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Navigating low-carbon transition pathways of the mobility sector: an inquiry into experts' mental models

Inéz Labucay[a,b], Bärbel Fürstenau[a] and Maria Neubauer[a]

[a]Faculty of Business and Economics, Chair of Business Education and Management Training, Technische Universität Dresden, Dresden, Germany; [b]Faculty of Law, Economics and Business, Martin-Luther-University Halle-Wittenberg, Halle (Saale), Germany

ABSTRACT
Finding viable pathways to a low-carbon transition of the mobility sector is central to the United Nations Sustainable Development Goals. Mobility-transition research could benefit from exploring experts' mental models on how to facilitate this transition. Experts serve as intermediaries, acting as brokers between more institutionalized actors such as technology adopters and incumbents. Against the backdrop of sustainability-transitions research, this article examines the mental models of sustainable mobility experts, which shape potential pathways to the mobility transition. We employ the innovative, exploratory modeling method GABEK®, which allows for a mapping of a shared mental model of experts. The results can be input into scenario-analyses methodologies such as "backcasting," which enables the alignment of long-term sustainability visions on mobility with feasible short-term solutions. Thus far, the method has not been employed in any comprehensive approach to navigating pathways to a low-carbon mobility transition.

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Low-carbon transition; sustainability transition; mobility; mental model; transition management; GABEK®

Introduction

Future pathways to a low-carbon transition center on economic sectors, particularly the mobility sector (Reichenbach and Puhe 2018). This sector is closely intertwined with the energy transition (Papachristos 2018), climate change and resource depletion (Nikitas, Thomopoulos, and Milakis 2021), land use (Sopjani et al. 2020), and economic growth (Guivarch, Lempert, and Trutnevyte 2017). In the European Union (EU), mobility is the only sector in which emission levels are on a growth trajectory (Pape 2021), which contrasts with the goal of reducing emissions by 90% to achieve climate neutrality by 2050 (European Commission 2020). For any mobility transition to be successful, long-term lifestyle transitions among consumers are required (Köhler et al. 2009). To meet the goal of climate neutrality, research is needed on both technologies and behavior of the different stakeholders and actors involved, including those who have adopted sustainable mobility modes and those who have not.

To date, research on the mobility transition has been dominated by a technocentric view (Köhler et al. 2013; Weiss and Scherer 2022). While technology plays a central role, mobility-transition analyses must also consider socio-ecological implications, particularly the roles of different actors (Sonnberger and Graf 2021; Dijk et al. 2019; Turienzo, Cabanelas, and Lampón 2022) and their routines, practices, and discourses (Geels et al. 2017). Regarding actors, research on the mobility transition has tended to focus on niche players such as mobility service and alternative fuel providers (Schippl and Arnold 2020; Hillman et al. 2008), technology adopters (Zolfagharian et al. 2021; Bell 2019), and incumbents (Mirzadeh Phirouzabadi et al. 2020). Experts such as mobility scientists, eco-mobility lab practitioners, and urban planners assume an intermediary role as brokers between, on the one hand, "highly institutionalized" automobile companies and their suppliers and, on the other hand, mobility-service providers as niche players (Hoffmann, Weyer, and Longen 2017; Murto et al. 2020). Previous work has indicated that sustainability transitions have been oversimplified to conform to a "systemic fight" between alternative systems striving for dominance while undervaluing the role of actors and their visions of desired futures, which shape actions in the immediate present (Haan and Rotmans 2018; Muehlberger et al. 2024; Ruhrort 2023). Existing literature has explored the role of transition

CONTACT Inéz Labucay inez.labucay@tu-dresden.de Faculty of Business and Economics, Chair of Business Education and Management Training, Technische Universität Dresden, Dresden, Germany

intermediaries in sustainability transitions (Kundurpi et al. 2021; Gliedt, Hoicka, and Jackson 2018; Kanda et al. 2020). Such intermediaries can catalyze transitions and highlight contested issues, such as inclusive mobility during the pandemic (Drexler et al. 2022). They also act as purposive facilitators of alternative future pathways to a mobility transition, including low-carbon transitions (Nordt et al. 2024; Geels et al. 2017; Haan and Rotmans 2018).

Since consensus on the most favorable and efficient transition pathways in mobility has yet to be reached, we argue that a broader perspective should incorporate the views of experts from both science and practice in transition analyses. Prior literature has emphasized the need to address intermediaries acting as go-betweens between different actors in transitions and having the ability to articulate visions of desirable transition pathways (Kivimaa 2014; van Lente, Boon, and Klerkx 2020). While Kivimaa (2014) concentrated on government-affiliated agencies and foundations, we focus on experts as goal-oriented actors pursuing their own objectives (Wittmayer et al. 2017). We argue that expert scientists and practitioners could help to build a more inclusive transition arena and contribute to broader regime shifts (Rotmans and Loorbach 2009; van Sluisveld et al. 2020). The mental models of experts may overlap with those of incumbents and those of niche players. Both experts and incumbents may strive to rebalance the existing regime (Geels et al. 2016). Experts may also seek to destabilize or replace the regime, like some niche players do (van Sluisveld et al. 2020; Reike, Hekkert, and Negro 2023). Given that some "future-making practices" in sustainability transitions, such as a car-centered regime, tend to dominate imagined mobility futures at the expense of others, the need arises to establish "approaches which can counteract these tendencies" (Hawxwell, Hendriks, and Späth 2024, 2; Drexler et al. 2022). As a heterogeneous group with multiple "agencies" and shifting roles (Wittmayer et al. 2017), experts are expected to envision alternative future pathways to the mobility transition, regardless of whether they will be further pursued. Taking account of different experts' mental models can accelerate transition dynamics (Ruhrort 2023; Reike, Hekkert, and Negro 2023), inform policymaking, and speed up the mobility transition (Jittrapirom, Boonsiripant, and Phamornmongkhonchai 2021).

Our research question is as follows: What are the views of experts from science and practice on alternative pathways to the mobility transition, and how are these views represented in a shared mental model of experts?

This article contributes by highlighting the utility of mental models for sustainability-transitions research. Furthermore, we present a method that allows us to uncover the views of experts on alternative future pathways to a mobility transition and examine their representation in a shared mental model. Methodologically, we make an original contribution by employing the innovative and explorative modeling method GABEK® (*GAnzheitliche BEwältigung von Komplexität* meaning "holistic coping with complexity") in the explication of mental models of mobility experts from science and practice. GABEK® has not been previously used to analyze potential future pathways to a mobility transition. Pechlaner et al. (2021) focus on global freight transport, which is a different perspective from ours, and Schmid (2020) conducted a single firm secondary data study on electromobility, while we analyze future pathways to a land-based low-carbon mobility transition more generally, based on original interview data. As opposed to screening companies' public communication (e.g., Drexler et al. 2022) or retrospective interviews (Murto et al. 2020), the mental models extracted by means of GABEK® are projected into different future scenarios, which experts deem thinkable and feasible.

The article offers insights into the mental models of sustainable mobility experts, including city planners, mobility-research scientists, and practitioners. It builds on the sustainability-transitions literature when investigating alternative futures of the socio-technical system of mobility, in particular of land-based transportation (van Bree, Verbong, and Kramer 2010). Few sustainability-transition studies to date have addressed mental models and their role in shaping pathways to a mobility transition (e.g., Harrison et al. 2022; Jittrapirom, Boonsiripant, and Phamornmongkhonchai 2021; Ho and Tan 2023; Schröder and Klinger 2024; Kallenbach 2020). Studies of other sectors have investigated the mental models of plastics-recycling experts (Schultz and Reinhardt 2023), entrepreneur-investor dyads (Maureau and Tarillon 2024), and textile producers (Reike, Hekkert, and Negro 2023).

We proceed as follows. The second section presents the theoretical background, followed by a description of the method in the third section. The results are presented in the fourth section, and we discuss the implications of our findings in the fifth section. We conclude the article by describing how our method can be fruitfully applied in scenario analyses and policymaking.

Sustainability-transition research and the role of mental models

The analytical background of our study is sustainability-transition research, in particular, the approach of transition management. Sustainability-transition research allows for the analysis of both historical and contemporary transitions (Wittmayer et al. 2017). Transition management can "counter policies and approaches that are typically focused on improvement of existing regimes," as well as "challenge these and create space for transformative change to just, sustainable futures" (Loorbach et al. 2021, 2). This affords a clarification as to the role of actors in transitions. Socio-technical systems are shaped by actors, each with their own interests, strategies, and perceptions, which, for example, wish to maintain "car-centered cities" or envision "climate resilient cities" (Kallenbach 2020; O'Neill et al. 2014). The emergence of a particular pathway (including future sustainability transitions to low-carbon mobility) has been described as a multi-actor process and the result of how different actors' narratives and interpretations frame transitions (Geels 2005; Geels 2019). Nevertheless, in research on sustainability transitions, actors' views have received less attention than particular transition pathways or whole system transitions (Schröder and Klinger 2024; Haan and Rotmans 2018). Also, views of intermediaries like expert scientists and advisers have been less in focus (Kivimaa 2014; Gliedt, Hoicka, and Jackson 2018). More recent work on intermediaries underlines the need to explore the conditions under which the "visions, demands, and expectations" of transition intermediaries shape transition policies by amplifying the views of disconnected actors (Nordt et al. 2024).

We analyze pathways to a mobility transition through the analytical lens of actors' mental models. Mental models are "'viable' assumptions about reality" that implicitly guide behavior but are rarely made explicit, although they can "help the system solve real-world problems with its environment" (Hielscher and Will 2014, 709). Mental models refer to the deep and often unexpressed cognitive structures that actors draw on in bringing their actions to bear on the sustainability transition (Geels 2012). We define mental models as individuals' internal representations that are relevant for cognitive processes such as reasoning, decision-making, or problem-solving (Gentner and Stevens 1983; Johnson-Laird 1983). Individual mental models can be compared in terms of their overlaps and differences. Cannon-Bowers and Salas (2001) address different ways in which individual mental models can relate to those of other individuals: Mental models can be (1) overlapping, (2) similar, (3) dissimilar and complementary, or (4) distributed stocks of knowledge. In the case of (3), mental models are different but compatible and complementary, whereas in (4), mental models of different actors may contradict and conflict with each other.

An aggregation of individual mental models, including overlaps as well as potential contradictions, can be conceptualized as a shared mental model. In contrast to the prevalent notion, our understanding of sharedness—for this study—is not reduced to just overlaps in different individual mental models. Likewise, sharedness does not refer to the process of sharing in the sense of knowledge exchange between persons. Rather, a shared mental model is gained by comparing and combining individual mental models based on data such as interviews or other sources that experts use to explicate their opinions, such as documentations. Thus, a face-to-face exchange between persons is not necessary to gain a shared mental model since they are reconstructed by researchers from individual mental models that have been retrieved from different sources—in our case, interview data. In prior research, shared narratives or, similarly, shared imaginaries or shared values have also been retrieved from interview data (Haan and Rogers 2019; Wolfram 2018) and, in addition, from public transition discourses (Wittmayer et al. 2017; Proka, Loorbach, and Hisschemöller 2018; Loorbach et al. 2021; Muehlberger et al. 2024), with "shared" often meaning that actors directly exchange views and opinions (Loorbach et al. 2021; Proka, Loorbach, and Hisschemöller 2018; see, however, Hoffman, 2014).

We argue that our concept of a shared mental model of experts can offer a useful analytical category to transition-management research. We acknowledge that the actor group of experts is not a monolithic entity, and the "individual is still free in choosing narratives that she accepts as credible and discard others" (Hermwille 2016, 239). We therefore assume that experts, on the one hand, have different individual mental models and, on the other, that they are not uniformly following common beliefs (Wittmayer et al. 2017).

Instead, experts' mental models may clash with incumbents' established cognitive rules, which are attuned to the dominant technology (Geels 2005; Papachristos 2018). The mental models prevalent in niches, like the niche of autonomous driving, are only partially compatible with concepts such as inclusive mobility favored by some experts (Kanger and Schot 2016). This is where "outside professional scientists or engineers may have specialist knowledge that allows them to criticize technical details of regimes and propose alternative courses of action" (Geels and Schot 2007, 406).

In summary, our concept of a shared mental model arises from the comparison and combination of individual mental models derived from interview data. Furthermore, we employ an encompassing concept of sharedness, which includes not only overlapping but also complementary and potentially contradictory mental models.

We explicitly acknowledge that experts' views are themselves contestable and that different mental models compete in shaping sustainability transitions, determining "whose reality gets to guide political and normative action" (Ballo and Vaage 2021, 140). Regardless of which views and solutions prevail, social acceptance of mobility solutions and the viability of transition pathways increase when supported by the broadest possible societal coalition.

Method

Our study aims to identify and map a shared mental model of experts to gain insights into alternative future pathways to a mobility transition. To that end, we conducted 25 interviews, each lasting 45–60 minutes, with mobility experts from a variety of institutional backgrounds, including urban planning and mobility-research scientists, practitioners from eco-mobility labs, and future and technology-assessment experts from Germany and, in one case, from Switzerland. The interviews were conducted between March 2022 and August 2022, and the experts were selected based on their expertise in sustainable mobility, such as in the context of city-planning and mobility-transition projects or as facilitators of sustainable mobility, including sharing and electromobility services.[1] The recruitment of experts was conducted based on a thorough, multi-round search in search engines and a screening of the retrieved company/university web pages. In cases where experts had published in journals, results were cross-checked with literature databases to verify the relevance of the experts for the topic of sustainable mobility transitions. Several respondents conducted city-level projects that combined integrated mobility planning with city development. Half of the experts come from scientific fields and half from applied backgrounds. Within the group of practitioners, participants come from various fields of operation, such as resources, energy, transport, infrastructure, and urban development. The group of scientists covers a range of disciplines, including human geography, logistics, urban planning, and sociology. Experts also differ in the goals they pursue. While some focus on alternative future mobility systems, such as in urban planning, others concentrate on sustainable technology solutions, and still others are involved in connecting actors and making mobility solutions accessible and affordable for society. The heterogeneity of the expert group reflects the various actor roles deemed crucial in sustainability-transition arenas (Haan and Rotmans 2018; van Lente, Boon, and Klerkx 2020). All interview sessions were conducted using the collaborative platform MIRO, video-recorded, and transcribed verbatim, except for four interviews, which could not be fully processed due to technical restrictions, leaving us with 21 processable interviews. The ratio of scientists to practitioners and non-executives to executives was 11:10, with the majority of respondents being male (16 out of 21) (see Table 1).

Table 1. Overview of experts.

No.	Expert position	Hierarchical level (EL: executive level, NEL: non-executive level)	Gender	Type of organization
1	Urban planning scientist	NEL: employee	M	Science
2	Mobility research scientist	NEL: employee	F	Science
3	Urban planning and mobility research scientist	NEL: employee	M	Science
4	Eco-mobility lab practitioner	NEL: employee	M	Practice
5	Future technology assessment expert	EL: function lead	M	Practice
6	Urban planning and mobility research scientist	NEL: employee	M	Science
7	Eco-mobility lab practitioner	EL: function lead	M	Practice
8	Eco-mobility lab practitioner/Consultant	EL: director	M	Practice
9	Urban planning and mobility research scientist	EL: function lead	F	Practice
10	Eco-mobility lab practitioner	EL: function lead	M	Practice
11	Mobility research scientist	NEL: employee	M	Science
12	Mobility research scientist	EL: director	M	Practice
13	Eco-mobility lab practitioner	EL: function lead	M	Practice
14	Urban planning and mobility research scientist	NEL: employee	M	Science
15	Eco-mobility consultant	NEL: employee	M	Practice
16	Urban planning and mobility research scientist	NEL: employee	M	Science
17	Urban planning and mobility research scientist	EL: function lead	M	Science
18	Urban planning and mobility research scientist	NEL: employee	F	Science
19	Urban planning and mobility research scientist	NEL: employee	M	Science
20	Urban planning and mobility research scientist	EL: director	F	Science
21	Mobility research scientist	EL: director	F	Practice

The interviews were loosely structured and open-ended, allowing respondents to spontaneously elaborate on system relationships in low-carbon mobility (Maureau and Tarillon 2024).

For data analysis, we employed the explorative modeling method GABEK®, which offers both a qualitative (coding and categorization) and a quantitative method of analysis (clustering and aggregating) (Schultz and Reinhardt 2022). GABEK® facilitates the translation of rich and distributed expert knowledge into a landscape of associations, value judgments, and perceived causal relationships from the viewpoint of the community under study (Zelger 2019). The analytical steps (Figure 1) are as follows:

The textual data from each interview transcription was subcategorized into text units consisting of 3–9 sentences representing a coherent train of thought. These text units were then systematically coded with 3–9 key terms. The coding process retained colloquial terms used by respondents, i.e., if a respondent used the expression "thought-terminating cliché" (*Totschlagargument* in German), it was taken as a key term without reformulation. This procedure ensured that the implied meaning was retained. Synonyms (such as ticket and coupon) were subsumed under a single term. Co-occurrences of key terms within and across all text units were displayed in key-term networks, serving as graphical representations of the interviewees' mental models (Hielscher and Will 2014). From the interview transcripts, 464 text units were obtained and further processed through multiple iterative coding cycles, resulting in a network of 732 key terms connected by 18,353 relations. Furthermore, expert evaluations of the present and future were coded, leading to the creation of value-judgment lists. Additionally, causal relationships from the respondents' perspectives were documented. Value judgments and causal relationships indicated relevant variables, which were measured using a relevance score. Finally, a shared mental model was visualized using a Gestalten tree. We provide an example in what follows.

In Figure 2, text units from different interviews are displayed in which *sharing services*, *space*, and *individual motorized transport* are identified as key terms (in bold type) (Steps 1 and 2). In this example, the key term *sharing services* is mentioned in Interview 11 and Interview 5 (excerpts are displayed as green and orange text units). The key terms *space* and *individual motorized transport* appear in text units of Interview 8 and Interview 1 (yellow and blue text units). Since these key terms appear together in the same text unit within the statements of several interviewees, they are positioned close to each other in the key-term network (Step 3). The strength of the tie between two key terms increases the more frequently they occur together (co-occur) in the text units of respondents, thus forming key-term networks. The rationale behind key-term networks is that the meaning of a term can be derived from its position in a network of related terms, which form the context of the term's everyday usage in the community under study (Zelger and Oberprantacher 2002). Positive, negative, or neutral value judgments made by interviewees on their own initiative, referring to the status quo or future

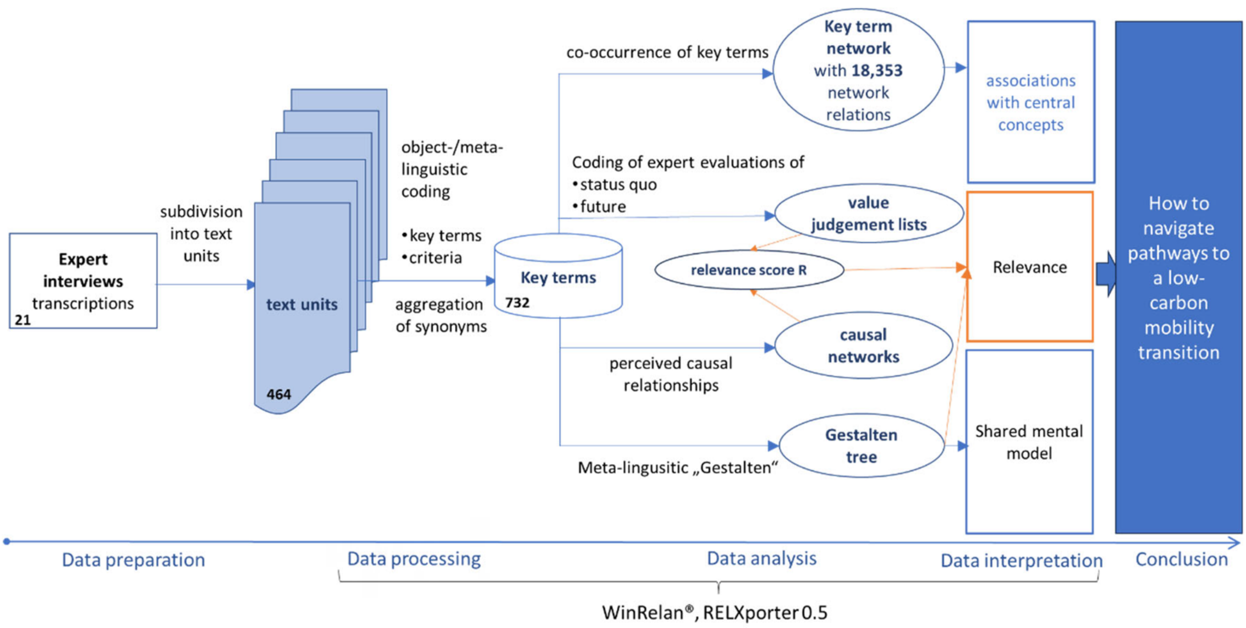


Figure 1. Analysis procedure of GABEK®.
Source: Own elaboration.
Note: Procedural steps follow the description in Zelger (2019).

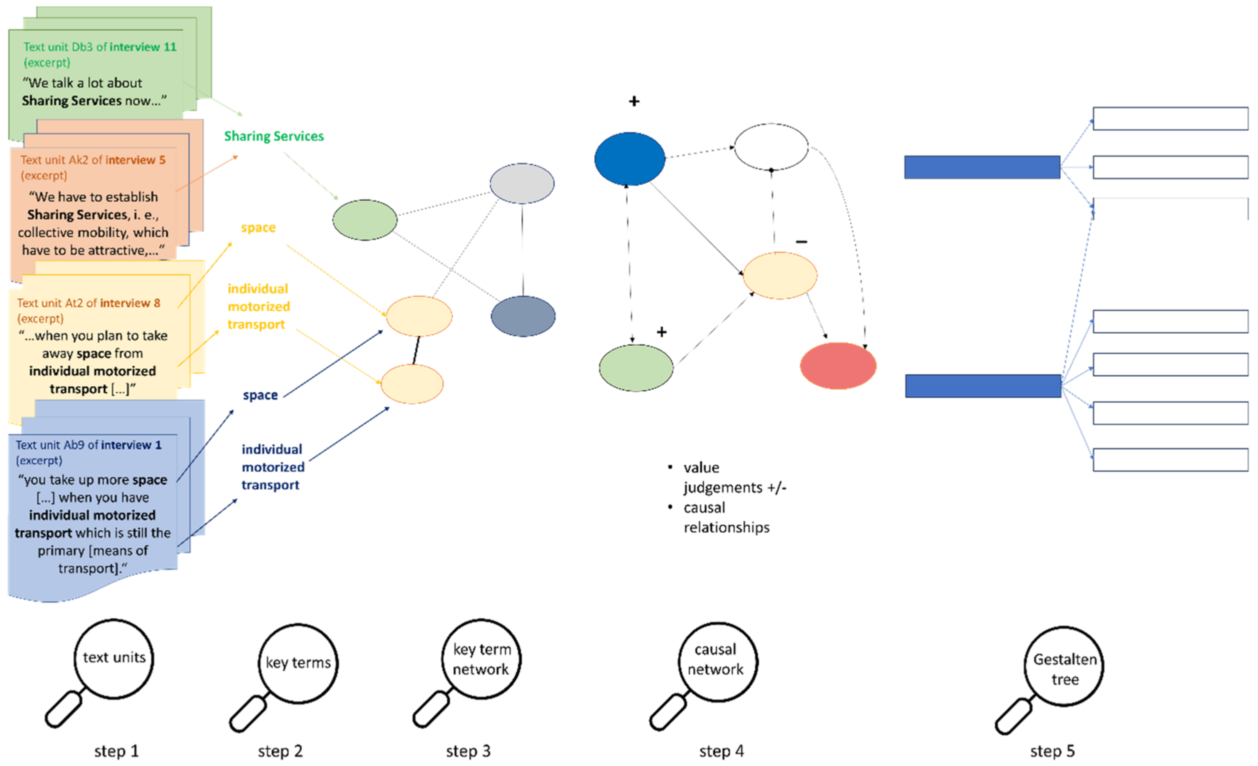


Figure 2. Example of the analysis procedure in GABEK®.
Source: Own elaboration. Magnifying glass symbol is a Microsoft 365 pictogram.

conditions, were coded into value-judgment lists. These judgments reflect perceived risks and opportunities of current or planned policy measures. Causal relationships between key terms are aggregated into causal networks (Step 4).

In Step 5, the Gestalten tree is generated by ordering the textual data hierarchically from the lowest level of linguistic Gestalten (retrieved from a cluster analysis based on interview-text units) to more aggregated Hyper-Gestalten and finally to the most aggregated Hyper-Hyper-Gestalten. The "tree top" (Hyper-Hyper Gestalten) represents the most commonly held opinions and experiences as expressed by respondents in an aggregated form (Zelger 2000).

The Gestalten tree is obtained in two steps. In the first step, a cluster analysis at the level of text units is performed (automated).[2] While the cluster analysis was supported by WinRelan®, a software for qualitative text analysis, the second step involved a multi-round aggregation of text units (conducted manually but according to specific rules). This second step is necessary for the following reason: Two types of text units can be disregarded in the cluster analysis—those that would not add any further information to the text units already included and those that are not well connected to the included text units. However, the latter—such as views held by only a few respondents—are still included in the Gestalten tree, allowing potentially contradictory mental models to be manually incorporated, as explained further below.

After the cluster analysis, the resulting Gestalten, Hyper-Gestalten, and so forth are manually checked for compliance with the semantic rules of GABEK®, such as the rule of formal variety. The rule of formal variety entails that all pairs of text units in a Gestalt, Hyper-Gestalt, and so forth must differ by at least three key terms.[3] This means that text units originally excluded from the cluster analysis—for reasons such as their bearing little relation to other topics—are manually added to comply with the rule of formal variety. These text units are often statements made by only a few interviewees.

We provide two examples: The key terms *health costs* and *positive health outcomes of eco-mobility* were mentioned only nine times (for comparison, *public transport* was mentioned 104 times). Less than one-third of respondents addressed *economic sustainability* (6 out of 21), and fewer than half discussed *social sustainability* (9 out of 21). Nevertheless, some of the text units containing these key terms were included manually to comply with the rule of formal variety. Including these less central but still important issues in the Gestalten tree helps avoid overlooking rarely mentioned or potentially contradictory mental models present in the data. In the Gestalten tree, a key term is considered more relevant if it has been frequently evaluated, is enmeshed in many causal relationships, and is positioned high in the Gestalten tree. A change in the variable represented by this key term is expected to have a stronger impact (Zelger 2019) on the system of sustainable mobility compared to more peripheral terms. As overlapping, complementary, and potentially contradictory views enter the Gestalten tree, our data can be said to cover three of the dimensions of a shared mental model defined earlier: overlapping, complementary, and distributed, potentially contradictory mental models (Zelger 2019; Cannon-Bowers and Salas 2001).

Our approach to data analysis is an inductive one (coding process, cluster analysis, and subsequent rule-based multi-round aggregation of the data) starting from the text units, to Gestalten, to Hyper-Gestalten, and to Hyper-Hyper-Gestalten. The approach has been complemented by an additional structuring of data based on central concepts in transition management, namely *Technology, Institutions,* and *Actors,* at the highest level of Hyper-Hyper-Gestalten (after they have been inductively aggregated). This last deductive step complements the overall inductive approach. Each of these three concepts represents a Hyper-Hyper-Gestalt. *Technology* refers to solutions or "artifacts" regarding the application context of technologies and their effects (Mahzouni 2019; Markard 2020; Haan and Rotmans 2018). The concept *Institutions* includes rules, regulations, practices, and public policies (Haan and Rogers 2019) while the concept *Actors* refers to stakeholders in transitions and to their business models (Andersen et al. 2023; Berggren, Magnusson, and Sushandoyo 2015; Haan and Rotmans 2018).[4] Each step of the analytical procedure is intersubjectively reproducible (Zelger 2000) and allows for a high level of accuracy in content analysis due to its stringent rule-based procedure (Schultz and Reinhardt 2022). In addition to the software WinRelan®, the tool Gephi was used for visualization (Bastian, Heymann, and Jacomy 2009).

The results of the analysis can be exploited in the following way: The concrete use of the Gestalten tree is that it can be employed to detect important topics, set transition goals, identify problems in need of a solution (Hyper-Gestalten), and connect them with proposed solutions and the context conditions to which interview statements refer (Gestalten). At the lowest level of the Gestalten tree (one level below the Gestalten), these solutions can be traced back to concrete interview statements, highlighting situations where these solutions can be applied. That way, concrete topics, such as all statements referring to the key term Mobility-as-a-Service (MaaS) platforms,[5] can be singled out and complementary, as well as contradictory mental models identified (see Appendix 3). Overall, the approach enables one to view the matter from different perspectives, regarding (1) the meaning of a term derived from its everyday usage in the community under study (key-term network), (2) the value judgments and causal relationships from the viewpoint of interviewees which highlight relevant transition variables, and (3) the aggregation of mental models in a Gestalten tree, based on a comprehensive concept of sharedness of mental models that also takes into account potentially contradictory mental models.

Results

Relevant variables for exploring alternative future pathways to the mobility transition

In this section, we present results pertaining to the most relevant variables (key terms with the highest relevance score) concerning future pathways to the mobility transition, co-occurring key terms (key-term network), and the aggregation of mental models in a shared mental model (Gestalten tree). Table 2 provides an overview of the 10 most relevant key terms. The relevance of a key term is derived (1) from the number of evaluations (green) it received by experts regarding the status quo and the future, (2) the number of causal relations (red) in which it is enmeshed as either a dependent (–'o) or independent variable (o–'), both feeding into the relevance score (yellow), and (3) from its position in the Gestalten tree (with Table 2 restricted to key terms present in Hyper-Hyper Gestalten).

The most relevant variables, understood to be key terms that have been evaluated in many interviews and are therefore positioned high in the Gestalten tree, are considered to have an important causal impact on future pathways to the mobility transition (Zelger 2019). *Public transport* holds the highest relevance score (100). This is also the variable with both the highest number of evaluations (34) and causal relationships (76). The high relevance of *public transport* might be attributed to its embeddedness in the system, i.e., changes in this variable or closely connected variables are likely to have a higher impact on system development than lower-ranked variables. Following public transport, the key terms/variables of relevance are *individual motorized transport* (relevance score 69) and *emissions* (relevance score 67); number 10 in line is *participation* (relevance score 45).

Some quotations from the interviews reveal how these key terms matter from the perspective of respondents.[6] The interplay between *public transport* and *individual motorized transport* is considered key in transitions toward sustainable mobility:

Table 2. Ten most relevant variables based on value-judgment lists, perceived causal relations, and their position in the Gestalten tree.

		Evaluation of status quo			Evaluation of future			Evaluations	Causal relations		
Key terms	Relevance score R	+	−	o	+	−	o	Sum	−'o	o−'	Sum
Public transport	100	4	2	3	22		3	34	43	33	76
Individual motorized transport	69		12	3		10	2	27	23	22	45
Emissions	67		15		1	8		24	36	12	48
Land-use designation	55		4	2	14	3	1	24	23	7	30
Sharing service	53				22			22	13	19	32
Rezoning	50				19			19	6	28	34
Short trips	48	1			17			18	19	14	33
Attractiveness_public transport	46		2		13			15	26	10	36
Green spaces	46		1		19			20	10	15	25
Sustainability_social	45	3	3		11			17	29	2	31
Participation	45				19			19	20	6	26

Source: Own display based on an analysis using WinRelan®. Ranking based on relevance score, own translation. For a sample calculation of the relevance score, see Appendix 1.

> With mobility concepts (including public transport), it will always be the case that you have to take away space from individual motorized transport and push it back accordingly, because we have higher-order goals to consider (Interview 8, male practitioner, director, sentence As8).

A reduction of *emissions* is a central goal mentioned by respondents:

> Yes, the generation of emissions, this also entails explaining to people, on the one hand, what is generated (in terms of emissions) as a result of the driving itself but, on the other hand, of course, also that every car which is not produced will prevent emissions from occurring (Interview 20, female scientist, director, sentence Na8).

When exploring alternative future pathways to the mobility transition, experts emphasize *land-use designation* and, relatedly, *rezoning*, i.e., the allotment of land from one type of use (primarily *individual motorized transport*) to more promising uses when it comes to sustainability. Examples include recreational spaces, cycling paths, and sinks as buffers. Both *rezoning* and *sharing services* receive a high number of positive evaluations regarding the future. *Rezoning* is considered a driver for behavior change:

> Naturally, if parking is not made that easy anymore, both for residents and for people coming into town, this, of course, changes their behavior (interview 11, male scientist, employee, sentence Da5).

Sharing services are also highlighted as an enabler of a low-carbon mobility transition, but this depends on the type of sharing, i.e., whether cars need to be returned to a station (stationary) or can be returned anywhere (free-floating):

> It can be an advantage to have stationary sharing so that people are willing at all to part with their car. But, basically,…free-floating systems do not have such a huge advantage as regards the environment, i.e., advantageous environmental effects, as far as I know (Interview 4, male practitioner, employee, sentence Ah8).

Furthermore, the facilitation of *short trips* within city distances is considered a central enabler of a low-carbon mobility system:

> So here it is important that we enable people to travel on short routes and that we work towards density…Given a high density and a good mixture of different uses then allows for short trips (interview 6, male scientist, employee, sentence An8).

The *attractiveness of public transport* is seen as related to a transparent and affordable ticket system:

> And therefore, a lot depends on the design of the tariff and the (tariff) system and on whether you have a society where this is supported, e.g., through subsidies, as it is generally done with cars by means of commuter tax allowance and other things. And this is, of course, a way to make this ticket socially acceptable (interview 1, male scientist, employee, sentence Aa4).

One respondent argued in favor of *green spaces* based on a weighing of interests:

> Well, I have different types of land use. If I decide I would like to have green spaces, then, in principle, parking lots are the one type of land use with the least benefit for the city, as this is where cars stand about. We know that cars stand about for 23 hours of the day and take up a lot of parking space (interview 9, female practitioner, function lead, sentence Bc1).

Shifting land use from *individual motorized transport* to *green spaces* will increase *social sustainability:*

> First and foremost, one has to explain that a change in land use designation also benefits individual motorized transport…That this is an advantage for society as a whole is an important point. Exactly,

> sustainability not just in an ecological sense but also the social (dimension of sustainability) behind it all (Interview 8, male practitioner, director, sentence As8).

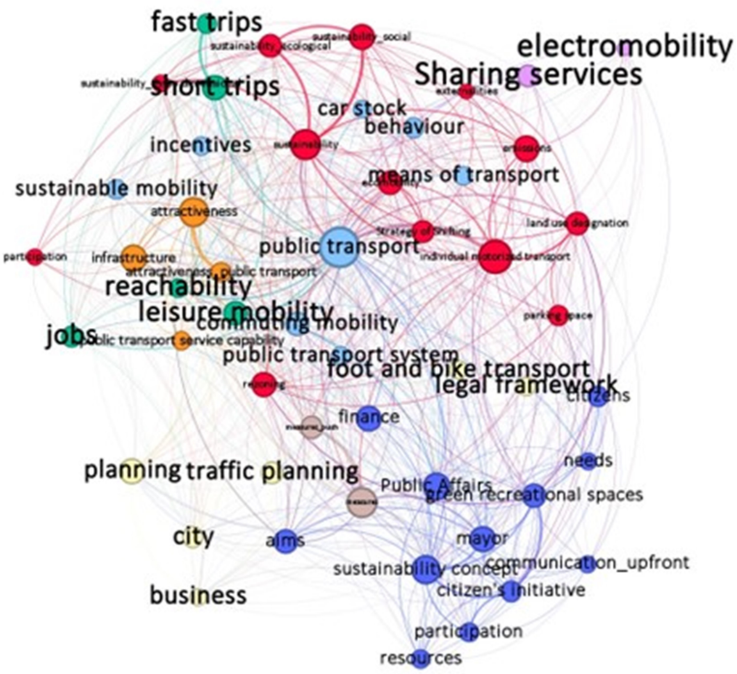
Participation is also considered crucial by respondents in bringing about a changed mobility system:

> What we can influence to some extent is that we actually have, for instance, participation by way of a random selection of citizens so that one can convince politicians that a majority of citizens backs up that (initiative) (Interview 8, male practitioner, director, sentence At3).

Co-occurrences of key terms in the key-term network

The semantic relations in key-term networks reveal the latent structures of mental models (Schuhbert, Muñoz Barriga, and Thees 2022). We identified eight thematic clusters (see Figure 3). The five dominant ones are:

1. A community pertaining to land-use designation (red).
2. A community revolving around pull factors of eco-mobility (i.e., public transport, foot, and bicycle traffic), like infrastructure and public transport service capability (orange).
3. A cluster pertaining to factors cementing current mobility behavior, such as the car stock and commuting mobility, but also centering on incentives and public transport (light blue).
4. The overarching planning level with the legal and institutional frame conditions (yellow).
5. The "human level" of low-carbon mobility transitions involving *public affairs*, *citizens' initiatives*, and the need for *participation* and *upfront communication* (dark blue).



Legend

	land use designation and rezoning		electromobility and mobility sharing
	pull factors of eco-mobility		space and mobility patterns
	incentives and behavior		push/pull measures
	legal and institutional frame conditions		
	needs and participation		

Figure 3. Excerpt of network of a low-carbon mobility transition.
Source: Own elaboration based on Gephi (https://www.gephi.org), communities partitioned based on their modularity class. Restricted to those nodes with weighted degree ≥3.0.

Electromobility and *sharing services*, alongside *space and mobility patterns* and *push/pull measures*, are addressed as well. The full network is displayed in Appendix 2.

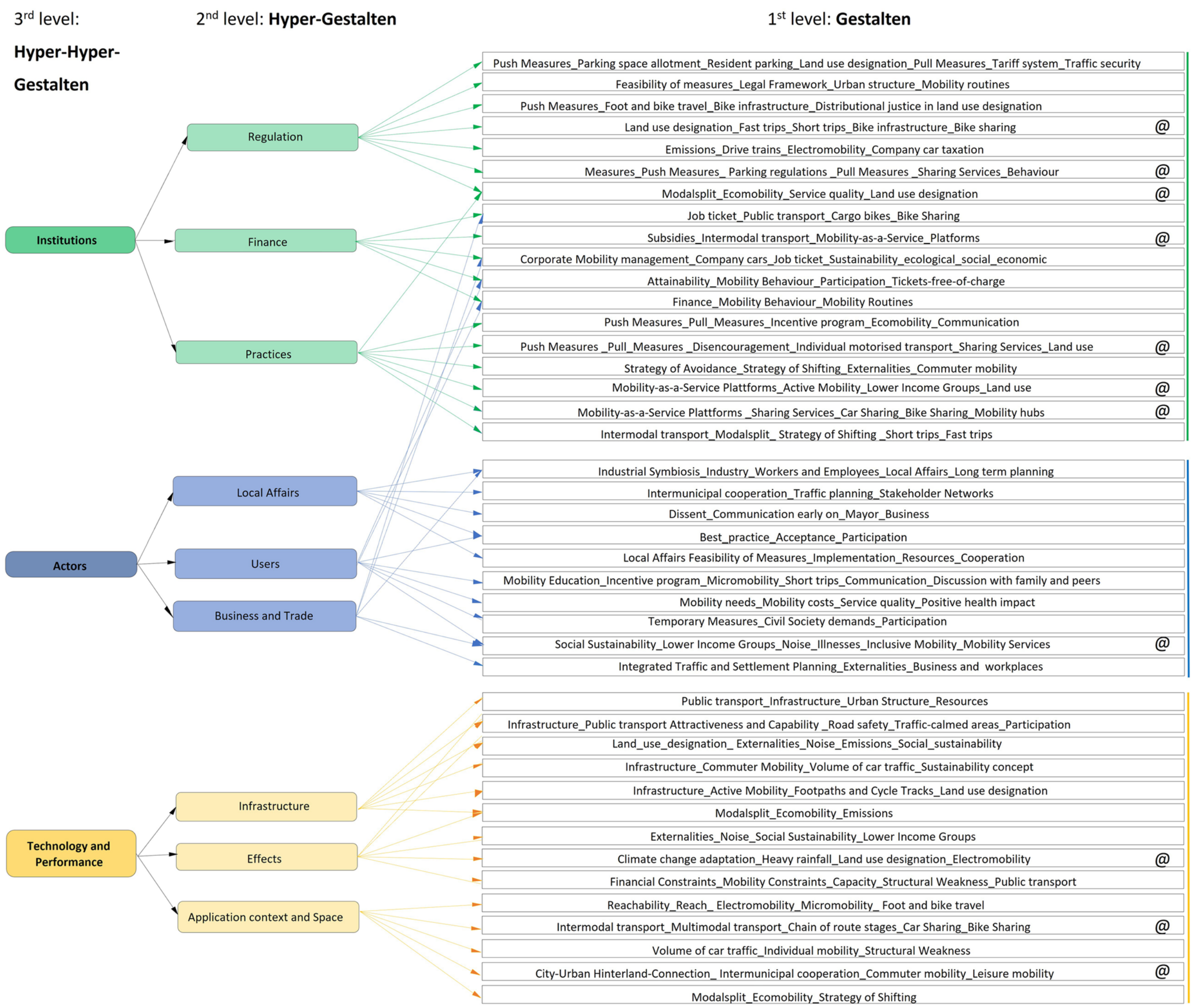
A shared mental model of experts as mirrored in the Gestalten tree

The Gestalten tree offers a condensed structure of the data. As a visual synthesis, the Gestalten tree can be understood as a shared mental model—i.e., according to the definition above, an aggregation of overlapping, complementary, or contradictory individual mental models—prevalent in the studied community of experts. When moving from right to left in the Gestalten tree (see Figure 4), one arrives at increasingly aggregated mental models (Zelger 2000). Based on a cluster analysis at the level of text units (one level below the Gestalten) and a subsequent multi-round aggregation of the data, resulting in Gestalten, Hyper-Gestalten, and Hyper-Hyper-Gestalten, we obtained the Gestalten tree in Figure 4. An example of how to navigate the Gestalten tree is given in Appendix 3.

Three Hyper-Hyper-Gestalten can be distinguished in line with prior work on sustainability transitions (see above for a description of the method): (1) *Institutions* (green), (2) *Actors* (blue), and (3) *Technology and Performance* (yellow), which form the highest level of the Gestalten tree (Figure 4). In each Hyper-Hyper-Gestalt, there are three Hyper-Gestalten, which in turn comprise several Gestalten (bundles of measures). The Hyper-Gestalten are clearly separated from each other, except for the Hyper-Gestalten Users and Business and Trade (blue), which also relate to the Hyper-Gestalt Finance (green). This can be seen from the blue arrows crossing the green arrows in Figure 4.

In what follows, we examine each Hyper-Gestalt and provide for each of them an illustrative statement drawn from one exemplary Gestalt.

Within the **Hyper-Hyper-Gestalt Institutions**, respondents identified three Hyper-Gestalten: Regulation, Finance, and Practices.



@: requiring digital infrastructure

Figure 4. Gestalten tree.
Source: Own elaboration based on the method GABEK® and the program WinRelan®.

The Hyper-Gestalt Regulation refers to push measures such as resident parking and changes in land-use designation, alongside pull measures such as a more transparent tariff system, improved traffic security, and a reform of tax regulations, among others:

> From a social perspective, these tax regulations are of course crucial. For example, company car taxation is what I already mentioned. Colleagues of mine have unambiguously found that it is the higher income levels who take advantage of it. There clearly is the need for reform (Interview 4, male practitioner, employee, sentence Ah4).

In the Hyper-Gestalt Finance, the inclusion of actors from business and trade in corporate mobility management, workflow adaptation, and in the provision of job tickets or job bikes, as well as by raising the level of company-car taxation, is seen as central. In the Hyper-Gestalt Finance, some respondents view digitization and MaaS platforms as controversial. Despite their potential to shift everyday public mobility services to the private sector and to bundle multiple services in one platform (Petzer, Wieczorek, and Verbong 2021), there is concern that mobility platforms may jeopardize established public transport.

> Then the biggest danger…is, of course, the topic of cannibalization, i.e…that the new Mobility-as-a-Service platforms, for instance, do attack public transport in a way and take something away from it. Therefore, it may be wise (to maintain) public transport as the heart of sustainable mobility (Interview 5, male practitioner, divisional head, Ak 8).

The Hyper-Gestalt Practices addresses a Strategy of Avoidance, primarily targeting social costs from emissions by discouraging car ownership, rechanneling commuter mobility, and changing the prevalent land-use designation. Conversely, a Strategy of Shifting involves multimodal mobility, such as switching between car-based mobility and public transport, supported by Park & Ride and Mobility Stations. Respondents focus on a strategic combination aimed at making incremental but steady improvements by emphasizing on-demand mobility and micromobility (i.e., short and fast trips within city distances) (Avoid), sharing services and MaaS platforms (Shift), and electromobility as instrumental in reducing local emissions (Improve)[7]. Sharing Services are viewed critically by some respondents, especially regarding the side effects of sharing, as the following statement exemplifies:

> We talk a lot about sharing services now, but I would not expect any large-scale impact in the short run… but these sharing services also impact on mobility behavior in a way, they may increase automobile use (Interview 11, male scientist, employee, sentence Db3).

Another related concern raised by respondents is the exclusion of "unplugged" citizens (Tomor et al. 2019), who are not sufficiently digitally literate, as the following two statements underline:

> Experience tells us we still need to have analog offerings to enable people to participate, to make sure that accessibility is provided (Interview 5, male practitioner, divisional head, sentence Al1).

This statement mirrors earlier findings on the need to address transport poverty as a "lack of physical access, vicinity, or affordability of mobility" to avoid unjust mobility transitions (Loorbach et al. 2021, 2).

The **Hyper-Hyper-Gestalt Actors** comprises the three Hyper-Gestalten: Local Affairs, Users, and Business and Trade.

Concerning the Hyper-Gestalt Local Affairs, respondents point out that peer and family networks function as a "resonance amplifier" of mobility transitions by shaping mobility behavior and routines. Furthermore, industrial symbiosis is addressed, with one respondent mandating to establish "approaches where parked electric cars or electric buses can serve as a temporary storage in the energy grid" (interview 19, male scientist, employee, sentence Mb3).

In the Hyper-Gestalt Users, respondents envision a broad participatory approach through user and stakeholder-participation formats, including mobility education in schools:

> Sometimes there are action days in schools where you count the kilometers traveled by pupils when commuting to school for the duration of a week. This may motivate them to come by a different (means of transport) (interview 14, male scientist, employee, sentence Gb5).

Temporary measures are also mentioned in the Hyper-Gestalt Users, such as "pop-up cycling paths," participatory flagship projects (e.g., "Berlin Citizens' Cycle Tracks," "Ottensen makes room!"), and a broad consultation with randomly selected citizens. Moreover, respondents mention the need to address structural weaknesses in a mixed urban structure through integrated traffic and settlement planning and a reduction of commuter mobility (also in inter-municipal cooperative projects).

With regard to the Hyper-Gestalt Business and Trade, respondents discuss measures like "car-free inner cities," which involve rezoning space at the expense of car-based mobility:

> This is where politicians need to muster enough courage to implement things, perhaps even when faced

> with opposition. Mostly, it is businesspeople who oppose when you plan to take away space from individual motorized transport…even if they (politicians) run the risk of losing a vote or two (interview 8, male practitioner, business executive, sentence At2).

The **Hyper-Hyper-Gestalt Technology and Performance** consists of the three Hyper-Gestalten Infrastructure, Effects, and Application Context and Space.

In the Hyper-Gestalt Infrastructure, respondents mandate building more footpaths, cycling tracks, and anti-noise barriers to promote social sustainability, as lower-income groups are particularly affected by noise and emissions-related health costs:

> After all, these are costs that you can hardly factor in: what is the (monetary) value of a working day that must be foregone due to emission levels? Or if the health of a person is impaired or damaged, and this eventually also shortens their lifetime (interview 1, male scientist, employee, sentence Ac5).

In the Hyper-Gestalt Effects, respondents address the need to combat climate change and its impacts, such as heavy rainfall and excessive heat accumulation in cities. Consequently, more climate-adaptation measures, such as carbon-dioxide (CO_2) sinks and heat sinks, are called for:

> And then I think an important point related to climate adaptation is that one really takes into account that it's not only about small trees, some hedges, and a little lawn but that we plant trees that will grow tall and can somehow withstand climate change in the decades to come (interview 19, male scientist, employee, sentence Mb4).

The Hyper-Gestalt Application Context and Space centers around the diffusion of electromobility and public transport and their integration with new players like MaaS platforms organized via mobility stations which bundle sharing services, park-and-ride, and ticketing:

> The goal would be, as it were, to encourage citizens to organize their mobility as a succession of route stages and seamlessly switch between mobility offerings. And since we already have local public transport, it would of course be great to tie in mobility stations at appropriate spots (interview 21, female practitioner, employee, sentence Ob5).

The reach and speed of public transport, in addition to becoming more affordable, are considered crucial in breaking mobility habits and routines.

Discussion

Our study provides insights into the mental models of mobility experts, specifically the aggregation of those models in a Gestalten tree. The Gestalten tree can be interpreted as a shared mental model of experts, including similar, complementary, and potentially contradictory contents. We agree with Hielscher and Will (2014, 709) that "an effective management of the 'pictures of sustainability' requires unearthing the tacit assumptions present in (the development of) mental models."

Our findings contribute to the literature on the mental models of experts in sustainability transitions, especially in mobility (Schröder and Klinger 2024; Wittmayer et al. 2017). Our approach systematically revealed views of experts like mobility scientists, eco-mobility lab practitioners, and urban planners—relevant for pathways to a low-carbon mobility transition—that have so far received little attention as transition intermediaries. Our most important insights are that experts' mental models cover a wide array of suggestions on how to navigate alternative future pathways to a mobility transition, including a transition based on low-carbon objectives. These include regulation, pull factors, incentivizing eco-mobility, and the "human level" of a low-carbon mobility transition, such as participation and affordable mobility. As mentioned in the first section, the contributions of different actors, including transition intermediaries, to exploring alternative pathways to a mobility transition are only just beginning to be considered (e.g., as mentioned by Nordt et al. 2024; Drexler et al. 2022). We address experts as goal-oriented transition intermediaries pursuing their own objectives and having different mental models, be they similar, complementary, or contradictory. Furthermore, we contribute to the literature on shared mental models by introducing a method that allows us to systematize, compare, and combine individual mental models to form a shared mental model. Sharedness has often been associated with actors directly exchanging views and opinions (Loorbach et al. 2021; Proka, Loorbach, and Hisschemöller 2018). Our concept of sharedness neither implies that the mental models of different people need to be directly exchanged nor that they converge in one identical mental model for all. Our concept of a shared mental model (the aggregation of mental models in a Gestalten tree) is based on an encompassing concept of sharedness, which includes not only overlapping but also complementary and, potentially, contradictory mental models.

We furthermore establish some convergent and divergent lines of argument between experts' mental models and EU mobility policies. Overall, experts prioritize tangible policy measures over digital ones, which contrasts with the high priority that EU mobility-transition policies ascribe to digitization. Some experts primarily mandate changes in land-use designation and built infrastructure through redensification and climate adaptation, while others emphasize the need for an integrated approach to the mobility transition as a symbiotic transition of energy, construction, logistics, and so forth. Rezoning and sharing services are considered drivers of behavior change toward eco-mobility. Although most experts acknowledge the opportunities arising from digital MaaS platforms, some also fear a cannibalization of public transport. They underline the need for accessibility for all societal groups and their inclusion—factors that impact the social acceptance of alternative future pathways to the mobility transition.

The EU's mobility policies almost uniformly target the year 2050, when member states aim to achieve climate neutrality (European Commission 2020). This is a time frame that in itself causes deep uncertainty due to the complex issues involved, such as when dealing with the interconnected systems of mobility and energy (Guivarch, Lempert, and Trutnevyte 2017). The mental models conveyed through EU mobility policies (Hoffmann, Weyer, and Longen 2017) can serve as a reference for a more in-depth discussion of our results. In doing so, the following commonalities between respondents' mental models and current EU mobility policies (see Appendix 4) can be identified: the need for multimodal hubs integrating public transport with mobility services that offer "pay per use" instead of car ownership (Caballero and Tanzilli 2021) and shared mobility (European Commission 2021); the strategy of shifting, including logistics and commuting, toward sustainable modes of mobility (European Commission 2019); and the mobility-health nexus (European Commission 2020).[8]

However, some divergent lines of argument between our experts' mental models and EU mobility policies also emerge. While most of the Gestalten tree measures are of a "brick-and-mortar" type, like those requiring a change in land-use designation in favor of footpaths and cycle tracks, only a minority of measures (11 out of a total of 42 Gestalten, indicated by the @ sign in Figure 4) require digital infrastructure such as the establishment of MaaS platforms in conjunction with sharing and mobility hubs. This contrasts with the high priority given to digitization by the EU's Sustainable and Smart Mobility Strategy of the European Commission, which envisions digitization as "an indispensable driver for the modernization of the entire system" by increasing "safety, security, reliability, and comfort" (European Commission 2020, 2) through interoperable MaaS platforms.[9]

Further measures mentioned by experts but not centrally addressed in policy documents include climate adaptation—having only appeared since 2019 as part of the European Green Deal and not as part of the 2021 New Urban Mobility Framework—and the need for a wide-reaching industrial symbiosis. Although early policy documents cursorily mention the need to interlink the transport and energy sectors in an integrated approach (European Commission 2009, 2016, 2011), subsequent documents tend to treat the mobility transition as a closed box, comprising only the transport and logistics sectors without considering symbiotic sector relations—a point mentioned by respondents and addressed by scientists for some time now (Kodukula 2017). This meta-systemic aspect of the mobility transition has been particularly stressed by the respondents of this study, who mandate that the implementation of the mobility transition be in sync with the energy transition, low-carbon transition pathways of the construction sector, mobility education, and participation.

Conclusion

This study offers insights into experts' mental models, which delineate alternative future pathways to the mobility transition. We addressed a subtle system level that is seldomly a focus in transitions research concerning the mental representations of systemic relationships from the viewpoint of experts. Although our study is not the first to underline the importance of integrating expectations, views, and emerging narratives in transitions research, we argue that our concept of mental models can offer greater conceptual clarity than previous frameworks by adding an informative layer to transitions research. Our mapping of mental models is broader than case data but more specific than the transition narratives, which are the most commonly applied approaches in transitions research. We furthermore employ an encompassing concept of sharedness, which includes not only overlapping but also complementary and, potentially, contradictory mental models. The shared mental model of experts, mapped in a Gestalten tree, did not require face-to-face exchange but was retrieved from interview data. The results have provided a "thick description" (Vega, Arvidsson, and Saïah 2023, 74) of experts' mental models.

Our findings contribute to the literature on sustainability transitions by revealing the views of experts, such as mobility scientists, eco-mobility lab practitioners, and urban planners, relevant to potential pathways to a low-carbon transition. The results are not generalizable to mobility experts' views because our interviewees are not representative of the mobility expert population in Germany. However, we covered a diversity of mental models from both scientists and practitioners specializing in fields such as resources, energy, transport, infrastructure, and urban development. The comparison with EU mobility policies did not include interviews with policymakers but was based on a thorough content analysis of policy documents.

In policymaking, the shared mental model uncovered by GABEK®, especially the key-term network and the Gestalten tree, can be employed in the first stage of "backcasting" scenarios, as they help systematize and visualize the outcomes of the reflection process on future developments (Robinson et al. 2011). In this case, key-term networks may help curtail relevant transition pathways (Kemp and Rotmans 2004) and offer support in the crucial stage of translating shared beliefs (such as "car-reduced cities") as well as contradictory views into new institutional structures (Schröder and Klinger 2024). In particular, sustainability-transition projects drawing on a multi-scale setup of participants from different sectors and continents, where room for mutual learning in person is often limited, can use this method in the qualitative scenario stage. The unique approach of extracting and mapping a shared mental model in a Gestalten tree simulates a real conversation among participants, creating a cognitive solution space. This space can then be used to visualize results for the practitioners, experts, and scientists who are involved while also easing communication with non-experts, including politicians.

GABEK® can support further analyses beyond those we have undertaken; the Gestalten tree can be used in conflict resolution, such as in cases where opposing parties cannot or would not meet in person (Zelger 2019). Furthermore, the Gestalten tree can be compared with the results of other projects, not only interviews but all types of textual data, including internet documents. This allows for the analysis of overlaps and differences between Gestalten trees for different communities and respondents.

Notes

1. This research is part of a more encompassing project in which the mental models of sustainable mobility users (novices) and experts were confronted with each other. This article focuses exclusively on the experts' mental models.
2. For project sizes such as ours, a cluster analysis at the level of text units is considered sufficient while for larger projects (e.g., including text units of hundreds of respondents), a cluster analysis should also be conducted at the level of Gestalten, see Zelger (2019).
3. Rule implementation is supported by the program and rule violations are marked in the user surface. For all semantic rules applied at each level of the Gestalten tree, see Zelger and Oberprantacher (2002).
4. For a similar approach, see Schultz and Reinhardt (2023).
5. Mobility-as-a-Service (MaaS) platforms offer multimodal mobility services such as switching between car-based mobility and public transport. These platforms function as a digital hub for one-stop booking, ticketing, and payment as well as non-transport-related services such as parking. For a detailed definition and critical discussion, see Hensher, Mulley, and Nelson (2021).
6. All interview excerpts have been translated by the authors.
7. The phases Avoid, Shift, and Improve have also been addressed by Griffiths, Furszyfer Del Rio, and Sovacool (2021).
8. It has been shown that there is a link (*nexus*) between, on the one hand, active mobility such as walking, cycling, and use of public transport in cities and, on the other hand, physical and mental health benefits to city dwellers. This mobility-health nexus is supported further by providing access to green recreational spaces, see Koszowski et al. (2019).
9. Interoperable Mobility-as-a-Service (MaaS) platforms enable passengers to plan trips, buy tickets, and seamlessly switch between different modes of transport, such as car-based mobility and public transport that use different mutually compatible platforms.

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Appendix 1. Calculation of the relevance score

The relevance score R in GABEK® is derived from the number of evaluations a key term has received by experts and the number of causal relations in which it is enmeshed. The relevance score is calculated according to the following formula:

$$R = \frac{1}{2}\left(100\frac{e}{e_{\max}} + 100\frac{c}{c_{\max}}\right)$$

with e = number of evaluations of a key term, c = number of causal relationships of a key term, e_{max} = number of evaluations of the key term with the highest number of evaluations, andc_{max} = number of causal relationships of the key term with the highest number of causal relationships

Example calculation for the key term *emissions*:

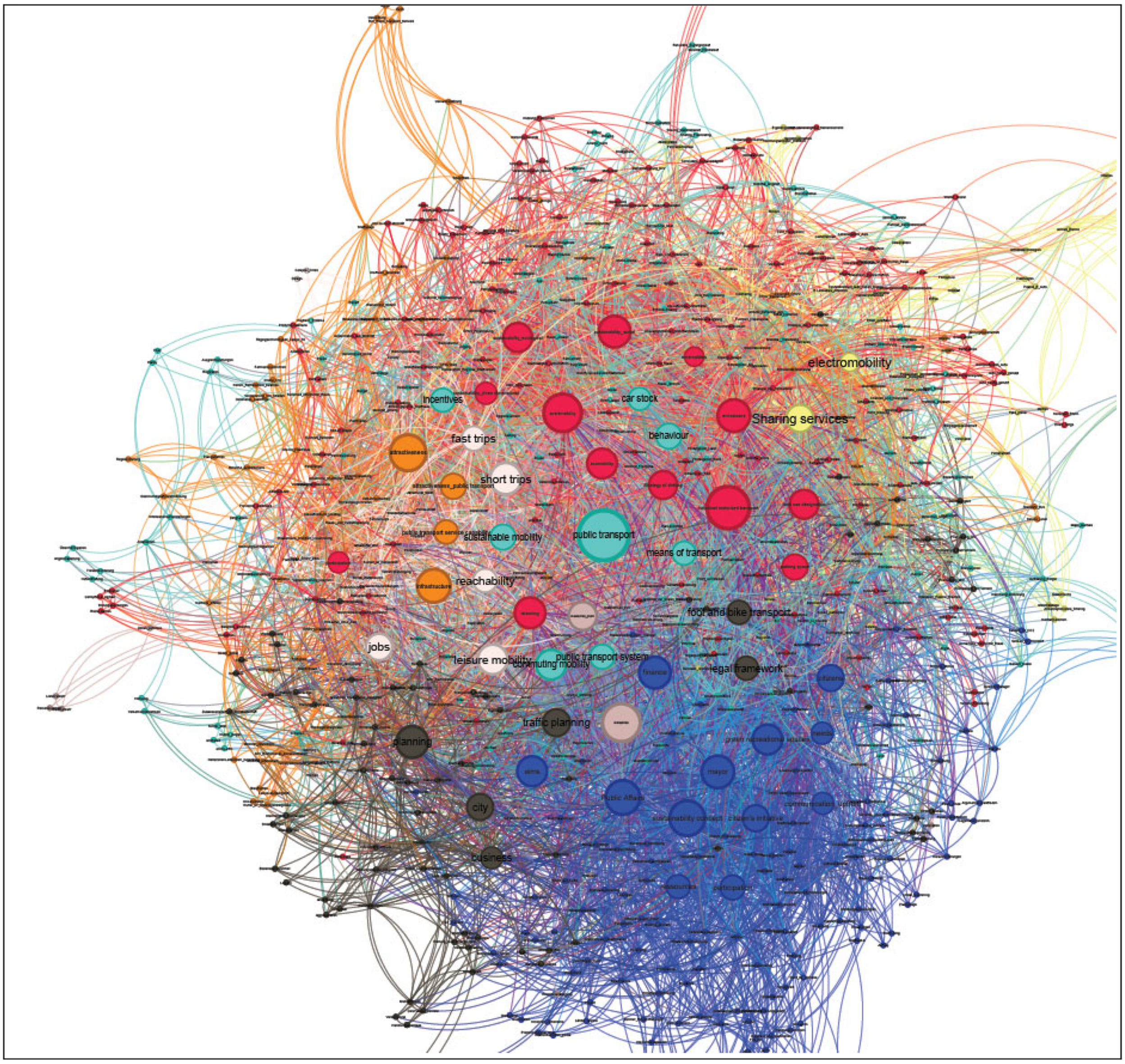
As *public transport* is the key term with both the highest number of evaluations (e) and of causal relationships (c), the relevance score of *public transport* is set to represent a relevance score of 100. The relevance score of all key terms is then calculated with reference to $e_{max} = e_{public\ transport} = 34$ and $c_{max} = c_{public\ transport} = 76$.

For the key term *emissions*, which has received 24 evaluations and is enmeshed in 48 causal relationships, the relevance score R is thus:

$$\text{Relevance Score}(\text{Emissions}) = \frac{1}{2}\left(100\frac{24}{34} + 100\frac{48}{76}\right) = \frac{1}{2}(71 + 63) = 67$$

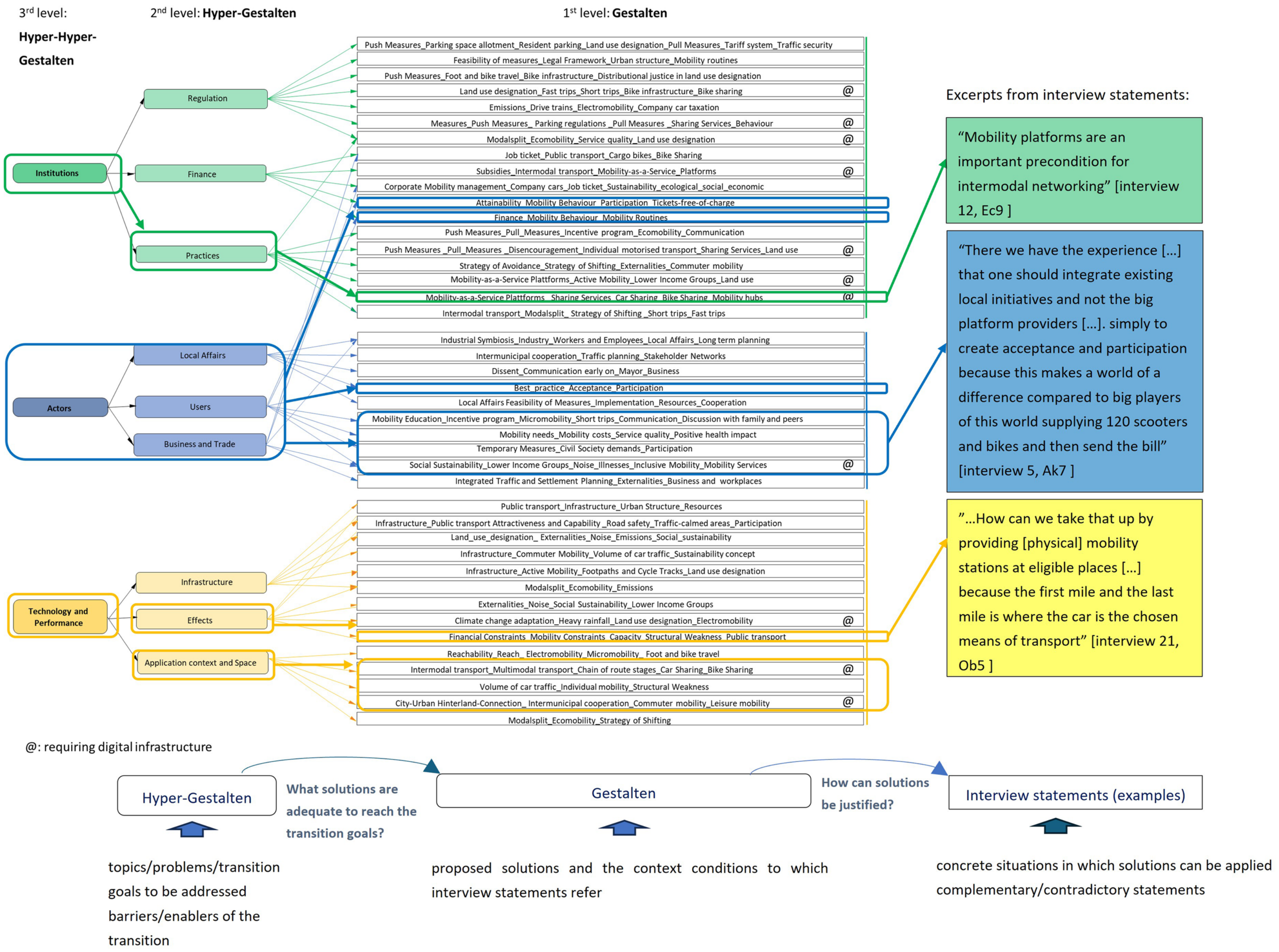
The value of 67 for the key term *emissions* can be found in Table 2.

Appendix 2. Full network of a low-carbon transition pathway of the mobility sector



Source: Own elaboration based on Gephi (https://www.gephi.org), communities partitioned based on their modularity class.

Appendix 3. Example of how to navigate the Gestalten tree (for key terms mobility-as-a-service platforms and platform providers)



Appendix 4. Timeline of EU mobility policy packages