapter 14.

**Drag area** The product $c_d A$ of drag coefficient and frontal area; the quantity that actually sets aerodynamic force; see Chapter 12.

**Drag coefficient** Dimensionless number $C_D$ rating how slippery a shape is; multiplied by frontal area $A$ it sets aerodynamic drag; see Chapter 12.

**Friction circle** Visual budget of a tire's combined longitudinal and lateral force capability; see Chapter 7.

**Horsepower (hp)** Imperial unit of power, $1\,\mathrm{hp} \approx 0.746\,\mathrm{kW}$; metric PS differs slightly; see Chapter 4 and appendix B.

**Kinetic energy** Energy of motion, $K = \frac{1}{2}mv^2$; the quantity brakes must absorb; see Chapters 3 and 9.

**Load transfer** Change of tire normal loads under acceleration or braking, proportional to $mah/L$; the car's weight itself does not move; see Chapter 8.

**Moment of inertia** Rotational inertia about an axis, $I$; appears in $K_{\text{rot}} = \frac{1}{2}I\omega^2$ and in yaw behaviour; see Chapters 11 and 16.

**Momentum** Mass times velocity, $p = mv$; the quantity collisions exchange; see Chapter 3.

**Normal force** Contact force perpendicular to the road, $N$; sets the grip budget together with $\mu$; see Chapter 7.

**Oversteer/understeer** Balance of front versus rear lateral grip: the car rotating more or less than the steering requests; see Chapter 11.

**Power** Rate of doing work, $P = Fv$ for a moving car and $P = \tau\omega$ for a spinning shaft; see Chapter 4.

**Power-to-weight ratio** Power divided by mass [kW/t]; sets the slope of the high-speed acceleration ceiling $a = P/(mv)$; see Chapter 18.

**Regenerative braking** Recovering part of the kinetic energy as electrical energy during deceleration; limited by power, battery, and traction; see Chapters 6 and 9.

**Resonance** Build-up of motion when disturbances arrive at a system's natural frequency; for suspensions near 1–1.5 Hz; tamed by damping, not stiffness; see Chapter 15.

**Rolling resistance** Force opposing rolling, approximately $F_{rr} \approx C_{rr}mg$; dominated by tire deformation; see Chapter 17.

**Slip angle** Angle between where a wheel points and where it actually travels; the source of lateral tire force; see Chapter 11.

**Sprung/unsprung mass** Mass carried above the suspension springs (body) versus below them (wheels, brakes); low unsprung mass keeps tires following the road; see Chapter 15.

**Torque** Twisting force on a shaft, measured in Nm; multiplied by gearing it becomes wheel force; see Chapters 4 and 5.

**Traction limit** The maximum force a tire can transmit before sliding; see Chapter 7.

**Velocity** Rate of change of position, with direction; speed is its magnitude; see Chapter 1.

**Wheel torque** Torque arriving at the driven wheels after the gearbox and final drive; divided by tire radius it gives tractive force; see Chapter 5.

**Yaw** Rotation of the car about its vertical axis; see Chapter 11.

# Bibliography and Notes

This compact bibliography favors readable, widely available sources. Each item includes a short note on scope and style. The internal technical foundation of this book is the companion physics volume; the engineering titles below are the standard references for readers who want the full depth.

## Internal Reference


- **Y. J. Hilpisch, *Newtonian Physics — A Self-Contained Introduction with Mathematical Foundations* (companion volume).** Develops the mechanics used throughout this book—kinematics, Newton's laws, friction and drag, work, energy, and power, momentum, torque and rotation, oscillations, and dimensional analysis—with full mathematical derivations and additional automotive examples.


## Vehicle Dynamics


- **T. D. Gillespie, *Fundamentals of Vehicle Dynamics*, SAE International.** The standard engineering introduction to acceleration, braking, cornering, and ride; the natural next step after this book.
- **W. F. Milliken and D. L. Milliken, *Race Car Vehicle Dynamics*, SAE International.** Deep, practical, and data-driven; the reference for load transfer, tires, and yaw behaviour at the limit.
- **G. Genta, *Motor Vehicle Dynamics: Modeling and Simulation*, World Scientific.** A systematic, model-based treatment connecting simple point-mass models to full vehicle simulation.


## Tires and Aerodynamics


- **H. B. Pacejka, *Tire and Vehicle Dynamics*, Butterworth-Heinemann.** The definitive account of why real tires go beyond the simple $\mu N$ picture, including load sensitivity and slip.
- **W.-H. Hucho (ed.), *Aerodynamics of Road Vehicles*, SAE International.** The classic engineering reference on drag, lift, and the aerodynamic design of cars.
- **J. Katz, *Race Car Aerodynamics: Designing for Speed*, Bentley Publishers.** Accessible and visual; excellent on wings, downforce, and drag trade-offs.


## Powertrains and Energy


- ***Bosch Automotive Handbook*, Wiley.** The encyclopedic desk reference for everything from combustion fundamentals to driver-assistance systems.

- **J. Larminie and J. Lowry, *Electric Vehicle Technology Explained*, Wiley.** Clear coverage of batteries, electric motors, and the energy budget of EVs.

## Physics Background

- **R. Feynman, R. Leighton, and M. Sands, *The Feynman Lectures on Physics*, Vol. I.** Big-picture viewpoints on energy, motion, and force; unmatched for intuition.
- **D. Morin, *Introduction to Classical Mechanics*.** Problem-driven and witty; excellent for turning the ideas of this book into calculational skill.

# Disclaimer

This book is provided for general informational and entertainment purposes only. The text, illustrations, and worked examples have been prepared in good faith to make the ideas of physics approachable and enjoyable; they do not constitute professional, scientific, engineering, or pedagogical advice and should not be relied upon as a substitute for expert instruction, peer-reviewed texts, or your own careful calculations. While every reasonable effort has been made to ensure accuracy and clarity, the author and publisher make no warranty—express or implied—regarding the correctness, completeness, or fitness for any particular purpose of the material contained in this volume. The reader assumes full responsibility for any conclusions drawn from or actions taken on the basis of the material presented here.

All vehicle figures quoted in this book—masses, powers, torques, drag coefficients, accelerations, and braking distances—are illustrative values for generic archetypes, not specifications of real production vehicles. Nothing in this book is driving instruction or safety advice: physics explains what cars do, not what you should do. Always drive within your abilities, follow traffic laws, and consult the vehicle manufacturer's documentation and qualified professionals for any modification, maintenance, or safety question.

Research, structuring, drafting, and visualizations were assisted by different LLMs as a co-writing tool under human direction.

This is the final page of the book.