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Driving change? Exploring the role of socio-technical experiments in shaping autonomous mobility transitions

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ABSTRACT

This systematic literature review inquires into the role of socio-technical experiments for autonomous driving and their potential to shape mobility transitions towards sustainability. As an emerging technology in an early stage of transition, AVs are increasingly being tested in different spatial contexts with diverse actor constellations in order to enhance the technology further. This article critically examines the added value of these experiments, how they affect the scaling-up of autonomous driving, and highlights key themes that researchers and practitioners should consider when designing experiments. The most striking aspect of our sample is the lack of continuous participatory methods, as well as weak linkages to the transition literature. Reflecting upon how existing experiments link to the core characteristics of socio-technical experiments, we derive central findings for future research avenues: Scaling-up of AVs requires greater involvement of policymakers and enhanced place-specific approaches, while comprehensive co-design experimentation relies on robust, long-term research infrastructures.

1. Introduction

Autonomous vehicles (AVs) are increasingly positioned as a key component of future mobility systems by advocates of this emerging technology, framed as a politically desirable solution. However, the question of how AVs can contribute to sustainable development and integrate society in a meaningful and strategic way remains open for debate (Hess, 2020). Notions of a sustainable mobility system of the future include the integrated use of renewable energy, mobility diversity, shared mobility, and improvement of accessibility, particularly for groups with reduced mobility (Nemoto et al., 2021). Various global players and governments proactively promote the innovation process towards autonomous mobility. However, different perceptions and ambitions in the understanding of the technology lead to several global differences regarding the governance, business models, and meaningfulness of the technology. Approaches in the US follow a highly explorative attitude in testing AVs, which is currently dominated by private key actors such as Alphabet's subsidiary Waymo and driven by tech-oriented narratives of Silicon Valley. Hence, forerunner cities such as San Francisco became pioneers in providing services with self-driving cars. In contrast, the development in Europe is characterized by smaller-scale projects that often run under strict regulatory requirements regarding speed limits, predefined routes or safety drivers on board. Despite the different allocation of responsibility and liability in each regulatory environment, all local integrations face the same basic

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challenge: How can experimental settings with autonomous mobility solutions lead to an adequate integration into an existing mobility system, support the transition process of the innovation, and to what extent do they enrich our knowledge about this new mobility form as researchers and citizens?

In a best-case scenario for the technology assessment of AVs, they would create an incentive for inclusive and shared transport services that are tailored to place-specific needs of society and address sustainability issues in a meaningful way (Strömberg et al., 2021). Nevertheless, this ambition comes with complex challenges that encompass questions regarding economic, ecological, social, and governance dimensions and, therefore, stress the need to strengthen the dialogue and learning process towards autonomous mobility futures. Scenarios that see autonomous vehicles as a solution for increasing shared mobility stand in contrast to those scenarios that emphasize the risk of consolidating the paradigm of car-centered individual transport (Dowling and McGuirk, 2022; Schippl et al., 2022). Favorable scenarios stress the systemic opportunities that might arise with the support of AVs as a new mobility solution. Among others, these include the reduction of vehicle ownership, traffic delay, congestion and greenhouse gas emissions, energy consumption, and traffic crashes involving human errors. Moreover, these effects may have a long-term impact on encouraging dispersed urban development and increasing the capacity of existing transport systems (Rahman and Thill, 2023). In contrast, the development of AVs and other autonomous mobility solutions is accompanied by obstacles and concerns not only in society, but among other involved stakeholders, such as planners and policymakers. These uncertainties primarily include worries regarding personal safety, security, and privacy, and can be linked to the disruptive nature of (digital) innovations and the ethical dilemmas that come along with their integration (Martin, 2019; Rahman and Thill, 2023). Moreover, researchers need to take rebound effects due to changes in travel behavior into account when evaluating the systemic implications of AVs in a specific spatial environment (Garus et al., 2022).

As an emerging technology that is in an early stage of transition, AVs are increasingly being tested in different spatial contexts with varying actor constellations in order to address the need for further technological development. It remains unclear, if or to what extent these experimental settings contribute to a continuous further development, and whether they are oriented towards a goal beyond (technological) feasibility. We therefore postulate a need to strengthen the conceptual understanding of experimental settings within autonomous mobility and to build a strong link to pathways that embed these experimental approaches in the context of the mobility transition from a systemic perspective.

For this purpose, we draw on the literature on transition theory and refer, more specifically, to the understanding of *socio-technical experiments*. In transition literature, experiments are seen as a key element for socio-technical change to improve (technological) novelties under real-world conditions and induce learning processes towards societal challenges and emerging sustainability configurations (Ceschin, 2014; Sengers et al., 2019). They aim to contribute to a transition through the *broadening, scaling-up*, and *deepening* of the innovation (Van den Bosch and Rotmans, 2008). Experiments should therefore not only be seen as a space for testing and demonstrating technological solutions, but also as a vital component in a socio-technical system that can have a decisive influence on the governance, surrounding discourses, and the multi-scalar understanding and sustainability dimensions of a transition. Transition studies mainly consider experimentation in relation to niche formation, such as networking, collaboration, or creating a shared vision of the innovation. The role of experiments regarding the integration of a niche development into a stable socio-technical regime, such as regulatory questions or social dynamics, often remain understudied (Marres, 2020). Hence, it is important to emphasize the role of experimentation beyond niches and how it may contribute to the scaling and mainstreaming of a transition (Fuenfschilling et al., 2019). We argue that experiments on autonomous driving, regardless of their specific practical terminology, must aim to advance the innovation along multiple dimensions such as technological improvement, market creation, costumer experience, and political, regulatory, environmental, cultural, and social dimensions. Hence, they must be embedded in an overlaying strategy or intention of how autonomous mobility may enhance the mobility system of the future.

Consequently, we are interested in understanding the current role that socio-technical experiments play in the integration of autonomous driving as a cornerstone of a sustainable mobility system of the future. This paper follows the overarching research question:

How can socio-technical experiments with autonomous vehicles lead to an adequate integration into existing mobility systems and support the transition process of the innovation?

To further develop the analytical steps, we disentangle the research question into the following sub-questions:

a) How are socio-technical experiments in the context of AVs currently framed, to what extent do they enrich our knowledge about this new mobility form as researchers and citizens, and which shortcomings should be addressed?
b) What are future research avenues that can support the design of meaningful experiments in the context of AVs and deepen the understanding and potential of the sustainability transition?

The article is structured as follows: The next section contextualizes socio-technical experiments in the transition literature and defines our conceptual framework for the review process. Chapter three provides an overview of the methodology. In the following, we present the results and summarize the state of the art based on our theoretical framework. Subsequently, we conclude and point out aspects towards designing meaningful experimental settings as well as future research avenues.

2. Contextualizing real-world experiments on autonomous driving

Research on the importance and potential of socio-technical experiments has spawned a large body of literature in the fields of sustainability transitions, environmental governance, and related disciplines concerned with the outcomes of experiments for emerging technologies in a real-world setting. Nevertheless, the meaning and definitions of experiments as well as the understanding how they may influence the directionality of an innovation varies greatly across different domains (Ansell and Bartenberger, 2016). With respect to transition studies, experiments can matter to encourage socio-technical and design innovations to support a transition towards sustainability (Hoogma et al., 2002; Van den Bosch, 2010) or foster social and political learning to mobilize support (Brown et al., 2003; Ceschin, 2014; Voß et al., 2009). Experimentation is also understood as a potential governance mechanism that enables policymakers and practitioners to purposefully translate visions and urban agendas into the real-world, and gain insights about the unfolding of a novelty in their specific spatial setting (Bulkeley et al., 2016; Sengers et al., 2019). With regard to the transition to autonomous mobility, this raises the question how real-world experiments actually relate to the overarching innovation development and industry dynamics that shape the narratives and directionalities of the transition. This chapter aims to contextualize the link between transition studies and the emergence of autonomous driving by (a) outlining the understanding of autonomous driving as a transition process, (b) reflecting on the relevance, terminology, and meaning of experiments, and (c) providing a conceptualization of socio-technical experiments based on the concept of van den Bosch and Rotmans (2008).

2.1. A socio-technical transition perspective on autonomous driving

Transition studies have evoked a variety of conceptual frameworks and heuristics, such as the multi-level perspective or strategic niche management (Köhler et al., 2019). As a common and shared understanding, these approaches distinguish between three central levels that have manifested as a common understanding of socio-technical systems (Geels, 2002; Geels and Schot, 2007; Smith et al., 2010): first, *socio-technical niches* are domains in which a small number of cooperating actors advance, test, and market innovation and act as incubators outside of the existing regime; second, the *regime* embodies a socio-technical fabric of diverse actors and practices. It represents existing configurations that ensure certain connections and modes of action between the social sphere and existing technologies; third, the *landscape* captures exogenous and overarching change (outside of niches and regimes) that tends to be continuous and slow. The idea of socio-technical experiments is closely tied to this common conceptualization. Experiments are primarily regarded as singular and localized endeavors that attempt to introduce a technological novelty, new services, or social and institutional arrangements on a small scale and are driven by long-term and large-scale visions, such as advancing the sustainability agenda (Brown et al., 2003; Raven et al., 2019). They are embedded in (partially) protective environments to enable learning processes about the integration of radical innovations and explore improvements in a real-world setting (Ceschin, 2014).

Mobility systems mirror this core idea of socio-technical transition in various ways, as changes within these systems have a historical impact on industrial paradigm shifts (and vice versa), including new value chains, infrastructural upgrading, and social change such as creating legitimacy for an emerging technology (Fraske et al., 2024). Autonomous driving exemplifies these multi-level developments between an emerging technology and mobility solution (niches), existing mobility systems and their institutional and infrastructural diversity (regimes), and overlaying discourses and industry dynamics (landscape). AVs might lead to both sustainable or non-sustainable path-dependencies, which makes it crucial to understand the different factors that may influence the direction of the path development (Schippl et al., 2022). Put in simplified terms, the path development for autonomous driving essentially points in two opposite directions. In the first scenario, new collective mobility solutions such as on-demand and ride-pooling services emerge alongside autonomous driving, which should eventually become a sustainable element of public transport. In contrast stands the scenario of a car-centered development, in which autonomous vehicles adopt existing mobility solutions (e.g., robotaxis) and should be understood primarily as adding value in terms of comfort and safety.

While many technological forerunners and national policy agendas emphasize the potential benefits of autonomous mobility, some studies observe rather contrary dynamics. Milakis and Seibert (2024) argue that the ambition of shared mobility emerges slowly on the niche level due to a resistance from key actors on the regime level and only moderate pressure on the existing automotive industry to foster changes regarding, safety, congestion, and environment issues on the landscape level. Hence, the transition might likely promote privately-owned electric AVs over shared AVs (Milakis and Seibert, 2024). Regarding the technological development, authors observe a bias on the development of the automation software and vehicles, but a shortcoming concerning the surrounding operation infrastructure. Pel et al. (2020) highlight that framing the development of autonomous vehicles (AVs) as a "race to automation" distorts the reality of its pace and directionality. They argue that advancing this transition requires a more deliberate and strategic cultivation of AV technologies. This includes aligning governmental traffic management objectives with collaborative efforts between public and private sectors to develop "cooperative systems" that integrate AVs more effectively into broader mobility frameworks (Pel et al., 2020). Recent developments reveal significant disparities in expectations, potential milestones, and objectives. This lack of clarity in the discourse stems largely from the inability to empirically substantiate a comprehensive technology assessment, given the absence of market creation and the limited number of broadly integrated examples, such as Waymo in the United States. However, these forerunners are confined to a single business model and operate under the umbrella of a single company. As a result, while they provide insights into technological maturity, they offer little information about alternative mobility solutions, operating systems, or broader integration in other contexts. In this dynamic space between expectations and possibilities, real-world experimentation fulfills a crucial role in driving the transition process.

2.2. The role of experiments as labels and platforms for participation

Real-world experiments serve as a platform for testing, evaluating, and ultimately implementing changes within society (Ansell and Bartenberger, 2016; Parodi et al., 2024; Van den Bosch and Rotmans, 2008). These experiments often operate on a micro-scale, specifically through funded research projects conducted in real-life settings, such as on streets or in dedicated and isolated environments such as premises. It is at this level that the impact of an innovation becomes tangible, allowing for broader involvement of diverse actors beyond industrial development, including civil society and policymakers.

This raises the question of suitable formats or principles for framing and conducting experiments, and how the methodological setting of the experiment must be framed to fulfill the intended purpose of the outcome (Fuenfschilling et al., 2019). Research on experimenting with emerging technologies has evoked a multitude of terminologies to describe methodological approaches that aim at finding a solution for existing problems in a specific socio-technical system. Frequently used terms, among others, include "pilot project", "living lab", "real-world lab", or "incubator". Often, these terms include a geographical dimension such as "urban" to emphasize an explicit territorial focus on finding place-specific solutions that tend to address global problems, such as climate change or energy transition (Steen and van Bueren, 2017). The question of whether and how socio-technical experiments can induce systemic change is closely tied to this geographic dimension of transition processes. A crucial aspect here is how such local experiments can scale-up and transcend their initial place-specific context (Hansen and Coenen, 2015; Truffer et al., 2015; Turnheim et al., 2018).

In practice, experiments are initiated mainly through applied research projects and associated consortia. Besides the challenges in defining and operationalizing the terms adequately as a researcher, the usage of the terms is heavily influenced by policymakers, planners, and other stakeholders, who increasingly use terms such as living lab in projects or policy guidelines such as mobility plans. However, this policy perspective tends to fulfill a labeling purpose rather than the actual ambition of an innovative co-design process. The policy implications should therefore be sensitively separated from academic comprehension of the terms and concepts, while researchers must acknowledge the mutual influence of both. This also underlines the fact that experiments never occur without an underlying interpretation and intention. Hence, experiments cannot be understood as non-normative endeavors, but they rather entail different values, purposes, and stances toward knowledge of the involved actors that represent the associated project (Ansell and Bartenberger, 2016). This emphasizes the importance and co-production between society and projects/experiments as a part of democratic and participatory knowledge production (Ryghaug and Skjølsvold, 2021). Moreover, it prompts us to ask whether technological-oriented experiments can also test society in a sense that they reshape and question existing social dynamics to derive implications for a long-term integration (Marres, 2020). Hence, it becomes even more crucial to better understand the intentions and outcomes of these experimental settings, even if they are not directly reported and discussed in transition literature or other conceptually based research strands.

With respect to the context ofautonomous driving, practical experimentation with AVs derives from two different perspectives. First, a focus on the vehicles and their associated technologies (such as sensors, routing systems, V2X communication). These projects primarily aim at the upgrading, problem identification, and further development of the hardware and software applications to increase the viability of the vehicles themselves. Second, a focus on the mobility systems and how AVs can become an element within an existing transportation system that contributes to its long-term efficiency and accessibility. While both starting points are crucial for the further development and evaluation of the socio-technical development towards autonomous mobility, technology-oriented pilot projects account for the majority of experimental settings so far. However, many of these attempts are criticized for being disconnected from questions of governance and primarily supporting knowledge creation directed towards consortia and industry interests (Stilgoe and O'Donovan, 2023). This bias counteracts the ambition to contribute to public life or motivates planners and policymakers to play a more active role in shaping and learning from these experiments (Stilgoe and O'Donovan, 2023). In addition, transportation-focused perspectives on experimenting with AVs run the risk of not considering the responsibility of the local government́s role and the operational needs of a city (or region) to reduce its environmental pressures (Cremer et al., 2021).

In the light of those different understandings and the variety of experiments, this study will follow the understanding of van den Bosch and Rotmans (2008). For the purposes of this study, they provide a suitable framework, as they a) define core characteristics of socio-technical experiments that allow for sufficient contextualization and comparability, and b) provide an understanding of the causal dynamics within the transition process.

2.3. A conceptual understanding of socio-technical experiments

While there are a variety of conceptual approaches that aim to define specific types of experiments in the transition literature (Sengers et al., 2019), a central empirical research interest can be placed on the question of the extent to which experiments can actually foster a transition, or whether they remain stuck on improving the technology itself. Transition experiments therefore aim at stimulating transitions towards specific societal goals and rely on frontrunners to initiate these ambitions (Van den Bosch and Rotmans, 2008). In order to delimit and operationalize our understanding of socio-technical experiments in the literature review, we focus on the core characteristics that the socio-technical experiments are expected to fulfill (Ceschin, 2014; Van den Bosch and Rotmans, 2008). Hence, such experiments…

(1) focus on a ***radical innovation***, that, in addition to its technological complexity, requires substantial changes on several dimensions (regulatory, institutional, and socio-cultural) and has the potential to trigger transformative change within the mobility system.
(2) are carried out in a ***real-world setting*** outside of R&D infrastructures, thus enabling the use of a specific technology in a societal environment. We also include virtual realities or digital formats, as long as they are part of a participatory approach within an experiment.
(3) involve a ***wide range of actors*** that include those that are not directly linked to industrial development and mobility research, but also to policy actors, civil society, and all those embedded in the specific socio-technical environment. This implies participatory and co-design approaches to adequately address these different stakeholder groups.

(4) are integrated in a ***protected space*** outside of market selection to foster the nurturing of the innovation and learning processes about societal challenges for future mobility scenarios.
(5) aim to create learning processes and improvements of the innovation in ***multiple dimensions*** rather than focusing on a single element, such as testing an algorithm on a test track.
(6) aim at stimulating ***changes in the socio-technical context*** and are strategically used to affect their specific context such as in the context of an urban agenda or mobility plan.

In sum, we understand experimentation as "collective search and exploration processes in which a broad suite of stakeholders like firms, universities and actors from government and civil society are navigating, negotiating (and ideally) reducing uncertainty about new socio-technical innovations through real-world experiments, gaining knowledge and experience along the way in an iterative learning-by-doing and doing-by-learning iterative process (von Wirth et al., 2018:231)." For experiments to enable and succeed in their attempt to support a transition, three central mechanisms can be highlighted (Van den Bosch, 2010:187). **Deepening** refers to the ability to strengthen the meaningfulness and learning processes within and between experiments. Such processes entail providing the actual space for conducting the experiment (spatial, regulatory, or institutional) in specific contexts, providing the support to overcome existing barriers, structuring the activities within the experiment, and an adequate monitoring and evaluation of the outcome. **Broadening** aims to provide resources to replicate and repeat the experiment in different contexts. Hence, it is necessary to facilitate interactions between similar experiments, stimulate network building, and make the experiences and knowledge accessible to actors outside of the experiments. **Scaling-up** refers to selecting and supporting key actors with the ability to experiment and scale up. Therefore, there is the need to involve regime actors who have the power to change existing structures or rules, realize agreements, and create feedback loops between the experiment and regime actors.

We postulate that an actual contribution to advancing our knowledge on potential solutions towards a more sustainable mobility system that involves autonomous mobility is only possible, when real-world experimentation is thoroughly based on or embedded within a research design that reflects the desired outcome. Hence, we want to contextualize the empirical outcomes and methodologies identified in our literature review on AVs based on the proposed conceptual framework of the core characteristics. Ultimately, we want to provide key recommendations on the primary shortcomings that we overserved regarding the deepening, broadening, and scaling-up.

3. Methodology

This article draws on a systematic literature review of the existing research body that reflects on experimental approaches for engaging with autonomous driving in a real-world environment. Hence, we primarily aim to identify papers that either explicitly or indirectly (e.g., through a review) outline and discuss the empirical outcomes of such experimental settings. The systematic literature review follows five methodological steps (Denyer and Tranfield, 2009): question formulation, locating studies, study selection and evaluation, analysis and synthesis, reporting and using results. This guideline has established itself as an appropriate and investigatory methodology to collect literature that fulfills the sense and intention of the research purpose and is applicable across different disciplines (Tranfield et al., 2003). The data set is based on the SCOPUS database. Besides the limitation on a single database, the review process runs the risk that the research string does not cover all relevant papers or that some papers are not accessible, whether by subscription or language barriers. To address these potential shortcomings, we reflect on every single step of the review process and address flaws such as the lack of equivalents in the research string.

Step 1: Question Formulation

Our initial intention was to gain an overview of the general research trends in autonomous driving and their implications for sustainability. First, the loose use of the term as a buzzword has led to a vast amount of literature that does not analytically address questions of the sustainability of AVs or a sustainable mobility system of the future. Moreover, the term is rarely operationalized or contextualized, even if it is part of the theoretical or analytical approach of the article. Second, the sheer volume of literature identified made detailed screening almost impossible. While these observations were already relevant and instructive for the next methodological steps, a review without a more specific focus did not seem viable or feasible for advancing the topic. We therefore sharpened our focus on empirical evidence and practical experience with AVs, and the extent to which experiences of AV experiments are reported in the academic literature – and the role sustainability might play in that. The analysis criteria for the first screening were therefore, whether a paper discussed or reviewed insights from practical experiments with AVs in a real-world environment.

Step 2: Locating studies

The research string of the review consists of four selective categories: (1) an emphasis on the mention of sustainability in the full text of the paper, setting a basic cornerstone for selecting studies that engage with questions for designing a sustainable mobility system; (2) selecting studies with a focus on experimental settings for AVs; (3) a selection regarding terms addressing the autonomous and self-driving aspects in the abstract of the paper, including equivalents; and (4) a selection of terms considering the vehicle and mobility dimension in the abstract of the articles, including equivalents. Table 1 presents the keywords of the research string used in this systematic literature review. The research string identified 346 papers on SCOPUS that were included in the screening of the review.

Step 3: Study selection and evaluation

Table 2 summarizes the inclusion and exclusion criteria of the literature review. Subsequently, we excluded papers that neither addressed autonomous driving nor practical experimentation with this technology in either an empirical or practical-oriented manner. Therefore, we only included those papers that refer directly to empirical findings on the subject or at least reflect on empirical experiences, e.g. through a review process or reference to technical reports. We also specifically focus on road-based autonomous vehicles, such as cars and shuttles, and exclude other forms of autonomous mobility, such as ferries or advanced air mobility.

Fig. 1 provides an overview of the screening and selection process of the literature review. A first abstract screening identified 83 papers that were considered for a full text review. The number dropped to 59 papers after full text review. Based on the inclusion criteria, 33 of them can be categorized as closely related to the research topic, while 26 papers are partially related to the subject.

Step 4: Analysis and synthesis

In the actual analysis of the paper sample, we analyzed each paper with a specific look at how to categorize them according to the type of content, such as their methodological approach, their implications for the mobility system, and unique insights from the respective studies. We collected and structured what could be found in the reported literature in relation to each of the six core characteristics of socio-technical experiments according to Ceschin (2014) and Van den Bosch & Rotmans (2008) and reflected on how these findings may affect progress in socio-technical change.

Step 5: Reporting and using results

Finally, we present the results based on a suitable categorization of the discussed themes and research gaps and provide a discussion to highlight future research avenues.

4. Results

There is a general criticism across the literature that the debate on real-world experiments for autonomous driving is still too conceptual and that there is a lack of knowledge creation that especially addresses public authorities, policymakers, and planners (Choosakun et al., 2021; Falzon and Lewis, 2022; Stilgoe and O'Donovan, 2023). Considering the total number of pilot projects that exist today, only a fraction of the conducted projects has been reported in the current literature. Due to this general lack of case reporting, there are not enough practical insights on safety and systemic issues such as the interaction with other mobility forms (Islam et al., 2023; Stilgoe and O'Donovan, 2023). For instance, our review identified nine papers that explicitly refer to Germany as an empirical focal point, including five different cities or regions. In contrast, the Association of German Transport Companies alone lists 63 projects with autonomous shuttles (VDV, 2024). This observation of low case reporting towards a scientific audience can have different reasons: some projects are still ongoing, and no publications have been realized yet, the findings seem redundant or not relevant, the publications appear in the form of technical reports rather than journal papers or the consortia have strict political guidelines regarding the sharing of knowledge. This links to the criticism that knowledge creation produced in the trials primarily serves industry interests and strives for even more testing rather than critically examining how this emerging technology contributes to public life (Stilgoe and O'Donovan, 2023). While we neither want to reject nor endorse this fundamental criticism in this article, we can state that a problem exists in the communication and cross-case learning between these projects. Not only does this create a bias regarding the involved actors and discourses, but at the same time, it hinders knowledge creation beyond the scope of each project.

In the following, we discuss the results of the literature review along alongside the six core characteristics of the socio-technical experiments to emphasize the identified strengths and weaknesses of the existing approaches.

4.1. Focus on a radical innovation

The core characteristic to focus on a radical innovation implies that besides the technological complexity, it requires changes in several dimensions to trigger the potential of transformative change within the mobility system. Based on what could be found in the reported literature in relation to this issue and its potential to support socio-technical change, we identify two shortcomings: First, a strong focus on social acceptance (alone), which, second, leads to a limited contextualization of the experiment, as can be exemplified for the issue of sustainability.

Several studies tend to limit their methodological approach and user engagement solely to the question of social acceptance of this

Table 1
Research string used for SCOPUS.

Research string
ALL (sustainab*) AND (ALL ("real-world lab*") OR ALL ("living lab") OR ALL ("pilot project") OR ALL ("socio-technical experiment") OR ALL ("urban experiment") OR ALL ("incubator") OR ALL ("transition experiment")) AND (TITLE-ABS-KEY ("autonomous") OR TITLE-ABS-KEY ("automated") OR TITLE-ABS-KEY ("cooperative") OR TITLE-ABS-KEY ("connected") OR TITLE-ABS-KEY ("self-driving")) AND (TITLE-ABS-KEY ("vehicle") OR TITLE-ABS-KEY ("driving") OR TITLE-ABS-KEY ("mobility") OR TITLE-ABS-KEY ("transport") OR TITLE-ABS-KEY ("cars"))

Table 2
Inclusion and exclusion criteria of the literature review.

E/I	Criteria	Criteria Explanation
Exclusion	Language	A paper is not in English in its full text.
	Non-related “Mobility and autonomous driving”	Mobility and, more specifically, autonomous driving are not the analytical focal point of the paper.
	Non-related “socio-technical experiment”	A paper reviews the topic on a conceptual level without any linkage to practical and / or empirical examples.
Inclusion	Closely related	A paper has an explicit focus on real-world laboratories, living labs, or pilot projects in the context of autonomous driving.
	Partially related	A paper addresses or discusses empirical aspects of real-world scenarios for autonomous driving, e.g. through a review.

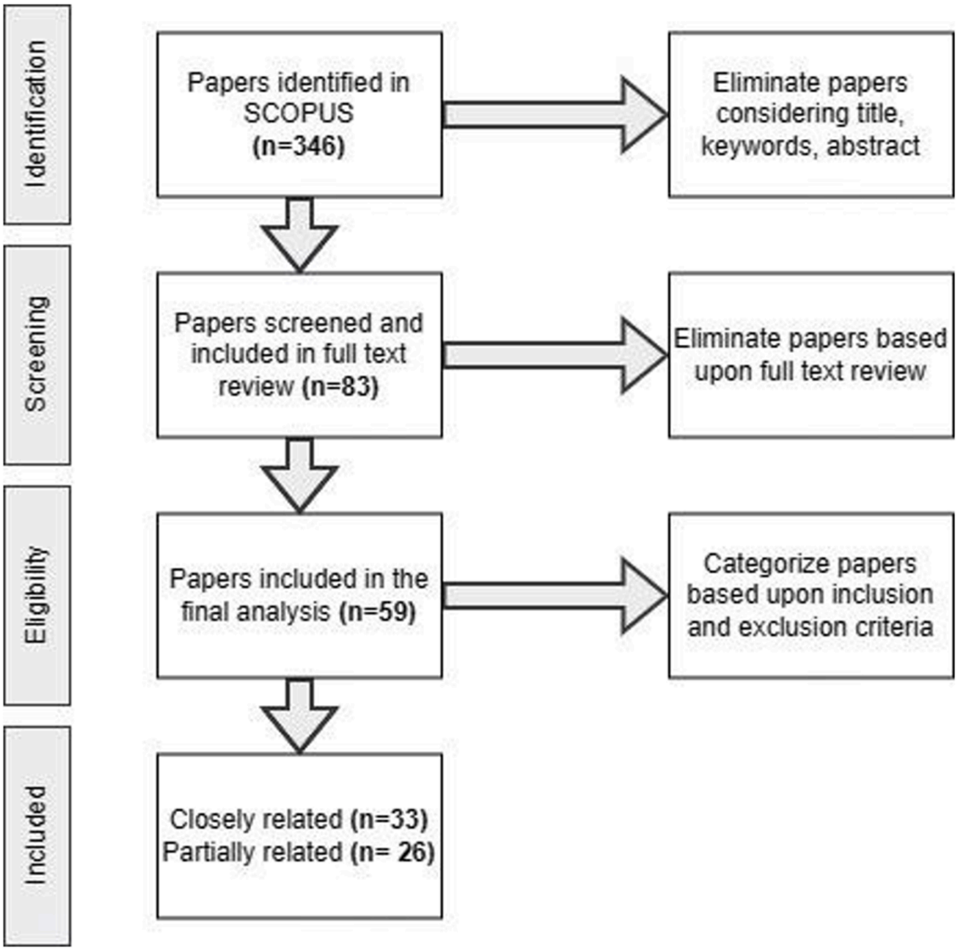

Fig. 1. Selection process of the literature review (data from: March 22nd, 2024).

emerging form of mobility. This bias affects both pre- and post-experiment surveys, with non-users often expressing high levels of skepticism, while real-world experience with the technology is more likely to result in positive surprises and increased support for the novelty (Amaral et al., 2023). While these approaches provide insights into people’s preferences and how they may change when confronted with emerging technologies, they lack complexity and neglect place-specific and psychological parameters. A more differentiated debate requires a stronger contextualization of the concept of acceptance, which should also link more clearly to the connection between the promises and expectations of the technology (Fleischer et al., 2022). While existing studies with self-driving vehicles predominantly focus on trust and acceptance as human factors, they also need to strengthen the focus on interaction with other road users in real-life traffic (Bjørnskau et al., 2023) and implications for potential job losses (Bhoopalam et al., 2023).

Building on this aspect of a limited contextualization, many projects typically commence with a focus on the technology or the vehicle itself rather than considering the broader system in which the experiment is embedded. This bias becomes evident when examining the normative dimension of experiments, such as different dimensions of sustainability. While there is a broad consensus on the potential benefits of AVs on urban transportation, such as the reduction of energy consumption or accessibility, studies on experiments rarely highlight these transition-related questions. Rather, the added value of AVs regarding sustainability is mentioned in a subordinate manner, for instance, as a component of a sustainable mobility of the future, but without contextualizing this aspect further. AVs in this debate are primarily seen as an accelerator and complementary element of carbon-free mobility, such as electric vehicles. However, this understanding stands in contrast with a stronger focus on the added value that automation itself can offer in terms of sustainable mobility. Some authors call for big-picture thinking and a shift of perspectives on governance issues, that also take potential rebound effects and the global scale into account. For instance, AVs show their environmental impact more in production and the global value chains rather than in the actual operation (Hopkins and Schwanen, 2018). While low levels of automation enable a potential reduction of energy consumption, high levels of automation may nullify these benefits or even increase traffic delay greatly due to the additional empty rides (Tajaddini and Vu, 2023; Wadud et al., 2016). These circumstances point to the question: How can local experiments engage in a more comprehensive manner with these multi-scalar issues regarding sustainability or provide us with potential solutions for these ambiguities? One starting point here would be to not center the sustainability understanding around a single parameter alone (such as the reduction of GHG emissions), but to clarify the actual indicators that can be observed or measured in the context of an experiment (Nemoto et al., 2021).

4.2. Carried out in a real-world setting

Socio-technical experiments aim to observe changes in a real-world environment outside of R&D infrastructures to enable and evaluate the use of the emerging technology in a societal environment. Based on the analysis of our paper sample, we make two central observations that point towards yet unused potentials regarding the real-world setting of experiments: First, socio-technical experiments are often carried out seemingly independent of the concrete place and (local) context. Second, the linkages of simulations and digital tools to support real-world experimentation are not fully explored yet. As a consequence, insights concerning e.g. the place-specificity and scalability of the technology are limited.

Place-specificity becomes a decisive factor when thinking about evaluating and replicating experiments for autonomous driving in a real-world setting (Ryghaug et al., 2022). For instance, cities with an already high share of sustainable transport modes might be less eager to integrate AVs as they do not offer additional benefits. However, in car-dominated cities, the public administration might have greater incentives to experiment with different mobility solutions, such as shared AVs (Cremer et al., 2021). Moreover, there is a strong bias towards urban settings that designate routes within the inner-city or urban areas that resemble different traffic scenarios. Besides the inner-city routes, other cases entail the use of AVs in transit malls (Namgung et al., 2023), port logistics (Lee et al., 2023), or campus mobility (Patel et al., 2023). In contrast, there is a strong lack of mobility scenarios beyond the urban areas, such as the connection of urban and peripheral or rural regions. This entails to be aware of micro-scale differences such as local narratives, cultural implications, or socio-demographic factors of specific districts and neighborhoods (Kyvelou et al., 2021; Nahmias-Biran et al., 2021).

Concerning this ambition of the scalability of AVs, some authors criticize that innovators intentionally dislocate AVs from particular places (Stilgoe and O'Donovan, 2023). Servou et al. (2022) argue that urban experimentation is often disconnected from public value principles and lacks integration with the everyday realities of cities. This disconnect leads to several challenges, including a project-centric logic and an expectation of finding a one-size-fits-all solution (Servou et al., 2022). Emphasizing the contextual nature of urban experimentation can lead to more effective and sustainable solutions that meet the diverse needs and realities of urban environments. While this observation appears obvious, many studies do not acknowledge the differences between different places and stakeholder groups sufficiently (Acheampong et al., 2023). As the often assumed "placelessness" of AV technology is difficult to realize, there is a growing need to intensely focus on the particularities of place-specific factors. Ryghaug et al. (2022) draw on an experiment for AVs in the Norwegian Arctic and emphasize how technologies are shaped by the location of the experiment and how this can contribute to changing visions and questioning the transferability of the innovation. In addition, substantial work and sizable infrastructure investments are required, which are unlikely on a global scale. Hence, some authors highlight that adapting road infrastructure to enable AVs should be avoided, instead, there is a need to prioritize fitting into the existing traffic environment and ecosystem (Anund et al., 2022). Social scalability and justice concerns are also place-specific issues and are not necessarily tied to population density or a specific traffic parameter alone (Ryghaug et al., 2022). These issues pose fundamental questions for the conceptual understanding of the transition, as they address the very foundation of the socio-technical configuration and to what extent autonomous driving can fit into or transform an existing regime.

Furthermore, the importance of simulations for traffic modeling and digital tools to support decision-making processes is growing in the design of experiments. This concerns two methodological perspectives: on the one hand, the simulation of traffic scenarios and their feasibility in the real world; on the other hand, the use of digital tools in the implementation of the experiments themselves (e.g., use of virtual realities). The transition from simulations and test tracks to the real world poses a major challenge due to the exponential increase in the number of scenarios, thereby complicating driving models (Bellone et al., 2021). While simulations can potentially serve as a tool to support experiments or reduce the number of possible scenarios, it's essential to note that they may never provide a perfect reflection of real-world conditions. For instance, Namgung et al. (2023) observe differences in the preferences between participants in real-world experiments and those who only gained video-based experiences. Nevertheless, digital tools may also enhance experimentation and reduce shortcomings in the regulatory environment (such as the speed limit for real-world trials). The actual added value of these approaches in concrete application scenarios to increase participation is not sufficiently reflected in our sample, which is probably due to the high technical effort and the hardware and software required. In addition, there is a lack of knowledge among stakeholders about what data is necessary or available. Data collection may be key for a sufficient performance evaluation of AVs (Giannopoulos, 2021), yet the questions remain: How do we collect this data, and what data do we actually need to adequately evaluate the role of AVs in the mobility system of the future? And how can data or virtual tools meaningfully contribute to the design of participative settings?

4.3. Involving a wide range of actors

Involving a wide-range of actors becomes crucial to address all those integrated in the socio-technical environment. While we observed a wide range of different methods regarding participatory approaches, only few research approaches involve several actors over a longer period time or provide the (infra-) structures to do so, pointing to unused potentials in terms of broad and meaningful participation. Experiments and their accompanying participatory research thus often remain temporary endeavors and struggle to visualize long-term scenarios for this new mobility form.

Table 3 provides an overview of the participatory approaches of the experiments reported in the literature. It should be noted that the table does not claim to be exhaustive and that not every empirical finding mentioned can be achieved in only one way. Rather, it provides a descriptive categorization of existing approaches. While at first glance there appears to be a diversity of methodological approaches, certain shortcomings become apparent. The majority of empirical studies focuses on a single methodology, mainly the use of surveys or questionnaires. They usually focus on users and/or pedestrians and aim to reflect preferences, perceptions, and experiences. However, this method often follows a rather one-directional approach, as it either reflects the opinions of people who have never used AVs before or directly after using an AV. The same can be stated for workshops and focus groups, which often center around a specific target group, but run the risk of only informing participants prior to the experimentation and not reflecting on their experiences afterwards. The most methodologically striking aspect of the literature review is the lack of mixed methods and continuous approaches that aim to follow a project over time. Furthermore, living labs or real-world labs, which would also allow for a continuous and integrated exchange with a broad range of actors over time, represent only a small fraction, and if so, their function is limited to being used as a method rather than as a comprehensive (transdisciplinary) research setting.

4.4. Integrated in a protective space

Socio-technical experiments are integrated into protective spaces outside of market selection, with the aim of fostering innovation and supporting learning processes about future mobility scenarios. Based on the analysis of this characteristic within our sample, we find that political incentives and global competition play a pivotal role in shaping the integration of AVs and hence the design of the experiments themselves. Hence, experiments are directly dependent on the regulatory and legal frameworks of their national context and we can rarely observe exceptions from these overlaying guidelines, such as the dependency of safety drivers on-board.

As most experimental settings are driven by governance, they are primarily linked to national guidelines or urban agendas that share a certain vision of the purpose that AVs may fulfill. Hopkins & Schwanen (2018) illustrate this example in the formation of experiments for AVs in the UK. While there is a comprehensive approach and the creation of new partnerships, they observe a lack of inclusivity, democracy, diversity, and openness. This is particularly linked to the global competition between countries in market creation for AVs, which heavily impacts the structures and visions of R&D and manufacturing. A critical aspect in this regard is

Table 3
Overview of the methodological approaches in the existing literature.

	Project Method	Primary empirical target	Examples
Survey	Online questionnaire	Passenger prevalence	(Fonzone et al., 2024)
		Preferences, Experiences, Perception	(Goldbach et al., 2022)
		Safety feeling and acceptance indicators	(Amaral et al., 2023)
	Field survey	Travel patterns and behavior	(Guo et al., 2022)
		Socio-demographic statistics	(Ariza-Álvarez et al., 2023)
		Interaction with other road users	(Bjørnskau et al., 2023)
Interviews	Expert interviews	Intentions of policymakers, governance	(Servou et al., 2022)
		Assessment of several pilot projects	(McAslan et al., 2021)
		Power relations and discourses	(Haugland and Skjølsvold, 2020)
Focus groups	Workshops	Policy recommendations	(Fagerholt et al., 2023)
		Scenario building	(Acheampong et al., 2023)
Mixed method	Qualitative (survey, interview, workshop)	Design accessible and affordable use cases	(Patel et al., 2023)
		Testing different operational approaches	(Schuß et al., 2022)
	Simulation, survey	Compare virtual with real-world scenarios	(Namgung et al., 2023)
	Living lab	Awareness building campaign	(Zajc et al., 2020)
		Design for efficient stakeholder involvement	(Tagliazucchi et al., 2023)
	Real-world lab	Transdisciplinary project	(Marsden et al., 2018)
Other	Scenario planning	Cost benefit analysis	(Lee et al., 2023)
		Place-specific conditions, e.g. weather	(Ryghaug et al., 2022)
	(Video) Observation	Behavioral changes, violation of traffic rules	(De Ceunynck et al., 2022)
	Document analysis	Policy and regulatory context	(Aoyama and Alvarez Leon, 2021)
	SWOT	Transfer of insights, e.g. to the Global South	(Choosakun et al., 2021)
	Operational focus	Safety, speed guidance, algorithms	(Choi et al., 2023)
		Road infrastructure adaptation across locations	(Anund et al., 2022)
		Driver support	(Lukasik and Khijniak, 2022)

identifying the risk-taker in AV integration. There is a contrast between the liability of the industry (common in the US) and the liability of policymakers (more prominent in many European countries). Understanding who bears the risk of a transition can influence the pace and nature of AV experimentation and scaling-up. However, this focus on national visions and guidelines also means that the specific local context and mobility needs are only given secondary consideration and are not at the center of the analysis. However, this would be necessary in terms of a successful upscaling of technology, as it will only play a leading role in the socio-technical system if it addresses this and the specific needs in a meaningful way.

4.5. Improvements of the innovation in multiple dimensions

Socio-technical experiments aim to create learning processes and improvements in multiple dimensions rather than focusing on single elements of the innovation. This entails knowledge generation among several actors and across different directionalities to enable a scale-up of innovative ideas in the specific local context. Within the context of this review, this puts the role of public actors in the governance of AVs into the center. In our sample, we could find that while generally city administration could take up a variety of roles, they are often limited to accompanying the process from outside the actual project consortia rather than being an active designer – with a considerable impact concerning the implications that experiments can have for the governance of AVs.

A critical blind spot remains in how expectations about the use of AVs play out in actual experiments, and how experiments can potentially reveal new pathways for the overlaying development. There is a need for a broader exchange of lessons learned from shuttle demonstrations to replicate them at other locations and, thus, to identify generalizable knowledge besides differences in brands and operators (Anund et al., 2022). This entails questions regarding the cost efficiency of AVs in the comparison of different business models (Lee et al., 2023), and to what extent AVs are rather a new platform for preexisting transport demand (Patel et al., 2023).

City administrations may fulfill several complementary roles in the experiments, such as regulator, promoter, mediator, or data catalyst (Aoyama and Alvarez Leon, 2021). However, this perspective and its significance remain underdeveloped, and experiments allow only scarce conclusions regarding this matter. Even though AVs may offer significant opportunities for the cities' jurisdiction to improve the current transportation systems - such as increasing accessibility and equity, or promoting sustainable transportation solutions - there is little evidence to show that cities are moving towards a proactive planning approach rather than a reactive one in terms of developing a vision for automated transportation. Thus, AVs as a "smart city solution" mirror numerous critiques of smart cities in general as promises for a cure-all for urban problems (McAslan et al., 2021). This entails critical areas including data management and privacy, cybersecurity, and implementing viable business models and ownership arrangements for AVs (Acheampong et al., 2023). In contrast, some findings indicate that AVs - as integrated elements into public transport - might provoke regime shifts from the conventional car to intermodal and individualized transport. For this, it is vital that AVs are combined with other niche innovations such as shared, electric, and on-demand mobility in intelligent transportation systems (Nemoto et al., 2021). The overarching question of future scenarios for AVs is therefore mirrored not only in the actor constellation, but also raises questions concerning the visions and intentions that shape the implementation of the experiments.

4.6. Stimulating changes in the socio-technical context

Ultimately, socio-technical experiments aim at stimulating changes in their socio-technical environment. Besides the regulatory barriers for a broad embedding of AVs, we find that a missing long-term vision for the role of AVs in a specific mobility system is the main gap for limited advances so far.

Only a limited number of the examined experiments approaches AVs from a standpoint that seeks to identify gaps in the current mobility system and depict AVs as possible solutions to address these shortcomings. This leads to a general lack of long-term visions and ideas about how AVs could actually fulfill a meaningful role in the mobility system (McAslan et al., 2021). Incentives towards AVs do not necessarily come with a higher acceptance of new business models (such as ride pooling, shared mobility); rather, studies indicate that existing patterns of privatized individual transport might as well prevail and consolidate existing regime structures, just as a focus on individual and privatized cars. Companies conducting the experiments also strongly guide expectations towards specific self-driving futures, thus rendering these futures more probable than others (Haugland and Skjølsvold, 2020). Hence, it becomes a necessity for public actors to engage more proactively with the topic besides just being the "platform" for experimentation.

A key objective is to identify experimental settings with a particular emphasis on providing accessible and affordable transportation to disadvantaged and underserved populations. This involves directing efforts towards areas characterized by high poverty rates or households without private vehicles, such as low-income individuals and students (Patel et al., 2023). While such experiments are certainly more difficult to realize depending on the regulatory environment of each city or country, the sole ambition of conducting research that goes beyond the established way of pilot projects with AVs is necessary to gain a bigger picture of this transition. A certain diversity and co-existence of different attempts in experimental settings remain important to add to public value and questions regarding sustainability (Servou et al., 2022).

The overall picture: A summary of the literature findings

The existing body of research on experiments related to autonomous vehicles (AVs) reveals a two-fold gap. First, there are only weak connections to the broader literature on transition processes, which limits our understanding of the involved dynamics. Second, current experiments primarily serve as isolated trials and are largely detached from overarching questions regarding the mobility system. While there are certainly many insights that we can draw from the literature regarding the emerging technology itself and its development, insights on sustainability issues as well as those that thoroughly reflect upon the place-specificity remain rare. Consequently, these experiments provide narrow insights into how AVs could practically enhance future mobility systems. Additionally, there is a lack of understanding regarding the potential business models or changes in mobility demand that might arise from the emergence of autonomous mobility. Another critical limitation concerns the scope of meaningful participation. While a variety of standalone methods are employed to engage stakeholders, these methods rarely extend beyond the immediate timeframe of the experiments. As a result, they fail to provide empirically grounded arguments about how AVs might integrate into and function within their socio-technical environments. Moreover, there is little differentiation in the vision for AVs as part of future mobility systems. Current discourses rarely distinguish whether AVs are conceptualized as a cornerstone for new mobility solutions (such as on-demand services) or merely as a replacement for existing modes of individual or public transportation. This lack of clarity further complicates efforts to develop a coherent vision for the role of AVs. Current settings of socio-technical experiments primarily lack clear contextualization regarding what is being tested and how these tests contribute to a broader systemic understanding of future mobility. Particularly in the context of sustainability, there is little emphasis on linking experimental findings to the larger goals of creating sustainable and integrated mobility systems.

5. Conclusion: discussing three key implications for meaningful socio-technical experimentation on autonomous mobility

The purpose of this systematic literature review was to shed light on the current state of research on socio-technical experiments for autonomous driving. Our primary research goals were to gain insights into the current state of socio-technical experimentation in terms of (1) how experimental settings are currently framed in the existing literature and what can (and cannot) be learned from them; and (2) what the research avenues that could support researchers in designing meaningful experimental settings that provide insights for both research and practice are.

Against this backdrop, we want to briefly discuss and address key themes that we draw from the results and aim to outline future research avenues to strengthen the design and meaningfulness of socio-technical experiments towards the transition of autonomous vehicles in the future.

5.1. Deepening: establish long-term research infrastructures

Long-term research infrastructures need to be established to continuously address stakeholder goals and regulatory changes, moving beyond "isolated" experiments that rarely extend beyond their initial project period and scope. This includes strengthening the place-based characteristics of the experiment and developing a shared vision among relevant stakeholders to create a mutual understanding of the real contribution that autonomous mobility can make to their specific context. Hence, more comprehensive approaches (such as living labs or real-world labs) may inform a meaningful design of the research process that supports a continuous involvement of relevant stakeholders and knowledge domains, making use of iteration and reflection and a reintegration of results into both science and practice. This insight can be tied to the potential barrier of projectification, which describes the phenomenon whereby project-based forms of organizing have become ubiquitous and shape the expectations about experimentation (Torrens and Von Wirth, 2021). This is linked to the central question of whether experiments can foster radical changes in the mobility system by accelerating new business models such as shared mobility, or whether they consolidate the car-centric mobility paradigm. So far, the empirical evidence points to the latter. Designing and governing long-term research infrastructures for AVs may inform a deeper understanding of current research avenues regarding the place-specificity and scalability of the transitions (Baatz et al., 2024; Ryghaug et al., 2023). A recent action plan by the European Commission emphasizes this gap of providing a favorable environment for the testing of autonomous vehicles, aiming at rapidly establishing large-scale cross-border testbeds by 2026 (European Commission, 2025). To address this matter, future research should focus on questions such as: How must long-term research infrastructures be organized to enable continuous advancement of the future vision of autonomous driving? To what extent can new funding policies overcome potential mechanisms of projectification in research projects? How can unequal power relations among the involved actors be addressed more transparently?

5.2. Broadening: strengthen participation in the sense of a co-design

Socio-technical experiments in the context of AVs, as shown in our analysis, frequently lack a comprehensive co-design process, with participation limited to a single sample or specific user group, and disconnected from place-specific parameters (Ryghaug et al., 2022; Servou et al., 2022; Stilgoe and O'Donovan, 2023). Socio-demographic and sustainability considerations are essential for promoting inclusivity and equitable access to mobility solutions. Only when the understanding of autonomous mobility and the associated implications for the mobility system become a public discourse in which local potential users can participate will we be able to identify realistic and pragmatic scenarios and make them comparable. This then includes a possible replication of these findings at similar locations. Socio-technical experiments must therefore be thought of much more in terms of the existing mobility system. Moreover, experiments fail to demonstrate potential benefits to society which does not currently enable the exploration of societal mobility futures (Marres, 2024). Relevant questions for further research include the following: How can we achieve meaningful participation and co-design in socio-technical experiments? How does this influence the fundamental design and formal implementation of these experiments? And how do we align the technological endeavor with a more meaningful perspective on sustainability issues, such as ecological externalities as well as socio-demographic characteristics?

5.3. Scaling-up: focus on place-specificity and integrating policymakers

The integration of autonomous driving into place-specific environments necessitates a strategic alignment with policymakers. Current experiments rather focus on their own regulatory framework to provide a protective space for experimenting, but rarely explore their broader implications for governance. Policymakers must be more closely involved in practical work and implementation, but also be part of the discourse on the future vision of this mobility solution, as they provide crucial knowledge concerning the local mobility demand. Too often, policymakers in socio-technical experiments tend to take on the role of enablers or associated partners during the funding process, but do not actively participate in the design process. This hinders meaningful iterations and a possible expansion of the experimental settings, which might be the main cause for the apparent redundancy of socio-technical experiments. Emphasizing the co-evolution between these regulatory scales will potentially drive transformative changes in mobility governance and challenge the perspective and roles of those who have the potential to change existing regime structures. In sum, it is not specified how and to what extent experimentation contributes to (de)institutionalization and how these processes play out across space (Fuenfschilling et al., 2019). This calls for a stronger empirical and practical consideration of research avenues such as: How can meaningful experiments lead to institutional change across different (legal) scales? How can experiments be structured to foster a reciprocal and efficient actor constellation, with policymakers playing a more proactive role? To what extent is the scaling-up of autonomous driving tied to associated niche innovations and planning paradigms, such as shared mobility or the general reduction of individualized car transport within cities?

6. Concluding remarks

Analyzing experimental approaches on AVs through the lens of socio-technical experimentation opens up a perspective on yet unused potentials that would allow for experiments to contribute to sustainable transformative change and extend beyond the niche level. For that to happen, our implications for deepening, broadening and scaling-up discussed above deliver relevant entry points. It must be noted that they must be approached in an integrated manner, as they play into each other: While a scaling-up calls for an integration of policymakers and a stronger consideration of place-specificity, the latter calls for more comprehensive co-design approaches to experimentation, which in turn depend on functioning long-term research infrastructures to support such endeavors.

This literature review also has its limitations. While it is limited to the SCOPUS database, the more important gap may be the lack of technical reports and other types of project documentation that do not appear in academic databases. A critical evaluation on the level of single experiments would therefore need to include a wider range of documents in the analysis, such as media analysis, as well as qualitative research such as expert interviews. In contrast, the purpose of this review was to identify and discuss research gaps rather than to evaluate or idealize a socio-technical experiment. Furthermore, it is essential to recognize that socio-technical experiments are never neutral undertakings; they actively shape the landscape for other actors, including potential users, stakeholders, and co-creators of the transition. Therefore, case studies on socio-technical experiments must carefully consider the discourses, normative dimensions, and intentions of the involved actors. Nevertheless, our study highlights important findings that researchers, policymakers, and practitioners need to consider when attempting to design more meaningful experiments that enrich the understanding and role of AVs in the mobility system of the future and ultimately have the potential to contribute to a sustainable transition.

CRediT authorship contribution statement

Tim Fraske: Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Annika Weiser:** Writing – review & editing, Validation, Project administration, Methodology, Formal analysis, Conceptualization. **Maximilian Schrapel:** Writing – review & editing, Validation, Methodology, Conceptualization. **Jens Schippl:** Writing – review & editing, Validation, Formal analysis. **Daniel J. Lang:** Writing – review & editing, Methodology, Conceptualization. **Alexey Vinel:** Writing – review & editing, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

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