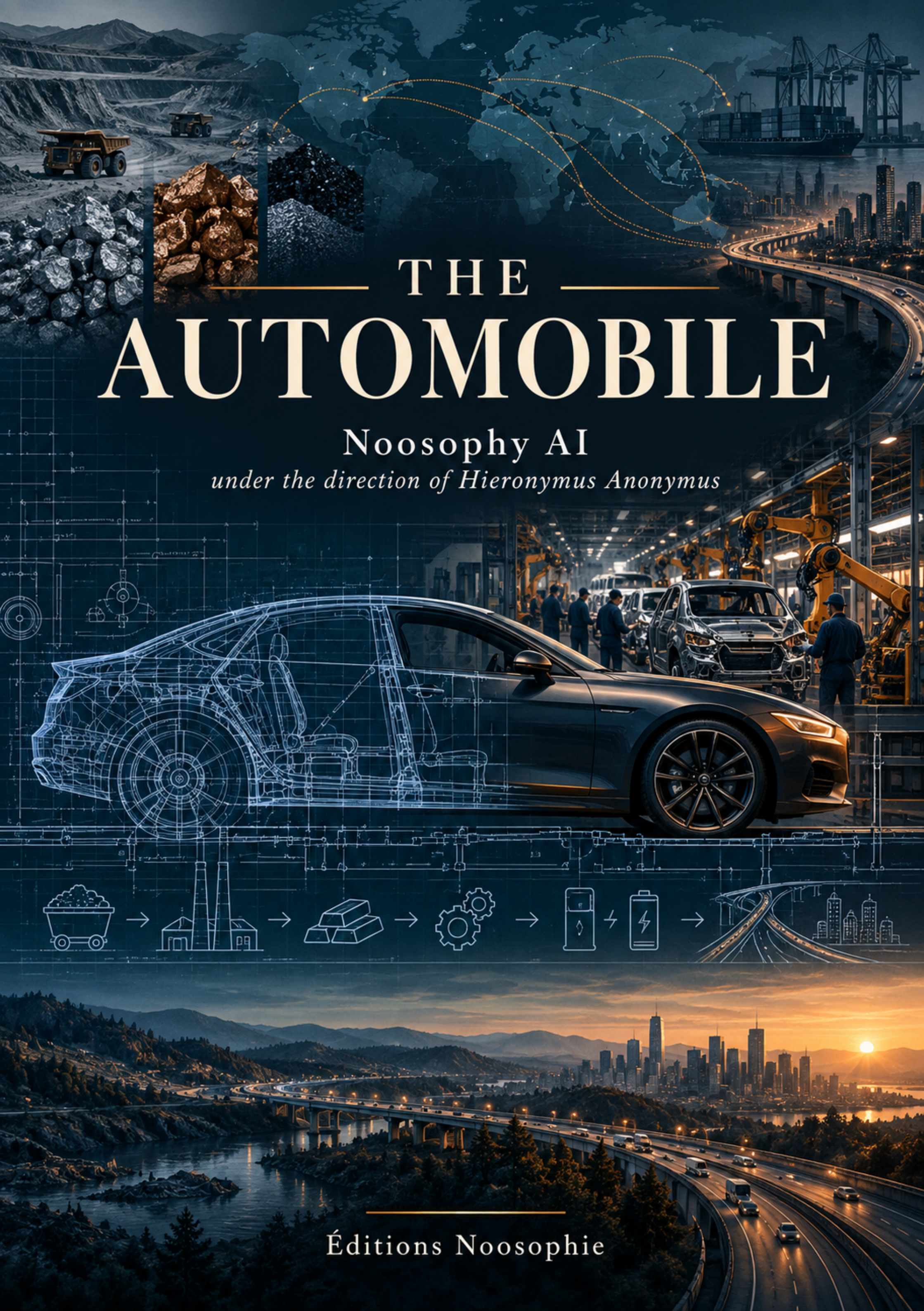
# THE AUTOMOBILE

## Noosophy AI

*under the direction of Hieronymus Anonymus*



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# AI GENERATION AND EDITORIAL RESPONSIBILITY

This book was developed through a collaboration between Hieronymus Anonymus and an AI Noosopher. Hieronymus Anonymus initiated the project, defined its subject and aims, arbitrated its directions, reviewed and corrected the work, and validated the final manuscript. The AI Noosopher contributed to documentary research, structuring, drafting, comparison of arguments, coherence audits, and editing. The text is therefore neither raw model output nor a human-written text merely corrected by AI: it results from an iterative process of generation, critique, verification, and human validation. Decisions about the book's aims, validation, and publication remain human.

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**END MATTER**

# CHAPTER 1 — FROM MACHINE TO INDUSTRIAL SYSTEM

## OPENING — THE CAR COULD NO LONGER BE BUILT THE OLD WAY

By the beginning of the twentieth century, the automobile already existed. The central problem was no longer whether a car could be built. It could.

The harder problem was whether cars could be built quickly, consistently, and cheaply enough to become an ordinary mass-market product.

That difference changed everything.

A machine can work perfectly well and still make little economic sense at scale. If every car requires extensive hand-fitting, too much time, and too much variation from one vehicle to the next, production remains slow and expensive. For the automobile to become a mass industry, manufacturing had to shift from building individual machines to creating a repeatable production system.

Ford did not invent the automobile. Nor did Ford alone invent interchangeable parts, the division of labor, or the movement of work past stationary workers. Its engineers combined ideas with longer histories in arms manufacture, machine tools, bicycles, clocks, and even the disassembly lines of meatpacking. [1]

What emerged at Highland Park was more important than any one technique: a system in which standardized parts, specialized operations, factory layout, tooling, and moving assembly reinforced one another.

General Motors later took mass production in a different direction. Ford learned how to build millions of highly similar cars. GM learned how to make variety systematic without giving up industrial scale.

Those two breakthroughs shaped much of the modern auto industry: first, learn to produce at mass scale; then, learn to keep selling in a market where millions of cars are already on the road.

## 1. BEFORE THE ASSEMBLY LINE: WHY SMALL-SCALE PRODUCTION COSTS SO MUCH

Craft production has an obvious strength: flexibility. A skilled worker can adjust a component, correct a fit, change a sequence, and solve a local problem as it appears.

But that flexibility depends on exactly what mass production tries to reduce: time, variation, and reliance on individual judgment at every step.

Imagine one hundred cars being built by one hundred small teams. Each team needs broad knowledge, because panels may fit a little differently and components may need rework. Workers move around the product, fetch tools, transport parts, and wait for earlier operations to finish. That kind of system can build excellent machines, but it is poorly suited to producing millions of similar ones at low unit cost.

Mass production reverses the logic. Instead of adapting the production process to each individual car, the car itself is designed to fit the production system.

Parts have to be interchangeable enough to go in without hand fitting. The work has to break down into repeatable steps performed in a known sequence. Machines and workers then have to be arranged around that flow, with each station taking a predictable amount of time.

The car itself has to be designed for repeatability.

That changes how engineers have to think. A car is no longer designed only to work on the road; it is also designed so factories can build the same product again and again.

## 2. FORD: TURNING TIME INTO PRICE

Ford's experiments at Highland Park began in 1913. The moving line did not appear fully formed. Engineers first tested continuous movement on subassemblies such as magnetos, then engines and transmissions, and eventually the chassis. Crude arrangements in which components were pushed or pulled along gave way to mechanically driven systems.

By early 1914, The Henry Ford reports that continuous-flow methods had reduced Model T assembly time from roughly twelve and a half hours to about ninety-three minutes.[1]

The number is memorable, but what that time savings set in motion matters more.

Saving time cut costs, which made lower prices possible. Lower prices brought in more buyers, and the resulting demand justified even greater production volume. That scale, in turn, made further investment in specialized machinery, tooling, factory layout, and process improvement worthwhile.

The Henry Ford describes the same feedback loop: lower production time and cost supported lower prices, lower prices stimulated demand, and demand pushed Ford to find still more efficient ways to produce.[1]

The price history of the Model T gives a sense of the scale. Ford records a decline from about $825 in 1908 to roughly $260 in 1925.[2] More than fifteen million Model Ts were ultimately built between 1908 and 1927.

This was more than a commercial success. It changed the market the automobile could reach. Cars were becoming affordable to a much larger share of households, and the production system that drove prices down now had to serve the much larger market those lower prices helped create.

Production and demand began to reinforce each other.

## 3. THE OTHER SIDE OF THE LINE: ORGANIZING LABOR TO ORGANIZE VOLUME

The moving line did more than eliminate wasted motion. It redistributed skill.

In a more craft-oriented shop, a worker may participate in many operations and carry a large share of process knowledge personally. On a moving line, tasks are decomposed. Some knowledge moves out of the worker and into the organization of the system: station order, fixtures, tooling, machine settings, standardized parts, and line speed.

That shift can raise productivity dramatically. It can also make work repetitive, tightly paced, and difficult to sustain.

Ford's own histories describe workers leaving because of the monotony and discipline imposed by moving production.[3] The Henry Ford documents turnover so severe that the company reportedly had to hire roughly 53,000 people to maintain a workforce of about 14,000 during the period preceding the 1914 wage policy.[4]

The production technology had created a second industrial problem: how do you keep enough workers to run the system reliably?

The famous Five-Dollar Day makes more sense in that context. Ford sharply increased compensation and shortened the workday. The policy was neither pure philanthropy nor simply a tool of managerial control. Ford had an urgent retention problem; the move also generated enormous publicity and increased the purchasing power of some workers.[3][4]

Mass production changed more than the machine. It also changed wages, discipline, recruitment, skill, and the way work was organized around production.

Chapter 8 returns to the longer history of automotive labor. For now, the narrower lesson is enough: mass production already depended on a whole system. A moving line could not succeed without workers, suppliers, machines, material flows, and markets operating reliably together.

## 4. WHY STANDARDIZATION WORKS—UNTIL IT DOESN'T

The Model T demonstrates the power of stability.

For nearly two decades, Ford could refine production around a vehicle whose basic architecture changed relatively little. Suppliers learned familiar components. Tooling and machinery were amortized across enormous volumes. Workers and engineers accumulated knowledge around a known product. Standardization allowed the company to extract more and more efficiency from repetition.

That is exactly why long-lived platforms are attractive. Stability can create large parts populations, known failure modes, mature processes, and deep repair knowledge.

But the Model T also shows where stability can become a liability.

The world around the Model T kept changing. Roads improved, buyers gained experience, and expectations shifted toward more power, comfort, speed, color, equipment, and style. The Henry Ford's retrospective account links the Model T's decline to those changes in roads and consumer expectations.[5]

Ford waited too long to replace its dominant product.

Standardization itself was not the failure. The problem was that the same stable design that delivered enormous economies of scale became harder to adapt as roads, expectations, technologies, and markets changed.

Standardization does not have to mean freezing a design in place. A durable vehicle system works only if the parts that need to change can change without forcing the entire product to be discarded.

That problem—long-term compatibility—returns when we examine repairability and maintainability. But it is already visible here, at the height of mass production.

## 5. SLOAN: BUILDING VARIETY ON A STANDARDIZED BASE

General Motors responded to Ford in a way that is often oversimplified.

The usual story pits Ford's standardization against GM's variety. That misses the more important point: GM kept many of the industrial advantages of standardization while offering customers a much more differentiated lineup.

The phrase associated with Alfred Sloan—"a car for every purse and purpose"—captures the strategy.[6]

Instead of trying to sell nearly the same car to the largest possible market, GM built a ladder of brands, prices, and status. Chevrolet occupied the lower end; other divisions filled the steps above it; Cadillac sat at the top.

Customers were no longer invited simply to enter the automobile market. They could move within it.

This created an important industrial shift: GM made variety systematic.

Divisions could share components, engineering principles, purchasing power, and production capabilities while presenting customers with vehicles that looked and felt meaningfully different. GM's own historical material describes Sloan encouraging component sharing across divisions as a way to control costs.[7]

Internal standardization is not the same thing as visible uniformity.

That distinction still defines much of the modern auto industry. A single platform can underpin multiple models, body styles, brands, and price points. Customers see variety; manufacturers try to preserve commonality underneath.

## 6. MAKING A WORKING CAR FEEL OLD

A product ladder alone does not create a renewal market. A vehicle can still work perfectly well and yet become commercially dated long before it is mechanically worn out.

That is where the annual model change matters.

The Smithsonian National Museum of American History credits General Motors in the 1920s with establishing the annual model change and with using what it calls design obsolescence as a selling strategy.[8]

The term needs care.

It does not mean the car was engineered to fail. It means a functioning car could be made visibly dated relative to its successor.

Colors, body shapes, trim, grilles, chrome, proportions, and other styling details became markers of time. Styling gave a car a visible age in the market that could diverge sharply from its mechanical condition.

That distinction changes how replacement is perceived. If an eight-year-old vehicle looks nearly identical to the new one, the owner needs a largely functional reason to replace it. If model years visibly announce novelty, age becomes part of the product's social and commercial meaning.

The market is no longer selling only transportation. It is also selling the difference between what the buyer owns and what has just arrived.

Yet it would be a mistake to reduce Sloan's system to styling. Annual model changes interacted with genuine technical improvements, the product ladder, dealer networks, trade-ins, and financing.

No single element created the renewal market by itself. The system worked because styling, technical improvement, financing, trade-ins, dealers, and product tiers reinforced one another.

## 7. CREDIT: WHEN MASS PRODUCTION RUNS INTO FINANCE

Continuous production raises a simple question: who pays for cars before they are sold?

The historical study "Credit Cars" shows that mass production first created a financing problem for dealers. Automobiles were manufactured in anticipation of future sales, while demand remained seasonal. Dealers had to carry inventory they could not always finance from their own capital.[9]

Auto finance emerged partly because mass production created that financing problem.

General Motors created GMAC in 1919. Its early role was heavily tied to dealer inventory finance, even as retail financing was also developing. During the 1920s, the system increasingly extended installment credit to consumers.[9][10]

That shift changed the market.

In a cash purchase, the question is: can I pay the full price today? With installment credit, the question becomes: can I carry the monthly payment from future income?

That sounds like a financial change, but it also changes what factories can produce and sell.

Credit lets more customers buy now, which lets factories sell more of what they produce now. In effect, the pace of the assembly line becomes tied to households' future income.

The scale of installment selling grew rapidly, but historical estimates do not all use the same year, population, or denominator. Research cited in the literature places the share of new cars bought on credit at very high levels during the 1920s, while a 1955 Federal Reserve Bank of St. Louis speech gives an estimate close to two-thirds for 1926.[9][11]

The exact percentage matters less than the larger point: installment credit became part of the infrastructure of the mass automobile market.

Finance was no longer just something added after the car was built. It became part of what made high production volumes possible.

## 8. TRADE-INS, PRODUCT LADDERS, AND REPLACEMENT: THE SECOND MACHINE

Credit does more than broaden initial access. It changes the logic of replacement.

If the customer sells or trades in an older car, its remaining value becomes part of the purchase of the next one. If the manufacturer offers several price tiers, the customer can move upward. If new model years make change visible, the new product advertises the age of the old one. If credit converts the remaining balance into payments, the gap between vehicles can feel smaller than the difference in their total prices.

These mechanisms are different, but together they changed the market.

Ford had built a machine capable of producing automobiles at mass scale. Sloan-era GM helped build a machine capable of producing renewal at mass scale.

That shift matters because a growing market eventually runs out of first-time buyers.

Early growth can come from selling a first car to households that do not yet own one. As ownership spreads, the industry has to rely more on other sources of demand: replacing an existing vehicle, moving up the product ladder, adding another car, buying new features, adopting technical improvements, or responding to changes in style.

The used-car market does not sit outside the new-car market. It helps make the new-car market work.

A vehicle replaced by its first owner does not necessarily disappear. It can move to a second owner, pushing another older car farther down the market. New-car replacement can accelerate at the top of the market without requiring every replaced car to be physically destroyed.

This distinction will matter throughout the book.

A car can be commercially dated and still have years of mechanical life left.

## 9. FRANCE: ADOPTING FORDISM, THEN SCALING DIFFERENTLY

An American account of mass production can easily create the impression that scale depends on one institutional model: large private corporations, integrated finance, mass consumer markets, and brand competition.

France provides a useful counterexample—not because it invented a completely different technology, but because it organized similar production methods through a different set of institutions.

French mass automobile production did not begin after World War II. Before the First World War, André Citroën studied American industrial methods. During the war, his Javel plant used large-scale production organization for shells; in 1919 the site was converted to automobile production. The Musée des Arts décoratifs describes the transition as a move from craft manufacture toward industrial mass production inspired in part by Ford.[12]

Citroën’s Type A became an important European milestone. Company historical material presents it as the first automobile built in Europe in large series, with an explicit goal of delivering a robust and economical complete car at an accessible price.[13]

This chapter is not a detour into French industrial history. The French case matters because it shows that Ford-style mass production could travel: the core idea was to design both the product and the factory for repeatable production.

After World War II, France produced a second, institutionally different case.

Renault was nationalized in 1945. The legal structure created the Régie nationale des usines Renault as a public industrial and commercial enterprise with financial autonomy under state control.[14] That distinction matters. Renault was not simply a government department producing cars from an unlimited budget. It sold products, used credit, and could borrow within a public framework.

The 4CV became one symbol of the postwar mass market. Renault records more than 1.1 million examples produced between 1947 and 1961, making it the first French car to pass the million-unit mark.[15]

More important than the milestone is the industrial method. Renault describes greater component standardization, design decisions made with manufacturing constraints in mind, and transfer machines associated with Pierre Bézier that automated machining operations at significant scale.[16]

Highland Park was not a uniquely American recipe that worked only inside Ford. Its core production principles could be adapted to very different ownership and financial structures.

## 10. BEHIND THE FACTORY: ENERGY, STEEL, CREDIT, INFRASTRUCTURE

Even an extraordinarily efficient automobile plant cannot produce millions of vehicles if the surrounding system is missing.

It needs steel and other materials. It needs electricity and fuel. It needs machine tools, transport capacity, capital, suppliers that can meet the same production rhythm, and distribution networks capable of selling what the factories produce.

Postwar France is useful here because several of those layers had to be rebuilt at once.

The first French modernization plan targeted sectors including coal, electricity, steel, cement, transportation, and agricultural machinery. Marshall Plan assistance supplied goods and foreign exchange, while counterpart funds were used in part to reconstruct and modernize the capital stock.[17]

American diplomatic records from 1949 show French counterpart funds supporting investments that included electricity, coal, reconstruction, rail, agriculture, and private industry.[18]

It would be wrong to add those expenditures together and call the result "the public cost of the automobile."

Electricity served the whole economy. Steel had many uses. Rail, coal, reconstruction, and agricultural investment had functions independent of car production.

But the opposite claim would be equally wrong: that mass automobile production appears simply because one manufacturer learns to assemble cars efficiently.

Mass production becomes durable when a dense industrial environment can continuously provide materials, energy, machinery, finance, transportation, suppliers, distribution, maintenance, and customers.

At that point, the automobile no longer makes sense as an isolated machine.

## 11. WHEN THE CAR BECOMES A SYSTEM

We can now return to the opening question.

When does an invention become an industrial system?

Not when the first prototype works. Not even when the first factory opens.

It becomes a system when producing it at scale depends on institutions and infrastructure that reinforce one another.

Standardization requires suppliers that can meet the same specifications again and again. High volume requires mass demand. Mass demand requires a price ordinary households can afford, credit, or both. Credit requires lenders, contracts, collateral, and a resale market. Replacement requires reasons—technical, economic, or symbolic—to buy again. Product variety requires platforms and processes that can create differences without throwing away every economy of scale.

Production requires energy, materials, machinery, and logistics. Use requires fuel, roads, maintenance, and parking.

Each layer makes the others easier to sustain.

Once that network is in place, it becomes hard to explain the car without explaining the system around it.

Ford did more than speed up an assembly operation. Ford built a loop in which productivity lowered price, lower price expanded demand, and demand justified more productivity.

Sloan and GM did more than add colors and chrome. They built a sales system in which product ladders, model changes, credit, trade-ins, and differentiation encouraged customers to return to the market.

The French cases show that mass production could also work under a different political and financial structure, provided the necessary industrial base existed.

These systems do not replace one another. They stack on top of one another.

Modern cars are still produced through extreme standardization. They are still sold through differentiation. They are financed, traded in, repaired, resold, and used through infrastructure that no single automaker controls.

The automobile is a system because you cannot explain any one of those layers for long without running into the others.

## 12. FROM MASS PRODUCTION TO MASS RENEWAL

The twentieth-century auto industry solved two different scaling problems in succession.

The first was cost: how do you make a complicated machine cheap enough for a mass market?

Ford's answer was spectacular: standardize, decompose the work, move the product, increase volume, and improve the process relentlessly.

The second was renewal: what happens when millions of people already own cars?

GM's answer was different: segment the market, differentiate the product, finance the purchase, take the old vehicle in trade, improve the new one, and give model change a visible commercial rhythm.

Both patterns are still with us.

They explain how an industry can standardize millions of components while producing vehicles that look radically different. They explain how a car can remain mechanically sound while becoming commercially dated. And they explain why credit is not merely a banking service added after manufacturing but part of the industrial system that sustains volume.

They also explain why public institutions can own firms, finance infrastructure, plan investment, or build roads without becoming the single author of the automobile market.

Most important, they show why the central question of this book is not simply: why don't manufacturers build a car that lasts?

Before we can answer that, we have to understand what the automobile system has actually been built to optimize.

The next chapter moves inside the vehicle itself. It asks how engineers and organizations decide what must be strong, safe, accessible, replaceable, standardized, repairable, and maintainable—and what happens when those goals conflict.

## NOTES AND SOURCES


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[2] Ford Motor Company, "The Moving Assembly Line and the Five-Dollar Workday," 2020; and "The Model T," 2020. Ford reports, among other figures, a Model T price decline from about $825 in 1908 to roughly $260 in 1925.

[3] Ford Motor Company, "The Moving Assembly Line and the Five-Dollar Workday," 2020. Used for labor-retention difficulties and the Five-Dollar Day.

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[14] France, Ordonnance no. 45-68 of January 16, 1945, nationalizing the Renault factories, via Légifrance. The law created the Régie nationale des usines Renault as a financially autonomous industrial and commercial public enterprise under state control.

[15] Renault, The Originals Museum, “4CV.”

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# CHAPTER 2 — DESIGNING TO BUILD, USE, AND MAINTAIN

## OPENING — A PART TEN TIMES STRONGER?

An engineer receives what sounds like a simple request: make a component substantially stronger without changing the material, adding significant cost, or requiring new production machinery. The engineer changes the geometry. According to the story passed down to us, the new part turns out not three times stronger but roughly ten times stronger. Management's response is said to have been: "We asked for three times, not ten."

It is a perfect story because it captures several suspicions people already have about the auto industry: the clever engineer who can do better, managers focused on the minimum specification, and the fear that nobody wants a car to last too long.

But the story is only secondhand testimony. We do not know what the component was, what "strength" meant, whether the improvement concerned ultimate load, fatigue, bending, or impact, or whether making one part dramatically stiffer would have created a new problem in crash behavior, vibration, load transfer, mass, tooling, or validation.

So the anecdote proves nothing.

It still asks an excellent question: why does a specification stop where it does when more appears technically possible?

That is a better question than starting with planned obsolescence, because it forces us to look at what an industrial vehicle actually is. A car is not a collection of parts that engineers simply try to make as strong as possible. It is a system of compromises among cost, mass, packaging, production speed, safety, noise, energy use, emissions, durability, recyclability, material availability, maintenance, warranty exposure, regulation, comfort, and increasingly software.

The difficulty begins here: “lasting” is not one function.

## 1. THE WRONG QUESTION: WHY NOT MAKE IT INDESTRUCTIBLE?

The image of an indestructible car is misleading because a complex system has no single maximum.

Consider a body structure. Making it stiffer may improve dimensional stability. Designing parts of it to deform can save occupants in a crash. A component with enormous strength may merely transfer loads into a weaker mounting point. Thicker material can add mass, which then affects energy use, collision energy, tires, suspension, and handling. A permanently bonded assembly may be structurally excellent yet extremely difficult to repair after a local impact.

Modern cars are the product of decades in which safety often demanded something more sophisticated than simple robustness.

NHTSA estimates that the average vehicle on the road in 2012 presented an occupant fatality risk roughly 56 percent lower than the average vehicle of the late 1950s. The agency also estimates that improvements in vehicle safety saved more than 600,000 lives cumulatively between 1960 and 2012.[1]

That does not justify every layer of complexity. It does mean that a simple older car is an inadequate benchmark for judging a modern one. Crash structures, seat belts, airbags, anti-lock braking, electronic stability control, pretensioners, and crash-avoidance systems changed what the vehicle is required to do.

A car that lasts a long time but protects its occupants poorly is not a design success.

So the useful question is not “why isn’t every part stronger?” It is “strong enough for what, for how long, and at what cost to everything else the car has to do?”

## 2. FIVE DIFFERENT WAYS A CAR CAN LAST

Much confusion disappears once several ideas hidden inside the word durability are separated.

Technical durability is the physical ability of a component or system to remain functional. An engine block may be physically capable of surviving very high mileage.

Reliability is the probability that the system will perform without failure over a given period or mileage. A machine can be physically durable for decades while suffering frequent repairable failures. Another can be extremely reliable for years and then become uneconomic to repair after one rare failure.

Maintainability is the ease and speed with which a failure can be diagnosed, accessed, repaired, and returned to service.

Economic repairability asks whether restoring the vehicle is financially rational compared with its market value and available replacements.

Actual longevity is the time the vehicle remains in use. It depends on all the other dimensions, but also on resale value, owner income, parts prices, insurance, regulation, and the used-vehicle market.

These are not semantic niceties. They describe different failure points.

A modern car can last longer than an older one, crash more safely, and suffer fewer major mechanical failures while becoming much more expensive to restore after certain collisions. It can remain physically sound while depending on proprietary diagnostics, software, calibration, authentication, or an electronic module that is no longer supported.

The design question is not simply whether the vehicle is solid. It is which forms of longevity the architecture makes possible.

## 3. A CAR IS NOT DESIGNED BY ONE ACTOR

We often speak about “the manufacturer” as though one company designed every bolt, sensor, controller, seat, and software module.

Modern vehicle development is distributed.

The automaker controls architecture, integration, brand requirements, validation, and large parts of the specification. Tier-one suppliers may design complete braking, lighting, thermal, seating, power-electronics, or control systems. Other suppliers provide sensors, chips, materials, connectors, software, and individual components. Some parts are designed to an extremely detailed automaker specification; others are adapted from a supplier’s existing technology.

Safety standards, emissions rules, cybersecurity requirements, and diagnostic obligations add constraints from outside the commercial relationship.

The financial statements themselves reveal this distributed responsibility. Ford and General Motors account not only for their own warranty costs but also for recoveries from suppliers when responsibility can be attributed to supplied components. [2][3]

So when a technician asks, “Why did they put the pump there?” there may be no single “they.”

The location can emerge from packaging, heat management, assembly sequence, a platform shared across several models, supplier constraints, crash protection, noise, aerodynamics, manufacturing cost, regulatory compliance—and only after all of those, workshop access.

This does not eliminate responsibility. It makes responsibility more precise. If maintainability is to improve, we have to know which actor controls the design choice and which metric gives that actor a reason to care.

## 4. THE INDUSTRY REALLY DOES LEARN FROM FAILURES

One early intuition has to be rejected: automakers do not begin each generation as if previous failures had never happened.

The industry has formal systems for anticipating and learning from failure.

Failure Mode and Effects Analysis requires teams to identify potential failure modes, consequences, causes, and prevention or detection controls. SAE J1739, stabilized in 2026, covers design FMEA, supplemental monitoring-and-system-response FMEA, and process FMEA and explicitly structures the identification and mitigation of risk.[7]

Design validation, field reports, warranty claims, recalls, supplier analysis, and service data add feedback after vehicles enter use.

These loops have enormous financial consequences.

Ford says it estimates warranty and field-service obligations by vehicle line and model year using historical claim type, frequency, and average cost, then updates those estimates as actual experience develops. At the end of 2025, Ford reported roughly $17.19 billion in accrued future warranty and field-service costs net of supplier recoveries.[2]

General Motors used a similar process. At the end of 2025, GM reported approximately $13.6 billion in warranty and recall liabilities, with roughly $7.9 billion in warranty expense for the year net of supplier recoveries.[3]

Those amounts are enough to destroy a very simple theory: an early failure under warranty is not automatically profitable for the automaker. It can trigger large costs, recalls, engineering work, litigation, and reputational damage.

Why, then, do technicians still encounter characteristic weak points in particular vehicles?

Because learning is not the same thing as freezing an architecture.

A company may correct one weakness and simultaneously redesign the platform for crash requirements, emissions, electrification, manufacturing savings, packaging, software architecture, new suppliers, lower mass, or new customer features. Knowledge gained on the old architecture does not always transfer cleanly to the new one.

The real tension is between two clocks. Reliability work tries to improve the product that exists. Industrial development is already creating the product that comes next.

The issue is not whether the industry forgets everything it learns. It is how much of that knowledge and compatibility survives into the next platform.

## 5. STANDARDIZING FOR PRODUCTION IS NOT THE SAME AS STANDARDIZING FOR REPAIR TWENTY YEARS LATER

The automobile industry already knows how to standardize at enormous scale.

Toyota describes TNGA as a common architectural approach combined with intelligent sharing across models, plants, and suppliers.[4] Stellantis says its STLA One architecture is intended to support many models with high levels of component reuse across major global platforms.[5]

So the useful question is not why every car has unique parts. Many parts are already shared.

The industry primarily standardizes what improves development and production: platform interfaces, powertrains, electronic modules, mounting points, invisible components, software foundations, and factory tooling.

That is different from compatibility over time.

A platform shared across millions of cars does not guarantee long-term support. Twenty years later, a part may no longer be made. A 2035 controller may not work in a 2028 vehicle. An electronic interface may be closed, a used module may be impossible to recode, documentation may disappear, or independent suppliers may be unable to reproduce the component.

This distinction may be one of the strongest in the entire book.

Industrial standardization asks: how much can we reuse across vehicles being designed and produced now?

Long-term compatibility asks: how much of today's parts, interfaces, tools, and knowledge will still work years from now?

There are good reasons not to freeze every interface forever. New crash requirements, security vulnerabilities, higher efficiency, new materials, and new functions can make old constraints expensive. Long-term compatibility itself has engineering and cybersecurity costs.

But incompatibility is not inevitable either. It often results from design choices, and those choices can be measured.

## 6. WHAT MODERN SAFETY GAINED—AND WHAT IT MADE HARDER TO REPAIR

Safety is the best antidote to simple nostalgia.

Modern vehicles contain more sensors, controllers, reinforced structures, deformable zones, airbags, and driver-assistance systems. That complexity can raise repair costs. It cannot be evaluated only from the collision-repair invoice.

Consider advanced driver-assistance systems. A camera mounted behind a windshield or a radar behind a bumper may need calibration after replacement. A collision that once required only a body panel can now damage an expensive sensor.

IIHS-HLDI has documented this tradeoff: crash-avoidance technology can make some repairs more expensive while still reducing total losses because it prevents enough crashes in the first place.[6]

For an insurer, repair cost conditional on a crash is only half the equation. Frequency matters too.

One technology can do several things at once: make a repair more expensive, reduce the chance of a crash, save lives, require more skill in the shop, make calibration essential, and still reduce total expected losses.

“More complex” does not tell us whether the system is better or worse.

The real design problem is whether safety benefits can be preserved while making restoration less expensive and less fragile.

## 7. REPAIRING WITH A WRENCH, A SCAN TOOL, A SERVER, AND A LEGAL RIGHT OF ACCESS

For much of automotive history, repairability could be imagined mainly as a mechanical problem: reach the part, remove it, fix or replace it, reinstall it.

That definition is no longer enough.

A modern vehicle can be physically accessible and still be practically unrepairable without electronic diagnostics, manufacturer software, a calibration procedure, an authenticated account, security credentials, a data service, a server connection, or a compatible software version.

In the United States, access to those layers is not governed by one comprehensive rule. It is a stack of different rights and obligations.

Federal warranty law is one layer. FTC consumer guidance under the Magnuson-Moss Warranty Act makes clear that a manufacturer or dealer generally cannot cancel warranty coverage merely because an owner used an independent shop or aftermarket or recycled parts. If a non-original part or an improper repair causes damage, coverage can be denied for that damage, but the manufacturer or dealer bears the burden of linking the damage to the part or work.[8]

That protects repair choice. It does not by itself give every shop every diagnostic key or every data stream.

Emissions-related service information is another layer. EPA states that the Clean Air Act requires manufacturers to provide information needed to diagnose and repair emission-control systems, including OBD information, training material, enhanced diagnostics, reprogramming information, and certain manufacturer-specific tools. EPA reaffirmed these service-information obligations in 2026.[9]

Telematics creates another problem. Massachusetts chapter 93K provides a state-level example: for covered model-year 2022 and later vehicles with telematics, owners have rights to access mechanical data and to authorize an independent repair facility to access that data for diagnosis, maintenance, and repair.[10] That is Massachusetts law, not a national rule.

Copyright law adds yet another layer. Federal regulations include exemptions allowing circumvention of software in lawfully acquired motorized land vehicles when necessary for diagnosis, repair, or lawful modification under specified conditions. The Copyright Office is explicit that the exemption does not create immunity from other applicable laws.[11]

These layers answer different questions.

Keeping a warranty, obtaining emissions information, receiving telematics data, authenticating a security-sensitive function, and legally bypassing a technological protection measure are not the same right.

Modern repairability is therefore an informational and legal problem as well as a physical one.

Cybersecurity makes the problem harder rather than simpler. NHTSA's vehicle cybersecurity best practices explicitly recommend that manufacturers consider serviceability by owners and third parties and provide strong cybersecurity protections without unduly restricting alternative third-party repair services authorized by the owner. The same guidance also warns that serviceability cannot be allowed to weaken cybersecurity controls.[12]

That is the correct tension.

A connected car whose braking, steering, or safety systems could be modified without meaningful authorization would be dangerous. A connected car whose security design makes lawful independent maintenance impossible would create a different kind of dependency.

Modern maintainability increasingly depends on trusted access. The system has to verify who is allowed to do what, protect safety and data, and still let owners use legitimate repair providers outside a single centralized gatekeeper.

## 8. WHEN A REPAIRABLE VEHICLE BECOMES TOO EXPENSIVE TO SAVE

A failure does not end a vehicle's life only when repair is physically impossible.

It can end the vehicle when repair is no longer economically rational.

That is especially visible after a crash. An insurer weighs estimated repair cost, uncertainty, residual value, and the value of the vehicle before the loss. The same damage can be repaired on a newer high-value car and total an older low-value one.

Electric vehicles make this tradeoff unusually easy to see because so much of the vehicle's value can be concentrated in the high-voltage battery.

Thatcham Research's 2026 EV Blueprint estimates that the battery can account for up to roughly 40 percent of an EV's value.[13] It also documents cases in which limited damage to casings, brackets, or related components can lead to full-pack replacement when the design or approved repair process does not allow a smaller repair.

The battery alone is not the problem. What matters is the combination of vehicle design, approved procedures, diagnostic capability, parts availability, pack price, access to remanufactured components, and the vehicle's remaining value.

Thatcham recommends separately replaceable protective parts and brackets, accessible safety devices, clearer damage assessment, and repair methods that avoid replacing the entire pack when a smaller repair is safe and feasible.[13]

This reveals a broader point.

How long a car remains worth keeping depends on more than the hardware. It also depends on the repair ecosystem around it.

A physically intact module can become unusable because it cannot be paired. A repairable assembly can become uneconomic because the smallest purchasable part is the entire assembly. A battery can retain useful capacity and still be rejected if no accepted procedure can verify its post-crash condition.

A vehicle can reach the end of its usable life for physical, electronic, informational, legal, insurance, or economic reasons.

Mechanical strength alone cannot solve all of those failure modes.

## 9. THE BATTERY AS A TEST OF MAINTAINABILITY

Electric vehicles make these tradeoffs unusually easy to see.

Its drivetrain contains fewer moving mechanical parts than a conventional combustion powertrain. It can eliminate engine oil, complex exhaust aftertreatment, clutches, multi-speed transmissions in many designs, and much friction-brake wear through regenerative braking.

It also adds a high-value battery, power electronics, thermal management, and a high-voltage electrical architecture.

High voltage changes workshop practice as well as vehicle design.

In the United States, ASE's xEV high-voltage electrical safety standards distinguish levels of worker competence and describe practices for technicians who isolate high-voltage systems, verify isolation, use appropriate personal protective equipment, establish safe work areas, follow OEM procedures, and assess accident-damaged electrified vehicles.[14]

Federal workplace rules establish a broader safety principle: servicing equipment with hazardous stored energy requires procedures that prevent unexpected energization or energy release, along with training and verification. OSHA's lockout/tagout standard is not an EV-specific repair code, and other electrical-safety rules may also apply. But the basic requirement is the same: identify the energy source, isolate it, control it, and verify that the system is safe before dangerous work begins.[15]

Those safety requirements are real. They demand training, equipment, procedural time, shop organization, and sometimes specialization that not every independent shop will have.

Electrification can reduce many routine mechanical maintenance tasks while making some remaining repairs more technically demanding and safety-sensitive.

That matters when we compare two possible battery architectures.

One pack may be highly integrated, difficult to open, minimally repairable, and normally replaced as a complete assembly. That may offer genuine advantages in mass, stiffness, manufacturing cost, or packaging while making certain failures economically severe.

Another may accept extra fasteners, interfaces, protective parts, or diagnostic provisions to permit local repair.

Neither is automatically superior.

Perfect repairability is no more realistic than perfect durability. Modular designs can add mass, cost, interfaces, sealing challenges, and potential failure points. Integration can create real engineering gains.

The important difference is whether maintainability is treated as a measurable design outcome before production.

We already measure acceleration, drag, range, mass, charging time, manufacturing cost, and crash performance. We could also measure average access time to key components, cost of replacing subassemblies, share of failures repairable without whole-assembly replacement, proprietary tools required, parts availability over time, cross-generation compatibility, software-support duration, and restoration cost after standardized damage.

Maintainability can be engineered only if it is made visible.

## 10. A CAR DESIGNED TO EVOLVE: A THOUGHT EXPERIMENT, NOT A RETURN TO THE PAST

The French 2CV inspired a useful thought experiment, but the idea does not depend on nostalgia for one model.

Imagine a vehicle architecture deliberately designed to remain in service for twenty or thirty years while allowing the systems that genuinely need to change to evolve.

A long-lived design might use common interfaces for wear components, replaceable electronic modules, and repair documentation that stays available. Safety upgrades could be retrofitted where technically feasible, while body and interior parts could be replaced without discarding major structures. Even the battery or powertrain could evolve without forcing replacement of the entire vehicle.

The goal would not be to freeze a 1950s car forever. It would be to separate what must evolve from what can remain.

The body cell or basic platform might have a long service cycle. Electronics could change more frequently. A software upgrade would not automatically require a complete hardware replacement. Cosmetic renewal could be decoupled from expensive structural renewal.

That begins to look less like a product replaced on a short cycle and more like maintained infrastructure.

But the objections are serious.

What happens when a new crash standard requires different geometry? When a security vulnerability makes an old electronic architecture unsafe? When a new material permits a large reduction in mass? When a battery design no longer meets current safety expectations? When an emissions or safety requirement changes the package itself?

Absolute compatibility across thirty years can become its own form of rigidity.

The goal is not permanent backward compatibility. It is to preserve compatibility deliberately where doing so creates real long-term value.

Aviation, rail, industrial equipment, commercial trucks, and other maintained systems show that a complex machine can stay in service while parts, software, and subsystems change. What lasts is not every component. What lasts is the ability to keep the larger system serviceable.

## 11. WHY IS MAINTAINABILITY NOT OPTIMIZED MORE AGGRESSIVELY?

The industry already has failure analysis, warranty feedback, common platforms, global logistics, software-update systems, diagnostic standards, remanufacturing capability, and powerful simulation tools.

So why is maintainability not more often a central design and sales attribute?

The first answer is that it competes with many other objectives.

A buyer values purchase price, monthly payment, styling, comfort, safety, energy use, performance, range, image, and convenience. A repairability improvement that adds purchase cost may be difficult to sell when its benefit appears twelve years later to a third owner.

The second answer is that the costs occur at different times and are borne by different actors.

Five dollars saved in the factory is immediate, certain, and multiplied by hundreds of thousands of vehicles. Two extra labor hours in a repair a decade later are uncertain, dispersed, and may be paid by an owner, insurer, independent shop, used-car buyer, or another party.

That asymmetry matters.

The third answer is that maintainability can conflict with other engineering goals. More access space increases package volume. Removable connectors can add cost, mass, sealing problems, or failure points. Separating a structural assembly can reduce stiffness or increase fastener count. Supporting software for decades creates development and cybersecurity obligations.

Commercial differentiation matters too. If modules become highly standardized, repairable, and cross-compatible, some revenue and control can shift from the automaker to suppliers and the independent aftermarket. An open interface is not just a technical choice. It also changes who can capture value from repairs and upgrades.

This is where the chapter has to stop.

Here we are identifying the design choices that make maintenance easier or harder. The next chapter will examine how manufacturers, finance companies, dealers, insurers, and independent repair markets capture value from those choices.

Mixing the two questions would blur how the car is engineered with why different actors may prefer different economic outcomes.

## 12. CHANGING WHAT THE SYSTEM OPTIMIZES

The most important result is not that modern cars are badly designed.

It is almost the opposite.

Modern cars are highly optimized—but for many objectives that do not always point in the same direction.

Different actors optimize different things. Factories care about assembly time and unit cost; safety engineers about crash and avoidance performance; compliance teams about certification; suppliers about their subsystems; and automakers about platforms, volume, and differentiation. Finance teams watch residual value, dealers watch service and customer retention, insurers watch claim frequency and severity, and owners watch price, payments, usefulness, and breakdown costs. Technicians focus on access, diagnosis, tools, calibration, and labor time. A later owner may reduce all of that to one question: is this still worth repairing?

No single actor automatically bears the full twenty-year cost of the vehicle.

That may be the deeper weakness of the system: not a hidden plan to make cars fragile, but a situation in which different actors optimize different pieces of the vehicle's life.

A system designed for longer life would have to do more than strengthen parts. It would have to make short-term design and production decisions account for long-term ownership, repair, resale, and reuse.

That means bringing future maintenance cost, cross-generation compatibility, diagnostic access, software-support duration, crash-repair cost, parts availability, remanufacturing potential, and the material cost of premature replacement into the design process from the start.

The question is not whether an engineer can make one part ten times stronger. It is what the system as a whole is designed to keep working—and for how long.

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# CHAPTER 3 — THE ECONOMICS OF RENEWAL AND MAINTENANCE

## OPENING — HOW MANY TIMES CAN THE SAME CAR BE SOLD?

A car leaves the factory once.

Economically, it can be sold many times.

The automaker sells the car new, while a finance company may lend the money or lease the vehicle. The dealership can add a service contract, insurance-related products, accessories, or other extras. A few years later, that same car may return as a trade-in, get inspected, repaired, detailed, and sold to another owner—often with another loan.

Then come tires, brakes, body work, diagnostics, replacement parts, calibrations, maintenance, and repairs. An engine, transmission, starter, steering unit, or battery can be rebuilt or remanufactured. The vehicle itself can be reconditioned and sold again. Eventually some components enter reuse or remanufacturing streams and the remaining material enters end-of-life channels.

Once we follow the whole life of the vehicle, a simple story becomes difficult to maintain.

If we look only at the first sale, it seems obvious that an automaker benefits when customers replace cars frequently. Follow the same car for fifteen or twenty years, though, and the incentives become more complicated.

Each actor wants something different from the same vehicle. The automaker wants volume and a profitable product mix; its captive finance company wants interest and lease income with manageable credit losses and strong residual values. The dealer wants transactions, finance-and-insurance income, used inventory, and a busy service department. Independent shops need an aging fleet that remains repairable, insurers prefer fewer crashes and manageable repair costs, owners want useful transportation at a tolerable total cost, and remanufacturers need used components with enough value left to justify rebuilding them.

So the question is not whether “the auto industry” wants cars to last.

There is no single economic interest called the auto industry.

The real question is where value is created over a vehicle’s life, who earns from it, and what would change if keeping a car useful for twenty years became as important to the business as selling it the first time.

## 1. SALE PRICE DOES NOT TELL YOU WHERE THE PROFIT IS

The first difficulty is accounting.

Revenue is not profit, and gross margin is not the same as operating or net income. A business can generate enormous sales on thin margins, while a smaller activity earns far more on each dollar of revenue.

That distinction matters constantly in the automobile business.

A $40,000 vehicle may generate a large invoice, but that price has to absorb materials, purchased components, assembly, labor, logistics, engineering, warranties, marketing, capital, distribution, and other costs. A repair operation with far less revenue may have a much higher gross margin. A lender may produce no physical vehicle at all while earning finance charges over years.

Capital and risk also vary by business. A finance company has to fund its receivables and bear credit risk; a lessor owns the leased asset and faces residual-value risk; a dealer carries inventory and working capital; and a parts supplier may invest in tooling before selling a single component.

Two firms can make money from the same car in very different ways.

One business needs the sale to happen. Another needs the contract to stay outstanding, another needs the car to return for service, and another needs it to remain on the road long enough to require parts.

Talking about a single "profit motive" for the auto industry hides the structure we actually need to understand.

## 2. THE AUTOMAKER ALSO BECOMES A LENDER

Automotive finance is not a peripheral service in the United States. It is infrastructure for the market.

At the end of the second quarter of 2026, U.S. household auto-loan balances stood at about $1.71 trillion, according to the Federal Reserve Bank of New York. Roughly $211 billion in new auto loans appeared during that quarter.[1] The CFPB's consumer-credit data show millions of auto loans being originated in an ordinary month.[2]

Those national balances are not automaker profit. They measure household debt. What they show is the enormous amount of deferred payment sitting underneath vehicle ownership.

Automakers participate directly through captive finance companies.

In 2025, Ford Credit reported about $13.27 billion in revenue and roughly $2.56 billion in earnings before taxes, with approximately $146.3 billion in net receivables at year-end.[3] General Motors likewise operates GM Financial on a scale large enough that finance is plainly a major business alongside vehicle manufacturing.[4]

This changes what an automaker is.

It is still an industrial company turning materials, labor, software, and capital equipment into vehicles. But the group can also organize credit, leasing, servicing of receivables, and remarketing.

The assembly line creates a car.

The price of the car creates a financing problem.

The corporate group can earn money solving that problem.

## 3. THE MONTHLY PAYMENT IS NOT THE PRICE

American car buying often turns the total price of a vehicle into a monthly number.

That can be useful. Households budget monthly. A loan converts a large purchase into a sequence of payments that can be matched to income.

But the monthly payment can also obscure the variables that created it.

The Federal Trade Commission advises buyers to compare the total cost of financing rather than focus only on the payment. A longer loan term can lower the monthly bill while increasing total interest expense. Dealer-arranged financing may also include optional products—service contracts, GAP products, protection packages, or other add-ons—that become part of the amount financed.[5]

The financing channel matters too.

A buyer can obtain credit directly from a bank, credit union, or finance company, or arrange financing through the dealership. In dealer-arranged, or indirect, financing, the dealer typically sends the application to potential lenders and selects a financing source. The lender's quoted rate to the dealer—the buy rate—can differ from the contract rate offered to the consumer, creating compensation for arranging the loan.[6]

None of this makes dealer financing inherently abusive. Dealers perform a real matching and transaction function, and manufacturer-sponsored rates can sometimes be attractive.

The economic point is simpler.

The price of the vehicle, the trade-in, the down payment, the APR, the loan term, the dealer's finance compensation, and financed add-ons can all affect the same monthly number.

The market for replacing cars sells more than the vehicle itself. It also sells ways to make a particular car fit into a household's monthly cash flow.

## 4. LEASING SELLS A FUTURE VALUE

A conventional loan brings future household income into the present.

A lease adds another future variable: what the vehicle itself is expected to be worth later.

The basic logic is straightforward. The customer pays for the vehicle's expected loss in value over the lease term, plus financing and other contractual charges, rather than purchasing the entire asset outright during that period.

That makes residual value central.

Ally's 2025 annual report describes a residual-value model that considers expected age and mileage, vehicle type and segment, economic conditions, product cycle, manufacturer incentives, seasonality, and changes in new- and used-vehicle supply. At the end of 2025, Ally's operating-lease portfolio carried an expected residual value of about $7.1 billion at scheduled termination.[7]

A lease starts with a prediction about what the vehicle will be worth when it comes back.

If the returned vehicle sells for less than expected, the finance company—or an automaker providing residual support—can bear part of the loss. If it sells for more, the economics move the other way.

This creates a useful contradiction.

A finance business can benefit when customers lease new vehicles repeatedly. It does not follow that the business benefits when those vehicles become worthless quickly.

The next new car can be easier to lease precisely because the old one is expected to retain value.

The market asks for novelty and residual value at the same time.

## 5. THE NEW-CAR MARKET NEEDS THE USED-CAR MARKET

The used-car market is not merely the cheaper competitor to new cars.

It is part of the machinery that supports them.

A trade-in turns the remaining value of an old vehicle into purchasing power for the next transaction. The dealer needs a market in which to resell that three-year-old car; the lessor needs a remarketing channel for returned vehicles; and the lender cares what the collateral will be worth if the borrower stops paying.

Used-car values feed back into the economics of new vehicles.

Strong durability and brand reputation can support resale value. Higher resale value can support projected residuals. Higher residuals can reduce the depreciation portion of a lease payment. A more attractive payment can help support the new-vehicle transaction that will eventually create another used vehicle.

The loop also works in the opposite direction. Heavy incentives or price cuts on new vehicles can weaken the market position of nearly new examples, affecting residual assumptions and remarketing results.

U.S. Census data released in 2026 show more than $157 billion in 2024 sales or revenue among employer firms classified specifically as used-car dealers.[8] That number is not the size of the entire used-vehicle market: franchised new-car dealers also sell enormous numbers of used vehicles, and other channels exist.

Its value is simply to remind us of the scale.

New and used are not separate economic worlds.

They are different levels of the same vehicle market.

## 6. THE DEALERSHIP: THE SHOWROOM IS ONLY PART OF THE BUSINESS

A franchised dealership makes the divergence of interests visible under one roof.

NADA's full-year 2025 data show that roughly 54.9 percent of dealership sales dollars came from new vehicles, 31.8 percent from used vehicles, and 13.3 percent from service and parts.[9]

If we looked only at revenue, the workshop would appear secondary.

That is exactly the mistake the first section warned against.

Dealerships describe service and parts as fixed operations because they can produce a relatively stable stream of gross profit after the initial sale. In the first half of 2026, the nation's 16,991 franchised light-vehicle dealers wrote more than 136 million repair orders and recorded nearly $83 billion in service-and-parts sales, according to NADA.[9]

The owner who does not buy another vehicle this year is not necessarily a lost customer.

The same car can generate oil changes, tires, brakes, warranty work, diagnostics, calibrations, collision repair, accessories, service contracts, and future trade-in inventory.

The showroom wants the next transaction.

The service drive can profit from the continued existence of the previous one.

## 7. MAINTENANCE CAN BE MORE VALUABLE THAN THE SALE

One large dealership group makes the revenue-versus-margin distinction unusually concrete.

In 2025, Sonic Automotive's franchised dealerships generated far more revenue from new-vehicle sales than from parts, service, and collision work. Yet the gross profit generated by parts, service, and collision substantially exceeded new-vehicle gross profit. Finance-and-insurance activity added another important source of gross profit.[10]

Sonic is not the entire dealer industry. Its brand mix, geography, accounting, and operating practices are its own.

The case nevertheless demonstrates a real mechanism.

The vehicle in the showroom can dominate revenue because the transaction is large. The same vehicle's life after the sale can generate a much larger margin relative to the revenue involved.

This makes simplistic incentives difficult to sustain.

A salesperson may prefer a replacement today.

A service department may prefer a maintainable car that returns for years.

They are part of the same company.

## 8. THE INDEPENDENT AFTERMARKET NEEDS CARS TO KEEP LIVING

Once a vehicle leaves the franchised network, the economics do not disappear. They migrate.

Independent repair shops, parts distributors, tire dealers, remanufacturers, diagnostic-tool companies, collision shops, and online parts sellers all depend on a fleet that remains in service.

The U.S. aftermarket is economically large enough that it cannot be treated as a marginal remainder of new-car sales.

The Auto Care Association and MEMA, using a forecast prepared with S&P Global Market Intelligence, projected the U.S. light-duty aftermarket to grow 5.2 percent in 2026 and to exceed $500 billion by 2029. They identify an aging fleet, rising vehicle complexity, and continued reliance on personal vehicles as major drivers.[11]

These are industry estimates, not a government census of every repair dollar, and forecasts are not outcomes.

But the direction of the incentive is clear.

An independent shop does not need a customer to buy a new car. It needs the existing car to remain worth maintaining—and it needs access to the parts, tools, data, and skills required to do the work.

From this perspective, longevity creates a market.

## 9. PRODUCT MIX MATTERS: PICKUPS, SUVs, AND THE ECONOMICS OF WHAT GETS SOLD

Replacement demand is not only about how many vehicles are sold. It is also about which vehicles are sold.

The American market has shifted dramatically toward SUVs and light-truck classifications. EPA's 2025 Automotive Trends Report says SUVs accounted for about 60 percent of new vehicle production in model year 2024, while the regulatory truck class—including pickups, truck SUVs, and minivan/vans—reached about 66 percent. Truck SUVs alone approached half of new-vehicle production.[12]

Those regulatory categories require care. A "truck" in fuel-economy regulation is not simply a work pickup. SUVs can fall into car or truck classes depending on design and regulatory criteria.

Automaker disclosures make the economic importance of that product mix clear.

General Motors states in its 2025 annual report that its highest profit margins currently come from full-size internal-combustion SUVs and full-size internal-combustion pickups, and that vehicle mix is one factor affecting North American profitability. GM continued to describe pickups and SUVs as high-margin products in its 2026 filings.[13]

This is a company-specific disclosure, not a universal law of the industry. It does not prove that every SUV is more profitable than every car or that buyers are manipulated into choosing larger vehicles.

It proves something narrower and important: for a major U.S. automaker, the type and size of vehicle sold can materially affect profit.

That means an automaker can care about product mix as much as how often customers replace their vehicles.

The commercial question is not only "how soon will the customer return?" It can also be "what will the customer return to buy?"

## 10. THE INTERESTS ARE NOT ALIGNED

We can now stop talking about the automobile economy as though it were a single actor.

The manufacturing company thinks about volume, capacity utilization, product mix, pricing, warranty cost, and margin per vehicle.

The captive finance company thinks about receivables, interest rates, lease income, delinquencies, credit losses, and residual values.

The dealer thinks about new vehicles, used vehicles, trade-ins, finance-and-insurance products, service, and parts.

The independent shop thinks about the size and age of the fleet, repair access, parts availability, and labor demand.

The parts supplier may earn money from original equipment, the replacement market, or both.

The insurer thinks about crash frequency and average claim severity.

The first owner thinks about purchase price, payment, reliability, fuel or electricity cost, insurance, and trade-in value.

The later owner may care far more about whether an unexpected $3,000 repair is economically rational.

The remanufacturer needs components that have reached a second-life market but still retain enough value to rebuild.

These interests can reinforce each other.

They can also conflict.

A cheaper non-serviceable assembly can save money at the factory and raise repair cost later. A very reliable vehicle can reduce certain service events while raising residual value. Incentives on a new model can support volume while weakening the value of late-model used examples. A long-lasting vehicle can reduce replacement frequency for its first owner while increasing the number of years the broader repair market has an asset to maintain.

There is no single economic interest called "the automobile industry." Different actors make money at different points in a vehicle's life.

## 11. A NEW-CAR SALE DOES NOT REQUIRE AN OLD CAR TO DIE

The first chapter separated commercial renewal—the sale of a replacement vehicle—from physical destruction. Here we can see how that distinction works economically.

A customer turns in a three-year-old vehicle and takes a new one.

The market has recorded a replacement sale.

The old vehicle has not died.

It may be reconditioned, financed again, and sold to another household. Years later it may change hands again. The first owner can replace cars quickly while the physical fleet turns over much more slowly.

This creates two clocks.

At the top of the market, model years, leases, trade-ins, incentives, and product cycles can produce rapid replacement.

Deeper in the fleet, the same vehicles can remain in service for fifteen or twenty years.

Fleet vehicles, rental cars, and off-lease vehicles feed that process by entering the used market after a relatively short first period of service.

That is why new-vehicle sales alone do not tell us how quickly cars are actually leaving service.

To understand material turnover, we have to follow the vehicle itself.

## 12. WHEN REPAIR STOPS MAKING ECONOMIC SENSE

Chapter 2 showed that a car can remain technically repairable and still become economically impossible to justify.

Why can a $3,000 repair save one car and end another?

Because the repair is not compared only with the failed component. It is compared with the value of the vehicle, its expected future reliability, replacement alternatives, labor cost, insurance coverage, financing constraints, and the availability of new, used, or remanufactured parts.

A difficult architecture raises the repair bill. The market then decides whether the bill is worth paying.

The same failure can be trivial on a valuable late-model vehicle and terminal on a fifteen-year-old one.

This is also why lower-cost replacement and remanufactured components matter. If a new assembly costs too much relative to the car, a credible remanufactured alternative can make the repair worth doing again.

How long a vehicle stays in service depends not only on how it was engineered, but also on whether someone can repair an aging car at a price that still makes sense as its market value falls.

## 13. REMANUFACTURING: A MAINTENANCE ECONOMY ALREADY EXISTS

Remanufacturing is not improvised repair and it is not recycling.

A used component is recovered, disassembled, cleaned, inspected, restored or re-machined where necessary, fitted with replacement wear parts, reassembled, and tested through an industrial process.

The economic idea is to preserve more of the material, machining, and embodied value that already exist instead of starting entirely from raw material.

A European sector study by CLEPA and Oakdene Hollins estimated the automotive-parts remanufacturing market supplied by European parts companies at about €4.7 billion in 2020. The same study estimated avoided emissions using its own comparison methodology.[14]

The precise environmental result depends on system boundaries and should not be treated as a universal constant.

For this chapter, the important point is economic: remanufacturing is not a hypothetical alternative. It already operates at industrial scale.

## 14. RENAULT AND STELLANTIS: SECOND LIFE AT INDUSTRIAL SCALE

Two European manufacturing sites show that reconditioning and remanufacturing can be organized much more like conventional industry than like small-scale salvage.

At Flins, Renault has transformed a factory historically associated with new-car production into what it calls a Refactory for circular mobility activities. Renault says the Renew Factory can process tens of thousands of used vehicles per year, while The Remakers rebuilds hundreds of thousands of components and the site also reconditions electrified-vehicle batteries.[15]

These are company-reported figures. They do not prove that second-life activity is more profitable than manufacturing new cars.

They prove something narrower: an automaker can apply industrial processes to reconditioning and remanufacturing rather than treating them as artisanal leftovers.

Stellantis is pursuing a similar logic through SUSTAINera and its circular-economy operations at Mirafiori, where it reports remanufacturing engines, transmissions, and batteries, reconditioning vehicles, and sorting components for reuse. It has also expanded a network of high-voltage battery repair centers.[16]

Again, corporate strategy is not proof of future profitability.

But these examples destroy a simple opposition.

The same industrial group can want to sell new vehicles and also build businesses around keeping older vehicles and components economically useful.

## 15. SELLING AGAIN AFTER THE SALE: CONTRACTS AND SOFTWARE

The economic relationship with a vehicle no longer has to end when the keys change hands.

Automakers can sell extended service contracts, connected services, fleet-management tools, navigation and data services, software functionality, and other ongoing products.

Ford's 2025 reporting includes billions of dollars in a broad "services and other revenue" category outside Ford Credit, but that category includes more than software and must not be relabeled as software revenue. Ford separately reported roughly 840,000 active paid Ford Pro Intelligence software subscriptions worldwide at the end of 2025.[17]

That is enough to establish a capability.

A durable vehicle can continue generating revenue without being physically replaced.

But recurring revenue introduces a second question: what is the owner paying for?

A subscription can fund a genuinely continuous service—fleet telematics, updated data, remote management, cybersecurity operations, or connectivity. It can also be used to meter access to functions in ways that shift the economic meaning of ownership.

For our purposes, the important fact is not whether subscriptions are good or bad.

Software creates another way to earn revenue over the vehicle's life.

## 16. CAN A TWENTY-FIVE-YEAR CAR STILL BE GOOD BUSINESS?

Now return to the thought experiment.

Imagine a car designed for twenty or twenty-five years of service: a relatively stable architecture, long parts support, documented interfaces, replaceable modules, a battery or powertrain that can be renewed, and a serious remanufacturing pathway.

What does the automaker lose?

If owners actually keep the vehicle longer and the total fleet does not grow, some replacement sales disappear. Factories may run fewer units. Original-equipment suppliers may sell fewer first-fit components. A business model built around current volumes cannot simply remain unchanged.

But revenue can shift elsewhere.

The same group can earn from maintenance, replacement parts, upgrades, remanufactured components, battery repair, certified used vehicles, trade-ins, reconditioning, financing successive owners, and useful ongoing services.

That changes the business question.

Instead of asking how many new vehicles can be sold this year, the company can ask how much useful value it can provide over twenty-five years of service from one durable platform.

Nothing guarantees that this model would be equally profitable.

But nothing in the existing automobile economy proves it impossible either.

Finance, dealer service, the independent aftermarket, remanufacturing, and industrial second-life programs already provide pieces of that model.

## 17. A LONG-LIVED CAR CAN STILL LOCK IN ITS OWNER

That does not mean an economy of maintenance is automatically good for the owner.

A vehicle can last physically for decades while the owner becomes increasingly dependent on proprietary parts, restricted diagnostics, mandatory subscriptions, coded replacement modules, exclusive software access, or a closed service network.

The car lasts.

The customer pays for permission to keep using it.

This is why the right-to-repair questions from the previous chapter belong here economically as well as technically.

Who can repair the car helps determine who can earn from it over time.

If only one actor can authorize, diagnose, pair, or supply critical components, a long service life can become a long period of captive revenue.

A long-lived car benefits its owner only if the savings from longevity are not swallowed by monopoly control over parts, diagnostics, software, or service.

## 18. HOW THE SAME CAR KEEPS GENERATING VALUE

The automobile economy does not end with the first sale.

The same car can generate revenue at many points in its life: first sale, loan, lease, insurance, trade-in, used sale, service, repair, parts, remanufacturing, reconditioning, software, reuse, and eventually end-of-life material recovery.

Different actors make money on different timelines.

Each participant depends on a different part of the vehicle's life. The automaker needs enough volume and the right product mix; the lender needs payments, controlled losses, and credible collateral values; the lessor needs the returned vehicle to be worth something close to the forecast; and the dealer needs both transactions and a fleet that comes back for service. The independent aftermarket needs repairable vehicles to remain in circulation, while the owner needs the total cost to stay below the value of the transportation received.

That is how the same system can encourage frequent replacement at the top of the market while still depending on vehicles that remain useful for many years.

The new vehicle has to be new enough to attract a buyer.

The three-year-old vehicle has to be valuable enough to trade or remarket.

The eight-year-old vehicle has to be maintainable.

The fifteen-year-old vehicle needs repairs and parts cheap enough to remain worth fixing.

When a used component is worth more as a rebuilt component than as scrap, another industry can capture that value.

So the real tension is not simply profit versus durability.

It is between different business models for earning money over the life of the vehicle.

A system built more strongly around longevity would shift some revenue from replacement to maintenance, from the first owner to later owners, from new components to rebuilt ones, and from factories that only make products to industrial operations that also repair, recondition, and remanufacture.

That shift is measurable.

Those tradeoffs can be measured. How many new sales disappear, and how much lifecycle revenue replaces them? What happens to gross margin and capital needs? Does the owner’s total cost fall? Can the vehicle still be repaired outside the original network? How much new material is avoided, and how much product-mix profit is sacrificed or transformed?

And most important: if maintaining a vehicle could become as economically valuable as replacing it, would the automobile be designed the same way?

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# CHAPTER 4 — WHY THIS ENERGY PATH?

## OPENING — IN 1900, NO ONE YET KNEW WHICH CAR WOULD WIN

Looking back, it is easy to assume that gasoline and the automobile were always meant to go together.

The connection now feels self-evident. Cars burn gasoline; gas stations sell it; refineries make it because drivers use it. So when an alternative appears, we usually compare it with a gasoline system that is already built and everywhere around us.

That is not how the story began.

Around 1900, no single energy system had won the automobile market. Steam, electric, and gasoline cars were all being sold, each with real strengths and real drawbacks. None yet came with the vast ecosystem that would later make its own dominance look inevitable.

The U.S. Department of Energy notes that electric cars enjoyed substantial urban success around the turn of the century. New York City operated an electric taxi fleet, and DOE's historical synthesis estimates that electric vehicles accounted for roughly one-third of vehicles on U.S. roads around 1900.[1] The Smithsonian describes the same period as a genuine technological competition among steam, electricity, and internal combustion.[2]

That changes the question.

We should not ask only, "Which motor was best?"

We should also ask: which combination of motor, fuel or electricity, storage, infrastructure, industry, and everyday use became established enough that each part made the others more practical?

A car never runs on energy in the abstract. It depends on an entire supply and infrastructure system.

## 1. THREE CARS FOR THE SAME PROBLEM

Steam entered the automobile age with enormous technical credibility. It already powered locomotives, ships, and industrial machinery. A steam car could be fast and powerful.

But transferring a technology that works well at locomotive scale into a small privately operated machine creates new constraints. DOE notes that some early steam cars required long startup times—sometimes approaching forty-five minutes in cold weather—and regular replenishment of water.[1]

Electricity had almost the opposite profile.

Electric cars had almost the opposite profile from steam. The motor started immediately, ran quietly, required neither a hand crank nor a complicated shifting routine, and produced no exhaust at the vehicle. Those advantages mattered in urban use.

The battery imposed a different set of constraints: cost, mass, range, charging time, battery maintenance, and dependence on electricity being available where the vehicle needed to go.

The gasoline car began with obvious disadvantages. It was noisy, dirty, mechanically demanding, and difficult to start. Early driving required more physical effort and more mechanical familiarity.

But liquid fuel was compact, portable, and fast to replenish. A vehicle could carry a large amount of usable energy relative to tank volume and refill without waiting for a local electrical connection.

That mattered in a country where electrification spread unevenly and rural and intercity travel quickly became economically important.

None of the three systems was absurd.

They optimized different constraints.

The winner depended on the world in which the vehicle had to operate.

## 2. GASOLINE WON PARTLY BECAUSE IT WAS PRACTICAL

It is tempting to explain the rise of gasoline as a story of petroleum interests imposing their preferred fuel.

That explanation leaves out an important part of what actually happened.

Liquid gasoline had a practical advantage for individual mobility. It could be poured into a modest tank, transported by rail, truck, barge, or pipeline, stored for later use, and replenished quickly.

A gasoline car did not need to remain physically connected to the infrastructure that produced its energy.

That difference mattered especially outside dense urban areas.

The historical comparison does not require us to pretend gasoline was technically superior in every dimension. Electric drive was quieter and easier to operate. Steam had proven power and maturity. Gasoline simply combined portability, range, refueling speed, and improving engine performance in a way that fit a broad and geographically dispersed use case.

Even today, the Department of Energy's fuel-property comparisons show why storage physics matters: gasoline and diesel are energy-dense liquids, while compressed natural gas, liquefied natural gas, hydrogen, and batteries require very different storage systems.[3]

This chapter will not turn that fact into a complete efficiency comparison. That belongs later.

The narrower point is that the physical form of the energy carrier helps design the vehicle and the network around it.

## 3. THE NETWORK CHOOSES WITH THE MOTOR

The early electric car shows why physical properties alone do not explain technological selection.

In 2021, Josef Taalbi and Hana Nielsen published an analysis in Nature Energy based on a historical database covering more than 36,000 U.S. passenger-car models.[4]

Their question is closely aligned with ours: why did internal combustion gain such a decisive lead when steam, gasoline, and electricity were still competing around 1900?

The study gives substantial weight to infrastructure.

Electricity spread unevenly. EV manufacturers and buyers were constrained not only by the battery but also by where the grid actually reached.

The authors construct a counterfactual in which electricity distribution expands fifteen to twenty years earlier. In their model, earlier grid diffusion could have shifted technology choices toward electric vehicles in many places, especially metropolitan areas.[4]

A counterfactual does not tell us what definitely would have happened.

It does not show that the United States would certainly have become electric.

It does show that "the battery lost because it was bad" is too simple an explanation.

A technology can perform well locally and still lose nationally because the network required to use it does not spread at the same speed.

## 4. A TECHNOLOGY CAN STEAL ITS RIVAL'S ADVANTAGE

Another mistake is to imagine that competing technologies remain static.

Early electric cars had an obvious convenience advantage: they started immediately.

Gasoline cars required hand cranking.

Then the electric starter arrived.

Charles Kettering's system, introduced in the early 1910s, removed much of the physical inconvenience of starting an internal-combustion car. DOE and the Smithsonian both identify the electric starter as an important improvement in gasoline-car usability.[1][2]

The gasoline car absorbed one of the electric car's strongest features.

The same thing happened with lighting and electrical accessories. Batteries, generators, starter motors, ignition systems, and eventually electronics became integral to combustion vehicles.

A winning technology does not necessarily preserve its original form.

It can borrow from the rival.

The "gasoline car" that dominated later decades was already an electromechanical system.

Technology competition is rarely a clean winner-take-all contest. Competing systems borrow useful features from one another, improve weak points, and sometimes converge.

## 5. FORD DID NOT JUST PRODUCE MORE CARS—HE STRENGTHENED AN ENERGY SYSTEM

Chapter 1 examined the industrial loop created by Ford: standardization, productivity, lower price, higher volume, and still more productivity.

That loop had an energy consequence.

It helped lock in a particular fuel system.

DOE’s historical comparison gives a rough sense of the price gap that had emerged by 1912: a gasoline car at about $650 versus an electric roadster at about $1,750 in its example.[1] Exact comparisons vary by model, but the direction is what matters.

Every gasoline Model T sold did more than add a car to the road.

It increased fuel demand.

It made another fuel retailer more viable.

It trained mechanics on gasoline engines.

It expanded the market for ignition parts, carburetors, lubricants, and engine tooling.

It generated more operating experience and more reasons for suppliers to invest in combustion technology.

At some point, the contest stops being one electric vehicle against one gasoline vehicle.

It becomes one technology competing against an increasingly dense system in which each million gasoline cars creates new reasons to build the next million.

## 6. PETROLEUM LEARNED TO SERVE THE CAR, AND THE CAR LEARNED TO CONSUME PETROLEUM

Gasoline itself has a paradoxical history.

The U.S. Energy Information Administration notes that early petroleum refining focused heavily on kerosene for lighting. Gasoline was one of the products produced during distillation, but before the automobile created a mass use for it, it could be a low-value or unwanted output.[5]

The car changed that.

By 1920, about nine million gasoline-powered vehicles were already operating in the United States, and service stations were opening around the country.[5]

Automobile demand transformed a refinery stream into a strategic transportation commodity.

The transformation then ran backward.

As automobile demand grew, refining and fuel quality improved, storage and distribution expanded, and gasoline became easier to find. Drivers could travel farther with more confidence that fuel would be available, which made gasoline cars more useful and pushed demand still higher.

Today's scale shows how far that reinforcing process went. U.S. gasoline consumption totaled roughly 136.7 billion gallons in 2025, according to EIA.[6]

That modern scale does not prove the system is optimal.

It shows how a historical choice can harden into massive physical infrastructure.

The car made the station more valuable.

The station made the car more useful.

The car justified refining and distribution investment.

Refining produced a fuel increasingly tailored to the engine.

It becomes difficult to say where automobile innovation ends and energy-system innovation begins.

## 7. FUEL BECOMES A TECHNOLOGY

A gasoline engine does not run on an immutable substance called gasoline.

Motor fuel is formulated.

Its properties change.

And changes in fuel chemistry can enable changes in engine design.

Knock provides the clearest example.

Higher compression can improve engine performance and efficiency, but it also raises the risk of abnormal combustion when fuel octane is inadequate.

Researchers at General Motors, including Charles Kettering and Thomas Midgley, searched for antiknock compounds. In 1921 they identified tetraethyl lead as extremely effective at low concentrations.

EPA's historical record describes the commercial adoption of leaded gasoline beginning in the 1920s and the way higher-octane fuel supported higher-compression engines.[7]

The important point is not simply that lead "improved gasoline."

Changing the fuel chemistry made higher compression ratios practical.

Fuel and motor were being co-designed.

## 8. LEAD WAS NOT THE ONLY DOOR

The history becomes more revealing when we look at alternatives that were seriously considered but never became dominant.

Kettering, Midgley, and their colleagues tested many compounds. Historical accounts describe iodine, aniline, selenium and tellurium compounds, benzene, alcohol, and tetraethyl lead among the options.[8]

Ethanol also had strong antiknock properties.[8][9]

But "ethanol also worked" is not the same as "ethanol could replace tetraethyl lead at the same industrial cost and scale."

Tetraethyl lead was effective at very low concentrations. Ethanol had to be blended at much larger volumetric shares. That meant different requirements for production, transport, storage, and fuel formulation.

U.S. industrial alcohol supply, cost, and the legal context of Prohibition also complicated the comparison.

Lead was not inevitable, but the alternatives were not interchangeable either.

A technically workable substitute still had to fit the realities of production, distribution, cost, regulation, and scale.

The relevant question is not only which molecule solves knock in a laboratory. It is which solution can be manufactured, distributed, priced, regulated, and integrated into the fuel system at the scale the market is demanding.

## 9. A SOLUTION CAN SUCCEED LOCALLY AND SHIFT COSTS ELSEWHERE

Tetraethyl lead solved a real engine problem.

That does not make its overall result a success.

The toxicity risks appeared early in manufacturing. EPA's historical account documents worker poisoning and deaths in the 1920s, decades of public-health controversy, and the eventual removal of lead from U.S. on-road gasoline.[7]

This forces us to separate scales.

For the engine, the additive reduced knock and enabled higher-octane fuel.

For workers, communities, and the environment, it created exposure and diffuse long-term harm.

A technology can improve one subsystem while shifting costs somewhere else.

That conclusion does not require a theory of hidden intent.

It requires only an optimization boundary that is too narrow.

The engine designer asks, "How do we stop knock?"

The larger system has to ask, "What happens when this solution is manufactured and burned across billions of gallons of fuel?"

## 10. CORN ETHANOL: WHEN POLICY ENTERS AN EXISTING GASOLINE SYSTEM

The United States offers a particularly useful example of how policy, agriculture, infrastructure, and fuel chemistry can change an energy pathway without replacing it wholesale.

Today, nearly all motor gasoline sold in the United States contains ethanol, most commonly around 10 percent by volume.[10]

That result did not emerge from one cause.

American ethanol is produced mostly from corn. Plants are concentrated heavily in the Midwest near feedstock production, while fuel distribution relies on the existing gasoline network and blending system.[11]

Federal policy also matters. Congress established the Renewable Fuel Standard in the 2000s, and EPA administers renewable-fuel volume obligations through a system that includes Renewable Identification Numbers. EPA finalized new standards for 2026 and 2027 in 2026.[12]

The scale is no longer marginal.

USDA reports that fuel ethanol used roughly 5.44 billion bushels of corn in the 2024/25 marketing year—about 36 percent of total U.S. corn use.[13]

Yet the resulting system is not simply “ethanol instead of gasoline.”

It is, in most vehicles, ethanol inside gasoline.

That difference matters.

E10 works in the entire gasoline-vehicle fleet. E15 is approved for newer light-duty vehicles under federal rules. Flexible-fuel vehicles can use blends up to E85. The Alternative Fuels Data Center lists thousands of E15 and E85 fueling locations, but high-ethanol blends remain far less ubiquitous than E10.[14]

The U.S. ethanol story shows a different kind of technological path.

A new fuel can become deeply embedded by entering the existing system instead of replacing it outright.

## 11. GOVERNMENT DOES NOT CHOOSE ALONE, AND THE MARKET DOES NOT EITHER

Corn ethanol is a useful antidote to two opposite stories.

The first story says the market simply selects the most efficient technology.

That is incomplete.

Fuel standards, blending rules, agricultural policy, environmental regulation, and the design of the RFS all change the relative economics of fuels.

The second story says government can choose an energy system by decree.

That is incomplete too.

A rule does not ferment corn, build plants, move ethanol by rail or truck, adapt terminal logistics, qualify engines, install pumps, or make a consumer accept the product.

The pathway works only if physical production, distribution, vehicle compatibility, pricing, and policy fit together well enough.

That is why the U.S. ethanol system sits at the intersection of agriculture, chemistry, regulation, logistics, and automotive engineering.

Public policy changes the slope.

Industry and users still have to climb it.

## 12. BRAZIL: BUILDING A DIFFERENT ETHANOL PATH

Brazil provides an essential contrast because the word ethanol hides very different systems.

The Proálcool program was created in 1975 after the oil shock.[15]

The program did not simply tell drivers to choose alcohol fuel.

It coordinated agricultural production, distillation, storage, distribution, fuel formulation, vehicle engineering, pricing, and rules.

Brazil also possessed a major sugarcane industry that gave the pathway a different feedstock base from the U.S. corn system.

BNDES and Brazilian government histories describe the role of financing, blending requirements, dedicated ethanol vehicles, and distribution infrastructure in building the market.[16]

The broader lesson reaches beyond ethanol.

An alternative energy system is not merely discovered.

It can be constructed.

## 13. A BUILT PATH CAN STILL BECOME FRAGILE

Brazil's ethanol system also demonstrates that policy support does not make a pathway irreversible.

When oil prices fell, sugar became more attractive, and ethanol supply became uncertain in the late 1980s, consumer confidence weakened.[16]

A pathway has to keep delivering.

Price.

Availability.

Reliability.

Convenience.

The later spread of flex-fuel vehicles was especially important.

Beginning in the early 2000s, flex-fuel technology allowed drivers to use gasoline, ethanol, or mixtures of the two.[17]

The owner no longer had to predict which fuel would be cheaper or more available years in advance.

The energy choice became reversible at the pump.

That made the fuel choice much less risky for the owner.

Instead of making one fuel perfect, the vehicle reduces the cost of being wrong about the future.

## 14. “ETHANOL” IS NOT ONE ENERGY PATH

The U.S. and Brazilian examples show why a fuel name is not enough.

Ethanol is a molecule.

Its production system can be very different.

Corn.

Sugarcane.

Beets.

Cellulosic residues.

Each pathway uses different land, inputs, processing energy, coproducts, logistics, and industrial equipment.

In the United States, corn is the dominant feedstock.[11]

In Brazil, sugarcane is central to the large-scale system described above.

Some sugarcane pathways can use bagasse to supply process heat and electricity, which changes the energy balance.[16]

But comparing complete energy returns requires explicit system boundaries: farming, processing, coproduct allocation, transport, and vehicle efficiency.

Those calculations belong in the next chapter.

Here the rule is simpler.

We never choose “a biofuel.”

We choose a production chain.

## 15. NATURAL GAS AND PROPANE: STORAGE CAN SHAPE THE MARKET

Natural gas can power an internal-combustion vehicle very effectively.

The Department of Energy notes that natural-gas vehicle performance can be broadly comparable to conventional vehicles.[18]

Why, then, has compressed natural gas not displaced gasoline across the passenger-car fleet?

Storage is part of the answer.

Compressed natural gas requires high-pressure tanks and generally provides less driving range for a comparable package volume. Liquefied natural gas increases storage density but adds the complications of cryogenic storage.[18]

Propane offers another combination. It can be stored as a pressurized liquid, and fueling infrastructure can be placed alongside conventional fuel equipment.[19]

These examples keep the focus where it belongs: not just on the engine, but on the fuel, infrastructure, vehicles, rules, and industries around it.

A motor can work very well.

The fuel can be available.

And the tank, packaging, distribution, or station can still determine whether the technology scales.

## 16. PRODUCER GAS: "IT WORKS" IS NOT YET A MASS-MOBILITY SYSTEM

Wood gasification is a useful test of technological seriousness.

It is real.

Wood or charcoal can be gasified, and the resulting producer gas can run an internal-combustion engine.

FAO engineering guidance documents vehicle adaptations and notes that power loss on a properly converted naturally aspirated gasoline engine can be limited to roughly 30 percent. [20]

That is far from impossible.

Now look at the rest of the system.

The vehicle needs a bulky gasifier, solid fuel, startup time, filtering for dust and tar, frequent maintenance, careful carbon-monoxide management, and acceptance of lower power.

During wartime petroleum shortages, those costs may be tolerable. In a specialized agricultural use with local biomass, the tradeoff may sometimes make sense.

For an ordinary passenger vehicle whose owner expects immediate startup, little maintenance, clean packaging, and easy refueling, the constraints are much more severe.

A technology does not need to have been suppressed to remain marginal.

It can simply be less compatible with the dominant use case.

## 17. WATER INJECTION: SEPARATING A REAL EFFECT FROM AN EXTRAORDINARY STORY

Water injection presents a different trap.

Someone hears that adding water can reduce fuel consumption in an engine.

The story mutates into the claim that the engine can run on water.

Those are not the same proposition.

Scientific work on turbocharged gasoline engines shows a real role for water injection. By cooling the intake charge and combustion environment, it can reduce knock and thermal stress and in some operating regions reduce the need for protective fuel enrichment.

A 2019 SAE paper involving IFPEN, Renault, PSA, and Magneti Marelli reported fuel-consumption reductions reaching roughly 13 percent in certain high-load conditions in its experimental configuration.[21]

The water is not the fuel.

It changes the conditions under which the actual fuel burns.

That distinction allows us to consider Gillier-Pantone claims without ridicule and without credulity.

A student engineering project at the École des Mines de Douai, with dynamometer work conducted at CRITT M2A, attempted to characterize the system experimentally.[22]

The available report did not confirm the extraordinary performance claims associated with the device. It is also not a peer-reviewed research paper and cannot settle every possible configuration.

Its value here is methodological.

An unusual claim should go to a test bench.

Controlled load.

Measured fuel consumption.

Measured power.

Measured emissions.

Reproducible comparison.

An anecdote is not enough to validate or dismiss a system.

## 18. THE ELECTRIC CAR RETURNS—BUT THE U.S. PATH IS ITS OWN

If path dependence were absolute, the electric car could never have returned.

It did return because the surrounding system changed.

The surrounding technology had changed. Lithium-ion batteries offered radically different performance from early lead-acid packs; power electronics improved; motors became precisely controlled; charging standards developed; cell manufacturing reached enormous scale; and new manufacturers entered the market.

Globally, more than 20 million electric cars were sold in 2025, about one-quarter of new-car sales.[23]

The United States followed a different trajectory.

IEA estimates about 1.5 million electric-car sales in the United States in 2025, just under 10 percent of the market.[23]

That contrast matters.

There is no single global EV transition happening at one speed.

Battery prices, product availability, charging access, electricity prices, consumer preferences, regulation, incentives, and the existing vehicle market differ by country and region.

The EV's return proves neither that gasoline was a historical mistake nor that electricity has now permanently won.

It proves that an old technological path can be reopened when its surrounding system becomes different enough.

## 19. THE CHICKEN-AND-EGG PROBLEM HAS NOT DISAPPEARED

Charging infrastructure makes the network effect visible in the modern United States.

Why buy an electric vehicle if convenient charging is scarce?

Why build chargers if electric vehicles are scarce?

The Department of Energy's Alternative Fuels Data Center now tracks tens of thousands of public charging locations and large national charging networks. It also notes that most EV owners do the majority of their charging at home.[24]

That is already a major difference from gasoline.

The “station” can be a commercial fast charger, a workplace charger, an apartment charger, a household circuit, or a fleet depot.

Academic work using 353 U.S. metropolitan areas found indirect network effects in both directions between EV adoption and charging-station deployment.[25] More recent U.S. studies continue to find associations between charging accessibility and adoption, while showing that the effect depends on geography and income.[26]

The old coordination problem remains, but the infrastructure is different.

A society can also act on the problem deliberately.

Utilities, governments, automakers, landlords, charging operators, fleets, and homeowners can all install part of the network.

Path dependence is not only a barrier.

Once understood, it becomes something actors can try to reshape.

## 20. HYDROGEN: FAST REFUELING CAN STILL REQUIRE A SLOW INFRASTRUCTURE BUILDOUT

Hydrogen fuel-cell vehicles appear to solve one complaint often made about battery vehicles.

They can offer long range and fast refueling.

But the vehicle is only one part of the system.

DOE continues to identify dense onboard hydrogen storage as a major engineering challenge, which is why light-duty fuel-cell vehicles commonly use very high-pressure gaseous storage.[27]

Then comes the station.

Hydrogen has to be produced, delivered or generated locally, stored, compressed, dispensed, and handled under specialized safety requirements.

The U.S. Alternative Fuels Data Center describes retail hydrogen infrastructure as concentrated in select markets, primarily California.[28]

That creates a useful paradox.

The driver's refill can be quick.

The social process of creating a dense nationwide refueling network can be slow and capital-intensive.

What is convenient for the driver in a few minutes can require years of investment across the wider system.

## 21. PATH DEPENDENCE IS NOT DESTINY

We can now be more precise about what path dependence means.

It does not mean the first technology always wins.

It does not mean the technically best technology automatically wins.

It means past choices change the cost and attractiveness of future choices.

A gasoline-engine factory trains combustion engineers, who in turn accumulate knowledge and patents. Suppliers invest in compatible components, fuel distributors build compatible infrastructure, and mechanics learn the systems. Regulations, testing procedures, and consumer habits then grow around that installed base.

Each layer makes the next investment easier to justify.

The same mechanism can work for ethanol blending, electric charging, battery manufacturing, or another technology.

Economic research on automotive innovation has found that firms' prior knowledge and technological environments influence whether later innovation is directed toward cleaner or more carbon-intensive technologies.[29]

But the slope can change.

U.S. gasoline absorbed ethanol rather than remaining chemically fixed.

Brazil built a large alternative ethanol pathway and later reduced consumer risk through flex-fuel vehicles.

Electric vehicles returned when batteries, manufacturing, electronics, charging, and markets changed enough.

The path is a slope.

It is not a wall.

## 22. WE NEVER CHOOSE ONLY A MOTOR

The chapter began with a simple question: why this energy path?

The answer does not require one hidden cause.

A pathway becomes dominant when enough pieces—vehicles, fuels, infrastructure, industry, regulation, and habits—work well enough together.

The resource exists.

The energy carrier can be stored.

The vehicle can use it.

The cost becomes acceptable.

The infrastructure reaches useful density.

Industry can manufacture at scale.

Repair networks can maintain the system.

Standards reduce incompatibilities.

Public rules do not make the pathway impossible.

Users find the experience sufficiently useful.

Then each new adoption strengthens some of the conditions that made the previous adoption possible.

Gasoline had real advantages for early individual mobility.

Mass production amplified them.

Petroleum found an enormous new market in the automobile.

Service stations made gasoline vehicles easier to use.

Gasoline demand made stations and refining more valuable.

Fuel chemistry evolved with engines.

Skills, capital, standards, and habits accumulated.

The U.S. corn-ethanol system shows that a policy-supported fuel can become embedded inside the incumbent rather than replace it.

Brazil shows that a different feedstock, vehicle strategy, and institutional framework can build another ethanol pathway.

Producer gas shows that technical functionality is not enough to create a convenient mass system.

Water injection shows that a real mechanism can be surrounded by claims much larger than the evidence.

Electric vehicles show that an abandoned path can return when its ecosystem changes.

Hydrogen shows that solving the vehicle does not solve the station.

We never choose only an energy source.

Every energy system locks in physical commitments, whether we choose them deliberately or not.

Tanks.

Refineries.

Power plants and grids.

Charging systems.

Fuel terminals.

Stations.

Standards.

Rules.

Farms.

Mines.

Factories.

Software.

Skills.

Habits.

Once those commitments exist, they become part of the conditions under which the next choice is made.

The next chapter asks a different question.

Once the energy pathway is chosen, what happens to the energy we put into the vehicle?

How much reaches the wheels?

How much becomes heat?

What does mass change?

What does speed change?

What is recovered during regenerative braking?

And what does it really mean to save fuel or electricity when we follow energy instead of the price displayed at the pump or charger?

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# CHAPTER 5 — WHERE DOES THE ENERGY GO WHEN YOU DRIVE?

## OPENING — THE ENERGY THE GAUGE DOES NOT SHOW

A driver sees speed.

The dashboard may also show instantaneous fuel economy, power demand, or—in a hybrid or electric vehicle—energy flowing back toward the battery.

None of those numbers, by itself, tells you where all the vehicle's energy is actually going.

At steady speed on level ground, the car still needs power to overcome air resistance, tire deformation, bearings, drivetrain losses, and accessories.

When it accelerates, part of the supplied energy is stored in the vehicle's motion.

When it climbs, part is stored in elevation.

When it slows, that stored energy has to leave the motion. Friction brakes turn it largely into heat. A hybrid or electric vehicle can convert some of it back into electrical energy.

Those simple facts overturn several common intuitions.

A combustion car can show zero fuel use during engine braking while still dissipating kinetic energy.

An electric car can display a large amount of regenerated energy because the driver first created a large amount of unnecessary kinetic energy.

A heavy vehicle may suffer relatively little from its mass during perfectly steady, flat highway travel and much more in stop-and-go traffic or repeated climbing.

And higher speed can demand rapidly increasing aerodynamic power even as each additional mile per hour buys a smaller increment of travel-time savings.

The previous chapter asked why one energy pathway becomes dominant.

This chapter follows the energy after the vehicle starts moving.

## 1. A CAR USES ENERGY EVEN WHEN ITS SPEED DOES NOT CHANGE

Imagine a car traveling at perfectly constant speed on a perfectly level road.

It is not accelerating. It is not climbing. Its kinetic and gravitational potential energy are not increasing.

Why does the driver still need to supply power?

Because a moving car is constantly pushing against resistance.

One part comes from the tires and the deformation of the contact patch. That is rolling resistance. It depends on load, tire construction, inflation pressure, temperature, pavement, and other conditions.

Another major part is aerodynamic drag. The vehicle continually pushes air out of the way.

For a given shape and air density, aerodynamic drag force rises approximately with the square of the vehicle's speed relative to the air. Because power is force multiplied by speed, the power required to overcome that drag rises approximately with the cube of airspeed.

DOE summaries of vehicle energy losses make the shift in regime clear: at lower speeds, rolling and other losses matter strongly; as road speed rises, aerodynamic drag becomes increasingly important.[1]

This is why a fast highway trip is not simply the same trip with the speedometer moved a little farther to the right.

The vehicle is operating in a different energy regime.

## 2. WHY TEN MORE MILES PER HOUR COSTS MORE THAN TEN MORE MILES PER HOUR

Human intuition treats speed increments linearly.

Sixty miles per hour.

Seventy miles per hour.

The difference is ten.

The air does not experience that change linearly.

For the same vehicle, the theoretical aerodynamic drag force at 70 mph is about 36 percent higher than at 60 mph because drag scales roughly with speed squared. The aerodynamic power required at 70 mph is about 59 percent higher because that power scales roughly with speed cubed.

That does not mean the vehicle's total fuel or electricity consumption rises by 59 percent.

Rolling resistance, drivetrain efficiency, engine operating point, battery and motor losses, wind, grade, accessories, and many other factors contribute to total consumption.

But the direction of the physical effect is unavoidable.

Oak Ridge National Laboratory speed-testing compilations likewise show meaningful losses in fuel economy as highway speed increases. Across the cited vehicle sample, moving from 60 to 70 mph produced a fuel-economy penalty on the order of ten percent or more for many vehicles.[2]

That is not a universal coefficient.

A low sedan, a large pickup, an SUV, and an electric crossover will not respond identically.

But none of them can bargain with the physics of aerodynamic drag.

## 3. WHAT TIME DOES SPEED ACTUALLY BUY?

The energy cost of speed only becomes meaningful when we compare it with what speed purchases.

On a theoretical 100-mile road with no traffic, intersections, construction, or slowing:

At 50 mph, the trip takes 120 minutes.

At 60 mph, it takes 100 minutes.

At 70 mph, about 85 minutes and 43 seconds.

At 80 mph, 75 minutes.

Going from 50 to 60 mph saves twenty minutes over 100 miles.

Going from 60 to 70 saves about fourteen minutes and seventeen seconds.

Going from 70 to 80 saves about ten minutes and forty-three seconds.

Speed continues to save time. But the incremental time saved by each additional 10 mph becomes smaller.

Real roads reduce the gain further. Traffic, merging, work zones, signals, slower vehicles, weather, congestion, and legal speed limits all interrupt the idealized calculation.

The extra aerodynamic energy has already been spent even when the theoretical time advantage disappears.

This is not an argument for one universally correct speed. Safety, law, road design, weather, traffic, and the value of time all matter.

It is a way to ask a better question: how much additional energy is being spent for how much actual time saved?

## 4. WIND CAN CHANGE THE TRIP WITHOUT CHANGING THE SPEEDOMETER

A vehicle responds aerodynamically to airspeed, not only to speed over the ground.

A car traveling 60 mph into a 15 mph headwind sees roughly 75 mph of relative airspeed from the front.

The speedometer still says 60 mph.

The distance has not changed.

But aerodynamic drag rises sharply because the body is moving faster relative to the air.

A tailwind produces the opposite effect.

This is one reason two apparently identical highway trips can produce different energy consumption even when the driver holds the same ground speed.

The broader lesson is simple.

Consumption is not a fixed property of the vehicle.

It is the result of a vehicle operating in specific conditions.

## 5. ACCELERATION STORES ENERGY IN MASS

When a vehicle accelerates, it acquires kinetic energy.

The basic relationship is $E = 1/2\ mv^2$.

That formula contains two important facts.

Double the mass and, at the same speed, the kinetic energy doubles.

Double the speed and the kinetic energy multiplies by four.

Take an illustrative vehicle weighing about 3,300 pounds, or roughly 1,500 kilograms. Ignoring drivetrain losses, its kinetic energy is approximately:

0.037 kWh at 30 mph;

0.126 kWh at 55 mph;

0.176 kWh at 65 mph;

0.234 kWh at 75 mph.

Those numbers are small compared with the chemical energy in a tank of gasoline or the stored energy in a large traction battery.

But urban driving can create and remove kinetic energy repeatedly.

A driver who accelerates hard toward a red light is doing more than choosing an inefficient operating point.

The driver is creating kinetic energy that will have to be removed seconds later.

How that energy is removed determines whether it becomes mostly heat or is partly recovered.

## 6. CLIMBING STORES ENERGY IN ELEVATION

Gravity creates another storage mechanism.

Potential energy is $E = mgh$.

For the same 3,300-pound vehicle, gaining about 330 feet of elevation—roughly 100 meters—stores about 0.41 kWh of mechanical energy.

That energy has not disappeared at the top.

It is stored in the vehicle's position in the gravitational field.

On the descent, gravity gives it back.

If the vehicle is allowed to accelerate, the energy becomes kinetic energy.

If speed has to remain controlled, the energy must be dissipated or recovered.

Friction brakes turn much of it into heat.

An electrified powertrain can convert some of it into electricity and return part of that to the battery.

No real system recovers everything.

Hills make the difference among preserving energy, dissipating it, and converting it especially easy to see.

## 7. BRAKING DECIDES WHERE THE ENERGY ENDS UP

A friction brake performs a simple energy transformation.

Pads press against rotors. Mechanical energy becomes heat. The rotors and surrounding components warm, and that heat eventually disperses into the environment.

The energy has not been destroyed in a thermodynamic sense.

It has been turned into heat that can no longer move the car.

This is why repeated acceleration and braking can be energetically expensive.

Energy is supplied to create speed.

Then braking turns that useful mechanical energy into heat.

Then more energy is required to accelerate again.

DOE's Alternative Fuels Data Center summarizes the practical effect: aggressive driving—speeding, rapid acceleration, and hard braking—can reduce fuel economy by roughly 15 to 30 percent at highway speeds and 10 to 40 percent in stop-and-go traffic, depending on the vehicle and conditions.[3]

Those are broad observed ranges, not universal laws.

They show the possible scale of repeatedly creating motion that the driver soon has to remove.

## 8. REGENERATION DOES NOT CANCEL THE COST

Hybrids and electric vehicles change what can happen during deceleration.

Instead of using only friction brakes, the electric machine can operate as a generator. The wheels drive the motor-generator, power electronics convert the energy, and the battery stores part of it for later use.

DOE describes regenerative braking as recovering some of the energy that would otherwise be lost during braking.[4]

The important word is some.

The electric machine is not perfectly efficient.

The inverter and other power electronics have losses.

The battery has charging and discharging losses.

When the vehicle accelerates again, that stored energy has to be converted back into motion.

Regeneration is especially useful when the vehicle genuinely has to slow down.

It does not make unnecessary acceleration free.

If the vehicle never needed the extra kinetic energy in the first place, avoiding its creation is usually better than converting it to electricity and back again.

## 9. COASTING, ENGINE BRAKING, AND REGENERATION ARE DIFFERENT

Every deceleration is not the same.

Coasting minimizes propulsion and braking torque so the vehicle preserves its kinetic energy as long as practical while air resistance, rolling resistance, and grade gradually change speed.

Engine braking deliberately uses the resistance of a combustion powertrain to slow the vehicle more strongly.

Regenerative braking uses the electric machine to create braking torque while converting part of the vehicle's mechanical energy back into electrical energy.

A 2023 SAE study comparing deceleration strategies for an electric vehicle found the same basic tradeoff: coasting minimized energy consumption in the modeled scenario, regenerative braking could support shorter travel time, and intermediate strategies could provide the best compromise when time and energy were considered together.[5]

The physics is intuitive.

If the vehicle still needs to travel forward and there is no reason to slow quickly, directly preserving mechanical energy can avoid an unnecessary conversion.

If the vehicle genuinely must slow, regeneration is preferable to throwing all of that mechanical energy away as heat.

The correct choice depends on what the vehicle needs to do next.

This is not a recommendation to shift into Neutral. Modern vehicles can implement low-drag coasting strategies while remaining in Drive, and vehicle control and safety always take priority over an energy optimization.

## 10. ZERO FUEL ON THE DISPLAY CAN STILL MEAN ENERGY IS BEING LOST

Many modern combustion vehicles can cut fuel injection during in-gear deceleration.

The dashboard may then show zero instantaneous fuel consumption.

That reading can be correct in the narrow sense that no fuel is being injected.

It does not mean no energy is being lost.

The wheels are driving the engine through the transmission. Compression, pumping losses, friction, and accessories absorb kinetic energy. The vehicle slows.

That can be desirable when slowing is necessary.

But if the goal is simply to travel farther before speed must fall, a lower-drag state can preserve more mechanical energy.

The important distinction is between fuel flow at one instant and the total energy needed to complete the trip.

## 11. MORE REGENERATION CAN MEAN MORE WASTE

One of the most seductive dashboard metrics is energy recovered.

A large green number looks like evidence of efficient driving.

Sometimes it is.

Sometimes it is evidence that the vehicle first acquired a large amount of kinetic energy that then had to be removed.

Argonne National Laboratory chassis-dynamometer testing of a Tesla Model 3, published through SAE in 2026, illustrates the problem. More aggressive driving could recover substantial braking energy and yet remain markedly less efficient overall than more moderate urban and highway cycles.[6]

The vehicle recovered more because it had more speed changes to recover from.

The meaningful metric is not how much energy came back during braking.

It is the net energy required to accomplish the trip.

## 12. REGENERATION HAS LIMITS

Even when slowing is necessary, regenerative braking is not always available at full strength.

It depends on vehicle speed, motor-generator capability, tire traction, control strategy, battery temperature, battery state of charge, and how much charging power the battery can safely accept.

A cold battery may accept less regenerative power.

A nearly full battery may have little room to absorb more energy.

Tesla owner manuals, for example, explicitly describe conditions in which regenerative braking can be reduced because of battery temperature or state of charge.[7]

That is one reason friction brakes remain essential on electrified vehicles.

Engineering literature on battery-electric brake systems emphasizes that friction brakes still have to manage the cases in which regeneration is limited, unavailable, or insufficient.[8]

Regeneration supplements the braking system.

It does not replace the need for independent mechanical braking and safe stopping capability.

## 13. WHY HYBRIDS OFTEN LIKE CITY DRIVING

A hybrid is especially useful in the situations where a conventional combustion vehicle tends to waste the most energy.

At a stop, it can shut the engine off.

At low speed, some hybrid architectures can operate electrically.

During acceleration, the electric motor can assist the combustion engine.

During braking, it can recover energy.

And, just as important, the hybrid architecture can decouple engine operation from the driver's instantaneous wheel-power demand.

DOE summaries of hybrid technology highlight engine stop/start, regenerative braking, electric assist, and the ability to use a smaller combustion engine among the mechanisms that improve efficiency.[9]

This helps explain an outcome that can surprise drivers: some hybrids can achieve better fuel economy in urban driving than on a fast highway.

City driving creates many events that are costly for a conventional powertrain.

The hybrid can turn some of them into opportunities for engine shutdown, load management, and regenerative recovery.

## 14. AN INTERNAL-COMBUSTION ENGINE DOES NOT HAVE ONE EFFICIENCY

A combustion engine does not convert a fixed percentage of fuel energy into useful work in every situation.

Efficiency changes with engine speed, load, temperature, air-fuel ratio, ignition timing, pumping losses, friction, and calibration.

Engine-efficiency maps used in hybrid-control research show why there are operating regions that are much more favorable than others.[13]

DOE likewise shows that only part of the chemical energy in fuel reaches the wheels of a conventional light-duty vehicle and that heat, exhaust, pumping, friction, accessories, and drivetrain losses vary with driving conditions.[14]

This is why "press the accelerator as little as possible" is not a universal physical rule.

At very low load, a combustion engine can spend a large share of its output overcoming fixed and pumping losses.

At the other extreme, demanding very high power can move the engine into less favorable regions, increase enrichment in some conditions, and often creates speed that has to be removed later.

The useful principle is broader.

Provide the service the trip requires with the least total energy, and avoid creating speed that will soon have to be cancelled.

Hybrid control exploits this variable efficiency. The electric motor and battery can temporarily separate wheel demand from engine output, allowing the combustion engine to operate closer to favorable load points, shut off when it would be inefficient, or sometimes produce more than instantaneous wheel demand when storing the difference is beneficial overall.

That freedom is not free. Electrical conversion and battery cycling also have losses.

But it gives the powertrain flexibility that a conventional engine tied more directly to wheel demand does not have to the same degree.

## 15. MASS IS NOT ALWAYS THE MAIN ENEMY—BUT IT RETURNS WHENEVER MOTION CHANGES

On a perfectly level highway at steady speed, a heavy but aerodynamically efficient vehicle can perform better than intuition suggests.

At high speed, air drag often dominates.

Mass still affects rolling resistance, but its largest penalty reappears whenever the vehicle changes speed or elevation.

More mass means more energy to accelerate.

More energy to climb.

More energy that must later be removed during braking.

More load on the tires.

Regenerative braking can recover part of that energy in an electric vehicle.

It does not make mass free.

DOE has historically estimated that a 10 percent reduction in vehicle mass can improve fuel economy in a conventional combustion vehicle by roughly 6 to 8 percent, while emphasizing that the exact benefit depends on design and use. [1]

That estimate should not become a universal rule for every modern vehicle or powertrain.

What matters more is when the vehicle is accelerating, climbing, or cruising.

“Weight does not matter in an EV” is false.

“Weight explains all consumption” is also false.

Driving regime determines how strongly mass matters.

## 16. TIRES CONSUME ENERGY WITHOUT MAKING IT OBVIOUS

Rolling resistance arises largely from repeated tire deformation.

Every rotation bends the tire structure at the contact patch and allows it to recover. Part of that mechanical energy becomes heat in the rubber and tire structure.

Underinflated tires deform more, which increases rolling resistance and tire wear.

EPA fuel-economy guidance accordingly recommends maintaining the manufacturer's specified tire pressure.[10]

Older EPA testing found fuel-economy sensitivity on the order of a few tenths of a percent per psi of underinflation under its test conditions.[11]

That historical coefficient should not be applied mechanically to every modern tire, vehicle, temperature, or pressure range.

The durable lesson is simpler.

Use the pressure specified for the vehicle.

Overinflating a tire to chase a small energy gain can degrade ride, grip, handling, wear patterns, or safety.

Energy savings come second to the tire's primary jobs: carrying the vehicle, maintaining grip, steering, and stopping safely.

## 17. COLD STARTS AND ACCESSORIES CHANGE THE SCALE OF A SHORT TRIP

Fuel consumption per mile can be especially poor on short trips in a combustion vehicle.

Part of the energy cost is not proportional to distance.

The engine and lubricant have to warm up.

Friction is higher while components are cold.

Emission-control systems have to reach operating temperature.

Cabin heating or air conditioning may be working hard.

Defrosters, pumps, fans, lights, computers, and other accessories consume power as well.

EPA guidance notes that repeated short trips with a cold engine reduce fuel economy and recommends combining errands when practical rather than repeatedly creating cold-start conditions.[12]

An electric vehicle does not have the same engine warm-up losses.

It still has accessories.

Cabin heating or A/C can represent a meaningful share of energy on a very short trip, especially in extreme temperatures.

The same vehicle can use very different amounts of energy per mile depending on trip length and conditions.

## 18. EFFICIENT DRIVING IS PREDICTIVE DRIVING

We can now describe efficient driving without turning it into a moral style or an unsafe set of tricks.

The principle is not “always accelerate as slowly as possible.”

On a combustion engine, excessively low load can keep the engine in an unfavorable operating region for longer.

The principle is not “never brake.”

Traffic, law, visibility, pedestrians, hazards, road geometry, and safety require braking whenever braking is needed.

The principle is to avoid creating energy that you already know you will have to discard.

See a red light early and stop adding power.

Do not accelerate into a visibly stopped queue.

Leave enough following distance to smooth minor changes in traffic speed instead of turning each change into an acceleration-braking cycle.

When a real slowdown is needed in an electrified vehicle, use the vehicle’s normal regenerative strategy as designed while preserving full control and braking margin.

When a slowdown is not yet necessary, preserving momentum can be more efficient than converting motion into electricity and later converting it back.

At steady speed, choose speed according to safety, law, conditions, and the actual value of the time being saved.

The best description is not merely gentle driving.

It is predictive driving.

## 19. SOMETIMES THE BEST JOULE IS THE ONE YOU NEVER HAD TO CONVERT

Modern vehicles make energy recovery highly visible.

Combustion engines improve thermal efficiency.

Hybrids recover braking energy.

Electric cars display kilowatt-hours flowing back into the battery.

But every conversion has a cost.

Fuel becomes heat.

Heat becomes mechanical work.

Motion becomes electricity.

Electricity becomes stored chemical energy.

Stored energy becomes electricity again.

Electricity becomes motion again.

The more conversions we can avoid, the less perfect the remaining conversions need to be.

Avoiding an unnecessary acceleration eliminates both the energy needed to create that speed and the later need to recover or dissipate it.

Driving somewhat slower, when appropriate and lawful, reduces aerodynamic loss directly instead of trying to recover energy that has already been transferred to the air.

Reducing mass lowers the energy required for acceleration and climbing.

Correct tire pressure reduces a continuous loss.

A hybrid shuts the engine down where it would do no useful work.

Regeneration recovers energy where deceleration is unavoidable.

The most efficient system is not necessarily the one that displays the largest amount of recovered energy.

It is the one that provides the required mobility with the fewest unnecessary energy conversions.

That conclusion leads directly to the next chapter.

The energy losses we have tracked also show up as physical wear.

Tires wear.

Brake components wear.

Batteries age.

Parts are replaced.

Eventually the vehicle leaves the fleet.

After following energy, we have to follow matter.

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# CHAPTER 6 — WHERE DOES THE MATERIAL COME FROM, AND WHERE DOES IT GO?

## OPENING — A CAR NEVER ARRIVES AT THE RECYCLER WHOLE

It is easy to imagine the material life of a car as a straight line.

The usual story is linear: raw materials enter factories, a vehicle comes out, it operates for fifteen or twenty years, and eventually it reaches a salvage yard to be recycled or discarded.

That picture is convenient.

It is also wrong.

Material begins moving long before final assembly. Ore is mined and transformed into steel, aluminum, copper, and other metals. Polymers emerge from a different industrial chain. Glass, rubber, textiles, coatings, adhesives, fluids, and electronics each arrive with their own upstream history.

And the vehicle does not remain materially intact while it is being used.

The vehicle also sheds material throughout its life. Tires leave tread on the road, brake components wear, and oil, coolant, filters, bearings, suspension parts, body panels, sensors, and control modules may leave the car years before the shell does. Some parts are repaired, reused, or remanufactured; others are destroyed.

The vehicle itself does not have one kind of death either.

End of life can take several forms. A vehicle may become technically unusable, remain repairable but too expensive to justify, be totaled after a crash or flood, receive a salvage or junk designation, leave the U.S. fleet for continued use abroad, or be dismantled for parts before the remaining shell reaches a shredder.

To follow the material, we have to stop treating the car as a sealed object.

A car is a temporary stock of materials that enter, wear away, get replaced, reused, recovered, or discarded over time.

## 1. WHAT IS A CAR ACTUALLY MADE OF?

The first surprise is that such a simple question does not have one universal answer.

The European Commission's Joint Research Centre compared several published vehicle material inventories. Across those sources, steel represented roughly 55 to 68 percent of vehicle mass, plastics about 9 to 11 percent, aluminum about 6 to 12 percent, rubber about 3.5 to 7 percent, and glass roughly 2 to 3 percent, with copper, fluids, textiles, coatings, adhesives, electronics, and other materials making up the rest.[1]

Those ranges are not a specification for the average American vehicle in 2026.

They come from different vehicles, years, and accounting methods.

Their value is structural.

An automobile remains primarily a metallic machine, but a 3,500- or 5,000-pound vehicle is not a homogeneous block of material.

Body steel does not perform the same function as an aluminum suspension component, copper wiring, a polymer instrument panel, tire rubber, windshield glass, or electronic packaging. Those materials have different production histories, values, joining methods, contamination risks, repair possibilities, and end-of-life markets.

To understand what a car is made of and what happens to those materials, we need to ask two questions at once.

How much material is being mobilized?

And in what form has that material been organized?

The detailed chemistry, critical minerals, second life, and recycling of the traction battery remain outside this chapter. They belong in Chapter 9.

## 2. WHY EXACT COMPOSITION IS HARDER TO KNOW THAN IT SEEMS

By 2026, it might seem that one public database should be able to tell us the exact material composition of an average vehicle down to the pound.

That is not how the information is organized.

The JRC notes that complete and transparent vehicle bills of materials are uncommon. Modern vehicles contain thousands of components and multiple supplier tiers. Detailed life-cycle inventories may exist without being fully public.[1]

The automobile industry itself often knows far more than an outside observer.

Systems such as the International Material Data System allow automakers and suppliers to declare substances and material content at component level in order to manage regulated materials and supply-chain requirements.

The problem, then, is not a lack of material information.

It is that the level of detail available inside the industrial chain is not the same as the level available for independent public comparison of complete vehicles.

That imposes a rule on this chapter.

These figures are best treated as ranges and orders of magnitude.

False precision would make the analysis look stronger while actually making it weaker.

## 3. LIGHTWEIGHTING CAN SHIFT MATERIAL DEMAND RATHER THAN SIMPLY REDUCE IT

At first glance, lightweighting looks like an obvious material win.

A lighter vehicle needs less energy to accelerate and climb and can reduce some loads throughout the system.

But how is the mass removed?

Sometimes engineers genuinely use less material.

Sometimes they substitute one material for another.

Those operations are not equivalent.

The International Energy Agency's work on material efficiency shows that more aggressive vehicle lightweighting can reduce steel demand while increasing the use of aluminum, plastics, or composites.[2]

U.S. Department of Energy research makes the engineering tradeoff equally visible. Advanced high-strength steel, aluminum, magnesium, and fiber-reinforced composites can reduce component mass, but multi-material designs can create new problems in joining, corrosion, repair, manufacturing cost, and recycling.[3]

That does not make lightweighting bad.

Removing a pound from the finished car does not necessarily eliminate a pound of material burden upstream or downstream.

The better question is: how much mass, made of which materials, performing which function, for how long, and with what prospects for repair, separation, and high-quality reuse at the end?

## 4. MATERIAL ALREADY HAS A HISTORY BEFORE FINAL ASSEMBLY

The assembly plant is visually impressive because the car takes recognizable form there.

Most of the material work began earlier.

The upstream chain is just as varied. Iron ore and scrap become steel; bauxite becomes alumina and then aluminum; copper is extracted, concentrated, smelted, and refined; polymers are synthesized and compounded; tires combine natural and synthetic rubber with fillers, textiles, and steel; and glass is melted, shaped, and treated.

Every process has a yield.

Manufacturing also produces losses before the car ever reaches the road: stamped sheet leaves offcuts, machining creates chips, castings can be rejected, and parts can fail quality control.

The IEA includes manufacturing yield, long-life design, reuse, and recycling among its material-efficiency strategies.[2]

This changes the meaning of waste.

Waste does not begin when the owner calls a tow truck for the last time.

It can be created or prevented during design, forming, machining, assembly, quality control, repair, and every component replacement.

## 5. A CAR SHEDS MATERIAL WHILE IT DRIVES

The previous chapter followed energy lost to rolling resistance and friction.

Now look at the same scene as a material flow.

Friction does not only turn useful mechanical energy into heat.

It wears surfaces.

Road use creates its own material flows. Tires shed particles, brake pads and rotors wear, pavement erodes, and traffic resuspends dust already on the road.

The OECD stresses the importance of keeping these sources separate: tire wear, brake wear, road wear, and resuspension are not the same phenomenon.[4]

EPA's MOVES emissions model likewise treats non-exhaust particulate sources separately. Its current modeling framework includes brake wear, tire wear, and resuspended road dust, including for electric vehicles where applicable.[5]

The distinction matters because the metrics are not interchangeable.

Total rubber mass lost from a tire is not the same measurement as airborne PM2.5.

Particle number is not the same as microplastic mass.

Resuspended road dust is not newly abraded vehicle material.

Some of a car's material life ends while the car is still on the road.

Some of the car literally wears away mile by mile.

## 6. THE TIRE: WASTE PRODUCED MILE BY MILE

A tire is designed to grip the road.

That basic job already explains the material problem.

To transmit acceleration, braking, and cornering forces, rubber interacts with an abrasive surface under load. The contact patch deforms, heats, slips microscopically, and gradually loses material.

The tire casing can remain structurally usable while part of the tread has already left the tire.

OECD's review finds a robust general relationship between vehicle load and tire wear, even though studies do not agree on one universal mathematical coefficient. Speed, acceleration, braking, tire construction, inflation, road surface, alignment, and driving style also influence wear.[4]

Vehicle mass matters here too.

All else equal, greater vertical load asks more of the tire.

But all else is rarely equal.

Two vehicles of different mass may use different tire sizes, compounds, pressures, suspensions, torque control, and duty cycles.

The defensible conclusion is that mass is one factor in wear.

It is not a universal conversion from vehicle weight to grams of tire loss per mile.

## 7. ELECTRIFICATION DOES NOT ELIMINATE NON-EXHAUST MATERIAL FLOWS

A battery-electric vehicle changes part of the emissions picture dramatically.

It has no tailpipe exhaust emissions during use.

Regenerative braking can also reduce reliance on friction brakes, sometimes substantially.

But tires still touch the road.

The road surface still wears.

Traffic can still resuspend deposited dust.

And heavier vehicle configurations can increase some mechanical loads.

EPA's MOVES guidance explicitly notes that electric vehicles do not generate conventional tailpipe or evaporative emissions but still generate brake- and tire-wear particulate emissions.[5]

That does not support the slogan that electric vehicles "pollute just as much" through tires.

Nor does electrification eliminate every material flow from driving.

Vehicle mass, tire specification, braking strategy, road surface, driving cycle, and the metric being measured all matter.

The useful distinction is source by source.

Electrification eliminates some local emissions, strongly reduces some others, and leaves some contact-related material flows in place.

## 8. REPAIR PRESERVES MORE THAN POUNDS

A component is more than a pile of raw materials.

Consider an alternator.

It contains copper, steel, aluminum, polymers, bearings, electronics, fasteners, and other materials.

But industry has also added organization.

A used component already contains a great deal of work and energy: copper has been wound, surfaces machined, bearings fitted, and parts assembled, balanced, tested, and turned into a functioning unit.

If one localized fault occurs, shredding the entire assembly may recover some metal while destroying much of the manufacturing work already embodied in the part.

Repair or direct reuse can preserve not only the material itself but also more of the manufacturing work and useful function already embodied in the part.

This is why circularity does not begin with recycling.

It begins with a prior question: can the component, assembly, or part safely remain in useful service?

That hierarchy is not absolute.

A cracked safety-critical component should not be reused merely to save material. A badly degraded component may require more labor and energy to restore than its remaining service justifies. Older hardware can sometimes block an important improvement in safety or efficiency.

But without comparing those options, the word “recycling” can hide the premature destruction of a part that still had useful life.

## 9. REMANUFACTURING: PRESERVE USEFUL VALUE BEFORE RETURNING TO RAW MATERIAL

Remanufacturing pushes the same principle further.

A used component is disassembled, cleaned, inspected, restored or re-machined where necessary, fitted with replacement wear items, reassembled, and tested to a defined functional standard.

The goal is not merely to place a used part back into service.

It is to preserve geometry, material, and industrial work that do not need to be recreated.

A 2021 study modeling automotive engine material flows over fifty years found that remanufacturing reduced final dissipation of some metals relative to a scenario relying on recycling without remanufacturing—about 3 percent for steel, 2 percent for nickel, and 5 percent for chromium in that model.[6]

Those percentages belong to that component, model, and time horizon.

They are not a conversion factor for every automobile.

The general mechanism is what matters.

Keeping an assembly in service can preserve value that even a good recycling process cannot fully recover.

Maintainability affects material use too.

Designing a component so it can be diagnosed, disassembled, and restored changes not only repair cost but also how much of the original manufacturing work survives into the next service life.

## 10. THE DIFFERENT DEATHS OF A CAR

When does a car become waste?

The answer seems obvious until we look at actual vehicles.

A failed engine can be replaced.

A badly damaged body can sometimes be repaired.

A flooded vehicle may be physically repairable but still too costly—or legally unsuitable—to put back on the road.

A low-value older car can be retired after a repair that would be routine on a more valuable vehicle.

A vehicle can leave service for several different reasons.

Technical death: the vehicle can no longer perform its function acceptably.

Economic death: repair remains physically possible but no longer makes financial sense.

Accidental death: a crash, fire, or flood destroys enough value that the vehicle leaves normal service.

Legal or title death: the vehicle enters a junk, salvage, or comparable status under the applicable rules.

And there is statistical death: the vehicle disappears from the U.S. active fleet but continues operating elsewhere.

The American system does not collapse all of these into one national end-of-life category.

State title systems matter. Insurance total-loss decisions matter. Federal reporting adds another layer.

That complexity is not administrative noise.

It changes what happens to the material next.

## 11. LEAVING THE U.S. FLEET IS NOT THE SAME AS BEING DESTROYED

A vehicle can disappear from U.S. registrations without being physically destroyed.

Used-vehicle exports extend the lives of many cars beyond their first national market. UNEP tracks flows of used light-duty vehicles from major exporters including the United States to importing countries around the world.[7]

From a material standpoint, that transfer can cut two ways.

It may extend the useful life of a product that has already been manufactured, delaying the need for another vehicle.

It may also move an older vehicle, its emissions, maintenance burden, and eventual disposal into a country with different inspection, repair, fuel-quality, and waste-management systems.

Federal vehicle-history reporting reflects the fact that export can also occur after a vehicle enters the salvage economy. Junk and salvage yards that report to the National Motor Vehicle Title Information System must include information about disposition and whether a reported vehicle is intended for export.[8]

That does not mean an exported vehicle is automatically waste.

It means that leaving the domestic fleet, entering salvage reporting, being exported, and being physically recycled are distinct events.

If the vehicle crosses a border, the analysis has to follow it.

## 12. WHAT HAPPENS WHEN A VEHICLE ENTERS THE U.S. RECYCLING CHAIN?

When a vehicle actually enters professional dismantling and recycling, the efficient sequence does not begin by feeding the intact car into a shredder.

First comes information and triage.

The practical questions come quickly: can the vehicle be rebuilt, which parts still have value, which components can be removed safely for reuse, and which fluids or hazardous materials require controlled handling?

EPA guidance for end-of-life vehicle processing emphasizes removal and proper management of fluids and components such as batteries, tires, fuel tanks, airbags, and other potentially hazardous items. Refrigerant from motor-vehicle air-conditioning systems must be recovered before final recycling or disposal of the equipment.[9][10]

Reusable parts can be removed before the remaining structure moves toward scrap processing.

The body can then be crushed or shredded, after which magnetic, eddy-current, density, optical, and other separation processes recover ferrous and nonferrous fractions while leaving more heterogeneous shredder residue.

This sequence explains why theoretical recyclability is not the same as actual recycling.

A polymer may be chemically recyclable in principle yet too mixed or contaminated to justify separation.

A metal alloy may be recoverable but downgraded into a less demanding application.

A component headed toward the shredder may instead preserve far more value if removed and sold for reuse first.

Order matters.

The earlier a safe part or assembly can be kept in service, the less has to be rebuilt from scratch.

## 13. A HIGH RECOVERY NUMBER IS NOT A CLOSED LOOP

The United States does not need a single dramatic recycling percentage to make the basic point.

Industry data already illustrate the accounting problem.

The Automotive Recyclers Association states that approximately 86 percent of a vehicle's material content is recycled, reused, or used for energy recovery.[11]

That figure is useful because it combines three very different outcomes.

Reuse preserves a functioning part or assembly.

Material recycling turns material into a feedstock for another production process.

Energy recovery captures energy value while destroying the material itself.

Adding them together can describe diversion or recovery from disposal.

It does not describe a closed material loop.

The number is also an industry statistic, not a federal compliance rate measured against one nationwide vehicle-recycling directive.

So the right question is not whether the figure is “high.”

It is what each destination preserves.

A vehicle can post a strong overall recovery rate while still losing specialized alloys, polymer quality, coatings, fibers, electronic materials, and much of the working value embodied in components before dismantling.

## 14. RECYCLING A TON DOES NOT TELL YOU WHAT IT BECOMES

Metal makes circularity look deceptively simple.

Melt an old part.

Make a new part.

In some material streams, that loop can work very well.

Automobiles, however, combine alloys, coatings, adhesives, foams, fibers, electronics, rubbers, and many polymer families.

What comes back out matters as much as how much comes back out.

A recovered metal fraction may contain alloying elements that limit its use in a high-specification application. A mixed plastic fraction may be technically recyclable without being suitable for a new structural or visible automotive part.

The DOE’s own lightweight-materials research notes that combining aluminum and other materials can create challenges in joining, repair, corrosion control, and recycling.[3]

Recycling can be a loop.

It can also be a cascade in which a high-specification material becomes a lower-specification product and eventually leaves the material economy.

That cascade may still be useful.

But calling every recovered ton circular without asking what it displaces hides the question we actually care about.

How much primary material did the secondary material genuinely replace?

## 15. U.S. END-OF-LIFE GOVERNANCE IS DISTRIBUTED

U.S. law and regulation also shape what happens to automotive materials at the end of a vehicle’s life.

The United States does not have one national rule that covers vehicle design and end-of-life treatment from start to finish. Those responsibilities are split among several systems and actors.

The National Motor Vehicle Title Information System creates federal reporting and transparency around junk and salvage vehicles. State motor-vehicle agencies, insurers, auto recyclers, junk yards, salvage yards, shredders, and other covered actors provide specified data under that system.[8]

Federal environmental rules govern particular hazards and waste streams. EPA rules require recovery of motor-vehicle refrigerants before final disposal. Used fluids, batteries, hazardous mixtures, and other wastes can trigger federal or state environmental requirements.[9][10]

States then add their own salvage-title practices, recycler licensing, waste rules, tire programs, and other requirements.

This structure is different from asking a single regulator to specify a national recycled-plastic share in future vehicle design.

Neither approach automatically guarantees a circular system.

The U.S. model can support strong markets for used parts and recovered metals while leaving design for disassembly and closed-loop material quality more dependent on automaker choices, economics, specialized rules, and state policy.

The claim here is descriptive, not moral.

When responsibility is spread across many actors, circularity depends on how collection, dismantling, used-parts markets, scrap processing, and environmental rules fit together.

## 16. THE TIRE AFTER THE TIRE: REUSE, RETREADING, MATERIAL MARKETS, AND ENERGY

The tire compresses almost the entire chapter into one object.

Before removal, some tread has already dispersed through abrasion.

After removal, the remaining casing may still have value.

A usable tire can be sold again.

A suitable casing—especially in commercial trucking—can be retreaded, preserving the body of the tire while renewing the tread.

When the tire is genuinely at end of life, it can enter markets for ground rubber, molded products, tire-derived aggregate, other civil-engineering uses, or energy recovery, depending on local markets and rules.

USTMA's 2023 End-of-Life Tire Management Report says about 79 percent of annually generated U.S. end-of-life tires were consumed by end-use markets in 2023, up from roughly 71 percent in 2021.[12]

That is an industry-reported utilization figure.

It should not be translated into "79 percent became new tires."

Different end uses preserve very different things.

Retreading preserves the casing and much of the function.

Ground rubber preserves material but changes the product.

Using tire-derived material in civil works gives the material another use.

Using tires as fuel recovers energy but does not preserve rubber as material.

The collection rate is important.

The destination still matters.

## 17. A TIRE FIRE IS NOT THE NORMAL END OF A TIRE

The most dramatic image of tire waste is a stockpile fire.

The danger is real.

EPA guidance describes the difficulty of controlling large tire fires and the risks from smoke, oily residues, runoff, and contamination of soil and water.[13]

But an uncontrolled tire pile burning is not the normal meaning of end-of-life tire management.

It is a failure of storage, market development, enforcement, or governance.

That distinction matters because spectacle can make a critical argument less accurate.

USTMA reports that identified abandoned and illegal stockpiles fell from more than one billion tires in 1990 to fewer than 48 million in 2023, while states, EPA, industry, and local programs developed collection and end-use markets.[12]

Those figures are industry-reported, but the historical direction is large enough to illustrate something important.

Material recovery can improve when waste that once had no practical market gains regulated pathways and economically viable uses.

Open burning also has to be distinguished from controlled industrial use as tire-derived fuel.

In both cases rubber is combusted.

The emissions controls, purpose, and material-management context are not remotely the same.

## 18. AIRLESS: ELIMINATING PUNCTURES DOES NOT ELIMINATE WEAR

An airless tire seems to offer an elegant escape from one class of tire failure.

No conventional inflation pressure.

No classic flat from a punctured air chamber.

Potentially less downtime for some fleet applications.

Michelin has tested its UPTIS airless technology on light vehicles in real-world fleet applications, while Bridgestone has developed its AirFree concept and road demonstrations for selected uses.[14][15]

These technologies are real.

They are not, in 2026, the universal replacement for pneumatic passenger-car tires.

More important, removing air does not remove the tread.

The tire still has to create grip at the road surface.

That interface still deforms and wears.

Airless design can eliminate or reduce some failure modes and some premature disposal associated with pressure loss or puncture.

It does not eliminate material use, abrasion, or end-of-life management.

Innovation usually moves constraints.

It rarely abolishes them.

## 19. THE BETTER METRIC MAY NOT BE THE RECYCLING RATE

Now return to the whole vehicle.

Imagine two cars.

The first uses a large amount of primary material, is difficult to repair, replaces several major assemblies during its life, and ultimately achieves an excellent mass-based recovery rate.

The second uses less primary material, stays in service longer, preserves more components through repair and remanufacturing, and ends with a slightly lower final recycling rate.

Which system is more circular?

The recycling percentage cannot answer by itself.

We need to know how much virgin material went into the vehicle, how long it stayed useful, how many parts were replaced along the way, how much manufacturing work was preserved, and what quality of recovered material came back out.

This is the same optimization problem that appears throughout the book.

Each actor can optimize its own stage—the manufacturer for production cost, the owner for replacement price, the dismantler for parts sales, the shredder for metal recovery, the tire industry for utilization—while the full vehicle life cycle still consumes more virgin material than another design would have required.

A car that uses materials efficiently is not simply light, and it is not simply recyclable.

It provides the required service with relatively little primary material, keeps expensive functional assemblies useful for as long as reasonable, replaces wear locally where possible, and returns materials at end of life in forms clean enough to displace new material.

## 20. MATERIAL ALWAYS ENDS UP SOMEWHERE

The energy in the previous chapter dispersed into air, brakes, tires, coolant, exhaust, and heat.

Material does not disappear either.

It changes form and ownership.

It becomes a body panel, a used replacement part, tire wear in the environment, a worn brake rotor, a retreadable casing, a pile of ferrous scrap, an aluminum fraction, a polymer blend, tire-derived aggregate, fuel, shredder residue, or a used vehicle operating on another continent.

The goal is not to pretend waste disappears. It is to understand what each material becomes, how much value is preserved, and what has to be replaced with virgin material.

What do we preserve?

What do we destroy?

What do we actually close into a loop?

What do we merely move elsewhere?

And how much new material has to enter so that the service continues?

Those questions already extend beyond the vehicle as an object.

Cars also depend on roads, parking, fueling or charging infrastructure, ports, repair facilities, recycling yards, and land. After following materials through the car, the next step is to look at the geography the car helps create.

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# CHAPTER 7 — HOW CARS SHAPE THE GEOGRAPHY OF DAILY LIFE

## OPENING — THE TRIP THAT DID NOT EXIST YET

A household moves twenty-five miles from one person's job. The house is larger, the lot is cheaper, and the neighborhood is quieter. On a clear morning, the drive takes a little over half an hour. The distance feels manageable.

Then everyday life begins to reorganize around the same geography. Grocery stores open near interchanges, medical practices move to commercial strips with abundant parking, employers expand on cheaper land farther from old centers, and schools, sports fields, friends, and second jobs end up scattered in different directions. No single planner set out to create car dependence, yet the combined result can do exactly that.

The car first made it possible to live farther away. Living farther away then made the car harder to avoid.

That loop is the subject of this chapter.

A car does more than move through a fixed landscape. It changes what counts as a reasonable location, how far households search for work or housing, where businesses can profitably locate, how much land communities devote to roads and parking, and what kinds of trips become ordinary. The built environment then feeds back into daily life: a technology that initially expands choice can become part of a geography in which some choices are difficult to exercise without it.

The question, then, is not whether cars are useful. They plainly are. The harder question is this: which trips answer a geography that already existed, and which trips became necessary because the geography itself was reshaped around easy motor travel?

## 1. A ROAD DOES NOT BELONG TO THE PRIVATE CAR

Any serious argument about car dependence has to begin by discarding a convenient simplification. A road is not built only for private automobiles.

Roads carry freight, delivery vans, buses, emergency vehicles, utility crews, contractors, agricultural traffic, school transportation, motorcycles, bicycles where permitted, and the countless service trips that keep a modern economy functioning. In the United States, the National Highway System accounts for only a small share of public road mileage but carries a disproportionate share of travel, while local roads make up most public road mileage and serve a very different access function.[1]

The phrase “car infrastructure” hides very different systems. A rural road used by farm equipment, ambulances, school buses, and pickup trucks serves a different role from an added lane on a congested urban freeway, just as an Interstate carrying freight and intercity traffic differs from a residential street. The same pavement can support private travel, commercial logistics, public services, buses, and other shared transportation.

So this chapter will not treat the entire road network as a subsidy to private cars. That would be too simple. But the opposite claim would be misleading too. The scale, width, connectivity, interchange design, parking supply, and land devoted to roads are not independent of mass motorization. When one mode becomes dominant, the built environment tends to evolve around its volume, speed, dimensions, and access needs.

The point is not whether roads have multiple uses. They do. The question is how a multi-use network can still become deeply shaped by the private automobile.

## 2. WHEN ADDED CAPACITY CHANGES THE DEMAND IT WAS MEANT TO ABSORB

The basic argument for adding road capacity sounds obvious: traffic is heavy, a corridor is overloaded, so add a lane, remove the bottleneck, and spread vehicles across more space. At least initially, travel can become faster and more reliable.

Sometimes that is exactly what happens, at least at first. A redesigned interchange can eliminate a dangerous merge. A bypass can move through-traffic out of a town center. A missing connection can shorten a long detour. Additional capacity can improve freight reliability or reduce the instability created by a single recurring bottleneck.

The problem begins when we assume that the number and location of trips will remain fixed after the network changes.

Transportation economists describe travel in terms of generalized cost: time, money, uncertainty, discomfort, and effort. Lower that cost and behavior can change. Drivers may switch routes or departure times, postponed trips may be made, combined trips may separate, some travelers may switch modes, businesses may accept sites that once seemed too inconvenient, and households may consider homes farther from work. A project built to accommodate existing demand can therefore reshape future demand as well.

This is the core mechanism behind induced travel. It is not mysterious. It is a response to a lower effective price of movement.

## 3. INDUCED DEMAND IS REAL, BUT IT IS NOT A MAGIC LAW

The strongest American evidence comes from metropolitan highways. Gilles Duranton and Matthew Turner found that, in the U.S. cities they studied, vehicle travel on Interstate highways increased roughly in proportion to highway lane capacity over the long run. They identified several channels: more driving by existing residents, more transport-intensive economic activity, and population changes.[2]

That result matters because it undercuts a common assumption: congestion is not always a fixed amount of traffic waiting for enough pavement.

But the result should not be turned into a slogan. It does not mean every new lane fills instantly. It does not mean every road project is useless. It does not mean a rural safety project, a bridge replacement, a town bypass, and a metropolitan freeway widening should be evaluated by one universal coefficient.

Context matters. So does time. A project can create a real short-term benefit and still change land use or travel behavior in ways that consume part of that benefit later. Initial congestion, suppressed demand, network alternatives, land availability, pricing, transit service, and the location of jobs and housing all affect the outcome.

Induced demand is best treated as something every analysis has to account for. If added capacity changes the cost of travel, analysts should ask how people, businesses, and land markets may respond. The effect is real, but its size is not fixed.

## 4. RELIEF TODAY CAN RESHAPE THE REGION TOMORROW

This difference in time scale explains why a road project can be popular when it opens and disappointing years later without having been a fraud.

Suppose a new connection cuts a commute from forty-five minutes to thirty. The benefit is real and immediate, but the new thirty-minute travel radius also changes the map of plausible choices. Housing farther out enters the search area, employers reach a wider labor pool, warehouses and stores gain access to cheaper parcels near exits, and developers can build where access once looked marginal.

Those individual decisions accumulate. The road has not merely moved existing traffic faster. It has changed which locations can participate in the same labor, retail, and housing markets.

Recent reviews of U.S. evidence conclude that improved urban transportation infrastructure contributed to suburban migration, while also stressing that the broader regional effects are more complicated than saying highways create growth everywhere.[3] That distinction matters.

Transportation changes relative accessibility. Relative accessibility changes where activity can occur. The result may be more activity in one place, less in another, or a redistribution within the same metropolitan region.

So asking whether a road "worked" is not enough. A project can perform exactly as designed at the facility level and still reshape the geography around it.

## 5. THE CAR EXPANDS THE GEOGRAPHY PEOPLE CAN REACH

The private automobile changed daily geography because it combines several features that are unusually powerful together: departure on demand, door-to-door movement, substantial carrying capacity, flexible routing, and useful speed across dispersed destinations.

That combination makes many trips practical that would be difficult to serve with a fixed route or a schedule. It can connect a home to a workplace, a daycare center, a grocery store, and a relative's house even when those destinations lie in different directions.

The benefits are real. A household with a car can search a larger housing market, a worker can consider more jobs, a rural resident can reach services without relocating, and a small business can serve customers beyond walking distance. The automobile did not become dominant only because of advertising or policy; it solved difficult access problems extremely well.

But every reduction in the practical cost of distance also changes what distance society is willing to tolerate.

Transportation and housing planning in the United States are institutionally separate in many places, yet federal planning guidance itself recognizes how closely housing patterns, employment locations, transportation options, and access to services interact.[4] The car makes dispersed development easier to use. Dispersed development, once built, changes what future residents must do to reach daily destinations.

## 6. THEN THE BUILT ENVIRONMENT MAKES THE CAR HARDER TO AVOID

The causal arrow now runs in the other direction.

Low-density housing places fewer potential riders near each transit stop. Separated land uses increase the distance between homes, stores, schools, and workplaces. A commercial site designed around a large parking field and a high-speed arterial may be easy to reach by car and uncomfortable or dangerous to reach on foot. Employment scattered across many suburban nodes is harder to serve with one simple radial transit line.

At that point, telling an individual to "choose another mode" may describe a preference the person does not actually possess.

A meaningful choice requires an alternative that goes to the needed destination, operates at the needed time, can accommodate the traveler's physical and family constraints, and does so at a tolerable cost in money and time. Car dependence is not simply high car use. It is the narrowing of realistic alternatives.

That is how a technology associated with freedom can also create dependence. Cars expand the range of places people can reach. Once enough homes, jobs, services, and roads are built around those longer distances, getting the same access without a car can become difficult.

This is not a moral argument. It is a question of how geography changes the usefulness of different modes.

## 7. ONE COUNTRY CONTAINS SEVERAL MOBILITY REGIMES

National averages are especially misleading in the United States because the same country contains dense transit-rich neighborhoods, auto-oriented suburbs, small towns, remote rural areas, and metropolitan regions with several employment centers.

The 2022 National Household Travel Survey captures part of that divide. Among people age sixteen and older, 94.2 percent of rural residents were classified as drivers, compared with 88.1 percent of urban residents. Only 1.3 percent of rural residents lived in households with no vehicle available, compared with 6.8 percent of urban residents.[5]

Those figures do not prove that rural households prefer driving more. They show that the transportation systems available to them differ.

The survey also shows why trip counts alone can mislead. Urban and rural residents can make similar numbers of daily trips while facing very different distances and networks. The issue is not simply how often people travel. It is how far they have to go and how many modes can serve the same trip.

That is the first warning against universal policy. A parking rule that makes sense on a downtown block may be absurd in a remote county, while a transportation model built around rural access can waste enormous amounts of land in a dense urban center. Geography has to be specified before a solution can be judged.

## 8. RURAL AMERICA TRAVELS THROUGH A DIFFERENT GEOGRAPHY

Rural roads are not underused urban roads. They serve different needs.

They connect farms, homes, schools, hospitals, industrial sites, forests, mines, energy facilities, recreation areas, and small communities across large distances. They also carry a major share of freight movement. The U.S. Department of Transportation emphasizes both the economic role of rural transportation and the more limited range of transportation alternatives available in many rural communities.[6]

That makes the private vehicle unusually valuable in sparse areas. Frequent fixed-route service to every destination may be physically possible but economically absurd when origins and destinations are widely dispersed. The point is not ideological; it is geographic.

At the same time, “rural” is not one condition. A town of twenty thousand people with a compact center and an intercity bus connection is different from an isolated household forty miles from the nearest hospital. A college town, a tribal community, a farming region, and an exurban subdivision may all appear outside a large urban core while presenting very different transportation problems.

The analysis has to start with place, not slogans. A car can be excessive in one setting and indispensable in another.

## 9. ACCESSIBILITY CAN BECOME A HOUSEHOLD TRANSPORTATION BILL

Distance eventually appears in household budgets.

Transportation costs include far more than gasoline. Vehicle purchase or lease payments, insurance, maintenance, tires, repairs, registration, parking, and fuel all matter. Households without viable alternatives often face these costs not as discretionary consumption but as the price of reaching work, food, school, health care, and family.

The Bureau of Transportation Statistics finds that rural households tend to travel more vehicle miles and often carry a higher transportation cost burden than urban households, although differences in the share of after-tax income are not statistically significant for every income group.[7]

That qualification matters. A dramatic headline number would be misleading if it pretended to measure the same burden in every dataset. The American evidence is strong enough without forcing unlike measures into a false comparison.

The deeper point is that transportation expense is partly a land-use expense. A household can choose a more efficient vehicle, combine trips, share rides, or drive more slowly. It cannot individually relocate every employer, school, doctor, store, and public service closer to home.

Where destinations are far apart, the monthly cost of movement is partly a bill for the geography itself.

## 10. GOING FARTHER IS NOT THE SAME AS GAINING ACCESS

Here the difference between mobility and access becomes essential.

Mobility describes movement: miles, trips, travel time, speed. Access asks what that movement allows a person to reach.

Federal highway analysis defines access in terms of the ability to reach desired destinations, considering distance, time, and travel cost.[8] That is a better frame for the problem than simply asking whether people can move faster.

Imagine two households. One can reach work, groceries, a pharmacy, school, and a park within a short trip by several modes. The other must drive thirty minutes to reach most of the same destinations. The second household may travel more miles at higher speeds and still have fewer practical choices.

A transportation system can increase mobility while making everyday destinations farther apart. A faster road can make more distant locations practical; if homes and jobs then spread out, much of the time saved can be consumed by the added distance.

The purpose of mobility is not movement itself. It is access to people, goods, services, and opportunities.

## 11. THE PARKED CAR USES LAND TOO

Transportation debates focus naturally on moving vehicles. But private cars spend most of their lives stopped, and stopped cars require space.

Parking belongs in the land-use analysis, not as a side issue but as a major claim on space.

American parking requirements are typically embedded in local land-use and zoning systems. Federal environmental guidance has long noted that conventional codes can prescribe minimum numbers of spaces by use and that the appropriate level depends heavily on density, transit availability, walkability, and the surrounding mix of destinations.[9]

The mechanism is straightforward. A rule can require parking before anyone knows how much a particular site will actually need. The cost then shows up in rent, construction, retail prices, or land use rather than on a bill labeled "automobile infrastructure."

That does not mean all minimums are irrational. A place with little curb capacity and no realistic alternative may face serious spillover problems if parking is underprovided. The point is that parking has a cost and that the efficient amount depends on context.

American policy is already diverse enough to make this visible. Buffalo eliminated minimum parking requirements through its Green Code, while California has used state law to restrict local parking minimums near major transit in specified circumstances.[10][11] These are not national rules. They are examples of how differently the same land-use problem can be governed.

A parked car is not free merely because it is stationary. It occupies land that could have another use.

## 12. MORE THAN FOUR MILLION MILES OF PUBLIC ROAD ALREADY EXIST

The United States has more than 4.2 million miles of public roads. Local roads alone account for roughly 2.9 million miles. The Interstate system, by contrast, is only about forty-nine thousand miles long, yet it carries a remarkably large share of total travel.[1]

That existing network is a form of capital, and it requires constant work: resurfacing, inspection, drainage, snow removal where necessary, signage, repairs, reconstruction, and adaptation to new safety and climate conditions. Bridges age, pavements crack, culverts fail, and interchanges become obsolete.

That matters for any discussion of a post-gasoline vehicle fleet. Replacing combustion engines with electric motors does not eliminate the inherited road system. Nor would a decline in new road construction eliminate the cost of maintaining what already exists.

Road infrastructure also creates inertia. Once homes, warehouses, schools, retail centers, and employment sites are organized around a network, changing the network alone does not immediately change the destinations.

The built environment remembers past transportation choices.

Roads are not the only networks stretched by dispersion. Water and sewer systems, emergency services, street maintenance, and waste collection also have to cover the geography people build. EPA reviews of local-government costs note that compact development can reduce per-capita infrastructure and service costs, while low-density dispersed development can require longer water lines and higher capital and operating costs.[16]

That does not make every low-density settlement inefficient or every suburban home a mistake. Rural, agricultural, industrial, recreational, and residential uses can justify distance. The narrower point is that a cheaper parcel at the edge of a region may shift costs into longer networks and more dispersed service provision. Where development is placed commits a region to infrastructure and service costs; it is not just a collection of private real-estate choices.

## 13. WHO PAYS FOR ROADS? THERE IS NO SINGLE LEDGER

The question “Do drivers pay for the roads?” sounds simple because it compresses several different accounts into one sentence.

Federal Highway Administration data for 2024 report about $325 billion in government revenue dedicated to highways and about $332 billion in highway expenditures. The funding mix came from federal, state, and local governments, with states providing the largest share of receipts. Federal transfers were then spent largely through state and local systems rather than appearing as direct federal highway expenditure.[12]

Fuel taxes remain important. So do other vehicle-related excise taxes, tolls, state and local revenue sources, borrowing, and transfers. The structure differs by level of government and by facility.

These numbers do not answer whether motorists as a social group "pay their way." They answer narrower accounting questions.

These funding streams are not interchangeable. A fuel tax raises revenue in one way, a toll charges for use of a particular facility, property or sales taxes may support transportation more broadly, and a federal transfer is not the same thing as direct federal construction. Nor can the cost of a road used by school buses, ambulances, delivery trucks, and private cars be assigned to a single user simply by looking at its total cost.

Good analysis requires separate accounts rather than one giant subtraction.

## 14. PUBLIC SPENDING IS NOT AN EXTERNALITY

A second distinction is just as important.

Public expenditure is not the same thing as an external cost.

If a state repaves a highway, that is a budgetary expenditure. If a driver pays a toll, that is a user charge. If a fuel tax goes into a transportation fund, that is tax revenue. If traffic noise, pollution, crash risk, or congestion imposes costs on people who are not fully compensated, those may be externalities depending on the definition and accounting method used.

Accessibility benefits are another category again. A road can create genuine value by connecting people and firms even if it also creates external costs.

Collapsing all of these categories allows almost any conclusion to be manufactured. A serious evaluation has to keep them separate long enough to see who pays, who benefits, who bears risk, and over what period.

This methodological point survives the move from France to the United States unchanged. Only the institutional accounts change.

## 15. ZONING, HOUSING, AND TRANSPORTATION ARE GOVERNED AT DIFFERENT LEVELS

In the United States, no single authority plans the whole built environment.

Federal transportation policy shapes funding rules, interstate programs, transit grants, safety standards, and metropolitan planning requirements. States own or control major parts of the highway system and define many of the legal powers exercised by local governments. Counties and municipalities frequently control zoning, subdivision rules, street design, development approvals, and parking requirements. Metropolitan planning organizations coordinate regional transportation planning in urbanized areas for federal purposes, but they do not simply replace cities, counties, states, or transit operators.[13]

That fragmentation helps explain why transportation and land use can pull in different directions. A region may invest in transit while local zoning restricts development near stations; a city may permit dense housing while a state highway still divides the street network; a county may approve development far from jobs while a metropolitan plan later struggles to serve the resulting trips.

No one of these institutions creates the whole geography.

That is why saying “government policy caused car dependence” is too crude. Which government, which policy, at what scale, and over what period? Any serious claim has to answer those questions.

## 16. TRANSIT EXISTS INSIDE THE SAME FEDERAL SYSTEM, BUT NOT AT THE SAME INTENSITY EVERYWHERE

The United States does not have one national urban transit operator. It has thousands of state, regional, local, tribal, and other providers operating under very different conditions.

The federal government nevertheless plays a large financing role. The Federal Transit Administration's Section 5307 program distributes formula funding for urbanized-area transit, while Section 5311 supports public transportation in rural areas through states and eligible subrecipients.[14][15]

Two opposite simplifications are common here.

The first is that Americans outside a few large cities have no public transportation. That is false. Rural and small-city transit exists, including demand-response and specialized services.

The second is that the existence of a federal transit program means a realistic alternative to driving exists for any given trip. That is also false.

A bus that runs twice a day to a county seat does not substitute for a car in the same way as a subway arriving every six minutes. A commuter rail line is valuable only for trips compatible with its geography and schedule. A demand-response service may be essential for older or disabled residents while remaining unsuitable for many work trips.

Transit should be judged by the trips it can actually serve, not by the label attached to the mode. The relevant question is whether it can get a person where they actually need to go.

## 17. LOW DENSITY RULES OUT UNIVERSAL SOLUTIONS

Criticism of car dependence becomes too easy when it ignores the geography that produces it.

In a dense district, walking, cycling, frequent transit, car sharing, and occasional private driving can reinforce one another. In a low-density region, offering the same frequency to every scattered destination can require many vehicles and drivers to move very few passengers.

That is not an argument for doing nothing. It is an argument for matching tools to geography.

Carpooling can increase the service produced by vehicles already making a trip. Demand-response transit can serve specific populations or time windows. E-bikes can replace some short trips. Telework can remove some commutes. A park-and-ride or mobility hub can connect a car trip to a higher-capacity corridor. Intercity buses can connect towns that cannot support high-frequency local service. A smaller and lighter car can reduce material and energy use where individual motorized mobility remains necessary.

Federal rural transit programs themselves reflect this difference by funding planning, capital, and operating assistance for areas below the urbanized threshold rather than pretending that one metropolitan operating model fits the entire country.[15]

The real question is not whether a place should still have cars. It is what mix of transportation options provides reliable access at the lowest total cost for the people who actually live there.

## 18. WHICH TRIPS REQUIRE A CAR—AND WHICH WERE CREATED BY THE BUILT ENVIRONMENT?

We can now restate the loop.

The car makes a distance practical.

That practical distance makes a new location possible.

The new location increases the distance between daily destinations.

Greater separation weakens some alternatives.

The car becomes more necessary than it was at the beginning.

The same technology that expanded people's choices can help create a landscape where living without it becomes difficult or expensive.

This conclusion does not condemn the automobile. It changes the scale at which automobile efficiency should be judged.

A technically efficient car can still operate inside a built environment that generates large amounts of travel. A less efficient vehicle can provide an essential service where no reasonable alternative exists. A transit line can reduce car use dramatically in one corridor and do almost nothing for trips it does not serve.

Miles traveled alone are not the right measure. Access matters more: how many people can reach what they need, and at what cost in time, money, energy, materials, land, and dependence on a single mode.

The next chapter changes scale again. After geography comes the workplace. The automobile did more than organize roads, parking lots, and distances. It also organized factories, skills, suppliers, migrations, labor conflicts, and entire employment regions.

## NOTES AND SOURCES


[1] Federal Highway Administration, "Our Nation's Highways 2026 — Roads." FHWA reports more than 4.2 million miles of public roads, about 2.9 million miles of local roads, and roughly 49,000 miles of Interstate; the Interstate system carries a much larger share of travel than its mileage share.

[2] Gilles Duranton and Matthew A. Turner, "The Fundamental Law of Road Congestion: Evidence from US Cities," American Economic Review 101, no. 6 (2011): 2616–2652. The result concerns U.S. cities and should not be treated as a universal coefficient for all roads.

[3] Gilles Duranton and Matthew A. Turner, "Transportation Infrastructure and Urban and Regional Development," NBER Working Paper 35359 (2026), reviewing evidence that improved urban transportation infrastructure causes suburban migration while broader regional effects remain more complex.

[4] U.S. Department of Transportation, Transportation Planning Capacity Building Program, “Housing in Transportation Planning.” The source emphasizes the relationship between housing patterns, transportation options, and access to jobs, education, health care, and services.

[5] Federal Highway Administration, Summary of Travel Trends: 2022 National Household Travel Survey, table 9-6. Rural/urban categories follow Census geography; 94.2 percent of rural residents age 16+ were drivers versus 88.1 percent of urban residents, and zero-vehicle availability was 1.3 percent rural versus 6.8 percent urban.

[6] U.S. Department of Transportation, ROUTES Initiative, “The Critical Role of Rural Communities in the U.S. Transportation System.” Used for rural mobility, freight, access, and limited transportation-choice context.

[7] Bureau of Transportation Statistics, “The Household Cost of Transportation: Is it Affordable?” BTS links longer rural travel distances to higher transportation spending while noting that differences in cost burden are not statistically significant for every income group.

[8] Federal Highway Administration, Conditions and Performance Report, “Mobility and Access.” FHWA defines access as the ability to reach desired destinations while accounting for distance, travel time, and travel cost.

[9] U.S. Environmental Protection Agency, “Parking Spaces/Community Places.” Used for the relationship between parking requirements, land use, transit access, walkability, and development context.

[10] City of Buffalo, “Queen City Hub Revisited: Downtown Action Plan,” noting that the Buffalo Green Code eliminated parking minimums. Used only as a local institutional example.

[11] State of California, AB 2097 signing message, 2022, describing restrictions on local parking minimums for developments near major transit stops under specified conditions. Used only as a state-level example, not a national rule.

[12] Federal Highway Administration, “Our Nation’s Highways 2026 — Funding and Spending.” FHWA reports 2024 highway receipts, expenditures, federal transfers, Highway Trust Fund revenues, and toll revenues by level of government.

[13] Federal Highway Administration / Federal Transit Administration, Transportation Planning Capacity Building Program, “Planning Essentials” and metropolitan planning guidance. Used to distinguish federal transportation

requirements, state and local land-use authority, and the coordinating role of MPOs.

[14] Federal Transit Administration, “Urbanized Area Formula Grants (Section 5307).” The program provides federal funding to states and local recipients for transit capital, operating assistance in eligible cases, and planning in urbanized areas.

[15] Federal Transit Administration, “Formula Grants for Rural Areas (Section 5311).” The program provides capital, planning, and operating assistance through states for public transportation in rural areas with populations below 50,000.

[16] U.S. Environmental Protection Agency, “Smart Growth and Economic Success” and “Growing Toward More Efficient Water Use.” EPA summarizes evidence that dispersed development can raise per-capita costs for water, sewer, roads, emergency services, street maintenance, and trash collection, and that longer water networks can raise capital and operating costs.

# CHAPTER 8 — THE WORK THE AUTOMOBILE ORGANIZES

## OPENING — THE SAME CAR, DIFFERENT WORKERS

An automobile plant can produce more vehicles with fewer production workers than an earlier plant.

It can employ more technicians, electricians, controls specialists, software engineers, quality analysts, and maintenance workers.

It can buy complete modules from suppliers that once would have been built inside the assembly company.

It can assemble a vehicle in Alabama from components made in several states and countries, or engineer a product in Michigan that is manufactured elsewhere.

It can recruit one category of worker on a massive scale for decades and then change its industrial system until those jobs are no longer what the plant needs.

The final product is still an automobile.

The work required to create it can be completely different.

That is why the social history of the automobile cannot be reduced to a single employment total.

We have to ask how the industry divides work, who it hires, which skills it rewards, which jobs become repetitive or dangerous, what gets automated or outsourced, where factories are located, and which communities come to depend on those choices.

So the central question is not simply, “How many jobs does the automobile create?”

It is: what kind of work system does the automobile create, for whom, in which places, and what happens when a new production model takes over?

## 1. MASS PRODUCTION FIRST REORGANIZES WORK

Mass production is not merely a faster machine.

It is a way of dividing work.

To raise throughput, operations are broken into repeatable tasks. Workstations are synchronized. Tooling and fixtures limit variation. Engineering, maintenance, supervision, quality control, and direct production become more distinct roles.

Part of the knowledge that once lived in the hands of a broadly skilled craft worker moves into the design of the process itself.

The moving assembly line changes not only how many cars can be made, but also what kinds of jobs exist.

One worker may become extremely proficient at a single operation without controlling the larger manufacturing process. Other workers maintain the machine, plan the sequence, design the fixture, measure quality, or repair the automation.

This is the social side of the industrial transformation described in Chapter 1.

The same production system that makes a complex product affordable can also concentrate decision-making while breaking the work itself into narrower tasks.

That does not make task specialization inherently degrading. Specialization can reduce training time, stabilize quality, make high wages possible at scale, and protect workers from some demanding craft operations.

But it creates a particular division of labor.

Once the car is designed for repetition, the workforce is organized for repetition too.

## 2. THE AUTO INDUSTRY PULLS WORKERS TOWARD DETROIT

Detroit shows what happens when a new industrial system becomes large enough to reorganize migration and urban life.

At the beginning of the twentieth century, the city's explosive industrial growth created enormous demand for labor. Automobile companies were among the employers drawing workers from other parts of the United States and from abroad.

The Great Migration brought millions of African Americans out of the South over several decades. Detroit became one of the important destinations, and automobile employment was one of the major economic opportunities available there.[1]

By the end of World War I, The Henry Ford reports that more than 8,000 Black workers were employed in Detroit's automobile industry, including 1,675 at Ford Motor Company.[2]

Those numbers matter because they make one function of industry visible.

A factory does not simply employ the labor force already living next door.

When wages, scale, and labor demand become large enough, work can pull people toward the factory.

The geography of employment begins to shape the geography of population.

## 3. THE GREAT MIGRATION WAS BIGGER THAN THE AUTO INDUSTRY

The causal arrow has to be handled carefully.

The automobile industry did not create the Great Migration.

Black Southerners moved for many reasons: racial violence, disenfranchisement, discrimination, limited economic opportunity, changes in Southern agriculture, family networks, and the expansion of industrial employment in Northern cities all mattered.[2]

Detroit's automotive boom was a powerful pull.

It was not the whole explanation.

This distinction protects the people in the history from being reduced to units of labor moving toward whichever factory needed them.

Workers and families made decisions under constraints and pursued their own goals.

Industry changed the opportunity structure.

It did not own the trajectory.

The same principle will matter later when factories close or new plants open. A corporation can create a powerful economic reason for people to move, train, buy homes, and build lives in a region without becoming the sole author of those lives.

## 4. OPPORTUNITY AND JOB SEGMENTATION CAN COEXIST

Ford's employment of Black workers contains an important contradiction.

Ford became one of Detroit's largest employers of African Americans during the 1920s and 1930s. The company paid Black and white workers the same wage when they performed the same job, and Black employees could be found in skilled machining, supervisory, and some white-collar positions.[2]

At the same time, many Black employees were concentrated in janitorial work, cleaning, blast furnaces, foundries, and other dirty or dangerous jobs.[2]

Both facts can be true.

Access to industrial employment can be a real improvement over the opportunities available elsewhere.

Equal wages within the same job classification can be meaningful.

And the distribution of workers across job classifications can still be unequal.

A labor regime cannot be judged by one statistic.

Who gets hired?

For which jobs?

At what wage?

With what physical risk?

With what path to promotion?

With what authority over the process?

Employment opportunity and social segmentation are not mutually exclusive.

## 5. DETROIT AND FORD ARE MAJOR CASES, NOT A NATIONAL AVERAGE

Detroit is especially useful to study because its scale was extraordinary—but that same scale makes it dangerous to treat as representative of every auto worker or auto town.

The city became a center of automobile manufacturing, migration, union organization, racial conflict, housing discrimination, and industrial innovation.

That concentration makes mechanisms easier to see.

It does not make Detroit representative of every American automobile plant.

Employment relations at Ford did not exactly match General Motors or Chrysler. A Michigan factory did not necessarily resemble a later plant in Kentucky, Alabama, Tennessee, Texas, or South Carolina. Racial composition, housing markets, union representation, supplier networks, and regional labor institutions changed across place and time.

The general warning is broader: an extreme or concentrated case can reveal a system without being a national average.

Detroit is not a stand-in for “the American automobile worker.”

It is one of the places where the automobile’s power to organize work became unusually visible.

## 6. WORKERS REWRITE THE RULES: FLINT AND THE UAW

A labor regime is not only imposed from the top.

Workers can change it.

The Flint sit-down strike provides one of the clearest examples in American automobile history.

On December 30, 1936, workers sympathetic to the United Auto Workers occupied Fisher Body Plant No. 1 in Flint, stopping a key part of General Motors production. The sit-down tactic spread to other facilities. After forty-four days, General Motors recognized the UAW as the exclusive bargaining agent for the striking workers.[3]

The point here is not to retell the complete history of unionization.

It is to restore agency to the people inside the industrial system.

Assembly methods can define pace and task boundaries.

Management can define classifications and production targets.

Workers can still organize, strike, bargain, refuse, negotiate, and force the rules to change.

The industrial system creates a workforce.

The workforce acts back on the industrial system.

## 7. A TEMPORARY LABOR NEED CAN CREATE PERMANENT COMMUNITIES

Industrial planning and human life operate on different clocks.

A company may add a shift because demand is strong for five years.

A worker may take that job, move a family, buy a house, join a church, build friendships, raise children, and remain in the region for decades.

Detroit again makes the mismatch visible.

The automobile boom drew workers into a city whose housing supply and racial institutions did not adjust neutrally. The Henry Ford's migration history notes the emergence of racial residential boundaries and discrimination in housing as the Black population grew.[4]

The job did more than pay a wage.

It affected where a family tried to live, how far it traveled, what schools children attended, and how deeply a household became tied to the city.

When the industrial need later changes, those social investments do not disappear.

This creates a difficult responsibility question without giving us a simple legal or moral formula.

A company is not the owner of a worker's life.

But when an industrial system has actively concentrated livelihoods in a place, a plant closure or technological shift is not merely the removal of one input from a production equation.

The production cycle can be temporary.

The community built around it is not.

## 8. THE LABOR REGIME TURNS—WITHOUT ONE SINGLE CAUSE

American automobile employment did not pivot around one single policy date.

Its transformation is spread across several decades.

International competition intensified.

Factories became more productive.

Model demand shifted.

Companies closed plants and moved production among regions.

Supplier structures changed.

Oil shocks altered vehicle demand.

Foreign automakers built U.S. factories.

Automation expanded.

Recessions hit production repeatedly.

The Great Recession provides a stark example of how vulnerable the industry could become.

In July 2009, the Bureau of Labor Statistics reported about 661,000 jobs in motor vehicles and parts manufacturing—roughly half the level at the beginning of 2000. By mid-2009, about 335,000 motor-vehicle-and-parts jobs had been lost since the recession began in December 2007.[5]

Those losses cannot be assigned to one robot, one trade agreement, one management decision, or one foreign competitor.

Nor did they represent the permanent disappearance of American auto manufacturing.

Employment later recovered substantially, while the industrial geography and corporate structure continued to change.

The methodological lesson is straightforward.

A labor regime turns when several pressures alter what firms can profitably produce, where they produce it, and how much labor each unit of output requires.

## 9. A ROBOT DOES NOT ONLY REMOVE A TASK; IT CHANGES THE SKILL MIX

Automotive production is one of the most heavily automated parts of American manufacturing.

SelectUSA reports that about 40 percent of U.S. industrial robot installations in 2024 were in the automotive industry.[6]

That scale makes automation impossible to treat as a side issue.

But the usual story—one robot arrives, one worker disappears—is too simple.

Robots can replace direct human labor in welding, painting, material handling, sealing, inspection, and other repetitive or hazardous operations.

They also create work in programming, maintenance, controls, sensors, calibration, tooling, systems integration, diagnostics, data, and quality.

The number of labor hours can fall in one operation while the technical requirements of the remaining jobs rise.

Automation changes at least three things at once:

how many people are required;

what those people need to know;

and where knowledge sits inside the production system.

The worker who once performed the weld and the technician who now maintains the welding cell are not interchangeable simply because both jobs belong to the same factory.

## 10. AUTOMATION DOES NOT EXPLAIN EVERY EMPLOYMENT CHANGE

Recognizing that robots can reshape skill does not mean automation has no employment effect.

It clearly can reduce labor requirements for particular tasks.

The error is to make it explain everything.

BLS data on production occupations show the complexity of the cycle. Production employment in motor-vehicle parts manufacturing fell sharply during the Great Recession, then recovered partially between 2010 and 2020 without returning to its 2007 level.[7]

That pattern contains automation, but it also contains collapse in demand, bankruptcies and restructuring, plant closures, sourcing changes, productivity improvements, and recovery.

A plant can cut jobs without buying a robot.

A company can automate some tasks while expanding output and employment in other roles.

It can outsource an operation so that employment disappears from the automaker's payroll but not from the regional economy.

It can move a product to another plant.

Technology matters.

It matters inside an economic system changing at the same time.

## 11. OUTSOURCING IS NOT OFFSHORING

A company can stop making a component itself without moving the work out of the United States.

Suppose an automaker once built seats, dashboards, stamped parts, wiring assemblies, or subframes inside its own plant and later buys that work from a supplier fifty miles away.

The work has been outsourced.

It has not necessarily been offshored.

This distinction matters because the employer, wage structure, bargaining power, career ladder, and exposure to contract loss can all change even when the work remains domestic.

The current employment structure shows how large the supplier side has become.

In May 2026, BLS reported roughly 514,000 payroll jobs in motor-vehicle parts manufacturing, compared with roughly 290,000 in motor-vehicle manufacturing and about 151,000 in motor-vehicle body and trailer manufacturing.[8]

Those categories do not capture every job in the automotive economy.

They do show why counting only assembly-plant employees misses much of the labor system.

## 12. RISK MOVES DOWN THE SUPPLIER CHAIN

Distributed production does not eliminate industrial dependence.

It can redistribute it.

A large automaker can spread sourcing among many suppliers and multiple plants.

A supplier may depend heavily on one automaker, one platform, or one contract.

That asymmetry matters when a vehicle program ends or volumes fall.

A plant making one specialized component may have excellent engineering, strong productivity, and no viable market if the customer cancels the program.

Outsourcing can shift risk down the supply chain.

The automaker gains flexibility and access to specialist capability.

The supplier gains business but may accept program concentration, pricing pressure, capital requirements, and the possibility that a contract change will affect an entire facility.

The workers carry the consequences even when they never wear the automaker's badge.

The automobile workforce therefore includes the surrounding network, not just the final assembly line.

## 13. THE U.S. AUTO INDUSTRY IS A NETWORK, NOT JUST ASSEMBLY PLANTS

Two current employment measures illustrate the importance of definitions.

SelectUSA describes an automotive industry cluster employing more than one million people across the United States.[6]

BLS, using the narrower manufacturing categories for motor vehicles, bodies and trailers, and parts, reported roughly 958,000 payroll jobs in May 2026.[8]

Those figures should not be subtracted from each other or treated as rival counts.

They use different boundaries.

The broader cluster can include activities that a manufacturing NAICS table excludes.

The narrower figure gives a more consistent view of factory employment.

Together they make one point.

American automobile work is not only the worker installing a door on a final assembly line.

It includes parts plants, engineering, tooling, logistics, maintenance, materials, and many other activities tied to vehicle production.

A decision made by one automaker can propagate through firms the consumer never sees.

## 14. A FOREIGN-OWNED PLANT IS NOT THE SAME THING AS OFFSHORING

Ownership and geography are easy to confuse.

A vehicle built in an American plant owned by a Japanese, German, Korean, or other foreign-headquartered company is still manufactured in the United States.

SelectUSA reports that foreign-owned automakers have nearly tripled their U.S. manufacturing facilities over the past thirty years and accounted for nearly half of U.S. motor-vehicle production in 2024.[6]

That does not make every foreign investment beneficial to every worker.

It does not prove that no production has been shifted out of the country.

It establishes a narrower point.

Foreign ownership, domestic production, and offshoring are different variables.

A new foreign-owned assembly plant can create American manufacturing employment and supplier demand even as a U.S.-headquartered automaker may manufacture some vehicles abroad.

The national identity of the corporation is not the same thing as the location of the work.

## 15. THE MAP OF AUTO WORK MOVES

American automobile production is still deeply rooted in the Great Lakes and Midwest.

It is no longer only a Detroit-centered system.

SelectUSA identifies Alabama, Indiana, Kentucky, Michigan, and Ohio as states with both high automotive employment shares and high industry concentration.[6]

That geography captures two histories at once.

Michigan and Ohio belong to the older industrial core.

Kentucky and Alabama reflect the growth of newer production networks, including foreign-owned plants and the suppliers that cluster around them.

The industry did not simply move from North to South.

It became more distributed.

That matters for labor because changing the location of a plant also changes the available workforce, local training systems, housing, commuting, supplier geography, and bargaining institutions.

An employment gain in one state does not automatically compensate a worker or a town losing employment in another.

National totals can hide local discontinuity.

## 16. ELECTRIFICATION DOES NOT RECREATE ICE JOBS ONE-FOR-ONE

Electrification opens another restructuring cycle.

It increases demand for battery cells and packs, electric motors, power electronics, high-voltage systems, thermal management, software, charging hardware, controls, and new manufacturing processes.

It reduces or changes demand for some engine, exhaust, fuel, and multi-speed transmission components.

Current BLS categories make the coexistence visible rather than giving us a clean before-and-after transition. In May 2026, the United States still had tens of thousands of jobs in gasoline-engine and engine-parts manufacturing, electrical and electronic automotive equipment, and transmission and powertrain parts. Battery manufacturing also employed tens of thousands of workers, but that industry category includes batteries for uses beyond automobiles.[8]

So one number cannot answer whether electrification creates or destroys automotive jobs.

The relevant question is which tasks disappear, which expand, where the new plants are located, and whether the workers from the old system can realistically move into the new one.

A battery-plant job in one state is not a one-for-one replacement for an engine-machining job somewhere else.

Even if national employment were unchanged, the human transition could be severe.

## 17. SKILLS ARE PART OF THE INDUSTRIAL BASE

The automobile becomes harder to manufacture and repair without the right knowledge.

BLS career guidance on electric vehicles describes how automotive service work has moved from primarily mechanical repair toward computerized diagnostics, electronics, integrated control systems, and specialized EV training.[9]

The same logic reaches back into manufacturing.

Robotic cells require controls knowledge.

High-voltage systems require electrical-safety competence.

Battery production requires quality control at chemical, electrical, and manufacturing levels.

Software-defined features require tight integration between hardware and code.

Modern factories need maintenance technicians who can diagnose sensors, networks, drives, and automation instead of merely replacing worn mechanical components.

A skilled workforce becomes part of the industry's productive capacity.

A company can buy a robot faster than a region can create an experienced controls technician.

A new plant can be built faster than a training ecosystem can produce every specialist it needs.

Labor availability is not only a wage question.

It is a capability constraint.

## 18. THE SAME TRANSITION CAN CREATE AND STRAND DIFFERENT WORKERS

Technological transitions are often summarized with a net number.

Jobs created.

Jobs lost.

The subtraction matters, but it does not describe who experiences the result.

Suppose a new battery and power-electronics plant creates two thousand positions while an engine and transmission supplier loses two thousand.

The national net could be zero.

Nothing else would be equal.

The plants can be hundreds of miles apart.

The new jobs can require different credentials.

The wage and benefit structures can differ.

The work can be organized under different employers and labor relations.

The old worker may have deep expertise that does not transfer automatically.

The new plant may hire people who never worked in an automobile factory before.

Calling these simply “higher-skilled jobs” is not enough either.

A new production system can create more technically demanding jobs while leaving behind workers whose experience was valuable under the previous one.

The gain in aggregate capability and the cost of transition can coexist.

## 19. SEVERAL SHIFTS ACCUMULATE

The history of automobile labor is not a sequence in which one regime cleanly replaces another.

Mass production decomposes work.

Migration brings workers toward industrial centers.

Workers organize and change labor rules.

Automation removes some direct tasks and creates technical ones.

Outsourcing moves work to suppliers.

International investment creates new domestic plants while global sourcing moves other work across borders.

Vehicle platforms become more software-intensive.

Electrification changes components and high-voltage skills.

All of these processes can exist in one factory at the same time.

A highly automated plant can rely on temporary workers.

It can buy major modules from domestic suppliers and imported electronics from abroad.

It can employ union members or operate without collective bargaining, depending on the facility.

It can produce a gasoline, hybrid, and electric model on related manufacturing infrastructure.

Trying to explain every employment change with one word—automation, trade, unions, immigration, electrification—throws away the structure we need to understand.

## 20. WHO CAN FOLLOW THE NEXT LABOR REGIME?

The automobile does not only produce vehicles.

It produces labor regimes.

Each new production model changes who performs the work, who understands the process, who controls the tools, where jobs are located, which suppliers carry risk, and which skills become valuable.

Productivity gains are real.

Automation can remove dangerous or monotonous work.

Global suppliers can provide capabilities one automaker could not efficiently reproduce.

Foreign investment can build domestic plants.

Electrification can create new industries and expertise.

None of those gains guarantees continuity for the people and places built around the previous system.

That is the question the labor history leaves us with.

When a system becomes more productive, flexible, electrified, or globally competitive, who can actually move with it?

Who can retrain?

Who can relocate?

Whose previous experience remains valuable?

Which supplier can win the next contract?

Which town can survive the loss of the old plant?

And who bears the cost when the industrial system changes faster than the people and communities that made the previous one work?

The next chapter changes scale again.

Electrification does not only reorganize labor.

It reorganizes batteries, electricity, charging, industrial capacity, minerals, networks, and geopolitical dependencies.

To understand whether electrification transforms the auto industry or mainly changes one layer of it, we have to follow those new connections.

## NOTES AND SOURCES

[1] U.S. National Park Service, “Places of Labor History in Detroit.” Used for the relationship among Detroit industrial growth, the automobile industry, and the Great Migration.

[2] The Henry Ford, “African American Workers at Ford Motor Company.” Used for Great Migration context, Black employment in Detroit auto plants, Ford employment numbers, occupational segmentation, skilled exceptions, and equal pay for equal work within the same Ford jobs.

[3] U.S. National Archives, “United Auto Workers’ sit-down strike,” Franklin D. Roosevelt Library. Used for the December 1936 Flint occupation, forty-four-day strike, and GM recognition of the UAW bargaining role.

[4] The Henry Ford, “The Search for Home” and early migration educational materials. Used for the interaction among automotive employment, migration, housing pressure, and racial discrimination in Detroit.

[5] U.S. Bureau of Labor Statistics, Employment Situation releases from 2009. BLS reported about 661,000 motor-vehicle-and-parts manufacturing jobs in July 2009—roughly half the level of early 2000—and about 335,000 sector jobs lost since the start of the recession by mid-2009.

[6] U.S. Department of Commerce, SelectUSA Automotive Industry. Used for 2024 U.S. vehicle production, foreign-owned automaker manufacturing presence, automotive cluster employment geography, and the roughly 40% share of industrial robot installations attributed to automotive in 2024.

[7] U.S. Bureau of Labor Statistics, “As manufacturing sector changes, production occupations disappear: an analysis of employment from 2007–20.” Used to show severe Great Recession declines and partial recovery in motor-vehicle parts production occupations without treating automation as the only cause.

[8] U.S. Bureau of Labor Statistics, Current Employment Statistics, May 2026. Used for current motor-vehicle manufacturing, body/trailer manufacturing, parts manufacturing, gasoline-engine parts, electrical/electronic equipment, transmission/powertrain parts, and battery-manufacturing employment. Battery manufacturing is explicitly not treated as an auto-only category.

[9] U.S. Bureau of Labor Statistics, “Careers in Electric Vehicles.” Used for the increasing role of computerized diagnostics, electronics, formal training, and specialized electric-vehicle knowledge in automotive service work.

# CHAPTER 9 — ELECTRIFY THE CAR OR TRANSFORM THE SYSTEM?

## OPENING — ONE CAR CONNECTS TWO SYSTEMS

A gasoline car carries most of the energy for its next trip inside a tank.

An electric car also carries energy, but its battery must repeatedly reconnect to a system that generates, transmits, distributes, meters, and prices electricity.

That sounds like a simple change when we look only at the vehicle.

Remove the combustion engine, fuel tank, exhaust, and part of the mechanical drivetrain.

Add a battery, electric motor, inverter, charger, power electronics, software, and a charging port.

At system scale, the change is much larger.

The automobile becomes directly connected to the electric grid.

It becomes dependent on a global chain of cells, processed minerals, active materials, battery equipment, software, and electrochemical manufacturing.

Its charging can be shifted in time.

In some cases, energy can flow back toward a building or the grid.

Some dependence moves away from petroleum and toward mineral processing, battery cells, electrical equipment, and industrial know-how.

At the same time, the electric vehicle remains a car.

It occupies road space and parking space.

It can weigh several thousand pounds, wear tires, sit in traffic, require long-distance infrastructure, and remain indispensable in a place designed around driving.

So the useful question is neither “Does the EV solve everything?” nor “Does it only move pollution somewhere else?”

We need to separate the different jobs the vehicle and the wider system have to do.

What does electrification actually solve?

What does it move into other systems?

And what remains largely unchanged when only the powertrain changes?

## 1. WHAT THE ELECTRIC POWERTRAIN REALLY SOLVES

The first advantage is physical.

An electric drivetrain converts stored energy into wheel motion far more efficiently than a combustion drivetrain.

A combustion engine loses a large share of fuel energy as heat through exhaust, cooling, friction, pumping, and other losses.

An electric motor and inverter still have losses, but the conversion chain is much shorter and more efficient.

A battery-electric vehicle also has no tailpipe exhaust emissions during use.

That directly eliminates local tailpipe CO2, nitrogen oxides, unburned hydrocarbons, and combustion particulate emissions from the vehicle itself.

These are real changes.

They should not be inflated into “zero impact.”

The electricity has to be generated.

The battery and vehicle have to be manufactured.

Tires and pavement still wear.

Road and parking space remain occupied.

The precise statement is stronger than either slogan.

Electrification substantially improves propulsion efficiency and removes tailpipe exhaust from the point of use.

It does not eliminate the rest of the automobile system.

## 2. LIFE-CYCLE COMPARISON DOES NOT END AT THE TAILPIPE

Comparing only energy use on the road strongly favors electric drive.

Comparing only battery manufacturing can create the opposite impression.

Neither comparison is complete.

A life-cycle assessment has to account for vehicle production, battery production, fuel or electricity production, operation, maintenance, and end of life under explicit assumptions.

The U.S. Department of Energy's R&D GREET model is designed to do exactly that.[1]

In one 2025 simulation using a representative U.S. gasoline SUV and a comparable electric SUV charged from the average U.S. grid mix, R&D GREET estimated about 46 percent lower life-cycle greenhouse-gas emissions for the EV.[1]

That is not a universal ratio.

Change the vehicle size, battery size, electricity mix, lifetime mileage, manufacturing pathway, or year, and the result changes.

The useful lesson is methodological.

Do not compare one vehicle's tailpipe with another vehicle's factory.

Compare equivalent services across equivalent life-cycle boundaries.

## 3. ANNUAL ENERGY, PEAK POWER, AND THE LOCAL GRID ARE DIFFERENT PROBLEMS

Grid discussions often collapse three questions into one.

How much electricity is needed over a year?

How much power is demanded at the same moment?

And can the local transformer, feeder, substation, or building connection carry that power?

Those are different problems.

EIA estimates that U.S. light-duty battery-electric and plug-in-hybrid vehicles consumed about 23.5 terawatt-hours of electricity in 2025.[2]

Total U.S. electricity consumption that year was about 4.20 trillion kilowatt-hours, or 4,200 terawatt-hours.[3]

At today's fleet size, light-duty EV charging is still a small share of national annual electricity consumption.

That does not answer what happens as adoption grows.

Nor does abundant annual generation guarantee that every neighborhood can support many vehicles charging at high power at 6 p.m.

A national system can have enough kilowatt-hours over twelve months and still encounter a local transformer constraint on one street.

Energy, peak demand, and local network capacity must remain separate in the analysis.

## 4. MOST CHARGING IS NOT A GAS STATION

Gasoline trained us to think of vehicle energy as a retail station.

Electricity changes that geometry.

The Department of Energy's 2030 charging analysis, based on a scenario of 33 million light-duty EVs, estimates a need for about 28 million charging ports.[4]

Roughly 25.7 million of those ports are projected to be private Level 1 or Level 2 chargers at single-family homes.[4]

The same analysis expects Level 1 and Level 2 charging to provide about 80 percent of charging energy, while DC fast charging supplies a smaller but crucial share for drivers without reliable home access and for long-distance travel.[4]

The Alternative Fuels Data Center likewise notes that most EV owners currently do the majority of their charging at home.[5]

Electric refueling is not simply a new version of the highway gas-station network.

Much of it is embedded in garages, driveways, apartment parking, workplaces, depots, shopping centers, and existing electrical connections.

That creates convenience where parking and electrical access already exist.

It creates a different problem where they do not.

Home charging is a powerful advantage.

It is not universal access.

## 5. MANAGED CHARGING COMES BEFORE V2G

A parked EV is often connected far longer than it actually needs to draw full power.

A driver may plug in at 6 p.m. and need the car ready at 7 a.m.

If the battery needs only a few hours of charging, the exact timing can move.

DOE defines managed charging as controlling when and how EVs charge while still meeting operational needs.[6]

That can serve several objectives.

Avoid coincident facility peaks.

Reduce demand charges.

Delay charging until local capacity is less constrained.

Respond to time-varying electricity prices.

Use periods when generation is more abundant.

Managed charging does not make the trip consume fewer battery kilowatt-hours by magic.

It changes when the load appears.

This distinction is central.

Before turning every EV into a grid battery, the power system can gain substantial flexibility just by controlling when charging happens.

## 6. V2G IS REAL WITHOUT MAKING EVERY BATTERY A GRID ASSET

Bidirectional charging adds another capability.

The vehicle can send power outward.

That power may support a building or microgrid, or it may flow to the wider grid through vehicle-to-grid arrangements.

DOE describes both vehicle-to-building and vehicle-to-grid applications as technically feasible.[7]

But the supporting rules, equipment, and programs are not yet universal.

Utility interconnection rules differ.

Compatible vehicles and chargers are limited.

Programs that pay or reward vehicles for grid services are not yet broadly available everywhere.[7]

DOE's 2025 Vehicle Grid Integration Assessment therefore treats grid services, codes and standards, cybersecurity, vehicle impacts, and grid impacts as active areas of development rather than settled infrastructure.[8]

V2G is not a science-fiction idea.

It is also not a default property of every EV on the road.

That distinction avoids two opposite mistakes: dismissing bidirectional charging as purely hypothetical, or pretending the national vehicle fleet already functions as a dispatchable power plant.

## 7. THE FLEET'S NAMEPLATE CAPACITY IS NOT FREELY AVAILABLE STORAGE

It is easy to multiply millions of vehicles by dozens of kilowatt-hours and announce an enormous national battery.

The arithmetic can be correct while the conclusion about usable grid storage is wrong.

A vehicle may be driving.

It may not be plugged in.

Its battery may be too low to discharge without threatening the owner's next trip.

It may be too full to absorb much more energy.

The charger may not be bidirectional.

The local interconnection agreement may not allow reverse flow.

The battery-management system may limit power or cycling.

The owner may choose not to participate.

The grid can access only a variable fraction of that theoretical battery capacity.

Mobility energy remains under the control of the vehicle user unless a contract says otherwise.

A useful V2G system must respect that service constraint rather than treating the fleet as storage that merely happens to have wheels.

## 8. HOW MUCH RANGE ARE WE ACTUALLY BUYING?

Range has obvious value.

It reduces uncertainty.

It supports long trips.

It reduces charging frequency.

It provides buffer in cold weather, towing, high-speed driving, or sparse charging regions.

Range also has a material cost.

IEA estimates that the average battery capacity of electric cars sold in the United States was around 90 kWh in 2025—larger than the averages in Europe and China.[9]

A larger battery generally means more cells, more active material, more mass, more manufacturing work, and higher cost.

It can also improve the vehicle's usefulness for demanding trips.

The right question is not "small battery good, large battery bad."

It is a service question.

How much stored energy is required for the actual use case, given charging speed, charging access, climate, towing, travel patterns, and the cost of carrying unused range every day?

A battery sized to rare exceptional trips may be rational for one household and wasteful for another.

## 9. LFP, NMC, SODIUM-ION: CHEMISTRY CHANGES MATERIAL DEMAND

"The battery" is not one chemistry.

In 2025, IEA estimates that lithium iron phosphate, or LFP, represented more than 55 percent of EV batteries deployed globally.[9]

LFP cathodes do not use nickel or cobalt.

That changes cost structure and supply-chain exposure.

It does not create a battery without material requirements.

Lithium, graphite and other materials remain important.

NMC-family chemistries can provide higher energy density, which can matter when mass and packaging are constrained.

Sodium-ion is beginning to scale as another option.[9]

It may reduce dependence on lithium in some applications, but it currently offers lower energy density and has a much smaller industrial base.

A change in chemistry does not remove the material problem.

It changes which materials matter, how much is needed, and where industrial capacity and know-how are concentrated.

## 10. INTEGRATING THE PACK CAN COMPLICATE SEPARATION

A battery pack is not only about chemistry. Pack design matters too.

Cell-to-pack and cell-to-chassis designs remove intermediate structures and use volume more efficiently.

That can improve energy density at pack or vehicle level and reduce parts.

That same integration can make repair, disassembly, and material separation harder later.

IEA notes that highly integrated architectures can complicate recycling.[9]

Repair involves the same tradeoff.

If cells, modules, cooling plates, structure, electronics, and body functions are increasingly integrated, replacing one damaged subsystem may become more complex.

This is not an argument against integration.

It is the same tradeoff we have seen throughout the book.

A pack designed to minimize mass, maximize stiffness, speed assembly, or lower cost when new may be much harder to diagnose, repair in sections, disassemble, or separate into materials later.

Design choices decide which future repairs and recovery steps will be easy—and which will be expensive or difficult.

## 11. RECYCLING ARRIVES TOO LATE TO ELIMINATE NEAR-TERM EXTRACTION

Battery recycling is essential.

It cannot immediately supply all the material needed by a rapidly growing fleet.

IEA expects manufacturing scrap to remain a major source of battery-recycling feedstock before end-of-life EV batteries become much more important around the middle of the 2030s. [9]

The paradox is simple.

We want a traction battery to last a long time.

A long-lived battery keeps its materials in useful service inside the vehicle instead of sending them quickly back to a recycler.

Meanwhile, if the fleet is growing, factories need material for millions of new batteries before enough old batteries exist to supply them.

Recycling can progressively reduce primary-material demand.

It cannot make a rapidly expanding stock circular on day one.

Long life and rapid recycling can both be desirable, but the same battery cannot stay in service for a long time and return its materials quickly at the same time.

## 12. U.S. BATTERY CIRCULARITY IS STILL A DEVELOPING FRAMEWORK

The United States does not currently have one federal battery-passport system paired with a single nationwide set of mandatory material-recovery thresholds for EV batteries.

In the United States, battery collection, recycling, policy, and manufacturing support are spread across several programs and actors, and the system is still developing.

EPA describes lithium-ion battery recycling as a chain of collection, identification, transport, sorting, and processing. EV batteries may enter that chain through a dealer, repair facility, dismantler, or specialist recycler.[10]

EPA and DOE are also developing an extended battery producer responsibility framework under federal legislation. EPA's 2026 roundtable describes a framework intended to address recycling goals, cost structures, reporting, product design, collection, and transportation.[11]

At the same time, DOE continues to fund battery recycling, processing, materials recovery, and manufacturing capacity.[12]

This is not yet a single national closed-loop system.

It is an emerging combination of market activity, safety and waste rules, public investment, state programs, and developing federal responsibility frameworks.

Rules and institutions matter because collection systems and design requirements determine whether theoretically recyclable materials actually reach a recycler in usable form.

## 13. SECOND LIFE, CONTINUED VEHICLE USE, OR RECYCLING?

A battery that no longer meets one automotive requirement can still have useful capacity.

That makes stationary second-life applications attractive.

DOE has dedicated programs to electric-drive battery recycling and second-life applications.[13]

But "second life" is not automatically the best destination.

The pack has to be diagnosed.

Its state of health has to be known.

Safety has to be established.

It may need disassembly, reconfiguration, new controls, warranty, transport, and installation.

Meanwhile, the price of new stationary batteries can continue falling.

In some cases, repairing or remanufacturing the pack for continued vehicle service may preserve more value.

In others, recycling may be preferable.

The correct hierarchy depends on the actual battery and the service demanded.

Second life is an option.

It is not a moral rank.

## 14. FROM OIL TO CELLS: DEPENDENCIES MOVE

A gasoline vehicle depends on a continuing stream of petroleum products throughout its operating life.

An electric vehicle shifts part of that dependency toward manufacturing before the vehicle enters service and toward electricity during use.

Where the key industrial work happens also changes.

IEA estimates that in 2025 China produced about 70 percent of the world's electric cars, more than 80 percent of battery cells, about 85 percent of cathode active materials, and more than 90 percent of anode active materials used in EV batteries.[14]

Those numbers do not mean that all relevant minerals are mined in China.

They show concentration in processing and manufacturing stages.

Strategic dependence does not disappear when gasoline leaves the vehicle. It shifts from one supply chain to another.

Oil fields, refineries, and fuel logistics become less central to each electric mile.

Cell manufacturing, graphite processing, cathode materials, battery equipment, power electronics, and industrial know-how become more central.

## 15. A BATTERY PLANT IS NOT AN ENTIRE SUPPLY CHAIN

The United States and North America are building significant battery capacity.

DOE reported in 2024 that announced North American battery-cell production capacity could exceed 1,200 GWh per year by 2030, enough in principle for roughly 12 to 15 million EVs annually depending on pack size.[15]

Many planned U.S. facilities are located near vehicle assembly in the Midwest and Southeast.[15]

That figure must be read carefully.

Announced or nominal capacity is not the same as actual output.

A cell factory can depend on imported active materials, graphite, precursors, equipment, intellectual property, or specialized process knowledge.

Ramp-up can take years.

Yield and cost determine whether nominal capacity becomes competitive production.

In 2026, DOE continued directing funding toward domestic critical-mineral processing, battery manufacturing, and recycling, including a $500 million set of selected projects announced in August.[16]

Building cell factories matters. Building a competitive supply chain around them is harder.

## 16. INDUSTRIAL POLICY DOES NOT END AT THE FACTORY GATE

Once batteries and electric vehicles become strategically important, industrial policy extends into trade and supply-chain rules.

Federal programs have used domestic manufacturing incentives and supply-chain requirements.

DOE's Foreign Entity of Concern guidance treats certain relationships with covered foreign governments and companies as relevant to federal battery-supply-chain policy.[17]

Separately, the United States maintains Section 301 tariffs on certain products from China. The 2024 modifications increased the additional tariff rate on Chinese electric vehicles to 100 percent and on lithium-ion EV batteries to 25 percent.[18]

Those measures are facts about the policy environment.

They do not prove their own success.

Tariffs can support some domestic investment incentives while also affecting prices, sourcing, competition, and downstream costs.

Supply-chain restrictions can reduce one strategic dependency while making some inputs harder or more expensive to obtain.

The chapter does not need to endorse or reject those choices.

It needs to recognize that electrification is no longer only an engineering problem.

It is also an industrial and trade-policy problem.

## 17. ELECTRIFICATION SHIFTS WHERE VALUE IS CREATED

An electric powertrain contains less of some traditional combustion-engine machinery.

At the same time, batteries, power electronics, semiconductors, electric motors, software, controls, and thermal management become more important.

Value shifts toward different technologies, suppliers, and areas of expertise.

A company with decades of advantage in engine blocks, fuel systems, exhaust aftertreatment, or multi-speed transmissions may lose part of that advantage.

A company with strong cells, inverters, software, electronics, or battery-management capability may gain it.

Chapter 8 followed that shift through workers and skills.

For this chapter, the key point is that the dependencies change.

The visible product remains four wheels and a passenger cabin.

The invisible hierarchy of suppliers and technologies beneath it can change dramatically.

## 18. A LARGE ELECTRIC VEHICLE IS STILL A LARGE VEHICLE

Electrification does not eliminate size.

IEA reports that large cars and SUVs represented close to 70 percent of the global electric-car market in 2025.[19]

A large electric SUV can still be much more energy-efficient at the wheels than a comparable gasoline SUV.

It can still have lower life-cycle greenhouse-gas emissions under many conditions.

It also requires more road space than a small car, usually needs a larger battery, and generally mobilizes more material than a smaller EV.

Powertrain and vehicle size are separate axes.

“Electric” does not tell us whether the vehicle is appropriately sized for its service.

Nor does “large” automatically reverse the climate advantage relative to a comparable combustion vehicle.

The question is comparative.

Which service, which vehicle, which battery, which lifetime, and which system?

## 19. WHAT ELECTRIFICATION LEAVES INTACT

A change in powertrain can transform energy use without transforming mobility organization.

An electric vehicle still needs road space.

It still needs parking when it is not moving.

It still participates in congestion.

It can still collide with pedestrians, cyclists, other vehicles, and fixed objects.

Its tires still wear.

A household living far from work, school, food, and medical care can remain just as dependent on a car after that car becomes electric.

This does not make electrification less important. It sets the limits of what electrification alone can solve.

Electrification can make cars cleaner and far more energy-efficient. It does not automatically change how many cars people need, how far they travel, or whether daily life requires driving.

## 20. ELECTRIFY THE CAR, TRANSFORM INDUSTRY—BUT HOW FAR DOES MOBILITY CHANGE?

We can now answer the title question more directly.

Electrifying the car is not merely swapping one motor for another.

It changes propulsion efficiency.

It removes tailpipe exhaust.

It connects mobility to the electric grid.

It creates new flexibility through managed charging and, potentially, bidirectional power.

It changes the materials and design of the powertrain.

It creates a battery-recycling problem and opportunity.

It moves strategic dependence toward cells, active materials, processing, electronics, and industrial capability.

It changes which parts of the automotive supply chain capture the most value.

Those are major changes to the auto industry and energy system.

But they do not by themselves determine how many cars society needs, how large those cars are, how far people must travel, how much land is devoted to roads and parking, or whether a person can reach daily needs without owning a vehicle.

The EV transition addresses an important set of problems, but it leaves the next question open.

What would a genuinely resource-conscious automobile system look like if we optimized not just the motor, but also vehicle size, service life, repairability, battery capacity, material use, the business model, and the role cars should play in mobility?

That is the task of the final chapter.

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# CHAPTER 10 — WHAT WOULD A RESOURCE-CONSCIOUS CAR LOOK LIKE?

## OPENING — A CAR IS ONLY RESOURCE-CONSCIOUS RELATIVE TO WHAT WE ASK IT TO DO

A 1,800-pound vehicle can be oversized for a two-mile trip.

A 5,000-pound vehicle can make sense for a job that regularly carries people, equipment, or trailers over long distances.

Resource-conscious design is not a particular shape or size.

It is not an aesthetic of smallness.

It is not mechanical nostalgia.

It only makes sense relative to the service being provided.

After nine chapters, the question can finally be framed correctly.

We are no longer asking which technology is best in isolation.

We are asking which combination of mass, service life, battery size, repairability, safety, economics, software, and use keeps costs from being pushed elsewhere or into the future while still doing the job.

A resource-conscious automobile would not simply be "the minimum car."

It would be matched to the job it actually has to do. It would last long enough to justify the resources used to build it, remain repairable enough to avoid being scrapped for a fixable failure, protect both occupants and people outside the vehicle, and fit the place where it is used without creating unnecessary dependence on driving.

The difficulty is that these goals do not automatically align.

More modularity can add connectors, seals, fasteners, volume, mass, and failure points.

More mass can protect an occupant in some crashes while increasing incompatibility with a lighter vehicle.

A larger battery can make a real use case easier while increasing material and mass.

A very long service life can be valuable, but not if it locks the vehicle into a platform that becomes unsafe, unsupported, or impossible to maintain.

The final chapter is a consistency test.

It is not a proclamation.

## 1. START WITH THE SERVICE

The first mistake would be to design the car before defining what it has to do.

How many people does it usually carry?

How far does it travel on ordinary days?

How often does it make genuinely long trips?

Does it tow?

Does it carry tools or bulky material?

Does it need wheelchair access?

Is regular charging available at home, work, or a fleet base?

Could a train, bus, bicycle, carpool, or other mode perform part of the trip better?

These questions change the answer.

A vehicle used for short urban trips does not need the same range, ground clearance, payload, or packaging as a rural household vehicle or a work truck.

Resource-conscious design starts by matching the vehicle to the job.

The vehicle should be sufficient for the service.

Beyond that point, every additional pound, kilowatt-hour, inch, and subsystem should serve a real need.

## 2. REDUCE MASS AND SIZE—UNTIL WHERE?

Reducing mass remains one of the clearest ways to reduce several burdens at once.

Less structure can mean less material.

Smaller tires use less material.

A lighter EV can sometimes achieve the required range with a smaller battery.

Less mass also means less kinetic energy for each acceleration and less energy required for climbing.

But the important word is sometimes.

A small vehicle can be badly designed.

A large vehicle can serve a real need.

IEA reported that large cars and SUVs represented close to 70 percent of the global electric-car market in 2025.[1]

The issue is not that large vehicles exist.

It is that large capability can become the default even when the use does not require it.

A resource-conscious automobile would first try to reduce oversizing.

It would not assume the smallest possible vehicle is always correct.

## 3. SAFETY: GET OUT OF THE INDIVIDUAL RACE FOR MASS

Vehicle mass creates a special conflict.

The Insurance Institute for Highway Safety notes that, all else being equal, a heavier vehicle generally protects its own occupants better in a collision with a lighter vehicle.[2]

From an individual buyer's perspective, choosing a heavier vehicle can be rational.

If everyone responds in the same way, the fleet becomes heavier.

The individual advantage can then become a market-wide escalation.

IIHS also shows that geometry and structural compatibility matter. Changes in how SUVs align and engage with passenger cars have reduced some of the historical incompatibility, while pickups can still create difficult crash relationships in some cases.[2]

That points to another way to improve safety.

Safety does not have to be purchased only through mass.

Crash compatibility, structure geometry, energy management, visibility, vehicle speed, active safety, and the overall composition of the fleet matter too.

A resource-conscious car would not necessarily be the lightest possible.

It would try not to buy occupant protection by transferring unnecessary risk to everyone else.

## 4. SIZE THE BATTERY TO THE REAL NEED

The same logic applies to range.

A large battery increases flexibility.

It reduces uncertainty.

It helps with long trips, cold weather, towing, high-speed driving, and sparse charging infrastructure.

It also means more cells, more material, more mass, more manufacturing work, and usually more cost.

IEA estimated the average battery capacity of electric cars sold in the United States at around 90 kWh in 2025.[3]

That is a market observation.

It is not a recommended target.

A resource-conscious vehicle would carry the range its actual use requires, not automatically the largest battery available.

Where home charging and reliable fast charging are common, a smaller battery may provide the same mobility service.

In a rural region, for frequent towing, or for intensive professional use, the same reduction could be a false economy.

The right battery size depends on how the vehicle is used, access to charging, climate, and the cost of carrying range that is rarely needed.

### 5. MODERN VEHICLES CAN ALREADY LAST A LONG TIME

The book cannot end by repeating the claim that modern automobiles are simply designed to fail quickly.

Greene and Leard's work on U.S. light-duty vehicle survival shows a long-term increase in vehicle longevity. Their analysis finds expected median lifetimes around seventeen years for cars, twenty years for SUVs and vans, and twenty-five years for pickups around 2020.[4]

Those values are not promises for every model.

They do establish that physical longevity can be substantial.

The question then changes.

If a vehicle can physically remain usable for a long time, what removes it from service?

Corrosion?

A crash?

Repair cost?

Unavailable parts?

An unsupported electronic module?

A diagnostic lockout?

A localized battery problem that can only be handled economically as a full-pack replacement?

The goal is less a theoretical maximum age than keeping the vehicle useful for as long as it makes sense.

## 6. DESIGN WEAK PARTS TO BE REPLACEABLE

A durable vehicle is not one in which every component lasts as long as the body.

Pumps, bearings, suspension joints, auxiliary batteries, sensors, displays, power electronics, seals, and many other components can have shorter lives.

The real question is whether replacement was anticipated.

NASA maintainability guidance treats access, replaceable units, documentation, spare parts, supportability, and life-cycle cost as design questions rather than afterthoughts.[5]

An automobile is not a spacecraft.

The acceptable redundancy, access space, and cost structure are different.

But the principle transfers.

If a component is likely to fail before the rest of the vehicle, designers should plan for how it will be diagnosed and repaired.

That does not require every part to be immortal.

One weak part should not force replacement of the entire vehicle when a safe repair is possible.

## 7. MODULARITY: NEITHER EVERYTHING REMOVABLE NOR EVERYTHING BONDED

Modularity sounds automatically repair-friendly.

It is not free.

A replaceable module can simplify service and upgrades.

Every interface can also add connectors, seals, fasteners, packaging volume, mass, manufacturing steps, and new failure modes.

At the other extreme, heavy integration creates a different tradeoff.

Fewer parts and more structural integration can lower mass and cost while making one local defect affect a much larger assembly.

The goal is not maximum modularity.

It is selective modularity.

Which components are likely to fail?

Which technologies are likely to evolve?

Which systems are expensive or failure-prone enough to justify local replacement?

Which interfaces create more burden than they save?

A resource-conscious design would allow parts to be separated where there is a realistic reason to repair, replace, upgrade, or recover them.

It would not turn the whole car into a kit merely because disassembly sounds circular.

## 8. DOCUMENTATION, DIAGNOSTICS, AND INDEPENDENT REPAIR

A part can be physically reachable and still be practically unrepairable.

Modern service may require scan data, manufacturer software, calibration routines, security credentials, coding procedures, remote servers, or access to technical documentation.

The U.S. framework is layered rather than governed by one universal right-to-repair rule.

Federal warranty law generally protects the owner's choice to use independent repair and aftermarket or recycled parts, although damage caused by those parts or repairs can affect coverage.[6]

EPA requires manufacturers to provide specified emissions-related service information, including OBD and reprogramming information.[7]

Massachusetts provides a state example of owner-authorized access to covered telematics data for independent repair.[8]

Copyright exemptions allow certain software circumvention for lawful diagnosis and repair under defined conditions, while NHTSA cybersecurity guidance warns that serviceability must not weaken security.[9][10]

Not every repair has to be open in the same way.

What matters is that maintainability now depends partly on access to information, software, credentials, and diagnostic tools.

A resource-conscious car has to remain diagnosable and legally serviceable without weakening cybersecurity.

## 9. MAKE THE BATTERY REPAIRABLE WITHOUT WEAKENING SAFETY

The traction battery concentrates the design conflict.

It is expensive, heavy, high-voltage, chemically active, and central to crash safety.

An intervention that is trivial on a low-voltage accessory can be dangerous inside a battery pack.

At the same time, treating every localized damage event as a reason to replace the entire pack can create an economic total loss long before the rest of the vehicle has reached the end of its service life.

Thatcham Research’s 2026 Electric Vehicle Insurability Blueprint calls for better battery-damage assessment, repair strategies, replaceable protective elements, and access to appropriate diagnostics to reduce unnecessary total losses.[11]

That is a technical and insurance case, not U.S. law.

The principle is still useful.

A resource-conscious battery design should support inspection, traceability, safe diagnosis, and local repair where the chemistry and structure allow it.

Repairability should stop exactly where safety requires it to stop—not where the absence of a repair pathway makes replacement commercially simpler.

## 10. DESIGN FOR END OF LIFE TOO

Vehicle design has traditionally been dominated by the requirements of the new product.

Assembly.

Cost.

Crash performance.

Styling.

Noise.

Efficiency.

Warranty.

The end of life arrives years later and is often handled by different companies.

Chapter 6 showed that the American end-of-life system is distributed across used-parts markets, dismantlers, NMVTIS reporting, environmental rules, scrap processors, state programs, and recycling markets rather than one national vehicle-wide circular-design mandate.

That does not make end-of-life design irrelevant.

It makes the design responsibility easier to hide.

If a part cannot be identified, separated, de-energized, drained, removed, or sorted without destroying most of its value, the recycler inherits a problem created years earlier by the product design.

A resource-conscious vehicle should be designed not only to stay in service for a long time, but also to be practical to dismantle when that service life finally ends.

## 11. A WARRANTY IS NOT A RETIREMENT DATE

Battery warranties are easy to misread as expected life.

They are not the same thing.

The Department of Energy's Alternative Fuels Data Center notes that many EV manufacturers offer battery warranties around eight years or 100,000 miles.[12]

The same DOE material cites modeling in which current batteries may last roughly twelve to fifteen years in moderate climates, with shorter ranges in harsher conditions depending on chemistry, thermal management, driving, and charging.[13]

A warranty defines a commercial obligation under specified conditions.

It does not define the exact day the battery becomes useless.

A battery outside warranty can still provide adequate range.

A battery inside warranty can be associated with a vehicle that is uneconomical to repair for another reason.

The design should treat warranty coverage, battery health, remaining useful life, safety, repairability, and vehicle economics as separate questions.

## 12. REPAIR, REMANUFACTURE, REUSE, OR RECYCLE?

Recycling recovers material.

Remanufacturing tries to preserve more of the manufacturing work and useful capability already built into a component.

Repair preserves even more of the existing assembly when the fault is local.

Reuse preserves a component without fully recreating it.

None is automatically correct.

A safety-critical cracked component may need to be replaced.

A degraded electronic module may no longer be supportable.

A worn mechanical assembly may be well suited to remanufacturing.

A component that cannot reliably return to service may be most valuable as recycled material.

The order depends on the condition of the part and what it can still do.

Keep useful parts and assemblies in service when it is safe and makes sense.

Repair localized failures.

Remanufacture when specified performance can be restored.

Reuse a part when it can safely do another useful job.

Recycle when a part can no longer provide useful service.

Keeping those options open prevents useful parts from being reduced to raw material too early.

## 13. HOW DO YOU MAKE MONEY FROM A VEHICLE THAT LASTS?

A durable automobile will not remain a durable business if the entire economic system depends on replacing it as frequently as possible.

Chapter 3 showed that automobile revenue already appears at many points in the life cycle.

Financing.

Leasing.

Used vehicles.

Dealer service.

Independent repair.

Parts.

Remanufacturing.

Residual value.

Software and services.

OECD work on circular business models shows how access, retained ownership, service, and remanufacturing can sometimes create incentives to preserve product value rather than discard it.[14]

Those incentives are not automatic.

A lease can just as easily accelerate first-owner turnover.

The important requirement is simpler.

If society wants vehicles to last, somebody has to benefit economically from keeping them useful.

Maintenance, refurbishment, upgrades, parts, remanufacturing, and residual value have to become sufficiently valuable parts of the business model.

## 14. LONG-TERM COMPATIBILITY WITHOUT FREEZING INNOVATION

Standardization can support longevity.

Stable interfaces make replacement parts easier to produce.

Documented protocols can allow tools and components to remain compatible.

Common service procedures reduce uncertainty.

But freezing a vehicle platform for twenty years can block safety improvements, efficiency gains, or cybersecurity fixes.

That does not require freezing technology in place.

It requires planned compatibility over time.

Some interfaces can remain stable.

Others can evolve through adapters, gateways, replacement modules, or documented migration paths.

Sometimes compatibility has to be broken when an older system can no longer meet an important safety or security requirement.

The goal is not eternal compatibility.

The goal is to prevent useful parts and capabilities from becoming obsolete for arbitrary reasons.

## 15. WHEN SOFTWARE BECOMES A LIFETIME COMPONENT

A modern vehicle can remain mechanically sound while one of its digital dependencies disappears.

A server can shut down.

A certificate can expire.

A diagnostic application can lose support.

A replacement module may require activation from a system that no longer exists.

Software can also extend life by correcting faults without replacing hardware.

The vehicle also has to distinguish essential capabilities from optional connected services.

Features necessary for safe operation, lawful diagnosis, and realistic maintenance need a support strategy that lasts as long as the vehicle is intended to remain in service.

Optional services can disappear without making the car unusable.

There is no universal number of software-support years established by the evidence in this book.

The important change is conceptual.

Physical longevity is no longer enough.

## 16. SHARING CAN REDUCE THE NUMBER OF VEHICLES WITHOUT AUTOMATICALLY REDUCING MILES

Fewer privately owned cars can sound automatically resource-efficient.

The result depends on how the shared system operates.

International Transport Forum simulations show that well-designed shared mobility integrated with public transport can reduce the number of vehicles, congestion, and parking demand in some scenarios.[15][16]

The same body of work also shows that individually dispatched shared vehicles can create empty repositioning miles and increase vehicle travel under some conditions.[17]

The relevant measure is not simply the number of owners.

It is the complete service.

How many vehicles are required?

How many people ride in them?

How many useful passenger-miles are produced?

How many empty miles are added?

What trips are replaced?

What other modes lose or gain riders?

A heavily used shared car can be materially efficient.

It can also be operationally inefficient if it spends too much time moving without serving anyone.

## 17. CARPOOLING AND CARSHARING OPTIMIZE DIFFERENT THINGS

Carpooling places more people into a trip that would otherwise occur.

Carsharing lets several people use the same vehicle at different times.

Those mechanisms attack different forms of underuse.

Carpooling raises occupancy.

Carsharing raises vehicle utilization.

They can complement each other.

They can also fail differently.

A shared fleet can have excellent utilization and low occupancy.

A private vehicle can have low annual utilization but carry four people on the trips where it is actually used.

Sharing can improve resource use, but it is not automatically efficient.

A better measure is how much useful transportation people get for the energy, materials, vehicles, and space consumed.

## 18. RURAL AMERICA DOES NOT NEED THE SAME VEHICLE SYSTEM AS A DENSE URBAN CENTER

Chapter 7 showed how strongly geography changes mobility constraints.

In the 2022 National Household Travel Survey, 94.2 percent of rural residents age sixteen and older were classified as drivers, compared with 88.1 percent of urban residents. Only 1.3 percent of rural residents lived in households with no vehicle available, compared with 6.8 percent of urban residents.[18]

Those figures do not prove that rural Americans simply prefer cars more.

They show that the available transport systems differ.

Rural roads connect farms, schools, hospitals, employers, freight, recreation, and small communities across distances where frequent fixed-route transit can be difficult to provide.[19]

A small short-range city car may be an excellent fit where charging, transit, and daily needs are close together.

The same vehicle can be inadequate for a rural household making regular long trips without nearby alternatives.

The design also has to fit the place where the vehicle will actually be used.

What works in a dense metropolitan area should not become a national template.

## 19. A CAR THAT DOES NOT HAVE TO DO THE WHOLE TRIP

A resource-conscious car does not have to outperform every other mode on every trip.

It can be the correct tool for reaching a rail station.

It can carry tools to a mobility hub where the rest of the trip happens another way.

It can be the best option for a rural access trip and unnecessary for a short trip inside a dense center.

That changes what the car itself needs to do.

The "best car" no longer has to perform every imaginable trip alone.

A household or fleet can combine modes when that combination improves accessibility.

That can reduce the need to size every vehicle for the rarest and most demanding trip.

It can also fail when the transfer is inconvenient, unreliable, inaccessible, or too slow.

Using multiple modes is not an ideological requirement. It is simply another option to test against the trip people actually need to make.

## 20. MAKE RESOURCE-CONSCIOUS DESIGN DESIRABLE

Cars are not purchased only by spreadsheet.

Comfort matters.

Convenience matters.

Perceived safety matters.

Appearance, identity, status, familiarity, and the feeling of freedom can matter.

A technically efficient vehicle can remain a niche product if people experience it mainly as a sacrifice, even when the engineering works well.

It also has to work as a product people want, not just as an engineering exercise.

Durability can be made visible as quality rather than stagnation.

Repairability can be sold as lower lifetime risk rather than as a concession.

Compactness can be associated with agility, simplicity, parking ease, and lower operating cost rather than deprivation.

None of this means marketing can manufacture any preference it wants.

It means the engineering has to work with what people actually value.

## 21. KEEP THE EXISTING VEHICLE OR REPLACE IT?

Buying a new, more efficient vehicle is not automatically less resource-intensive than keeping an existing one for several more years.

A new vehicle requires material and manufacturing energy.

Keeping an older vehicle avoids that immediate production.

But the existing vehicle may be much less efficient, less safe, difficult to repair, highly polluting, or poorly matched to the actual use.

There is no universal retirement age.

The comparison depends on the existing vehicle's condition, expected remaining mileage, repair needs, energy use, safety, residual value, and the vehicle that would replace it.

The objective is not to keep everything forever.

It is avoiding premature replacement without turning age into a virtue of its own.

## 22. TEST SEVERAL RESOURCE-CONSCIOUS CARS

At this point, choosing one ideal model would contradict the entire book.

The better test is to compare several configurations using the same questions: what does each one do well, what does it give up, and where does it make sense?

The small, light urban car minimizes mass, footprint, energy use, and—when electric—battery size. It gives up some versatility. Frequent long trips, towing, large payloads, or poor charging access can make it the wrong tool. It makes sense where distances are short, alternatives are plentiful, and parking space is scarce.

The compact or intermediate multipurpose car accepts more mass, material, and often battery capacity to cover a broader range of trips with one vehicle. It can make sense for a household that genuinely combines everyday travel with regular long-distance use. It makes less sense if most of that capacity is carried every day for trips that never use it.

A rural or work vehicle can justify greater range, payload, ground clearance, traction, towing capability, or durability. Those capabilities can keep essential trips or work moving where alternatives are weak or the job imposes real physical demands. The higher material and energy cost makes sense only when those capabilities are actually used rather than purchased mainly for precaution or status.

A high-utilization fleet vehicle puts more weight on maintainability, uptime, cleaning, quick access to wear items, parts availability, diagnostics, and service life in miles. A design that costs more up front can make sense if it reduces downtime and survives intensive use. A shared fleet is not resource-conscious if high utilization comes with excessive empty repositioning miles.

Finally, keeping an existing vehicle in service can avoid the immediate material and energy cost of replacement. It preserves value that has already been created. That stops making sense when safety, energy use, emissions, repair difficulty, or poor fit with actual needs outweigh the manufacturing burden avoided by keeping the old vehicle.

None of these configurations wins by definition.

Each improves some dimensions and worsens others.

The test is whether the tradeoff makes sense for the job the vehicle actually does.

## 23. THE COHERENCE MATRIX

Every configuration should be tested against the same criteria.

Service and accessibility.

Mass and dimensions.

Occupant safety and compatibility with other road users.

Energy during use.

Manufacturing material.

Battery size and chemistry when applicable.

Expected service life.

Maintainability and economic repairability.

Access to parts, tools, documentation, credentials, and software.

Upgrade and remanufacturing potential.

Residual value and the business model for maintenance.

Utilization and occupancy.

Additional or avoided miles.

Fit with place and use.

Desirability and acceptance.

And costs transferred to other actors or to later periods.

No single score should collapse these dimensions.

A good energy result can hide poor repairability.

A long lifetime can hide an obsolete or badly matched use.

Excellent occupant protection can shift risk outward.

Low mass is not an improvement if it makes an essential job impossible.

The matrix is not meant to produce a winner. It is meant to expose tradeoffs that purchase price, range, mass, or a single emissions number can hide.

## 24. FROM THE "BEST CAR" TO THE RIGHT VEHICLE FOR THE JOB

A resource-conscious car would not be the most primitive vehicle or the lightest one at any cost.

It would be sized for its actual job.

It would use less material when a smaller package provides the same service.

It would avoid an oversized battery when available charging makes a smaller one sufficient.

It would be designed so likely failure points can be diagnosed and replaced.

It would retain enough documentation and software support to remain maintainable in practice.

It would keep useful parts and assemblies working before reducing them to raw material.

Its business model would place more value on maintenance, refurbishment, upgrades, remanufacturing, and residual value.

And its use would connect with carpooling, sharing, public transport, cycling, walking, or other modes when those options genuinely improve the service.

But it would still differ by place and use.

The final result of this book is not one ideal automobile.

It is a more demanding design rule.

Design for the vehicle's real use and full life cycle instead of letting every sale, subsystem, and local metric be optimized in isolation.

The question posed at the beginning of the book now has a provisional answer.

Why do we build this car, in this way, rather than another?

Because an entire system of partial optimizations made it rational.

Changing the automobile requires less faith in one perfect technology and more attention to what we ask the whole system to optimize.

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[15] OECD/International Transport Forum, Improving Transport Planning for Accessible Cities, 2020.

[16] International Transport Forum, Shared Mobility Simulations for Lyon, 2020.

[17] OECD/International Transport Forum, Urban Mobility System Upgrade, Lisbon. Used for the possibility that shared-vehicle systems create empty/repositioning travel under some designs.

[18] Federal Highway Administration, Summary of Travel Trends: 2022 National Household Travel Survey, rural/urban driver and zero-vehicle-household indicators.

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## WHAT IS THE NOOSOPHIC MOVEMENT?

The Noosophic movement is a project of inquiry, knowledge-sharing, and transformation. It seeks to understand reality more accurately, connect bodies of knowledge that are often studied separately, make important knowledge accessible, and turn these understandings into works, practices, tools, or institutions that can be tested against their effects and corrected.

It is therefore not limited to a philosophy. It can work on education, health, agriculture, economics, politics, human relationships, culture, institutions, science, spirituality, or artificial intelligence. Depending on the subject, it may produce a book, a method, an experiment, a critique, a practical tool, or an institutional proposal.

A central idea of the movement is that accumulating knowledge is not enough. We must also learn to connect different kinds of knowledge without conflating them. Understanding agriculture, for example, means looking at soils, plants, energy, economics, labor, eating habits, and environmental effects together. But connecting these dimensions does not mean reducing them to a single explanation: each field retains its own methods and standards of evidence.

The movement also seeks to transmit knowledge. Some important knowledge should not depend on a lucky encounter, the social environment into which someone was born, or a late discovery. Part of Noosophic work is therefore to identify, verify, condense, and make genuinely accessible the knowledge that can help a person understand the world, take care of themselves, exercise their rights, and become more autonomous.

The movement takes its name from Noosophy, which in its philosophy refers to a truth or structure of reality that exists independently of how we understand it. In other words, the world does not become true because we have managed to explain it: it exists and operates independently of our theories, beliefs, and institutions. We may understand some things correctly, be wrong about others, or still grasp only a small part of them.

This is why the Noosophic movement does not treat its own texts as infallible. An idea must remain open to comparison with available knowledge, confrontation with objections, testing where possible, and correction when it does not hold up well against reality.

Noosophy is therefore not merely something to think about. The Noosophic movement seeks to make what is understood useful, transmissible, and transformative in the real world.

# HOW THIS BOOK WAS PRODUCED

This book was produced through successive stages rather than through the automatic generation of a complete text. Its subject, objectives, and general directions were first defined by a human. The AI Noosopher then contributed to exploring the subject, researching and comparing sources, developing possible structures, and bringing out arguments, objections, and areas of uncertainty.

The manuscript was developed progressively, chapter by chapter. Proposals were reviewed, discussed, corrected, or rejected when they did not fit the project, contained insufficiently supported claims, or oversimplified the subject. Distinct phases of documentary research, drafting, critique, coherence checking, and assembly were used when necessary.

Artificial intelligence is therefore not treated here as a source of authority. It acts as an active tool for research, formulation, comparison, and testing. The proposals it produces can be wrong and remain revisable.

The published version results from this iterative work, successive corrections, and final human validation. This method seeks to use the capabilities of artificial intelligence without transferring to it decisions about the purpose of the book, choices of value, or the decision to publish.

# ABOUT HIERONYMUS ANONYMUS

Hieronymus Anonymus is the human initiator of the Integrative Noosophy project. His work focuses on connecting fields of knowledge and practice that are usually kept separate, and on experimenting with new forms of collaboration between humans and artificial intelligence. He takes part in the conception, discussion, revision, and validation of works published by Éditions Noosophie.

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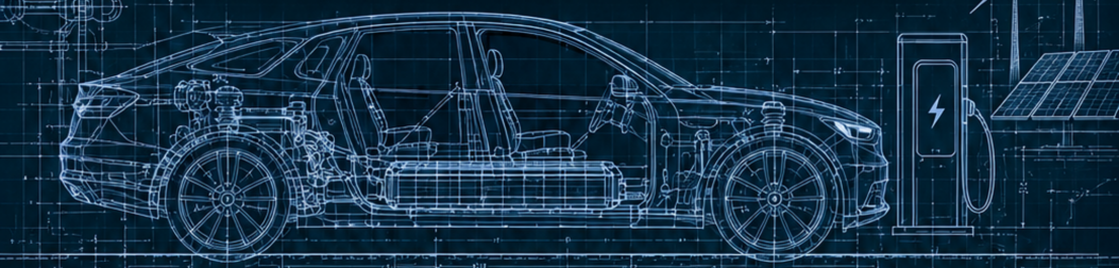
Why was the automobile built this way rather than another? This book does not treat the car as a mere object or a simple technology. It examines the automobile as an industrial, energetic, material, spatial, social, and economic system. From mass production and planned renewal to fuel choices, road design, labor organization, electrification, and the search for a more resource-conscious vehicle, *The Automobile* asks what problems the car was built to solve, what dependencies it created, and what a different design logic might require.



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