

From wheels to systems: Characterizing automobility as technosphere

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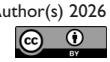
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From wheels to systems: Characterizing automobility as technosphere

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Abstract
Automobility's global role in providing mobility services but with adverse impacts on climate change and land use makes it a critical topic at a planetary scale. So far the role of cars has been mostly addressed from a techno-economic perspective, with complementary but fragmented insights from other social sciences. We provide evidence that understanding automobility as a sub-system of the technosphere compromising human-made artifacts and structures with impacts at planetary scale enables investigations from a systems perspective. Our empirically grounded characterization of causal loops provides insights on intervention points guiding co-evolutionary trajectories between automobility, societies, and local and planetary dynamics along different temporal and spatial scales. We systematically draw on existing modeling approaches for outlining how to model automobility as technosphere in a reduced form. We conclude that policies, measures and cultural shifts should be systematically evaluated according to their impact on car-dependent systems. Our approach offers novel insights for reorienting automobility toward pathways consistent with low planetary impact and high well-being.

Keywords
automobility, technosphere, coupled land use transport systems

Introducing automobility as a technosphere

The geological concept of the Anthropocene emphasizes the profound influence of humanity on the atmosphere, hydrosphere, geosphere, and biosphere (Lewis and Maslin, 2015), starting around the mid-20th century. The concept is widely used despite a recent decision that the Anthropocene does not qualify as an official geological epoch (Witze, 2024).

The technosphere is useful as an analytical concept in the Anthropocene for understanding *why* the structures, processes and practices of people continue to impose deep and lasting impacts upon earth systems (Bergthaller and Horn, 2022). The technosphere has its roots in general systems theory, defined as systems of human technology, comprising physical elements such as machines, devices, buildings and infrastructures, but also behavioral structures, rules, bureaucratic processes, and related matters. For Zalasiewicz (Zalasiewicz, 2018), the technosphere:

> . . .comprises not just our machines, but us humans too, and the professional and social systems by which we interact with technology – factories, schools, universities, trade unions, banks, political parties, the internet (and) includes roads, railways, airports, mines and quarries, oil and gas fields, cities, engineered rivers and reservoirs.

A natural science and systems theoretical perspective positions the technosphere as the defining feature of the Anthropocene. Haff et al. describe it as autonomously self-reproducing and unfeeling, with autocatalytic biophysical dynamics which are outside of human agency (Haff, 2014, 2017). However, this view of the technosphere as beyond human agency remains contentious, particularly given that humanity is central to its creation, maintenance and the utilization of its functions (Donges et al., 2017). Clearly conceptualizing the role of human agency and socio-ecological feedback dynamics *vis-a-vis* systemic autocatalytic features of the technosphere remains an important task (Donges et al., 2017), not least because of the need for human intervention to reverse or mitigate the worst impact of the technosphere on key earth system processes such as climate change while keeping its benefits such as improvements in welfare (Abson et al., 2017).

The current technosphere is largely powered by fossil fuels, and is linear rather than circular in the manner of natural systems (Haas et al., 2020).

In this review, we apply the technosphere perspective on automobility as a system. Studies of automobility are not new, and follow the groundbreaking world of Urry, who states:

> Automobility can be conceptualised as a self-organising autopoietic, non-linear system that spreads worldwide, and includes cars, car-drivers, roads, petroleum supplies and many novel objects, technologies and signs. The system generates the preconditions for its own self-expansion. (Urry, 2004: 27).

Yet, automobility also has agency. Calling automobility a "system" lets carmakers, oil companies, planners and politicians off the hook: it presents as emergent what is in fact produced and held in place by identifiable actors (Böhm et al., 2006). From this view, automobility is a regime that is actively built, legitimized and resisted, requiring analysis that recovers the collective human agency the "system" idiom obscures. A concurrent work on the political economy of automobility identifies five interlocking elements: the automotive industry, road infrastructure, urban sprawl, public transport, and car culture (Mattioli et al., 2020). This work also shows how each component is reproduced by concrete interests in addition to systemic momentum. A key insight is that the industry overproduces by design: high fixed costs in R&D, plants and machinery push manufacturers toward ever-larger production runs, and international competition between OEMs accelerates the race (Nieuwenhuis and Wells, 2015; Niewenhuis and Wells, 2003) The resulting glut depresses prices for new and used cars, so households hold onto vehicles they no longer need; when sales slump, states step in with scrappage schemes, sales incentives and emergency loans, keeping the industry afloat and demand high. Low-density suburban development, on the same logic, originated partly as a Depression-era outlet for surplus cars, oil and consumer durables.

We here build on but also extend John Urry's foundational framing of automobility as a self-organizing system (Urry, 2004, 2006), departing from it in five ways, partially taking up the agentic perspective emphasized by Bohm, Mattioli and colleagues. First, we relocate automobiltiy from a "system of civil society" to a sub-system of the technosphere, embedding automobility in Anthropocene Earth-system science instead of cultural sociology. Second, where Urry's system was autopoietic and largely descriptive, the four-subsystem architecture (S1–S4) specifies the direction and content of feedbacks and anchors them in quantitative evidence on emissions, material stocks, inequality, mortality, and resource use. Third, we neither take Haff's "beyond agency" perspective nor completely align with Urry's autopoietic closure, and instead understand human agency as key leverage points for intervention. Fourth, we suggest to combine a diverse set of modeling approaches into a reduced-form model. Fifth, we also incorporate developments postdating Urry's work, such as financialization, electrification and the mass-based regulatory inversion, "mobesity," post-2008 bailouts, vehicle-to-grid integration, petro-masculinity, and battery-mineral geopolitics, all of which have reshaped automobility's political economy. By this, we shift from a sociology of automobility to a geoanthropology of automobility: up the scale ladder toward planetary dynamics, and down the operational ladder toward modeling and policy levers.

Our objectives are threefold. First, we aim to reframe automobility as a sub-system of the technosphere, specifically, as a self-reinforcing system of physical infrastructure, regulation, economic production, and socio-cultural dynamics with planetary-scale impacts, thus going beyond the conventional techno-economic lens, and offering an entry point for co-evolutionary analysis. Second, we map the causal feedback loops within and across four subsystems (Infrastructure, Production, Legal, Culture) to show how they jointly generate biophysical consequences, climate and ecosystem impacts, social harms, and utility, and to locate intervention points where coordinated policies and cultural shifts can break car dependence (Figure 1). Specifically, we show how automobility

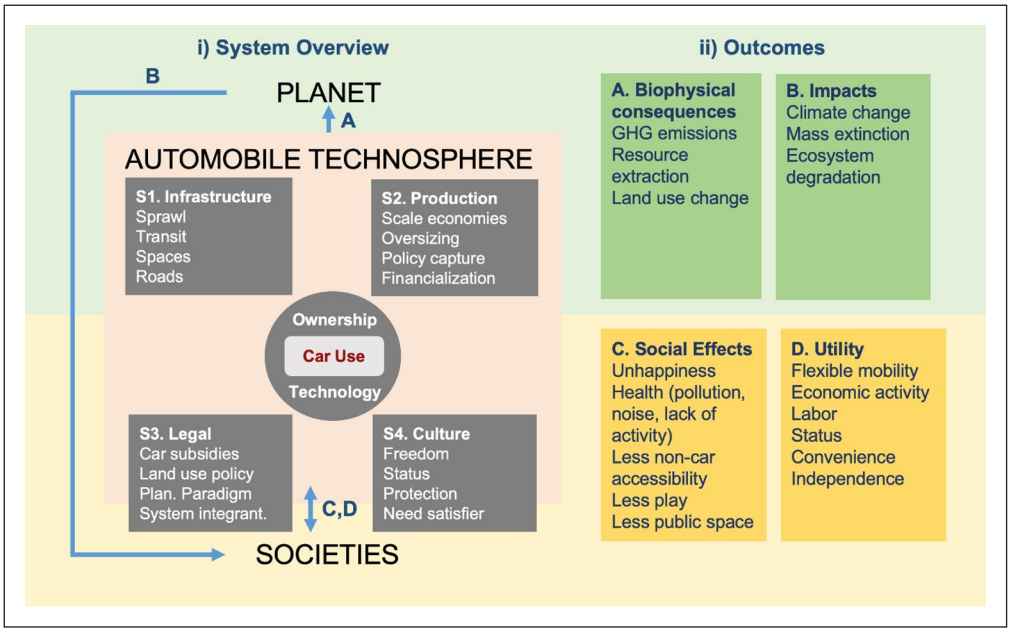


Figure 1. Conceptual relationships displaying the system overview (left) and the system outcomes (right). Partially based on the socio-ecological interaction model (Fischer-Kowalski and Weisz, 1999; Pauliuk and Hertwich, 2015).

drives fossil fuel depletion, the expansion of rubber plantations and the accumulation of carbon in the atmosphere, while also exhibiting autonomous and self-perpetuating features along physical, regulatory, economic and socio-cultural dimensions. Third, building on existing domain-specific models, we outline a reduced-form, interdisciplinary modeling approach capable of evaluating interventions against the whole car-dependent system rather than its isolated parts.

Automobility as technosphere between human well-being and the earth systems

The historical evolution of automobility has had profound societal and environmental impacts, shaping the earth system and human well-being. Automobility has enabled unprecedented increases in the mobility of people, material resources and physical goods, underpinning the development of a globalized economy (Miner et al., 2024). Figure 1 highlights the outcomes of the Technosphere (A, B, C, D) and then describes its inherent subsystems (S1, S2, S3, S4) and their reinforcing feedback loops. As automobility relates to social, individual, and environmental domains, Figure 1 also conceptualizes these interactions.

A: Biophysical consequences

Automobility is responsible for a large share of global resource use, greenhouse gas (GHG) emissions and accumulated infrastructure stocks, which constitute a spatially materialized lock-in. Including emissions from electricity for car production, road transport caused 6.2 Gt of CO2eq, or 10.7% of global GHG emissions in 2018 (Lamb et al., 2021). Producing passenger

vehicles alone caused 3.5–3.9 Gt of CO2eq in 2023 (Pauliuk et al., 2021). Automobility also requires infrastructure, comprising 254–440 Gt of material stocks in the form of roads, bridges and tunnels (Rousseau et al., 2022; Wiedenhofer et al., 2024). This accounts for about a third of all societal material stocks in buildings, infrastructure and machinery (Wiedenhofer et al., 2021, 2024). Industrial and construction activity required to maintain and expand these mobility infrastructures amount to ~6% of global resource use and ~1% of global CO_2 emissions (Wiedenhofer et al., 2024). Indirect GHG emissions are also caused by increased construction activity in suburban or exurban development enabled by automobile access. Further increase of resource use and GHG emissions for expanding and maintaining mobility infrastructure stocks can be expected due to aging infrastructure in the Global North and rapid development dynamics in the Global South (Wiedenhofer et al., 2024).

B: Impacts

While biophysical consequences refer to the direct measurable changes resulting from automobility as technosphere, impacts refer to second order effects; for example, climate change results from increased GHG emissions. Planetary change impacts humanity in many different ways, including through the adverse impacts of climate change on the global economy (Kotz et al., 2024). Some climate impacts are specific for automobility (Jaeger and Torres, 2021; Laurance et al., 2014; Soanes et al., 2024). The expansion of urban areas, facilitated by automobility, is set to triple urban land cover from 2000 to 2030, threatening biodiversity and driving tropical deforestation (Seto et al., 2012). High temperatures compromise road infrastructures, such as the joints of bridges (Bastidas-Arteaga, 2018). Extreme precipitation can lead to flooding of roads (de Abreu et al., 2022). Extreme heat reduces active mobility (Böcker and Thorsson, 2014), and increases energy demand for cooling in conventional cars (Hasselwander et al., 2022). The system of automobility also contributes to biodiversity loss and the ongoing sixth mass extinction through the material demand of vehicles. This includes natural rubber for vehicle tires accounting for roughly 70% of global natural-rubber consumption, having caused extensive land use changes, including the deforestation of more than 4 million hectares since 1993 (Wang et al., 2023); rubber expansion has converted forests to monoculture plantations with documented negative impacts on bird, bat, and invertebrate biodiversity (Ceballos et al., 2015; Warren-Thomas et al., 2015; Warren-Thomas et al., 2023). Automobility also degrades ecosystems through the spatial infrastructures that make car dependence possible: roads create barrier effects that subdivide populations and disrupt ecological flows, and in the Amazon nearly 95% of deforestation occurred within 5.5 km of roads or 1 km of rivers, making transport networks a proximate driver of deforestation and habitat fragmentation (Barber et al., 2014; Forman and Alexander, 1998). In biodiversity-rich tropical nations, roads contribute to forest loss and fragmentation, as well as illicit land invasions. For example, "ghost roads" not mapped anywhere are 3 to 6.6 times more prevalent than thought, almost always preceding forest loss (Engert et al., 2024).

C: Social effects

The societal impacts of automobility include detrimental effects on human health and well-being (Table 1). The car contributes to health problems and deaths including through increased air and noise pollution, and traffic accidents (Creutzig and He, 2009; Münzel et al., 2021; Murphy and King, 2022). Automobility causes 1 in 24 deaths – over 1 million deaths per year (Miner et al., 2024). Road traffic injuries remain the main cause of death for children and young people between 5 and 29 years (WHO, 2023).

Table 1. Dimensions of car harm, based on Miner et al. (2024).

Dimension	Description	Quantification
Violence	Traffic crashes causing fatalities and injuries; intentional violence using vehicles	Approximately 1.3 million deaths annually from traffic crashes; 102 million injuries per year.
Ill Health	Health issues from pollution (air, noise), sedentary lifestyles, and social isolation.	246,000 deaths annually from traffic-related air pollution; significant contribution to cardiovascular and respiratory diseases.
Social Injustice	Unequal impact on different demographics; accessibility issues; consumption of public space.	Higher crash and pollution exposure rates among economically disadvantaged and minority communities. Automobility and infrastructure development have historically facilitated segregation along racial and class lines, particularly in the development of the U.S. highway systems.
Environmental Damage	Carbon emissions, resource extraction, habitat destruction, and pollution of land and water.	Transport accounts for 23% of global energy-related CO2 emissions; extensive land use and habitat destruction.
Dependence and Isolation	Car-dependent infrastructure creates social isolation, limiting access to essential services and community engagement, especially affecting non-drivers.	Isolation increases risks of cardiovascular disease, cognitive deterioration, and mortality; Delays in emergency response times in car-dependent areas.
Intentional Violence	Use of vehicles in violent acts, including car bombs and vehicle-ramming attacks. Traffic stops and other encounters can also lead to police violence.	Hundreds of cities have fortified public spaces against vehicle attacks; The largest consumer of oil, with wars for oil access motivating 25%–50% of interstate wars since 1973.
Pollution and Resource Extraction	Automobility leads to significant pollution, including air, land, and water pollution, and extensive resource extraction for vehicle production and maintenance.	2–3 billion tires produced annually, contributing significantly to microplastic pollution; Major source of global pollution and resource use, including extensive mining activities.

Automobility is also inefficient. For example, congestion in large cities costs each driver thousands of dollars annually (INRIX, n.d.) and spatialized economic evaluation makes clear that automobility is overprovided and underpriced, especially in cities (Creutzig et al., 2020a). Over-sized vehicle designs contribute further to financial and energy inefficiencies (Schipper, 2011).

At the same time, car ownership is highly unequal with a lower bound Gini coefficient estimate of 0.77. This is a more unequal distribution than global income (Zimm, 2019). As transport systems globally tend to be car-oriented, those who cannot afford, can only marginally afford, or are unable to use a car suffer from mobility-related social exclusion with severe impacts on their life chances and overall well-being (Hess, 2022; Mitra and Saphores, 2020; Morris et al., 2020). Within-country inequality of car use and associated negative impacts pose social and environmental justice questions (Cubells et al., 2024).

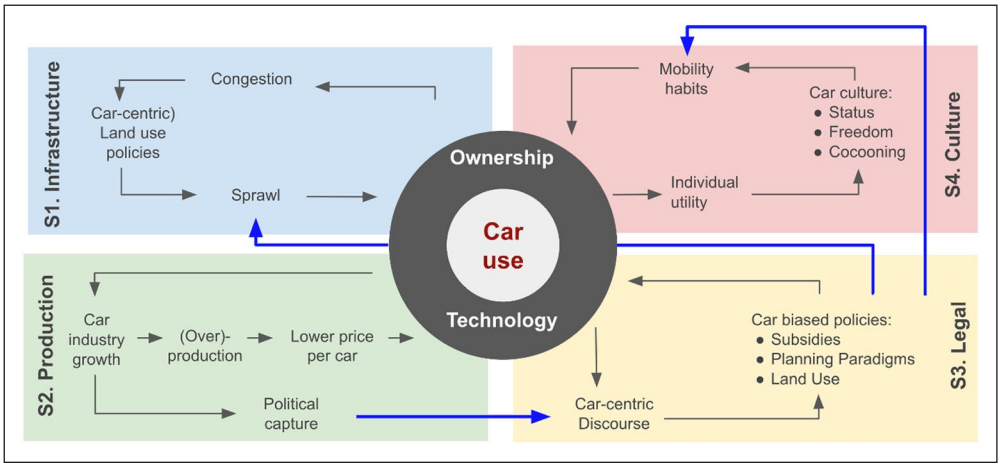


Figure 2. The four subsystems of automobility as a technosphere, including S1. Infrastructure (blue, top left), S2. Production (green, bottom left), S3. Legal (yellow, bottom right) and S4. Culture (red, top right) and their interlinkage with Car Ownership, Car Technology and Car Use (dark gray and light gray circles, center).

D: Utility

Automobility serves instrumental, symbolic, and affective functions (Steg, 2005). Instrumentally, cars can provide access, independence, time saving, flexibility and autonomy, particularly in rural areas (Hagman, 2003; Hiscock et al., 2002). Car use, especially car ownership, plays a role in social differentiation and serves other symbolic functions such as signaling social status, dominance, or gender norms (Hiscock et al., 2002; Steg, 2005). In addition, the car has a wide range of affective values, from community to escape or rebellion (Gatersleben et al., 2013; Gross, 2023). For some, the car is an important means of social inclusion, recognition, self-actualization, and a provider of self-esteem. However, beyond a certain threshold, dependence on the car reduces life satisfaction (Saadaoui et al., 2025).

Having established these outcomes and impacts of automobility as technosphere, we now delineate its four constituent subsystems – infrastructure (coupled transport-land-use), legal, economic production, socio-cultural–within an overall systems model (Figure 2).

Subsystem S1: Infrastructure – the self-reinforcing cycle of car ownership, Car use, and urban sprawl

Car use and land use are two sides of the same coin – each conditions the other (Wegener and Fürst, 2004). The ubiquitous availability of cars induces low-density suburban development, which in turn necessitates car ownership and use (Creutzig, 2014).

Spatial fragmentation

High levels of car ownership and investment in car-related infrastructure such as highways and parking create demand for lower-density, car-oriented forms of urban development. When most potential house buyers and tenants own and use cars, urban expansion is more likely to cater for their preferences and take the form of lower-density sprawl with off-street parking (Ostermeijer et al., 2022).

More roads

Serving car-dependent, spatially fragmented forms of urban development requires more road construction. More car dependence itself also creates pressure for road capacity expansion to alleviate congestion. Additional road capacity induces demand for additional car travel which also accelerates the degrading and obsolescence of road infrastructure (Duranton and Turner, 2011). Causal statistical modeling also shows that road expansion is inefficient, associated with additional time costs of travel (Anupriya and Graham, 2023). More roads also increase spatial fragmentation, contributing to "coercive flexibility" (Urry, 2006) as speed and flexibility is needed to cross increasingly expansive urban environments to access services and opportunities, further increasing car use. There is substantive evidence that building your way out of congestion by developing more highways and road infrastructure is not working and is inferior to demand management (Duranton and Turner, 2009; Hymel, 2019).

Challenging provision of public transit

User density is important for the financial viability of reliable and frequent public transit, making it easier to provide in medium-to-high density inner cities (Creutzig, 2014). Spatial fragmentation of land use makes it practically and financially challenging to provide high-frequency public transit to lower-density areas. In the absence of separated lanes, car traffic makes bus transport less attractive, leading to a further rise in car trips (Rodrigue, 2020). There are options to provide public transit in suburban areas, based on integrated public control and "network planning" of public transport services (Mees, 2009). However, this requires public control of the strategic and tactical level of public transport provision and road space allocation to public transit and cycling.

Subsystem S2: Production – the industrial system

Car industry and economies of scale

The automotive industry (Original Equipment Manufacturers (OEMs)) strongly shapes automobility as technosphere, following its own inherent logic (Keil and Steinberger, 2024), including the overproduction of vehicles driven by economies of scale (Niewenhuis and Wells, 2003). As the scale of production increases, the cost per unit of output can decrease because fixed costs are spread over a larger number of units (Besanko et al., 2010). In capital-intensive sectors such as automobile manufacturing, these fixed costs include product development, plant infrastructure, tooling, and machinery, which creates a strategic incentive to pursue high production volumes and capture scale economies (National Research Council, 1992, 2015).

From an even wider lens, the automotive industry has functioned as a central engine of 20th-century capitalist growth. Ford's mass production regime served as focal point for organization of wage relations, consumer demand, and national accumulation (Aglietta, 2000). OEMs remain among the largest industrial employers and tax contributors in both advanced and emerging economies. In turn that means that state fiscal capacity and political legitimacy hinge on industry health: policymakers anticipate industry preferences without their explicit lobbying because tax revenues, and jobs depend on a prosperous auto sector (Mattioli et al., 2020). This state-OEM co-dependent existence is materialized in state shareholdings (Lower Saxony in Volkswagen), bailouts (e.g. the bailout of GM and Chrysler in 2009), and developmental-state strategies in China where automotive industrialization is pursued as a geopolitical sovereign-power project (Doner et al., 2021). The resulting tight coupling of corporate capital and state authority effectively constrains regulatory action on emissions, vehicle size, and modal alternatives.

Increasing car size

Individual wealth, social differentiation, and protective safety are drivers of increasing vehicle mass toward "mobesity" (Axsen and Long, 2022; Ramírez-Díaz et al., 2022). The prevailing trend toward larger and more powerful vehicles is incentivized by weight-class specific EU regulation (car manufacturers get adjusted targets, meaning that more heavy vehicles are allowed to emit more, incentivizing by regulation heavier cars), company-car benefits, and larger profit margins for car manufacturers (Cozzi and Petropoulos, 2024; Creutzig et al., 2011). The transition toward EVs mean less or zero tail pipe emissions, but in average heavier cars reflecting the weight of batteries (Brand, 2024).

Financialization

Financialization by personal contract purchases (PCPs), prevalent in the UK, is a financial innovation designed to overcome profit realization problems in mature markets, increasing profits at the costs of higher financial risks that are moderated by high car dependency (Haines-Doran, 2024).

Political capture

The automotive industry's assumption of cars as the default mode of mobility and the engine of economic development and employment, results in incentives favoring car-centric infrastructure and subsidies, supported by the automotive, oil, highway construction, and various transportation industries, along with motorists' formal and informal representations (Haas, 2021). These entities create positive feedback loops, including via direct lobbying (InfluenceMap, 2021), through which increased provisions for automobility amplify these industries' size and political influence. Strategically this influence is used to prevent or delay change, and foster apolitical alignment (InfluenceMap, 2024). This alignment reflects both supply factors (e.g. car manufacturing's labor force significance) and demand factors (e.g. the necessity of long-distance commuting). Car culture (see also subsystem S4) is also driven directly by industry and the art of manufacturing, and is deeply ingrained in national identities, especially in regions with strong production capacities, such as southern Germany (Haas, 2020; Mögele and Rau, 2020) (see also Box 1).

Box 1. The policy landscape of automobility in Germany

In Germany, the regulatory framework significantly supports car use through various legal, planning, and economic mechanisms. The focus is on "fluidity of traffic" (Flüssigkeit des Verkehrs) as a key objective of road design and includes designating parking as "ruhender Verkehr" (stationary traffic) with prioritization over other street uses and imposing nationwide standards that restrict local innovation in areas like parking fees and speed limits (Taylor, 2021). Commuting tax deductions and transport-related fiscal benefits can subsidize longer home–work distances (Baumgart et al., 2025; Hirte and Tscharaktschiew, 2013); land-use, zoning, parking, and institutional barriers constrain proximity- and accessibility-oriented planning (Mathur and Gatdula, 2023; Shoup, 2005; Silva and Larsson, 2018); policies in health and education often embed car access as a practical assumption (Tao et al., 2020; Valant and Lincove, 2023); and traffic law, parking regulation, and public infrastructure funding continue to privilege automobility, exemplified in Germany by federal investment in trunk roads and the absence of a general speed limit on the Autobahn (Federal Ministry of Transport and Digital Infrastructure, 2016; Gössling et al., 2023; Shoup, 2005).

Subsystem S3: Legal system – Policy and regulation

Car subsidies

Automobility is significantly influenced by subsidies and incentives that encourage car ownership and use. Tax incentives for company cars effectively lower the cost of car ownership and promote car use over alternative modes of transportation. This drives up the number of cars owned by households, as well as average vehicle engine power and mass (Börjesson and Roberts, 2023). Urban planning and zoning practices prioritize car usage by allocating substantial space for parking and roads at the expense of public spaces or infrastructure for other modes of transport including cycling and walking (Creutzig et al., 2020b; Rhoads et al., 2021; Szell, 2018). Although improvements in vehicle technologies (e.g. battery-electric vehicles) might reduce travel emissions per kilometer, they use the same space as conventional internal combustion engine vehicles.

Land use policies

Land-use regulations extend beyond traditional transport policy, shaping car ownership and use dynamics. In the US, the funding model for highways puts engineers in charge, leading to large scale overbuild of interstate highways that provide improved mobility at high social and environmental costs (Brown et al., 2009). Single-use zoning (known as Euclidian zoning in the US) has fostered or required low-density sprawl in residential zones, making car ownership and use a requirement (Hall, 2007). Agglomerations of retail outlets at the outskirts of cities and exurban areas are another driver of car dependence (Lorch, 2005). The construction of these shopping centers, attracted by lower land costs and taxes, often results in neighborhoods designed without pedestrian infrastructure.

Planning paradigms

Government regulations play a key role in shaping transportation trends through planning paradigms that prioritize car-based infrastructure. The predict-and-provide approach, which anticipates future car usage and plans infrastructure accordingly, perpetuates and escalates car dependency (Hutton, 2013). Mandatory parking requirements for residential and commercial developments exemplify this paradigm, embedding car use deep within urban planning and design standards (McAslan and Sprei, 2023).

Integration of automobility into other systems

Policies and initiatives around vehicle electrification and autonomous driving are increasingly intertwining automobility with other technospheres such as electricity, information and communication technology (ICT), and aerospace. This integration expands car dependency into new realms and introduces potential new lock-ins, both geo-political and technical. Geo-political risks include new sectoral dynamics, where a few countries control significant parts of ICT-supply chains (Meckling and Nahm, 2019). Technological interdependencies become clear with vehicle-to-grid-systems that allow electric vehicles to interact with the power grid, offering new integrated solutions (e.g. vehicle battery storage enhancing grid flexibility) but creating new challenges for urban and transportation planning (Eltohamy et al., 2025; Zhong et al., 2025).

Subsystem S4: Culture – Socio-cultural dynamics

Cars as representations of individual freedom. Automobility is intrinsically influenced by socio-cultural and psychological factors, encompassing freedom, identity, status, and flexibility, some of it strongly gendered. In the early 20th century, the automobile served female emancipation, for example, used by suffragists for organizing, by individual women to breach the domestic-public boundary, and as a "movable field upon which women's struggle for power and autonomy would be played"; at the same time the industry simultaneously worked to code automobility as masculine and stigmatize the "woman driver" (Scharff, 1992). For some, the automobile embodies now values of (hyper-)individualism and libertarianism, intertwined with notions of petro-masculinity (Daggett, 2018). Here, petro-masculinity refers to the connection of (automobile) fossil fuel consumption with white patriarchal identity where defending high-carbon practices (e.g. "rolling coal" in diesel pickups, opposing wind power as emasculating, framing climate action as a threat to manhood) becomes a way of defending traditional gender and racial hierarchies against perceived loss. These elements are complemented by advertising and urban expansion ideologies that favor single-family homes outside urban centers and enshrine the car as a vital need (Cohen, 2012). In this way cultural influences reinforce land-use policies in creating suburban sprawl and car dependency. The "conversion effect" suggests that suburban living may lead to greater political support for automobility, reflecting a deep-seated cultural attachment to the ideals of suburbanism (Walks, 2015).

Cars as protection

Cars serve not only as a mode of transport but as protective "cocoons" for their occupants in environments perceived as increasingly hostile and unsafe (Wells and Xenias, 2015). However, though the car has protective functions for its occupants, it imposes safety risks on other road users. Aggressive driving and cars dominating road space feed a cycle of societal fears that increase interest in larger cars (cf *71*). This aspect of automobility feeds into a culture war over lifestyle, status, and vehicle types, amplifying societal divisions rooted in automobility preferences (Humpe et al., 2022).

Cars as status

The instrumental or functional benefits of cars ensure their continued use, while their symbolic value drives consumer preferences (Ramakrishnan and Creutzig, 2021). This is not only true for the Global North but has also been observed among upper middle-class individuals in the Global South (Ramakrishnan et al., 2020; Sovacool and Axsen, 2018). The relationship between car ownership and social status is manifest in the trend toward larger vehicles as a symbol of status as well as safety in a kind of arms race that reflects and reinforces diverse mobility cultures. Also environmental aspects, specifically the odd visibility of the Toyoto Prius as eco-efficient hybrid, translate into conspicuous consumption (Sexton and Sexton, 2014). This entwining of utility and status underpins the enduring appeal of automobility (Haustein, 2021; Rau and Matern, 2024; Steg, 2005).

Mobility practices and provisioning

Automobility serves as a primary "mobility need satisfier," driven by its versatility and habit formation. Mobility practices that characterize the routines of everyday life connect

dwelling, working, caring for others, recreating, and shopping (Rau and Matern, 2024). The dynamics of car-based mobility practices vary across the life course, and are influenced by life events and mobility milestones (e.g. buying your first car; Scheiner and Rau, 2020; Smart and Klein, 2020). The "consumption of distance" as an integral feature of everyday life points to the hegemony of mobility in modern societies (Mattioli et al., 2020). A relevant but small divergent trend is observed in inner cities, mostly in Europe, where foregoing car ownership ("car shedding") is becoming increasingly popular (Haustein and Nielsen, 2016; Mögele and Rau, 2020).

Integrated modeling is needed to understand interlinked subsystems of car use

A wide range of methods and approaches from different disciplines are used to model automobility and inform intervention design. Applied methods from economics, data science, agent-based models, and system dynamics each require in-depth knowledge in their specific fields of application that map onto discrete automobility sub-systems (Table 2). Such modeling is invaluable for evaluating discrete automobility issues, but falls short in assessing cumulative and interactive effects.

A reduced-form model is warranted for three reasons. First, the value of integrated analysis is in capturing and understanding the essential cross-subsystem dynamics that couple infrastructure, production, regulation, and culture; restricting representation to first-order feedbacks preserves this without reproducing the full complexity of subsystem models. Second, a reduced form models enables whole-system evaluation of policy interventions whose effects in one subsystem reinforce or suppress outcomes in others. Third, the resulting transparency eases interdisciplinary communication and integration and makes leverage points legible to modelers and policymakers alike.

An integrated modeling approach should cover most of the driving forces of the automobility system, drawing on domain knowledge and existing subsystem-specific models (Table 2). Each subsystem is characterized by a self-reinforcing cycle (positive feedbacks) that promotes car dependence across its own and other subsystems (Figure 2). As an example, the socio-cultural system increases automobility through the social status derived from car ownership that in turn amplifies the dynamics of land-use planning for lower-density cities stabilized by the interests of planners, politicians, and OEMs. This mutual reinforcement implies that addressing the negative impacts of automobility cannot be achieved by targeting a single subsystem alone. Conversely, coordinated interventions in some subsystems may have the potential to catalyze positive changes across others.

Integrated modeling needs to bring together expertise from each subsystem and related processes in an interdisciplinary or transdisciplinary endeavor that also includes extra-scientific expert and everyday knowledge. It should allow for both normative (sustainability-oriented) and explorative approaches. Co-evolutionary approaches that represent the interaction of many actors and subsystems can be calibrated with historical dynamics and foundational observations or "stylised facts" for automobility such as constant time budgets (Stopher et al., 2017).

These general features of integrated modeling belie epistemic and practical challenges. Even if individual subsystem models can be couple or combined, potential errors or uncertainties can propagate. For example, when utilizing machine learning to infer missing data about transport infrastructure stocks, the sensitivity of the stocks and flow model is not only dependent on its internal algorithm and assumptions, but also on uncertainties related to data prediction. These uncertainties

Table 2. Existing modeling approaches.

Modeling outcome		Subsystem	Example modeling approaches	Example papers
Environment	Planetary impacts	S1.Infrastructure	Integrated assessment models with transport sector modules	Edelenbosch et al. (2017)
			Analytical frameworks for GHG and Air pollution Interactions, f.e. GAINS	Höglund-Isaksson et al. (2020)
			System dynamic simulation models linking transport and macro-economic models	Pokharel et al. (2023)
			Global bottom-up material stocks and flow models of mobility infrastructure	Wiedenhofer et al. (2024)
	Regional developments	S1.Infrastructure	(Spatial) (computable) general equilibrium (SCGE) models	Bröcker et al. (2010)
			New economic geography (NGE) models	Tabuchi and Thisse (2011)
	Land Use	S1.Infrastructure	Land-use-transportation interaction (LUTI)	Wegener and Fürst (2004)
		S3. Legal	Agent-based land use models (ABLUM)	Moeckel et al. (2002), Matthews et al. (2007)
			Cellular Automata land use models (CALUM)	Stanilov and Batty (2011)
			Regression Models of land use-transport nexus (AI-based approaches)	Berril et al. (2024)
Economy	Cost and Benefits	S1.Infrastructure	General equilibrium models of transport infrastructure.	Robson et al. (2018)
	Accessibility	S1.Infrastructure	Land-use transport interaction (LUTI); mixed models.	Geurs and van Wee (2004)
		S3. Legal	Urban economics models with labor economics models	Zenou (2000)
	Industry	S2. Production,	Sociotechnical transitions using systems dynamics models	Papachristos (2019), Geels et al. (2017)
			Hybrid modeling approaches treating the relationship between industry and transport sector	Wiedenhofer et al. (2024), Thomas et al. (2024)
Society	Social equity	S1.Infrastructure	Agent-based models	ITF-OECD (2017), Miller (2019)
		S3. Legal	Structural equation models	Currie and Delbosc (2010)
		S4 Culture	(AI & big data based) regression Models of built environment, mobility habits and social equity	Wagner et al. (2022)
	Health	S3. Legal	Systems dynamics models	Harrison et al. (2021)
		S4. Culture	Integrated transport (VISUM) and emissions (MOVES) model	Sider et al. (2015)
	Well-being	S3. Legal	Theoretical psychological model, with input ranging from personal characteristics to infrastructure, resulting in subjective well-being	Delbosc (2012)
		S4. Culture	Regression modeling	Stanley et al. (2011)
	Gender	S4. Culture	Variety of intervention points identified	Scholten and Joelsson (2019)

need to be tackled using Monte Carlo simulations or sensitivity analysis, rigorous model validation against empirical data, as well as a modular integration of individual subsystem models, which allows independent testing.

Initial integrated modeling efforts reveal intervention points

There are already efforts underway to model automobility in an integrated manner in order to inform intervention design. Here we give six examples. First, partial non-rational vehicle purchase decisions and urban infrastructure decisions have been incorporated into global integrated assessment models to connect user preferences and behaviors to multi-decadal planetary scale dynamics (Creutzig et al., 2015; McCollum et al., 2017). Second, system dynamics modeling has been used to identify five intervention points to create causal loop dominance around sustainable urban transport: reallocation of road space; discouraging cars; investments into transit and active mobility; financial incentives for sustainability mobility users; high density/accessibility development (Pokharel et al., 2023); see also the system's approach used by the OECD (Box 2). Third, the Multi-Level Perspective (MLP) framework has been used in simulations of low-carbon mobility transitions in the Netherlands (Köhler et al., 2020), bridging niche-level technological innovations, regime-level stability in automobility practices, and broader landscape pressures like

Box 2. A system's approach reveals the importance of street space reallocation

The OECD has developed a methodology that, building on systems thinking and its tools, analyses the potential of policies in redesigning the current car-dependent system structure, applied to regional governments such as Ireland and Catalonia. The methodology combines a number of tools from systems thinking: causal-loop diagrams, the iceberg model, the Donella Meadows' 12 leverage-point framework and the concept of stocks and flows. The methodology determines the intent of a given policy- i.e. whether it aims at reacting to events, anticipating observed trends, or transforming those trends via transforming the system structure or key mental models that contribute to its lock-in. It then analyses the transformative potential of policies by contrasting their intent with the potential change they could have, given the level of lock-in of a given system (Figure 3).

A key result is that road space reallocation contributes to changing the car-dependent system structure, and its key dynamics: induced demand, sprawl and the low-attractiveness trap of unsustainable modes (Figure 4 in Appendix 1). Road-space reallocation helps to reduce the over-dimensioned stock of car-purposed capacity, which is a key stock locking-in and maintaining the car-dependent system structure. While doing this, it also creates a new stock of liberated space that can be used to create new (and more virtuous dynamics in the system) and shift away from vicious ones. It can contribute to shifting away from sprawl by providing the opportunity of breaking up large catchment areas into smaller ones, if liberated space is used to reallocate services and other amenities. It can also increase the impact of public transport improvements by allocating more and better space to improve their attractiveness. As a result, instead of the car traffic volume being constantly driven upward by public investment in roads (as is the case in typical induced demand), road space reallocation adjusts car traffic downwards, results in disappearing traffic, and creates a new induced demand of sustainable modes.

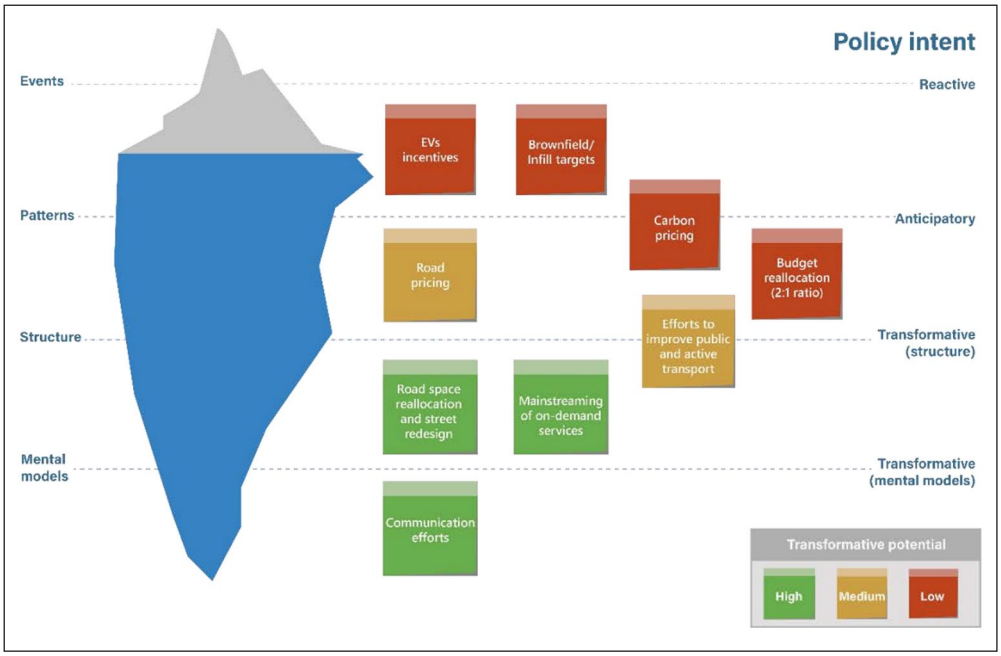


Figure 3. Policy categorization according to transformative potential for Ireland.
Source. OECD (2025).

climate policy. Deriving practical insights from modeling of socio-technical transition theory is an important next step (Hirt et al., 2020). Fourth, a political economy perspective has demonstrated how entrenched car dependence arises from intertwined systems of provision, including infrastructure, regulation, and cultural preferences (Mattioli et al., 2020). Fifth, a conceptual framework of automobility applied eight frames to investigate automobility transitions: private-instrumental frames such as cocooning and mobile digital offices; private-symbolic frames such a gender identity and social status; societal-functional frames such as environmental stewardship and suburbanization; and societal-symbolic frames such as self-sufficiency and innovativeness (Sovacool and Axsen, 2018). Sixth, integrated models of land use and transport have proven useful for anticipating the impact of future technological developments, such as shared and autonomous cars (Hawkins and Nurul Habib, 2019).

Toward a reduced form model for automobility as a technosphere

Despite their innovation and promise, these initial efforts at integrated modeling fail to capture the interplay between connected subsystems that make up automobility as technosphere (Figures 1 and 2). Given the complexity, scope, and uncertainty of individual subsystem models (Table 2), we propose the development of a reduced-form model that considers only essential relationships and dynamics for connecting different subsystems. Such a model would be less susceptible to uncertainties and errors inherent in detailed subsystem models. It would also allow for higher computational efficiency, ease of integration, and transparency.

A reduced-form model needs to capture socio-technological dynamics and be able to investigate issues including: travel demand as a function of electric, shared and autonomous

vehicle penetration; digitalization and AI in mobility platforms; future resource demand for vehicle stocks and associated infrastructures; the changing value of status symbols (e.g. from car ownership and home ownership to other values); and shared pooled mobility as a function of costs, time required, level of vehicle autonomy, social values, and industrial politics. Each of these topics are timely, impactful, and reinforce the complexities of automobility as technosphere.

Conclusion and future directions

We position automobility within the technosphere, framing it as a system of human-made structures and artifacts with global impacts. Unlike previous modeling approaches of automobility, this systems perspective integrates multiple fields to understand cross-sectoral linkages and feedback loops reinforcing car dependency and its worldwide effects. By doing so, we can distinguish forces that manifest the status quo from system intervention points that enable lasting change.

Automobility is sustained by interconnected subsystems, including transport-land-use systems, legal and regulatory frameworks, economic systems, and socio-cultural dynamics. Each subsystem reinforces the others, creating a self-perpetuating cycle of car dependence. The biophysical impacts include resource depletion, greenhouse gas emissions, and ecosystem fragmentation, while social impacts encompass health issues from pollution, increased accident rates, and social inequality due to car dependency. Our evaluation emphasizes the lock-in effects of car-dependent infrastructures, making it challenging to transition to sustainable mobility solutions. Policies and cultural norms have historically favored car use, further entrenching this dependence.

To transition to a future that breaks the self-perpetuating cycle of car dependence and its largely negative outcomes for humanity, we call for more adoption of integrated systems-modeling approaches. These should incorporate reduced-form models that effectively consider the most important system interactions without compromising relevant details, thereby evaluating the overall influence of individual subsystem components and modeling the effect of future interventions. In addition, a broader research agenda should emphasize the need for interdisciplinary modeling, integrating insights from natural sciences, social sciences, urban planning, and policy studies to address the multifaceted challenges of automobility. Co-evolutionary systems thinking is crucial to uncover the feedback loops and interdependencies sustaining automobility, providing a key role for human agency.

Understanding automobility as a technosphere aligns with the holistic perspective of an emerging geoanthropology, examining human-environment interactions on a planetary scale. Technological systems like automobility shape and are shaped by earth systems and human societies. Geoanthropology can inform interventions aimed at mitigating the technosphere's negative impacts, but also reshaping the technosphere, enabling sustainability and resilience. Developing geoanthropology requires shifts in education and epistemic frameworks, integrating knowledge from natural sciences, social sciences, and humanities to address complex, system-level challenges.

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Appendix I

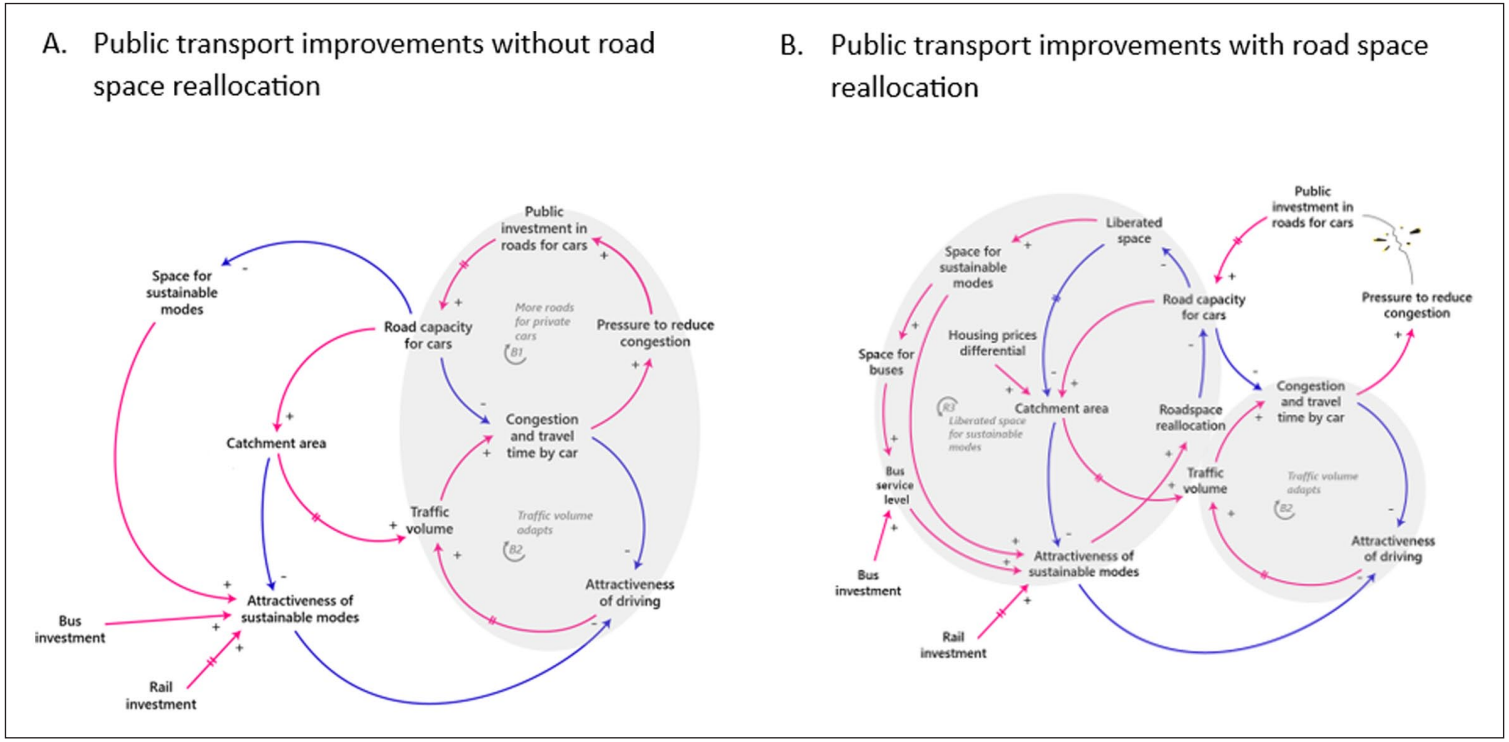


Figure 4. The systemic power of road space reallocation and its synergies with public transport improvements.
Source. OECD (2022).