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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. We conclude with central findings that emerged as future research avenues for the topic, such as the need to overcome projectification in the design process of the experiments, a more nuanced perspective on sustainability issues and place-related factors, and implications for local governance.

**Keywords:** sustainability transitions, mobility, autonomous vehicles, socio-technical system

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# 1. Introduction

Autonomous vehicles (AVs) are set to play a vital role in the mobility system of the future as both a technologically and politically desirable solution. However, the question of how AVs can contribute to sustainable development remains open for debate. 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 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 & 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 & 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 & 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, however, if or to what extent these experimental settings build up on or refer to each other to contribute to a continuous further development, and whether or how they are oriented towards a goal beyond (technological) feasibility of the concrete technology that is being tested – and how that influences the experimental setting as such as well as its embedding in the larger (project) context. 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). In an ideal scenario, they aim to contribute to a transition through the *broadening*, *scaling-up*, and *deepening* of the innovation (Van den Bosch & 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, is only addressed in a narrow way. 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. Therefore, we are interested in how the reported outcomes address spatial and systemic questions that link to the research agenda of sustainability transitions (Köhler et al., 2019). This entails: (1) the methodological scope and participatory approaches of the experiments, emphasizing the question to what extent experiments can foster public engagement and induce the design of long-term policies (Voß et al., 2009; Wittmayer & Schäpke, 2014); (2) implications for sustainability and the normative directionalities and orientation of the transition, as expectations and ambitions can differ greatly across different actors and

spatial contexts (Raven et al., 2019) ; (3) place and scalability, linking to a better understanding of the geography of the transition, which includes the scaling of policies, visions, market creation, and place-related factors for the technology itself (Hansen & Coenen, 2015; Truffer et al., 2015); and (4) to what extent the experiments address and reflect on governance issues, as novelties such as AVs require regulatory change and interventions that create uncertainties towards this transformative change (Grin et al., 2010).

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 contribute to a meaningful transition of autonomous vehicles into a (sustainable) mobility system of the future?*

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, and what can (and cannot) be learned from them?*
- b) *To what extent do socio-technical experiments on autonomous driving currently contribute to an enriched understanding of actors and participation, sustainability, place and scalability, and governance issues?*
- c) *What are future research avenues that can support the design of meaningful experiments in the context of AVs for both research and practice?*

The article is structured as follows: The next section contextualizes socio-technical experiments in the transition literature as well as terminologies associated with experimental settings for autonomous driving. Chapter three provides an overview of the methodology. In the following, we present the results and summarize the state of the art, with a focus on four research areas. Subsequently, we discuss our findings and point out aspects towards designing meaningful experimental settings as well as future research avenues.

## 2. Contextualizing real-world experiments on autonomous driving

### 2.1 Socio-technical experiments in the transition literature

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 small-scale interventions for emerging technologies in a real-world setting. Transition studies have evoked a variety of conceptual frameworks and heuristics, such as the multi-level perspective or strategic niche management. 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 & 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 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). 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). 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 & 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 & 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).” 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.

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). Nevertheless, this raises the question of ideal 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 & van Bueren, 2017). While some of these terms often are used in a fuzzy way, the understanding of experimentation can differ greatly. 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 and transcend their initial place-specific context (Turnheim et al., 2018). This calls for a stronger emphasis on spatial characteristics of sustainability transitions, such as urban policies, informal localized institutions, or the industrial specialization of a region (Hansen & Coenen, 2015; Truffer et al., 2015).

## 2.2 Contextualizing socio-technical experiments on autonomous driving

In a simplified understanding, practical experimentation with AVs derives from two different perspectives. Firstly, 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. Secondly, 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. 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 & O'donovan, 2023). In addition, transportation-focused perspectives on experimenting with AVs run the risk of not considering the responsibility of the local government's role and the operational needs of a city (or region) to reduce its environmental pressures (Cremer et al., 2021). In this regard, scholars suggest the design of more participatory and inclusive approaches, such as living labs, as a suitable way to engage citizens and create an environment for co-creation and knowledge sharing (Dos Santos et al., 2022). Designing and governing experimental settings for AVs addresses current research avenues regarding the place-specificity and scalability of mobility transitions, such as questions surrounding social justice, co-learning and knowledge production, and the role of spatial narratives, infrastructures, and regulations (Baatz et al., 2024; Ryghaug et al., 2023).

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.

The most frequently used terms in the literature on experiments regarding autonomous driving are the terms “pilot project” and “trials”. While trials also frequently refer to pure technological testing without any real-world focus, pilot projects encompass various attempts of designing, testing, and operating AVs in a real-world environment. It is most commonly used for technology-focused pilots, in which mere vehicle operation issues (e.g., driving behavior, routing) are examined and systemic or socio-technical issues are only marginally considered. Although these types of experiments are criticized due to their seemingly redundant execution and strongly political-industrially driven motives, they are of vital importance and essential for a holistic perspective on autonomous driving. Firstly, technological upgrading tackles important obstacles in the development of the innovation, such as an increase in the speed limit or communication with other road users, which allows the exploration of systemic questions



in the first place. Secondly, although acceptance surveys might often encounter methodological limitations, they do allow us to draw conclusions about the behavior and perception of users. For instance, a number of acceptance studies show that the practical experience with AVs can quickly raise trust among users despite a previous skepticism (especially in terms of the safety feeling on board). Findings about such a sudden change of opinion must also be considered when engaging in more participatory co-design formats, such as (urban) living labs (Bulkeley et al., 2016; von Wirth et al., 2018). Unlike pilots or trials, the living lab describes an environment, system, or methodology where experimentation itself is a part of, therefore emphasizing the need for a broader (research) infrastructure to integrate experiments. While there are many conceptual understandings and nuances of framing a living lab, certain cornerstones and characteristics can be highlighted as central (ENoLL, 2019; Hossain et al., 2019; Steen & van Bueren, 2017): (1) the *aims* of the living lab are centered around a focus on innovation and formal learning for replication, with a strong emphasis on (urban) sustainability. (2) the *activities* that include all phases of the development process, a co-creation approach and continuous iteration such as feedback, evaluation, and improvement; (3) the *participants* who consist of a broad range of actors such as public and private actors as well as users who are all involved in the decision-making process; (4) the *context* of a real-life environment where the living lab activities take place, with clearly defined spatial boundaries and can (potentially) also include virtual settings. In the German research community on participatory experimental settings, “real-world labs” have established themselves as an additional term with a similar meaning as the living lab approach. While we found no usage of the term outside of its national boundaries in our sample, it derives from an even stronger perspective on normative questions regarding sustainability issues and calls for a rigorous transdisciplinary and transformative (long-term) research setting that contains experiments at its methodological core (Bergmann et al., 2021; Wanner et al., 2018).

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-designing 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. While this contextualization only presents a fraction of the used terms in applied research overall, it is important to note that in practice they often overlap or are not defined in their specific context at all. 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.

### 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 & 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. Firstly, 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. Secondly, 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.

Table 1: Research string used for SCOPUS.

<b>Research string</b>
ALL (sustainab*) <b>AND</b> (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")) <b>AND</b> (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")) <b>AND</b> (TITLE-ABS-KEY ("vehicle") OR TITLE-ABS-KEY ("driving") OR TITLE-ABS-KEY ("mobility") OR TITLE-ABS-KEY ("transport") OR TITLE-ABS-KEY ("cars"))

### **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.

Table 2: Inclusion and exclusion criteria of the literature review.

<b>E/I</b>	<b>Criteria</b>	<b>Criteria Explanation</b>
<b>Exclusion</b>	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.
<b>Inclusion</b>	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.

Figure 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.

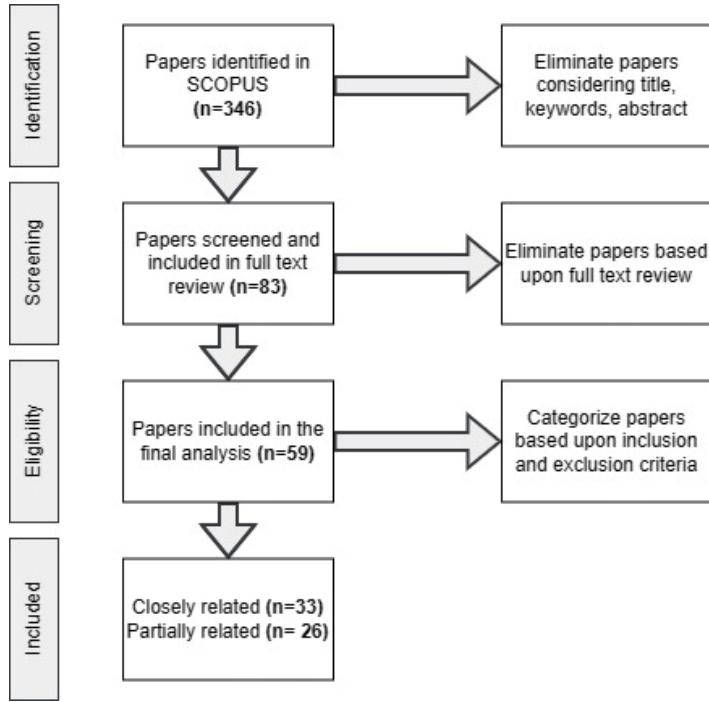


Figure 1: Selection process of the literature review (data from: March 22<sup>nd</sup>, 2024).

#### ***Step 4: Analysis and synthesis***

The last step of the actual review categorizes the papers based upon the type of content, such as their methodological approach, their implications for the mobility system, and unique insights from the respective studies, especially regarding the scope and success of the project. Moreover, we drew special attention to the intention and sustainability aspects of the presented projects and how they are being communicated and evaluated in the literature.

#### ***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 & Lewis, 2022; Stilgoe & 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 & 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 & 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 four overarching themes: (1) Methods, participation, and actors; (2) Sustainability and normative discourses; (3) Place and scalability; and (4) governance. For each topic, we emphasize striking results and describe the most important starting points for further research in this area.

#### 4.1 Methods, participation, and actors

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 focus 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 beforehand 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 represent only a small fraction of the methods.

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

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

Several studies tend to limit their methodological approach and user engagement solely to the question of **social acceptance** of this 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). Furthermore, various groups, including bus, taxi, and truck drivers, are narrowly represented in our sample. For instance, the impact of AVs on employment is underrepresented and plays a minor role in the experiments. Potential job losses can also play a crucial role in the acceptance of the technology, as autonomous driving or assistance systems also diminish the “nicest part of the job – driving” (Bhoopalam et al., 2023: 9). 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).

The overall feeling of **safety** improves significantly after individuals have experienced using AVs, comparable to the general acceptance of this mode of mobility (Amaral et al., 2023; Camps-Aragó et

al., 2022; Namgung et al., 2023). As researchers, we need to consider how to address this change in perception and whether it becomes problematic when attempting to derive generalized knowledge from experiments. Acceptance of AVs changes significantly depending on the level of supervision on board. In order to avoid overwhelming users, there is a gradual shift towards less reliance on safety drivers (Goldbach et al., 2022). Some studies indicate that people are still hesitant to use AVs without safety drivers on board (Fonzone et al., 2024). This raises the question, from which perspective do we as researchers aim to evaluate safety? This includes considering the perceptions of other passengers or bus drivers sharing the same vehicle. For instance, the absence of a driver on board may increase hesitation, especially in specific contexts such as late-night rides or in the presence of intoxicated passengers. These time- and case-dependent examples for the use of AVs have so far not been sufficiently addressed in experiments.

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 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 participation?

## 4.2 Sustainability and normative discourses

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 in the actual operation (Hopkins & 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 & 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). Furthermore, this issue is closely tied to the place-specificity of AVs (see chapter 4.3), as many studies run short of a sufficient contextualization of their environment and how the benefits of AVs can vary depending on their infrastructural and societal context (Cremer et al., 2021). 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. A notable example is a case study from Arlington, Texas, highlighted by Patel et al., (2023). The study focuses on understanding the efficiency of shared autonomous vehicles prior to their integration into existing transportation networks. A key objective is to identify **socio-demographic factors**, 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, with a particular focus on low-income individuals and students. 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).

### 4.3 Place and scalability

The practical experimentation with AVs exhibits a significant bias towards the US, Europe, and East Asia countries such as Japan and South Korea, while there is a notable absence of research conducted in the Global South. 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). Besides the global discourses and expectations towards autonomous mobility, researchers and policymakers need 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). Thus, **place-specificity** becomes a decisive factor when thinking about evaluating and replicating experiments for autonomous driving (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).

One criticism raised concerning the **scalability** of AVs is that innovators intentionally dislocate AVs from particular places and therefore neglect the place-specific factors concerning AVs (Stilgoe & 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). There exists a global regulatory divide, such as between the United States and Europe. Recognizing these distinctions is critical to addressing the unique challenges and opportunities presented by different regulatory environments and geographic contexts and to understanding the actual connection between the vision, promises, and experiences of the users, as well as the governance and market creation of the technology. 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 is 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. However, these connections have hardly been explored so far - also because the experimental contexts do not allow it on an analytical level.

## 4.4 Governance towards a transition

The main gap regarding the governance of experiments that we can draw from the literature is a general lack of **long-term vision** and ideas about how AVs could actually fulfill a meaningful role on 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 & Skjølsvold, 2020). Hence, it becomes a necessity for public actors to engage more proactively with the topic besides just being the “platform” for experimentation.

**Political incentives** and **global competition** play a pivotal role in shaping the integration of AVs. 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 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 Germany). Understanding who bears the risk of a transition can influence the pace and nature of AV experimentation and scaling-up.

Another research gap refers to the aspect of how experiments can foster **knowledge creation** by sharing insights with actors outside of the experimental scope. This entails knowledge generation among several actors and across different directionalities, such as between city representatives and national policymakers or between public actors and industry. 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 generalized 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).

The above-mentioned aspects point to the key question concerning the implications that experiments can have for the governance of AVs: the **role of public actors** in the transition process. City administrations may fulfill several complementary roles in this regard, such as regulator, promoter, mediator, or data catalyst (Aoyama & 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 AV 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.

## 5. Discussion

Our examination of the literature reveals two key deficiencies when comprehending the role of socio-technical experiments: a general low case reporting and weak conceptual linkages to the transition literature. The literature lacks comprehensive and comparative case reporting both in quantity and in depth, hindering thorough analysis and trend identification necessary for understanding the influence of the transition effectively. While there are certainly many insights that we can draw from the literature regarding the emerging technology itself and its development, insights on the future mobility system, sustainability issues, and spatial implications remain rare. Furthermore, weak conceptual linkages impede analytical insights into socio-technical experiments for autonomous driving. Future research should prioritize robust case reporting and comparative case studies to enable cross-case learning and deepen the analytical understanding of the transition. This addresses research questions such as: To what extent can experiments challenge preexisting assumptions and intentions among the involved actors? And how do we develop a more comprehensive monitoring and evaluation of the experiments, that allows conclusions beyond their initial setting?

Against this backdrop, we want to further discuss and address key themes that we draw from the results, and which aim to outline future research avenues as well as design principles for practitioners who engage in autonomous driving experiments. Based on our research, we see three major fields of action to address meaningful experimentation in the context of AVs: (1) Deepening the experiments to enable transformative change; (2) Broadening the experiments by co-design and cross-case analysis; (3) Scaling-up experiments by inducing changes in governance.

## 5.1 Deepening the experiments to enable transformative change

Firstly, transforming mobility systems requires a deepening of experiments to address their current limitations to enable transformative change. Current gaps in the design of experiments, such as a lack of spatial implications, hinder progress towards developing a bigger picture of this emerging technology in specific contexts. 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. 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 & Von Wirth, 2021). Moreover, it remains unclear to what extent an unsuccessful experiment can still contribute to a meaningful outcome, as there is often a clear framing and ambition (either industrial or normative) attached to a project, that predefines certain conclusions. Insights on the importance of experiments as "trial and error" settings are scarce. This raises the question, whether or to what extent experiments can break free from previous expectations (and is this even a desired goal)? From a transition perspective, this calls for stronger research regarding the overarching discourses and intentions of AVs and how they are intertwined with local governance and the design of the experiments. 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. How must long-term research infrastructures be organized to enable continuous advancement of the future vision of autonomous driving? How can unequal power relations among the involved actors be addressed more transparently?

## 5.2 Broadening the experiments by co-design and cross-case analysis

Secondly, the broadening of the socio-technical experiments requires greater co-design as well as cross-case analysis beyond single experiments. Experiments in the context of AV, 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 & O'donovan, 2023). This entails the need for a more nuanced perspective on sustainability in the participatory process. Ensuring sustainability in autonomous driving goes beyond single factors and models. Socio-demographic considerations are essential for promoting inclusivity and equitable access to mobility solutions. Discussions regarding the integration of experiments often overlook factors such as potential replication, which may be crucial to broaden the understanding of trust and novelty impacts. However, these considerations are vital for scaling successful interventions and ensuring their relevance across different contexts. Relevant questions for further research include

the following: To what extent can the replication of experiments offer us more comprehensive insights about the place-specific characteristics that affect the transition to autonomous driving? 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 experiments by inducing changes in governance

Thirdly, the potential of socio-technical experiments of scaling-up is closely tied to the question of changes in governance. The integration of autonomous driving into urban landscapes necessitates a strategic alignment with governance frameworks. Current experiments rather focus on their own regulatory framework to provide a protective space for experimenting, but rarely explore their broader implications for governance. Bridging the regulatory learning within the experiments to implications for the overlaying legal frameworks and ethical questions remains unclear in practice, 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, primarily the city administrations. 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? 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. Conclusion

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; (2) to what extent experimental settings enrich the systemic understanding and critical reflection of the role of AVs in a future mobility system; and (3) what are the research avenues that could support researchers in designing meaningful experimental settings that provide insights for both research and practice.

First and foremost, the current number of case reports of socio-technical experiments for autonomous driving in the academic literature is insufficient in comparison to the total number of projects. Moreover, the links to the conceptual discussion in the transition literature are rather thin and call for a more theoretically grounded, empirically comprehensive, and comparative case analysis. This is exemplified by the question of how the regulatory frameworks of the individual experiments can actually lead to changes in governance and legal frameworks at the national scale in the long run. Building on this aspect,

it also leads to the question of how intentions and visions at the local and regional scale can actually enforce a scaling-up of experimental settings beyond their place-specific context. A further deepening and broadening of the experiments are hindered by a lack of involvement of the participants into the research process, such as continuous co-design, insufficient consideration of sustainability issues, and the overcoming of redundancy effects, such as projectification. 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 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 of a single experiment would therefore need to include a wider range of documents in the analysis as well as qualitative research such as expert interviews. The purpose of this review is therefore to identify and discuss research gaps rather than to evaluate or idealize a socio-technical experiment. Nevertheless, it 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.

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## References

- Acheampong, R. A., Legacy, C., Kingston, R., & Stone, J. (2023). Imagining urban mobility futures in the era of autonomous vehicles—Insights from participatory visioning and multi-criteria appraisal in the UK and Australia. *Transport Policy*, 136, 193–208. Scopus. <https://doi.org/10.1016/j.tranpol.2023.03.020>
- Amaral, J., Viegas, J., Lemos, B., Almeida, P., Rosmaninho, R., Perna, G., Rito, P., & Sargento, S. (2023). *Autonomous Shuttle Integrated in a Communication and Sensing City Infrastructure*. 96–104. Scopus. <https://doi.org/10.1109/MOST57249.2023.00018>
- Anund, A., Ludovic, R., Caroleo, B., Hardestam, H., Dahlman, A., Skogsmo, I., Nicaise, M., & Arnone, M. (2022). Lessons learned from setting up a demonstration site with autonomous

- shuttle operation – based on experience from three cities in Europe. *Journal of Urban Mobility*, 2. Scopus. <https://doi.org/10.1016/j.urbmob.2022.100021>
- Aoyama, Y., & Alvarez Leon, L. F. (2021). Urban governance and autonomous vehicles. *Cities*, 119. Scopus. <https://doi.org/10.1016/j.cities.2021.103410>
- Ariza-Álvarez, A., López-Lambas, M. E., & Soria-Lara, J. A. (2023). Analysing the acceptance of autonomous buses in real-life traffic environments: Pilot project with tourists in Malaga, Spain. *Transportation Planning and Technology*, 46(1), 71–92. Scopus. <https://doi.org/10.1080/03081060.2022.2159407>
- Baatz, A., Ehnert, F., & Reiß, K. (2024). Sites for sustainability transitions: The interplay of urban experiments and socio-spatial configurations in transforming habits. *Urban Transformations*, 6(1), 3. <https://doi.org/10.1186/s42854-023-00060-0>
- Bellone, M., Ismailogullari, A., Müür, J., Nissin, O., Sell, R., & Soe, R.-M. (2021). Autonomous Driving in the Real-World: The Weather Challenge in the Sohjoa Baltic Project. *EAI/Springer Innovations in Communication and Computing*, 229–255. Scopus. [https://doi.org/10.1007/978-3-030-66042-0\\_9](https://doi.org/10.1007/978-3-030-66042-0_9)
- Bergmann, M., Schäpke, N., Marg, O., Stelzer, F., Lang, D. J., Bossert, M., Gantert, M., Häußler, E., Marquardt, E., Piontek, F. M., Potthast, T., Rhodius, R., Rudolph, M., Ruddat, M., Seebacher, A., & Sußmann, N. (2021). Transdisciplinary sustainability research in real-world labs: Success factors and methods for change. *Sustainability Science*, 16(2), 541–564. <https://doi.org/10.1007/s11625-020-00886-8>
- Bhoopalam, A. K., van den Berg, R., Agatz, N., & Chorus, C. G. (2023). The long road to automated trucking: Insights from driver focus groups. *Transportation Research Part C: Emerging Technologies*, 156. Scopus. <https://doi.org/10.1016/j.trc.2023.104351>
- Bjørnskau, T., Aasvik, O., De Ceunynck, T., Fyhri, A., Hagenzieker, M., Johnsson, C., & Laureshyn, A. (2023). “Game over” for autonomous shuttles in mixed traffic? Results from field surveys among pedestrians and cyclists on how they interact with autonomous shuttles in real-life traffic in Norway. *Transportation Research Interdisciplinary Perspectives*, 18. Scopus. <https://doi.org/10.1016/j.trip.2023.100781>

- Brown, H. S., Vergragt, P., Green, K., & Berchicci, L. (2003). Learning for Sustainability Transition through Bounded Socio-technical Experiments in Personal Mobility. *Technology Analysis & Strategic Management*, 15(3), 291–315. <https://doi.org/10.1080/09537320310001601496>
- Bulkeley, H., Coenen, L., Frantzeskaki, N., Hartmann, C., Kronsell, A., Mai, L., Marvin, S., McCormick, K., van Steenberghe, F., & Voytenko Palgan, Y. (2016). Urban living labs: Governing urban sustainability transitions. *Current Opinion in Environmental Sustainability*, 22, 13–17. <https://doi.org/10.1016/j.cosust.2017.02.003>
- Camps-Aragó, P., Temmerman, L., Vanobberghen, W., & Delaere, S. (2022). Encouraging the sustainable adoption of autonomous vehicles for public transport in Belgium: Citizen acceptance, business models, and policy aspects. *Sustainability*, 14(2), 921.
- Ceschin, F. (2014). *How the Design of Socio-technical Experiments Can Enable Radical Changes for Sustainability*. 8(3).
- Choi, S., Lee, D., Kim, S., & Tak, S. (2023). Framework for Connected and Automated Bus Rapid Transit with Sectionalized Speed Guidance based on deep reinforcement learning: Field test in Sejong City. *Transportation Research Part C: Emerging Technologies*, 148. Scopus. <https://doi.org/10.1016/j.trc.2023.104049>
- Choosakun, A., Chaiittipornwong, Y., & Yeom, C. (2021). Development of the cooperative intelligent transport system in Thailand: A prospective approach. *Infrastructures*, 6(3). Scopus. <https://doi.org/10.3390/infrastructures6030036>
- Cremer, A., Müller, K., & Finkbeiner, M. (2021). A Systemic View of Future Mobility Scenario Impacts on and Their Implications for City Organizational LCA: The Case of Autonomous Driving in Vienna. *Sustainability*, 14(1), 158. <https://doi.org/10.3390/su14010158>
- De Ceunynck, T., Pelssers, B., Bjørnskau, T., Aasvik, O., Fyhri, A., Laureshyn, A., Johnsson, C., Hagenzieker, M., & Martensen, H. (2022). Interact or counteract? Behavioural observation of interactions between vulnerable road users and automated shuttles in Oslo, Norway. *Traffic Safety Research*, 2. Scopus. <https://doi.org/10.55329/fbhr3456>
- Denyer, D., & Tranfield, D. (2009). Producing a systematic review. In *The Sage handbook of organizational research methods* (S. 671–689). Sage Publications Ltd.



- Dos Santos, F. L. M., Duboz, A., Grosso, M., Raposo, M. A., Krause, J., Mourtzouchou, A., Balahur, A., & Ciuffo, B. (2022). An acceptance divergence? Media, citizens and policy perspectives on autonomous cars in the European Union. *Transportation Research Part A: Policy and Practice*, 158, 224–238. <https://doi.org/10.1016/j.tra.2022.02.013>
- Dowling, R., & McGuirk, P. (2022). Autonomous vehicle experiments and the city. *Urban Geography*, 43(3), 409–426. Scopus. <https://doi.org/10.1080/02723638.2020.1866392>
- ENoLL. (2019, August 29). *Short History of Living Labs- Research and Policy Context by European Network of Living Labs—Issuu*. <https://issuu.com/enoll/docs/423662117-short-history-of-living-labs-research-an>
- Fagerholt, R. A., Seter, H., & Arnesen, P. (2023). How can authorities be enablers in the deployment of CCAM? An experienced-based expert study from Norway. *Transportation Research Interdisciplinary Perspectives*, 21. Scopus. <https://doi.org/10.1016/j.trip.2023.100874>
- Falzon, M., & Lewis, O. (2022). *Shared Automated Mobility: The Legal and Governance Considerations*. 445–454. Scopus. <https://doi.org/10.5220/0011114200003191>
- Fleischer, T., Puhe, M., Schippl, J., & Yamasaki, Y. (2022). Public Expectations Regarding the Longer-term Implications of and Regulatory Changes for Autonomous Driving: A Contribution to the Debate on its Social Acceptance. *2022 IEEE Intelligent Vehicles Symposium (IV)*, 1268–1273. <https://doi.org/10.1109/IV51971.2022.9827210>
- Fonzone, A., Fountas, G., & Downey, L. (2024). Automated bus services – To whom are they appealing in their early stages? *Travel Behaviour and Society*, 34. Scopus. <https://doi.org/10.1016/j.tbs.2023.100647>
- Fuenfschilling, L., Frantzeskaki, N., & Coenen, L. (2019). Urban experimentation & sustainability transitions. *European Planning Studies*, 27(2), 219–228. <https://doi.org/10.1080/09654313.2018.1532977>
- Garus, A., Alonso, B., Alonso Raposo, M., Ciuffo, B., & Dell’olio, L. (2022). Impact of New Mobility Solutions on Travel Behaviour and Its Incorporation into Travel Demand Models. *Journal of Advanced Transportation*, 2022. Scopus. <https://doi.org/10.1155/2022/7293909>

- Geels, F. W. (2002). Technological transitions as evolutionary reconfiguration processes: A multi-level perspective and a case-study. *Research policy*, 31(8–9), 1257–1274.
- Geels, F. W., & Schot, J. (2007). Typology of sociotechnical transition pathways. *Research policy*, 36(3), 399–417.
- Giannopoulos, A. T. (2021). Assessing the impact of case mobility: Issues and recommendations from Greece. *Journal of Engineering and Applied Science*, 68(1). Scopus.  
<https://doi.org/10.1186/s44147-021-00003-1>
- Goldbach, C., Sickmann, J., Pitz, T., & Zimasa, T. (2022). Towards autonomous public transportation: Attitudes and intentions of the local population. *Transportation Research Interdisciplinary Perspectives*, 13. Scopus. <https://doi.org/10.1016/j.trip.2021.100504>
- Grin, J., Rotmans, J., & Schot, J. (2010). *Transitions to Sustainable Development: New Directions in the Study of Long Term Transformative Change*. Routledge.  
<https://doi.org/10.4324/9780203856598>
- Guo, J., Susilo, Y., Antoniou, C., & Pernestål, A. (2022). Word of mouth and behavioural intentions of the automated bus service. *Cities*, 126. Scopus. <https://doi.org/10.1016/j.cities.2022.103668>
- Hansen, T., & Coenen, L. (2015). The geography of sustainability transitions: Review, synthesis and reflections on an emergent research field. *Environmental innovation and societal transitions*, 17, 92–109.
- Haugland, B. T., & Skjølsvold, T. M. (2020). Promise of the obsolete: Expectations for and experiments with self-driving vehicles in Norway. *Sustainability: Science, Practice, and Policy*, 16(1), 37–47. Scopus. <https://doi.org/10.1080/15487733.2020.1765677>
- Hopkins, D., & Schwanen, T. (2018). Automated Mobility Transitions: Governing Processes in the UK. *Sustainability*, 10(4), 956. <https://doi.org/10.3390/su10040956>
- Hossain, M., Leminen, S., & Westerlund, M. (2019). A systematic review of living lab literature. *Journal of Cleaner Production*, 213, 976–988. <https://doi.org/10.1016/j.jclepro.2018.12.257>
- Islam, M. M., Newaz, A. A. R., Song, L., Lartey, B., Lin, S.-C., Fan, W., Hajbabaie, A., Khan, M. A., Partovi, A., Phuapaiboon, T., Homaifar, A., & Karimoddini, A. (2023). Connected

- autonomous vehicles: State of practice. *Applied Stochastic Models in Business and Industry*, 39(5), 684–700. Scopus. <https://doi.org/10.1002/asmb.2772>
- Köhler, J., Geels, F. W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A., Alkemade, F., Avelino, F., Bergek, A., Boons, F., Fünfschilling, L., Hess, D., Holtz, G., Hyysalo, S., Jenkins, K., Kivimaa, P., Martiskainen, M., McMeekin, A., Mühlemeier, M. S., ... Wells, P. (2019). An agenda for sustainability transitions research: State of the art and future directions. *Environmental Innovation and Societal Transitions*, 31, 1–32. <https://doi.org/10.1016/j.eist.2019.01.004>
- Kyvelou, S. S., Bobolos, N., & Tsaligopoulos, A. (2021). Exploring the Effects of “Smart City” in the Inner-City Fabric of the Mediterranean Metropolis: Towards a Bio-Cultural Sonic Diversity? *Heritage*, 4(2), 690–709. <https://doi.org/10.3390/heritage4020039>
- Lee, S., Cho, K., Park, H., & Cho, D. (2023). Cost-Effectiveness of Introducing Autonomous Trucks: From the Perspective of the Total Cost of Operation in Logistics. *Applied Sciences (Switzerland)*, 13(18). Scopus. <https://doi.org/10.3390/app131810467>
- Lukasik, D., & Khijniak, D. (2022). San Diego Bus Rapid Transit Using Connected and Autonomous Vehicle Technology. *Sustainable Civil Infrastructures*, 691–703. Scopus. [https://doi.org/10.1007/978-3-030-79801-7\\_50](https://doi.org/10.1007/978-3-030-79801-7_50)
- Marsden, N., Bernecker, T., Zollner, R., Submann, N., & Kapser, S. (2018). *BUGA:Log—A Real-World Laboratory Approach to Designing an Automated Transport System for Goods in Urban Areas*. 2018 IEEE International Conference on Engineering, Technology and Innovation, ICE/ITMC 2018 - Proceedings. Scopus. <https://doi.org/10.1109/ICE.2018.8436361>
- Martin, G. (2019). *Sustainability prospects for autonomous vehicles: Environmental, social, and urban*. Routledge. <https://www.taylorfrancis.com/books/mono/10.4324/9781351109956/sustainability-prospects-autonomous-vehicles-george-martin>

- McAslan, D., Najar Arevalo, F., King, D. A., & Miller, T. R. (2021). Pilot project purgatory? Assessing automated vehicle pilot projects in U.S. cities. *Humanities and Social Sciences Communications*, 8(1). Scopus. <https://doi.org/10.1057/s41599-021-01006-2>
- Nahmias-Biran, B., Oke, J. B., Kumar, N., Lima Azevedo, C., & Ben-Akiva, M. (2021). Evaluating the impacts of shared automated mobility on-demand services: An activity-based accessibility approach. *Transportation*, 48(4), 1613–1638. <https://doi.org/10.1007/s11116-020-10106-y>
- Namgung, H., Chikaraishi, M., & Fujiwara, A. (2023). Influence of real and video-based experiences on stated acceptance of connected public transportation and autonomous vehicles in a transit mall: A hybrid choice modeling approach. *Transportation Research Part A: Policy and Practice*, 173. Scopus. <https://doi.org/10.1016/j.tra.2023.103695>
- Nemoto, E. H., Issaoui, R., Korbee, D., Jaroudi, I., & Fournier, G. (2021). How to measure the impacts of shared automated electric vehicles on urban mobility. *Transportation Research Part D: Transport and Environment*, 93, 102766. <https://doi.org/10.1016/j.trd.2021.102766>
- Patel, R. K., Etmnani-Ghasrodashti, R., Kermanshachi, S., Rosenberger, J. M., & Foss, A. (2023). Exploring willingness to use shared autonomous vehicles. *International Journal of Transportation Science and Technology*, 12(3), 765–778. Scopus. <https://doi.org/10.1016/j.ijtst.2022.06.008>
- Rahman, Md. M., & Thill, J.-C. (2023). What Drives People's Willingness to Adopt Autonomous Vehicles? A Review of Internal and External Factors. *Sustainability*, 15(15), 11541. <https://doi.org/10.3390/su151511541>
- Raven, R., Sengers, F., Spaeth, P., Xie, L., Cheshmehzangi, A., & De Jong, M. (2019). Urban experimentation and institutional arrangements. *European Planning Studies*, 27(2), 258–281. <https://doi.org/10.1080/09654313.2017.1393047>
- Ryghaug, M., Haugland, B. T., Søråa, R. A., & Skjølsvold, T. M. (2022). Testing Emergent Technologies in the Arctic: How Attention to Place Contributes to Visions of Autonomous Vehicles. *Science and Technology Studies*, 35(4), 4–21. Scopus. <https://doi.org/10.23987/sts.101778>

- Ryghaug, M., Subotički, I., Smeds, E., Von Wirth, T., Scherrer, A., Foulds, C., Robison, R., Bertolini, L., Beyazit İnce, E., Brand, R., Cohen-Blankshtain, G., Dijk, M., Pedersen, M. F., Gössling, S., Guzik, R., Kivimaa, P., Klöckner, C., Nikolova, H. L., Lis, A., ... Wentland, A. (2023). A Social Sciences and Humanities research agenda for transport and mobility in Europe: Key themes and 100 research questions. *Transport Reviews*, 43(4), 755–779.  
<https://doi.org/10.1080/01441647.2023.2167887>
- Schippl, J., Truffer, B., & Fleischer, T. (2022). Potential impacts of institutional dynamics on the development of automated vehicles: Towards sustainable mobility? *Transportation Research Interdisciplinary Perspectives*, 14, 100587.
- Schuß, M., Rollwagen, A., & Riener, A. (2022). Understanding Operator Influence in Automated Urban Shuttle Buses and Recommendations for Future Development. *Multimodal Technologies and Interaction*, 6(12). Scopus. <https://doi.org/10.3390/mti6120109>
- Sengers, F., Wieczorek, A. J., & Raven, R. (2019). Experimenting for sustainability transitions: A systematic literature review. *Technological Forecasting and Social Change*, 145, 153–164.  
<https://doi.org/10.1016/j.techfore.2016.08.031>
- Servou, E., Mögele, M., & Torrens, J. (2022). Experimenting with automated driving for technology or for the city? A matter of governance cultures. *Frontiers in Sustainable Cities*, 4. Scopus.  
<https://doi.org/10.3389/frsc.2022.956853>
- Smith, A., Voß, J.-P., & Grin, J. (2010). Innovation studies and sustainability transitions: The allure of the multi-level perspective and its challenges. *Research policy*, 39(4), 435–448.
- Steen, K., & van Bueren, E. (2017). The Defining Characteristics of Urban Living Labs. *Technology Innovation Management Review*, 7(7), 21–33.
- Stilgoe, J., & O'donovan, C., Sr. (2023). TRIALS AND TRIBULATIONS: Who learns what from urban experiments with self-driving vehicles? In *Artificial Intelligence and the City: Urbanistic Perspectives on Ai* (S. 38–52). Scopus. <https://doi.org/10.4324/9781003365877-4>
- Strömberg, H., Ramos, É. M. S., Karlsson, M., Johansson, M., Ekman, F., Bligård, L.-O., & Bergstad, C. J. (2021). A future without drivers? Comparing users', urban planners' and developers'

- assumptions, hopes, and concerns about autonomous vehicles. *European Transport Research Review*, 13(1), 44. <https://doi.org/10.1186/s12544-021-00503-4>
- Tagliazucchi, G., Della Santa, S., & Gherardini, F. (2023). Design of a living lab for autonomous driving: An investigation under the lens of the triple helix model. *Journal of Technology Transfer*. Scopus. <https://doi.org/10.1007/s10961-023-10009-x>
- Tajaddini, A., & Vu, H. L. (2023). Modeling the long-term regional impacts of autonomous vehicles: A case study of Victoria, Australia. *Journal of Intelligent Transportation Systems*, 27(4), 459–470. <https://doi.org/10.1080/15472450.2022.2053528>
- Torrens, J., & Von Wirth, T. (2021). Experimentation or projectification of urban change? A critical appraisal and three steps forward. *Urban Transformations*, 3(1), 8. <https://doi.org/10.1186/s42854-021-00025-1>
- Tranfield, D., Denyer, D., & Smart, P. (2003). Towards a Methodology for Developing Evidence-Informed Management Knowledge by Means of Systematic Review. *British Journal of Management*, 14(3), 207–222. <https://doi.org/10.1111/1467-8551.00375>
- Truffer, B., Murphy, J. T., & Raven, R. (2015). The geography of sustainability transitions: Contours of an emerging theme. In *Environmental Innovation and Societal Transitions* (Bd. 17, S. 63–72). Elsevier. <https://www.sciencedirect.com/science/article/pii/S2210422415300058>
- Turnheim, B., Kivimaa, P., & Berkhout, F. (2018). *Innovating climate governance: Moving beyond experiments*. Cambridge University Press. [https://books.google.de/books?hl=de&lr=&id=EdtPDwAAQBAJ&oi=fnd&pg=PP1&dq=turnheim+et+al+2018&ots=L6Phkuc\\_4y&sig=aybDuMDiFHNKg5Sp\\_VlyBLDvyOE](https://books.google.de/books?hl=de&lr=&id=EdtPDwAAQBAJ&oi=fnd&pg=PP1&dq=turnheim+et+al+2018&ots=L6Phkuc_4y&sig=aybDuMDiFHNKg5Sp_VlyBLDvyOE)
- Van den Bosch, S. (2010). *Transition experiments: Exploring societal changes towards sustainability*. <https://repub.eur.nl/pub/20714/>
- Van den Bosch, S., & Rotmans, J. (2008). *Deepening, Broadening and Scaling up: A Framework for Steering Transition Experiments*.
- VDV. (2024). *Autonome Busse in Deutschland: Liste & Details der Projekte | VDV - Die Verkehrsunternehmen*. <https://www.vdv.de/liste-autonome-shuttle-bus-projekte.aspx>

- von Wirth, T., Fuenfschilling, L., Frantzeskaki, N., & Coenen, L. (2018). Impacts of urban living labs on sustainability transitions: Mechanisms and strategies for systemic change through experimentation. *European Planning Studies*, 27, 1–29.  
<https://doi.org/10.1080/09654313.2018.1504895>
- Voß, J.-P., Smith, A., & Grin, J. (2009). Designing long-term policy: Rethinking transition management. *Policy Sciences*, 42(4), 275–302. <https://doi.org/10.1007/s11077-009-9103-5>
- Wadud, Z., MacKenzie, D., & Leiby, P. (2016). Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles. *Transportation Research Part A: Policy and Practice*, 86, 1–18. <https://doi.org/10.1016/j.tra.2015.12.001>
- Wanner, M., Hilger, A., Westerkowski, J., Rose, M., Stelzer, F., & Schöpke, N. (2018). Towards a Cyclical Concept of Real-World Laboratories: A Transdisciplinary Research Practice for Sustainability Transitions. *disP - The Planning Review*, 54(2), 94–114.  
<https://doi.org/10.1080/02513625.2018.1487651>
- Wittmayer, J. M., & Schöpke, N. (2014). Action, research and participation: Roles of researchers in sustainability transitions. *Sustainability Science*, 9(4), 483–496.  
<https://doi.org/10.1007/s11625-014-0258-4>
- Zajc, I., Sernec, R., Lenart, G., & Pucihar, A. (2020). *Autonomous mobility and user perception: A Case of City as a Lab in Slovenia*. 1843–1847. Scopus.  
<https://doi.org/10.23919/MIPRO48935.2020.9245147>