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System confluence and the reinvention of automobility

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The aim of the paper is to provide a longitudinal account of the emergence and stabilization of the automobility system and to assess the contemporary state of the system in the early stages of an ongoing sustainability transition. The production, use, and disposal of cars, in a pervasive global automobility system, are examined to reveal and explain the growing sustainability significance of overlaps with other systems. System-to-system confluence to varying degrees is ongoing with electricity, housing, aerospace, and information, software, and communications systems. The interfaces between multiple systems are evidenced by contestation for legitimacy via technological innovation and organizational experimentation. The result is uncertainty among key actors and stakeholders, institutional reforms, diverse corporate strategies, and emergent societal practices and behaviors. The paper thereby provides a contextualized account of the tension between barriers to change that may preserve the coherence of the automobility system and differential boundary effects arising from the impact of other production–consumption systems that may result in regime fragmentation. Confluence with other systems may resolve some sustainability contradictions but will also create new ones. Appeal to sustainability science will be key to evaluating how far existing sustainability problems will be resolved, and how far new ones will emerge in the automobility transition.

automobility | system | confluence | transition | re-configuration

Mobility is one of the defining features of the current nature–society system, structuring broader patterns of consumption, work, and residence. Automobility is the dominant mobility mode of contemporary societies (1) and is complicit in the twin features of the Anthropocene Nature–Society System identified by Clark and Harley (2): a contribution to increased human well-being through providing access to a greater range of opportunities to a greater number of people and the 'great acceleration' of humanity's impact on nature. Embedding automobility practices over more than 100 y has resulted in multiple social, economic, and environmental burdens (3), and a range of responses. For example, the use of lead in petrol and asbestos in brake pads were both banned, albeit after decades of use, with measurable health benefits (4, 5). As the global automobility consumption–production system expanded to over 1 billion cars in use by around 2010, so increasing demands were placed on natural capital stocks (rubber, copper, aluminum, steel, nickel, and petroleum), the extraction and processing of which results in multiple ecological burdens. The use of petrol and diesel cars is a major contributor to climate change via carbon emissions, to local toxic emissions, and to noise pollution. Car use has also caused multifaceted social costs through unequal transport justice and traffic congestion for example. Road traffic deaths and injuries also elicited decades of changes to car design standards, road design (often excluding other road users), and related societal measures such as drink–driving controls. Nonetheless, there are still over 1 million road deaths per annum, especially among vulnerable road users (6, 7).

At the heart of the automobility consumption–production system is the automotive regime, defined here as a dynamically stable set of behaviors driven by dominant corporate relationships. This automotive regime emerged in the early 1900s, spreading and stabilizing after the 1939–45 war, resulting in powerful lock-ins and path dependencies. This regime has faced increasing sustainability pressures from climate change, air and noise pollution, and congestion problems. The sustainability burdens and attempts at their resolution have shown that the automotive regime is facing an unprecedented and contested transformation (8, 9). Multiple products and/or service niches in mobility technology and practice have emerged in recent years, including diverse forms of autonomous mobility, micromobility, shared mobility, platform-enabled subscription mobility, ride-hailing, and the blurring of the public mass/private individual mobility divide under the broad rubric of 'smart mobility' (10). It is unclear how far this fragmentation of mobility choices into further subsystems is substitutional or additional to existing modal splits, or how profound and enduring their impact will be in social, business, and environmental terms (11).

The aim of the paper is to provide a longitudinal account of the emergence and stabilization of the automobility system and to assess the contemporary state of the system in the early stages of an ongoing sustainability transition. The literature on sustainable automobility transitions provides useful insights (12, 13) but tends to focus on individual phenomena such as electrification or car sharing within discipline discourses such as electrical engineering or business strategy.

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This paper's contribution is to offer a broader assessment of the linkages between phenomena (such as electrification with connectivity) to understand the tensions and synergies between these phenomena at a system level. Specifically, the paper will suggest that the automotive regime is being reinvented through confluence with electricity, information technology, housing, and other systems, potentially presaging shifts in consumer attitudes and behaviors. The sustainability outcomes will only be knowable retrospectively.

The automobility consumption–production system is here analyzed using a sociotechnical system perspective in which are identified technology, production, markets and use, regulation, infrastructure, and behavioral/cultural meanings (14). The regime at the heart of the multilevel perspective (MLP) defines the system, with external 'landscape' pressures for stability or pathway change, and with niche technologies and practices that may challenge the regime. The proposal advanced here is that sustainability issues at the landscape level are expressed as a dynamic tension between the coherence of the existing automobility regime at the heart of the automobility consumption–production system and the fragmentation of that regime at the boundaries of confluence with other systems. Regime coherence and stability are created as shared understandings of actor roles, regulatory rules, and the cultural-cognitive assumptions that define behaviors and beliefs (15). Where two or more systems that were previously legitimate but separate then come to interact there is a contested-collaborative process of institutionalizing the boundary conditions, which may be profound enough to destabilize the original constituent regime(s). Space is created for the emergence of new niches and the possibility of regime transition. In this paper, multiple system confluence is interpreted through the lens of contestation over legitimacy at both organizational and institutional levels (16). Legitimacy has multiple dimensions but is expressed here by the idea that the actions of organizations or the institutional setting they represent are deemed to be desirable or appropriate within socially defined behavioral and attitudinal norms.

The automobility regime has strong autopoietic tendencies, but resolving the pressures on the entire automobility system demands the crossing of traditional boundaries into multiple other systems simultaneously. Confluence is necessarily chaotic and highly uncertain. It is marked by diverse and contradictory strategies by the key corporate actors involved (17) and by distinct differences between places. As Suchman (16) argues, legitimacy is most likely to be contested in situations where large social institutions are underdoing transition. System confluence is evidenced by the ways in which separate systems show instances of overlap or penetration. It is also evidenced by transition in the automobility regime. The character of this confluence is hypothesized as arising from distinct system characteristics and the idiosyncratic features of key actors within each system, which in turn create distinct boundary conditions and varying claims to legitimacy.

Embedding The Automobility Consumption–production System presents a longitudinal MLP framing of the accretion of automobility, to outline how the automobility system came to be dominant and deeply institutionalized over time. This historical perspective is important because the resultant accumulated path dependency has come to structure the existing legitimacy of automobility (18) and hence the potential of transition pathways, in relation to the nature of confluence with other systems. Moreover, there has been a sequential spatial expansion of mass automobility, initiated in the United States from around the 1920s, spreading to Europe and Japan in the post-1950 period, and (still) expanding into new geographies in Eastern Europe, Asia, South America, and Africa. Global expansion has therefore been mediated through distinct national contexts, resulting in variations in mobility cultures and practices alongside the apparently monolithic character of the automotive regime. Consequently, the uptake of electrification for example is also highly uneven. As of mid-2022, the share of battery electric in total new car sales approximated from 75% in Norway, 23% in China, 12–15% in some European countries, 5% in the US, and less than 1% in Brazil (19–21).

The system focus is important because the achievement of more sustainable automobility is beyond the power of individual companies, regulatory agencies, or clusters of consumers or other audiences and requires societal-level changes in, e.g., behaviors and physical infrastructures (17). The sustainability burdens have become landscape pressures, created in part or entirely by the automobility system itself, which are then part of instigating regime transition pathways and niche developments.

Sustainability Challenges and System Confluence then uses the concept of institutional legitimacy and the typology of system interactions from Raven and Verbong (22) to give an empirical narrative of key actors and stakeholders, institutional reforms, diverse corporate strategies, and emergent societal practices and behavior. That is, confluence likely results abrupt changes in system rules and behaviors in consumption and production, with empirically significant consequences for sustainability.

Finally, *The Reinvention of Sustainability Challenges for a Reinvented Automobility Consumption–production System* assesses more recent developments in the past decade by elaborating the system confluence perspective. This section concludes that transition pathways in the automobility consumption–production system are often incoherent, geographically specific, and accompanied by new contradictions, while recourse to sustainability science is needed to evaluate and inform the rival claims to legitimacy. Moreover, beyond automobility, this paper highlights the potential significance for the nature–society system of confluence among two or more previously distinct systems.

Embedding the Automobility Consumption–Production System

The cultural embedding of automobility can be traced back to mass motorization that first emerged in the United States from the 1920s, enabled by innovations in the design of vehicles and their engines, in Fordist production methods, and in marketing. The pathway to petrol rather than electric or steam was established in part due to slow expansion of the electricity infrastructure (23). Ivory and Genus (24) argue that petrol cars came to dominate due to the cultural meaning of the car around male elite consumers' interests in long-distance touring and racing (25). Thus, cars came to first represent the cultural status of elite actors, and then ownership of cars came to signify membership of the elite. Only later do cars change from being something desired to being also a necessity as daily lives were constructed around the presumption of car ownership and use (1, 18).

The cumulative embedding of the automobility consumption–production system is expressed as a profound influence over the spatial structure of societies, infrastructures for automobility, lifestyles and mobility practices, and the political–economic significance of automobility, with strongly reinforcing feedback loops resulting in automobility dependency (18,26). The system has been stabilized by a multiplicity of vested corporate interests that support the production and use of cars, stable core technologies, and by the accretion of cultural expectations and practices around personalized automobility. In this sense, automobility as an institution has enjoyed strong legitimacy, as have the constituent organizations.

Governments contribute to the automobility consumption–production system, shaping system trajectories via direct support (R&D; investment) and market-shaping activities (regulatory definitions on, e.g., carbon emissions; incentives and taxation; import–export rules). Car manufacturing has in many countries enjoyed the status of being a 'pillar industry', conferring additional benefits to the wider economy and generating significant revenues for the government. In the United States in 2010, for example, the production and use of cars were estimated to generate US$91.5 billion in state revenues and a minimum of US$43 billion in federal tax revenues (27).

Automobility was an element of post-1945 economic recovery and then growth in Europe (28) with distinct national automobility cultures (29). There emerged a degree of synchronization between these automobility cultures and industrial systems. Hence, Germany became associated with long-range, high-speed autobahns and cars suited to that application, leading to the market positioning of German manufacturers as 'premium' brands and a recent bias in favor of fuel cells as a zero-emissions technology rather than batteries (30). Japan became known for its 'small 'Kei' cars suited to the narrow and congested streets of Japanese cities; France became the home of the 'voiture sans permit' that finds an echo in microcars like the Citroen Ami and Renault Twizy. In contrast, the United States became notable for 'light trucks' to the virtual exclusion of traditional saloon (sedan) cars today. Brazil became known for its flex-fuel cars using sugarcane ethanol, a feature that may hinder the penetration of electric cars in that market. In many Asian cities, three-wheel vehicles became an important transport mode, while in China, electric bicycles in urban areas and low-speed electric vehicles in rural areas have resulted in a unique 'mobilityscape' emerging in the post-2000 era.

The timing, pace, and depth of the embedding of the automobility consumption-production system around the world, along with the characteristics of specific locations, have resulted in distinct local 'twists' to sustainability concerns. The United States, as one of the largest and earliest car-dependent societies, experienced the early onset of the social costs of negative externalities like road traffic deaths and injuries or the health impact of exhaust pollution caused by cars (chiefly particulates, nitrous oxides, and carbon monoxide). In consequence, the pioneering remedial efforts of the California Air Resources Board in the 1950s and 1960s have since been taken up by regulatory agencies around the world, in a complex contested mix of policies, industry strategies, and user responses (31). Non-governmental organisations (NGOs) such as the Union of Concerned Scientists and T&E have galvanized informed agitation over carbon emissions and climate change (32).

This brief history illustrates that while there are global sustainability challenges for automobility, they are mediated through local structural conditions that shape lock-ins and path dependencies, which in turn inform the patterns of system confluence. This provides a background for assessing how far sustainability transitions are occurring and with what consequences.

Sustainability Challenges and System Confluence

Sustainability pressures on the automobility system have increased markedly in the past decade, particularly regarding climate change and air pollution. Carbon emissions from transport are both very large and growing at the global level. The World Resources Institute estimated that transport accounted for over 24% of global CO_2 emissions in 2016 (33), growing from just under 3 $GtCO_2eq/y$ in 1970, to just over 7 $GtCO_2eq/y$ in 2016. Of this total, 72% is due to road vehicles, which have also been responsible for 80% of the growth in emissions since 1970 and approximately 50% of all petroleum consumption. Car-derived air pollution healthcare costs in the United States were estimated at US$37 billion per annum (34).

The Volkswagen (VW) diesel scandal in the United States in 2015 became symbolic of a wider perception of a regulatory system that appeared to suffer from 'capture' by the industry. That is, legitimacy is undermined when there is a loss of regulatory validity (35,36). An important underlying narrative here is that over time, the employment and wealth-creation value of the industry has lost some (legitimizing) political power because a) the industry was able to achieve successive generations of production technology and new working practices (e.g., lean production; keiretsu style supply chain management) that radically increased labor and capital productivity, hence resulting in reduced employment and b) investments were increasingly made outside of the 'domestic' country of origin of the companies. Consumers were thus less inclined to follow nationalistic purchasing preferences, and traditional brand loyalties were eroded, in part because World Trade Organization (WTO) rules have acted to reduce tariffs on imported cars in many markets.

Partly in response to these sustainability and legitimacy problems, multiple niche innovations have emerged since the 1990s, which are at different stages of development and deployment in different locations. Raven and Verbong (22) propose that system interactions have four possible aspects: competition; symbiosis; integration; and spillover. However, at the niche level, all four are potentially present. First, niche innovations bring destabilization pressures on the automotive regime by allowing disruptive new entrants to offer competitive technological innovation in cars and buses. New entrant vehicle manufacturers like Tesla (US), Arrival (UK), and Build Your Dreams (BYD) and NIO (China) may enact market entry via business model innovation. Second, niche micromobility technologies have been introduced in the form of electric battery symbiotic or spillover innovation in scooters, bicycles, and even unicycles, mostly by agents outside the automobility system. These technologies for personal mobility may broaden the suite of mobility possibilities without necessarily undermining automobility. Third, niche mobility service providers and new symbiotic ways to 'own' or access automobility have emerged for ride-hailing (UBER, US), ride sharing (Bla Bla Car, France), car sharing (ShareNow, Germany), and other platform-enabled sharing services (Didi Chuxing, China; Lime, US). Fourth, others have sought to 'own' the customer with new integration partnerships to deliver software-enabled connectivity and entertainment that could become competitive to the automotive regime. Typical corporate examples here include Google and Amazon (the United States) and Baidu (China). Governments have introduced (disputed) measures to phase-out sales of new diesel and petrol engines, alongside localized intervention by cities to create car-free or low-emission zones as spatial niches. New niche consumers have emerged in limited numbers with a preference for the bundled services, flexible use patterns, and per-month payment approaches typified by the mobile telephone market.

The automotive regime initially had some success at resisting or managing destabilization (37) but the cumulative pressure of landscape sustainability challenges, competitive positioning, and the emergence of new technologies alongside new entrants has resulted in the ongoing destabilization and reconfiguration of the automobility consumption–production system (9,38). Industry leaders and analysts have highlighted a partial shift away from making and selling cars and into a rather benign vision of smart mobility provision. The preexisting automobility regime actors have largely sought to claim ownership of the transition process through emphasis on continuity and pragmatic claims to legitimacy as the primary orchestrators of automobility. It is, in terms of the regime position, normal automobility enhanced by the opportunities of confluence. In contrast, for the Information and Communications Technology (ICT) and software regime (and especially actors in search engines and social media), the car is an object with wheels that allows an extension of the ICT regime. The consequence is enhanced, unpredictable innovation, and novelty in technologies, governance, actor relations, and social practices with no certainty that the sustainability burdens of automobility will be reduced.

The increasing deployment of electric vehicles is driving confluence between the automobility system and the electricity system, shown by the electricity generation and distribution subsystems enabling and adaptingto electrified automobility, but not by the electricity system entering vehicle production or use. Conversely, the same confluence shows the automobility system appropriating some elements of the electricity system (energy storage and grid management and vehicle-to-grid systems). This is a largely symbiotic rather than competitive confluence, with some integration of the electricity system into automobility, albeit with complexities around institutionalizing the bridging technologies in charge point networks. Electric vehicles and the electricity grid can therefore be said to have coevolutionary features (13). Confluence here can result (eventually) in reduced toxic emissions to local environments and reduced carbon emissions, assuming that the total car population and existing driving practices do not substantially change. However, new contradictions emerge in the environmental and social costs of mining for battery materials, in geopolitical concerns over resource scarcity, and with battery recycling (39). In the realm of production, therefore, confluence brings the automotive regime into new supply chains and new material requirements, which may create new social justice concerns (40). Moreover, electrification alongside better communications (e.g., real-time location of suitable charge points or the provision of in-car Internet access) and enhanced autonomous capabilities is likely to result in lower cost and guilt-free, more appealing driving experiences and may therefore expand the demand for cars and car services even further via the rebound effect (41).

Confluence with the ICT system is rather different. Confluence here has more facets. Bringing real-time streaming, mapping, and searching capabilities into cars and via mobile phones is one key aspect, allowing the deployment of new added-value services like car sharing. Another is the sensor integration needed for advanced autonomous capabilities. Hence, the emergent automobility system is already heavily dependent on computers, telecommunications, and software across all parts of the consumption–production system. ICT actors may be financially powerful incumbents in their 'own' system or have distinct capabilities that are somewhat alien to automobility. In this case, there is evidence for the disruptive penetration of the automobility system by the ICT system in which core competencies, in, e.g., software and artificial intelligence alongside pattern recognition, give so-called 'tech' firms a competitive differentiator and advantage. The car represents an important and largely unrealized potential revenue stream for additionality or spillover in the form of Internet-enabled services including searching, networking, and content streaming. Digitalization and connectivity may act to enhance the eco-efficiency of automobility while simultaneously generating valuable user-related spatial data and new user experiences. Products in the ICT system are characterized by rapid cycles and version updates via software offering differentiation and subscription revenue or 'pay as you go' propositions, compared with the automobility system dominated by long product cycles and a user preference for long-term ownership. In this respect, the car represents just another hardware platform that the ICT system might attempt to capture. There is therefore mutuality but also antagonism. A frequent result is actor–actor alliances, of uncertain stability, to integrate the two systems.

Confluence with the housing or construction system was previously stable, but the possibility of domestic or workplace charging of electric cars is again a key driver for pathway change. The built infrastructure of urban and suburban development offered garages, driveways, carparks, fuel stations, and roads for traditional cars. Electrification is resulting in the cooption of some of these features and the creation of new integration requirements around charge points. The biggest sustainability benefits will be obtained when the building use of electricity is mediated by electric vehicle battery systems in smart 'vehicle to grid' applications. Here again, there is a strong element of mutuality in terms of potential synergies between the systems which can come at no significant 'cost' to the coherence of either of the systems. In many countries, the building stock is often both old and enduring, so an emphasis on the retrofit of domestic charging is likely along with appropriate deregulation of issues such as domestic solar power storage and resale to the grid. System confluence here therefore results in a complex policy environment, often with multiple intermediaries in a diversity of local initiatives (42). At its core, the automobility system is on a destabilization and restabilization pathway (43) but with elements of fragmentation. This pathway is expressed as shifts in the population of key actors and stakeholders, institutional reforms, diverse corporate strategies, and emergent societal practices and behavior. The themes illustrate characteristic evidential features of the contemporary processes of pathway change in the sustainability transition of the automobility consumption–production system.

Key Actors and Stakeholders. Fragmentation occurs due to niche emergence at the multisystem boundaries. The overarching concern to reduce and ultimately eliminate global carbon emissions finds its expression in innovative regulatory zero-emission mandates for vehicles but also via Mobility as a Service (MaaS) in the redefinition of the relationship between private and public transport. MaaS is adopted to establish mobility systems that are more symbiotic. However, MaaS cannot be realized without the enabling capacities of ICT and the cooperation of the automotive regime with other mobility actors, with whom the relationship may be competitive. Hence, there is a decoupling underway between the automobility system actors and those of the hydrocarbon fuel system that has endured over 100 y, while bringing together new actors and stakeholders from other systems.

Institutional Reforms. The institutional bases of the constituent regimes in the confluence discussed here have historically been quite distinct, with characteristics that can help shape the nature of confluence outcomes in terms of the automobility consumption-production system. Automotive markets have long been heavily regulated for economic, safety, and environmental reasons. This, coupled with long product lead times, enduring capital investments, and long product lifetimes, yields institutional inertia and a balance between innovativeness and incrementalism. Electricity generation and distribution in contrast remain, in many countries, an area of close government control and national strategic priority, with a conservative, risk-averse, culture.

Institutional reforms are needed to assist in bridging the boundary between systems via policy mixes that have direct and indirect impacts on multiple systems (44). New housing and office space often now have electric charge point installation mandated. Fiscal and regulatory reforms alongside technological innovation are needed to enable vehicle-to-grid applications. Users need to become accustomed to charging at home or in novel multicar electric forecourts.

Governments worldwide still support car use, and the uptake of battery electric cars through multiple mechanisms including subsidy of battery manufacturing plants, the conversion of factories to produce electric cars, and the provision of charge point networks. This destabilization and restabilization pathway emphasizes minimizing disruption to contemporary automobility, hence there is the focus on reducing battery costs, enhancing battery capacity and vehicle range, controlling the pace of pathway change, and providing for widespread public charging infrastructures but also with the risk of minimizing any sustainability benefits from electrification (45). Institutionalizing micromobility has proven more challenging, particularly over the use of physical infrastructures such as roads and sidewalks. This leads to conflicts with existing users such as pedestrians, cyclists, and drivers.

Diverse Corporate Strategies. Business model innovation, both by incumbents and by new entrants, has been key to the system transition observed to date, as it encapsulates the potential of technology innovation with new ways for users to unlock the value of mobility (46). Transitional incumbent corporate strategies include the phase-out of petrol and diesel models, ending research into new generations of combustion engines, and increasingly deploying vehicles designed specifically for electric power. The digitization and electrification of the automobility consumption–production system have simultaneously challenged the business practices of the regime incumbents (suppliers; vehicle manufacturers; dealerships; independent warranty providers; insurance and finance actors; marketing and advertising agencies; vehicle repairers; and recyclers) and provided an opportunity for new entrants. Not all new entrants have been successful. Failures include new entrants making cars (the appliance manufacturer Dyson and the China-based start-up Byton) and those offering car-carsharing concepts (the Bollore Group-backed Autolib car sharing scheme in Paris).

Emergent Societal Practices and Behavior. An important feature of the emergent 'new' automobility system is that confluence enables deepening or further embedding of the existing automotive regime. Car-sharing schemes and ride hailing can be understood as new ways of segmenting the market, making automobility in general more accessible to more people than hitherto (47).

New niche forms of mobility have emerged around electrification and/or sharing. These micro, electric, and shared mobility innovations include, e.g., e-scooters and e-bikes, and are often seen as a more benign form of urban mobility. Participation from the automobility regime actors is minimal, though some key component and material suppliers have become engaged. Niches are uneven, at different stages of development and spatial scales, and likely with different scopes for future expansion. In practice, new conflicts emerge around these attempts to fill the 'gaps' in existing mobility provision, especially with regulatory issues or accepted cultural practices in the use of public space and existing mobility infrastructures. Failed experimentation with these interstitial niche innovations can result in further underlining the embeddedness of automobility and the shocking levels of waste symbolized by mountains of scrapped bicycles from abandoned 'dockless' bike-sharing schemes. European cities are developing more stringent, localized policies to limit or exclude cars while promoting alternative modes of public or shared use. However, car sharing is of marginal importance even in settings that have the greatest prospects to be conducive to the reduction of automobility (48). Even in the cycling-intensive Netherlands, the rapid and large-scale deployment of privately operated bicycle-sharing schemes initially resulted in a powerful social backlash—mostly with concerns over the private appropriation of scarce public space for bicycle storage (49).

While there is a vision perhaps for seamless intermodal mobility in rational smart cities inhabited by intelligent and connected consumer-citizens, there is scant evidence for integrated, holistic, and sustainable mobility thus far as is discussed in *The Reinvention of Sustainability Challenges for a Reinvented Automobility Consumption–production System*.

The Reinvention of Sustainability Challenges for a Reinvented Automobility Consumption–Production System

According to Suchman (16), legitimacy is typically accumulated over long time periods but can be subject to episodic challenges. For the automotive regime, the current period is precisely such an episodic juncture, instigated by confluence with other regimes. In the institutionalization process, divergent interests seek to advance and demonstrate the instrumentality of their actions for various constituents. Alongside the acceleration in the uptake of (the previous niche) electric technologies, there is also only partial evidence of regime displacement. This obduracy may be attributed to a combination of the regime ability to retard the pace of change, the difficulty of replacing large stocks of high-value consumer items quickly alongside adaptations in mobility behaviors, and the challenge for interests outside the traditional automobility regime to establish their legitimacy in the emergent multiregime institutionalization process.

The transition of the automobility system offers multiple benefits in terms of reduced carbon emissions and other elements of the nature–society system. The isolating and cocooning features of car occupancy are more appreciated following the emergence of the COVID-19 pandemic that saw a mass avoidance of public transit. Yet, automobility remains a resource-intensive means of providing for personal movement. The automobility regime at the heart of the system, in confluence with other systems, is in the process of making automobility more attractive while simultaneously creating new sustainability challenges. Hence, at a system level, it is important to think about and measure negative consequences of 'sustainable' system transition (50).

Automobility that is electrified, connected, shared, and autonomous, that offers a digitally enhanced consumer experience, is likely to be of lower cost and less 'painful' than contemporary automobility and in consequence even more difficult to dislodge in the future. The distinctions between home, car, shop, and office begin to erode. Whichever participants become dominant regime actors in the future will be able to extend control over automobility into the aftermarket and the circular economy (51), but this will not mitigate all the new sustainability challenges.

An example in technology terms is electrification. Battery electric cars contribute sustainability and geopolitical burdens in terms of mining and processing key metals, while in use they are only as zero carbon as the electricity supply. Battery electric cars help on urban toxic exhaust emissions but less on emissions of brake and tire dust (52). The rapid substitution of petrol and diesel by electric cars will do little to resolve the costs of congestion or redress the privileging of urban space to vehicle uses.

As with the emergence of the Internet, the social consequences of system pathway change are not entirely predictable or necessarily entirely benign (53). Autonomous cars, for example, are not 'free' to move anywhere but rather are tightly controlled both by external infrastructures and internal algorithms and come with contingent new ethical dilemmas (54) and potential negative externality rebound effects (55).

However, the emergent automobility consumption–production system remains strongly informed by historic precedent, path dependency, and the power of self-reproducing legitimacy within the consumption–production system with repercussions for sustainability. Hence, for example, the transition to electric cars has to date been dominated by the production, sale, and use of very large, heavy, and resource-intensive Sports Utility Vehicle (SUV)-style vehicles that have become popular in the latter stages of the petrol and diesel era (56). In the United States, the eventual transition to electric vehicles could increase total electricity demand by 35% (57).

The appeal of personal automobility has not greatly reduced. Many recent and expected developments act to increase the ease, utility, and comfort of driving and are coupled with a lower total cost of ownership than petrol cars. Automobility, therefore, is not only more appealing than ever before but may be extended into other realms (such as electric vertical take-off and landing for taxi services) and other consumer segments hitherto excluded such as older, younger, or disabled drivers (and nondrivers).

The period of fragmentation and consolidation is expressed as a destabilization and restabilization pathway. The regime is destabilized in the switch to electrification, which opens the space for new actors. Restabilization occurs as the automobility regime settles again into new stability. What is uncertain is the time required for this transition in the consumption–production system. Many system actors are seeking government support to accelerate the process of change, after many years of slowing it down, in the face of the 'climate emergency' (see e.g., https://exponential-roadmap.org/). The pace of change is relevant, particularly as the automobility actors are often seen as 'slow' compared with those in ICT for example.

Most fundamentally, the social acceptance of personal mobility as both a need and a right appears unassailable despite the many sustainability burdens created. There is still no challenge to this accumulated legitimacy. Substitution of mobility has possibly occurred at the margins, creating an 'unmobility niche' in the form of, e.g., virtual meetings and virtual reality experiences, remote working and shopping, and the streaming of entertainment services that might all have previously required some form of physical mobility. However, the core of the automobility consumption–production system remains intact despite the surrounding volatility. What changes is the character and distribution of ecological and social burdens, and it is here that sustainability science has an important contribution to make in identifying and enumerating both the human benefits and ecological costs that emerge out of this nascent automobility transition.

These confluence processes may be impacted by episodic landscape events. An example is the Russian invasion of Ukraine which has highlighted European dependency on gas and petroleum imported from Russia. One 'solution' lies in nurturing more renewable, local, energy sources, which in turn requires widespread deployment of domestic smart vehicle-to-grid technologies to enable demand and supply electricity management (42). However, V2G and other examples of confluence require coevolutionary technical, economic, regulatory, and social practice innovations which in combination will pose new sustainability questions for sustainability scientists. The requirement for legitimacy as confluence unfolds is not reducible to sustainability science alone, but important contributions can be made in extending evaluation methodologies that are largely based on single products or services into these more combinatory settings.

Sustainability science has been key to ecological critiques of traditional automobility (e.g., via tools such as Life Cycle Analysis or models of planetary system boundaries) and to understanding contestation over the emergent new automobility (58). The seven key research questions articulated for sustainability science by Kates (59) remain fundamental, but confluence creates new levels of complexity. Confluence creates the possibility of new consumption bundles and patterns and new provision configurations. This means that nascent consumption phenomena cannot be fully comprehended in isolation but that the boundary of any scientific sustainability study will be a key methodological consideration.

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