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How accessibility instruments contribute to a low carbon mobility transition: Lessons from planning practice in the Munich region

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ABSTRACT

The accessibility concept provides a suitable framework for the achievement of sustainable land use and transport systems. Environmental and climate concerns have gained particular relevance among sustainability goals in recent years, thus reshaping political agendas all over the world. Against this background, this paper explores the practical relevance of accessibility instruments for low carbon mobility planning. A theoretical framework on usefulness is developed, which outlines potential application purposes related to identifying needs for interventions in the land use and transport system, assessing the impacts of potential solutions, as well as communicating between planning sectors and stakeholders. Three real-world planning issues in the Munich region serve to test the hypothetical usefulness of accessibility instruments for low carbon mobility planning in empirical applications. Practitioners were involved at various stages throughout the process in order to capture their perspectives on practical relevance. Both the identified planning issues and the types of accessibility implementations were diverse in nature, showing that accessibility analysis is applicable to a variety of tasks connected to the aim of reducing transport-related emissions. Earlier findings about the practical relevance of accessibility instruments were confirmed in this context, in particular the importance of communicative outputs. While more research in other spatial contexts is clearly needed, we conclude that accessibility instruments can contribute to a low carbon transition by enabling practitioners to plan for low carbon mobility options and communicate the benefits of these options. However, the implementation of accessibility instruments might be hampered by emerging barriers, such as the need to quantify emissions and emission savings, the desire to consider qualitative aspects in addition to quantitative indicators, and the lack of accessibility standards and reference values.

1. Introduction

Accessibility describes the potential to reach spatially distributed opportunities from a given place using a particular transportation system (Páez et al., 2012). The concept provides a suitable framework for integrated land use and transport planning, a key factor of enabling sustainable mobility (Curtis, 2008; Bertolini et al., 2005). Accessibility instruments help to measure and visualize accessibility for its operationalization in planning practice. Previous work has highlighted the potential usefulness of accessibility instruments for a variety of planning issues (Silva et al., 2019; Hull et al., 2012; Te Brömmelstroet et al., 2014). This paper aims to explore the practical relevance of accessibility instruments for the particular objective of low carbon mobility planning. Land use and transport systems influence transport-related CO_2 emissions via both long-term mobility behavior, such as location choice and car ownership, and short-term mobility behavior, such as destination choice and mode choice (Handy et al., 2005; Næss, 2012; Barla et al., 2011; Cervero and Kockelman, 1997). By means of accessibility planning, land use and transport systems can be shaped to provide for low carbon mobility options, an essential prerequisite for achieving emission reductions in the transport sector (Banister, 2008). Thus, we hypothesize that accessibility-based analysis methods are a good match for current planning and policy goals related to the urgent need of climate change mitigation.

Our work entails several novel aspects compared to previous research. While there are still only few accessibility applications involving practitioners, the addressed planning issues are often hypothetical rather than actual and up-to-date (Te Brömmelstroet et al.,

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2016). Furthermore, to the best of our knowledge, no previous planning practice applications of accessibility focus explicitly on low carbon mobility options. The achievement of environmental goals is typically assumed to be intrinsic to accessibility planning within a wider sustainability framework (Bertolini et al., 2005). Although some authors have linked accessibility analysis to transport-related emissions (Määttä-Juntunen et al., 2011; Vasconcelos and Farias, 2012; Kinigadner et al., 2019), the absence of an actual planning practice or policy context clearly limits the conclusiveness of such applications in terms of practical relevance.

Section 2 introduces a theoretical framework for the potential usefulness of accessibility instruments for low carbon mobility planning by outlining objectives and decision-making purposes for which such tools could be relevant. An empirical assessment of selected use cases is then conducted based on three real-world planning issues in the Munich region. Before discussing the results of these applications in section 4, the methodological process is presented in section 3. We conclude with reflections on the likeliness of future implementation and further research needs in section 5.

2. Accessibility instruments for low carbon mobility planning

2.1. Location-based accessibility measures

The concept of accessibility can be applied to various planning tasks, for which multiple types of accessibility measures (Geurs and Van Wee, 2004) and instruments (Papa et al., 2016) are available. Accessibility should be operationalized in line with the context, purpose, and objective of the analysis (Silva et al., 2017). While more sophisticated planning tools might increase theoretical soundness, they tend to be less suitable for applications with practitioners due to their limited transparency, understandability, and communication value (Te Brömmelstroet and Schrijnen, 2010). For this reason, our assessment of the practical relevance of accessibility instruments is based on comparably simple location-based accessibility measures, according to the following equation:

$$A_i = \sum_j D_j \times f(c_{ij}) \quad (1)$$

The accessibility A_i at location i is determined by D_j, representing the opportunities at destination j, and $f(c_{ij})$, a function of the travel costs between locations i and j. The cost function can have different forms, where cumulative opportunities measures sum up the number of opportunities within a defined threshold, whereas gravity-based measures weight opportunities based on a continuous function of c_{ij} (Handy and Niemeier, 1997). Travel costs can be measured in different cost categories (e.g. distance, travel time or monetary costs) and for different transport modes (e.g. car, transit, walking or cycling). Location-based accessibility measures are capable of producing visual outputs in map format, which are acknowledged for enhancing interpretability and communicability of the outputs (Te Brömmelstroet et al., 2016; Wulfhorst et al., 2017). Regarding the purpose of planning for low carbon mobility options, we focus on the following two specifications of location-based accessibility:

1. *Non-motorized accessibility:* Besides featuring a number of other benefits, walking and cycling are emission-free. An increase in walking and cycling, combined with other measures, could lead to reduced energy consumption and emissions (Scarinci et al., 2017). Hence, a first suitable specification for low carbon mobility planning measures accessibility by active modes based on network distance.
2. *Carbon-based accessibility:* Although the outputs of traditional accessibility measures (using distance, time or money as the underlying travel costs) could be linked to transport-related energy consumption, emissions should be more explicitly incorporated into accessibility analysis and planning (Kinigadner et al., 2021). Thus, the second specification uses per-passenger emissions by car and transit, measured in grams of CO_2-equivalents, as travel cost in the accessibility analysis.

2.2. Applicability

Useful planning instruments must feature relevant functionalities and serve relevant information needs linked to the underlying planning tasks and policy goals (Silva et al., 2017; Bertolini and Silva, 2019). This section outlines potential application purposes for which accessibility instruments could be useful in the context of low carbon mobility planning.

2.2.1. Identify options or needs for interventions

Compact, mixed-use urban development oriented towards a low carbon transport system is a prerequisite for low carbon mobility behavior. Such framework conditions provide travelers with the possibility to choose sustainable transport modes or minimize trip lengths (Geurs and Van Wee, 2006; Banister, 2011). Planning tools in this context should thus be able to identify options or needs for interventions in the land use and transport system. More precisely, options for interventions could refer to the identification of suitable urban development areas, which are embedded in dense urban structures and provide access to low carbon transport supply. Needs for interventions could refer to the identification of residential or commercial areas where low carbon mobility options are not available. Especially against the background of strict emission reduction targets, appropriate land use and/or transport policies need to ensure that activities can be reached within acceptable emission budgets.

Location-based accessibility instruments, as introduced in section 2.1, are capable of analyzing land use and transport systems with respect to the requirements outlined above. Regional scans make it possible to compare accessibility levels across different spatial units and identify accessibility deficits. Based on such analysis, potential land use and transport solutions can be deduced for any spatial context. Hence, large application potential lies in the generation of strategies for integrated land use and transport planning (Curtis, 2008). Regarding low carbon mobility planning in particular, accessibility instruments help to plan for accessibility by proximity, fostering favorable conditions for active, carbon-neutral mobility (Pajares et al., 2021). Also carbon-based accessibility analysis could be useful for a variety of objectives in this context, such as comparing accessibility levels for the same CO_2 limits among different urban structures and transport modes, assessing the impacts on accessibility if CO_2 emission limits were implemented or linking emission pricing and budgeting to a specific spatial context.

2.2.2. Assess the impacts of potential interventions

Besides identifying options or needs for intervention, the analytical capabilities of planning tools can enable an assessment of the impacts of proposed solutions (Pelzer, 2017). Considering the importance of climate change mitigation goals in policy and planning, the extent to which interventions in the land use and transport system enable low carbon mobility behavior should be assessed ex-ante. Since urban development decisions influence the transport-related emissions caused by residents, employees or visitors, land use policies should be carefully assessed to ensure that they complement rather than undermine decarbonization measures in the transport sector (Loo and Tsoi, 2018). At the same time, the emission impacts of transport investments deserve particular attention, as they determine individual mode choices, which are linked to relative emissions per passenger-kilometer.

Accessibility instruments enable an assessment of various intervention scenarios, since changes in both the land use and transport system reflect in accessibility outputs (Merlin et al., 2018; Levine et al., 2017). For example, land use policies targeting increases in density and diversity could be assessed in terms of their impacts on non-motorized accessibility. Improvements in the connectivity of pedestrian or

cycling networks will also increase accessibility and thus the attractiveness of carbon-neutral modes. Carbon-based accessibility instruments could evaluate how well urban development strategies are integrated with the existing public transport system based on accessibility outputs. Furthermore, the method can be used to assess the accessibility impacts of infrastructure investments, such as new public transport links, or measures aiming to reduce transport-related emissions, such as efficiency increases or increases in occupancy rates.

2.2.3. Communicate between planning sectors and stakeholders

Communication is of particular importance in the context of reducing transport-related emissions, since the identification and implementation of solutions require both cooperation and commitment of various stakeholders, including politicians, planners, and citizens (Hickman et al., 2010; Banister, 2011; Geels, 2012; Marsden et al., 2014). Lack of coordination across sectoral, institutional, and territorial boundaries might impede the implementation of sustainable land use and transport policies (Næss et al., 2011, Rode and Da Cruz, 2018). Also the active support of political decision-makers is a basic requirement for the realization of potential solutions towards low carbon mobility. Finally, private decision-makers, such as citizens or firms, need to embrace the available low carbon mobility options in order to realize low carbon mobility behavior.

Accessibility instruments are widely recognized for their ability to spatialize and visualize issues in land use and transport planning and enhance communication between various stakeholders (Stewart, 2017; Papa and Coppola, 2019). In terms of interdisciplinary communication, accessibility instruments help to develop common understanding across different planning sectors (Te Brömmelstroet et al., 2016; Silva et al., 2017; Wulfhorst et al., 2017). In particular, they enhance the understanding of land use and transport interactions (Curtis and Scheurer, 2010), which in turn fosters integrated land use and transport planning as a basic requirement for the provision of low carbon mobility options (see section 2.2.1). Both non-motorized and carbon-based accessibility analysis could serve as argumentation support in order to convince political decision-makers to promote investments in low carbon mobility options by making issues and benefits tangible. Easily understandable maps can be effective in creating awareness among non-expert decision-makers, such as citizens or firms, regarding the emission impacts of location and travel choices.

3. Research design

3.1. Process

Conclusions on the practical relevance of planning support systems cannot solely be based on hypotheses or hypothetical statements of practitioners, but require actual implementation (Te Brömmelstroet et al., 2019a). Three real-world planning applications in the Munich region serve to test the theoretical usefulness of accessibility instruments for low carbon mobility planning, as presented in section 2:

1. Mobility hubs: An application of non-motorized accessibility analysis to allocate mobility hubs and estimate their contribution to CO_2 emission reductions
2. Urban planning: A first application of carbon-based accessibility analysis to analyze urban planning options in terms of low carbon mobility
3. Express bus lines: A second application of carbon-based accessibility analysis to analyze the accessibility benefits of public transport compared to the car

The applications are described in more detail in section 3.2. While the general type of planning instrument to be used was given, the specific purpose and form of the accessibility analysis was developed in a co-creative process together with the concerned practitioners. All accessibility implementations remained open to more detailed specification and further refinement throughout the process, based on the exchange with planning practitioners (as suggested by Te Brömmelstroet and Schrijnen, 2010). The interdisciplinary group of stakeholders involved included both land use and transport planners on municipality and county level as well as representatives from other institutions, in particular the Munich Transport and Tariff Association (responsible for coordinating public transport in the Munich region) and the regional planning authority. An overview of the individual steps implemented in the Munich region and their outcomes is provided in Fig. 1. The process was inspired by the workshop procedure applied within the COST Action "Accessibility Instruments for Planning Practice" (Hull et al., 2012; Te Brömmelstroet et al., 2014). Common workshops with all involved stakeholders were supplemented by case-based meetings in smaller groups, focusing on only one application at a time. The participatory workshop settings alternated with back office work, serving to conduct the analysis and improve the analytical capabilities of the tools.

The first step was to identify current planning issues in the context of transport-related CO_2 emissions during *initial meetings*. Planning issues and application purposes of accessibility instruments were specified throughout the process. Next, all stakeholders gathered for a common *kick-off workshop*, where accessibility instruments were presented as tools which could be useful to support the identification and/or implementation of low carbon solutions in land use and transport planning. The benefits of the kick-off workshop were twofold: Firstly, it helped the developers to understand the practitioners' ideas, needs and expectations, a key prerequisite for developing useful tools (Papa et al., 2017). Secondly, it helped the practitioners to gain insights into the tools' capabilities and potential application purposes. The planning tasks were specified during *scenario workshops*, before preliminary analyses could be conducted with the tools. All stakeholders came together once again during the *strategy workshop*, which served to gather initial feedback on the practical relevance of accessibility instruments based on the preliminary results. The workshop participants were asked to rate a number of statements related to practical relevance on a 5-point likert scale from "strongly disagree" to "strongly agree". These statements were inspired by previous research assessing the practical relevance of accessibility instruments (Te Brömmelstroet et al., 2019a). Selected statements of the user survey can be found in Appendix A. This quantitative evaluation supplemented the qualitative evaluation in the form of observations and discussions during the workshop. The process continued with individual *action plan workshops*, which helped to further refine the application purpose of the tools. The refined analyses were presented during a *closing workshop*, which provided the setting for final evaluation and feedback. Two rounds of interactive formats were conducted for this purpose. In the first round, practitioners were confronted with the following questions:

- What are positive aspects of the tools from your point of view?
- What are negative aspects of the tools from your point of view?
- Do you have suggestions for the improvement and/or further development of the tools?

The workshop participants wrote their answers on sheets of paper and pinned them on a board with additional oral explanation. In the second round, the workshop participants were asked to jointly develop use cases for future planning practice applications in multi-disciplinary groups of three to four practitioners (land use and transport planners on municipality, county, and regional level). They were explicitly allowed to include potential further developments of the tools in their considerations. Eventually, all groups were asked to explain their use case, specify the added value of the tool, and describe the further development needed, if any. The closing workshop provided in-depth insights on the strengths and weakness of accessibility instruments for low carbon mobility planning.

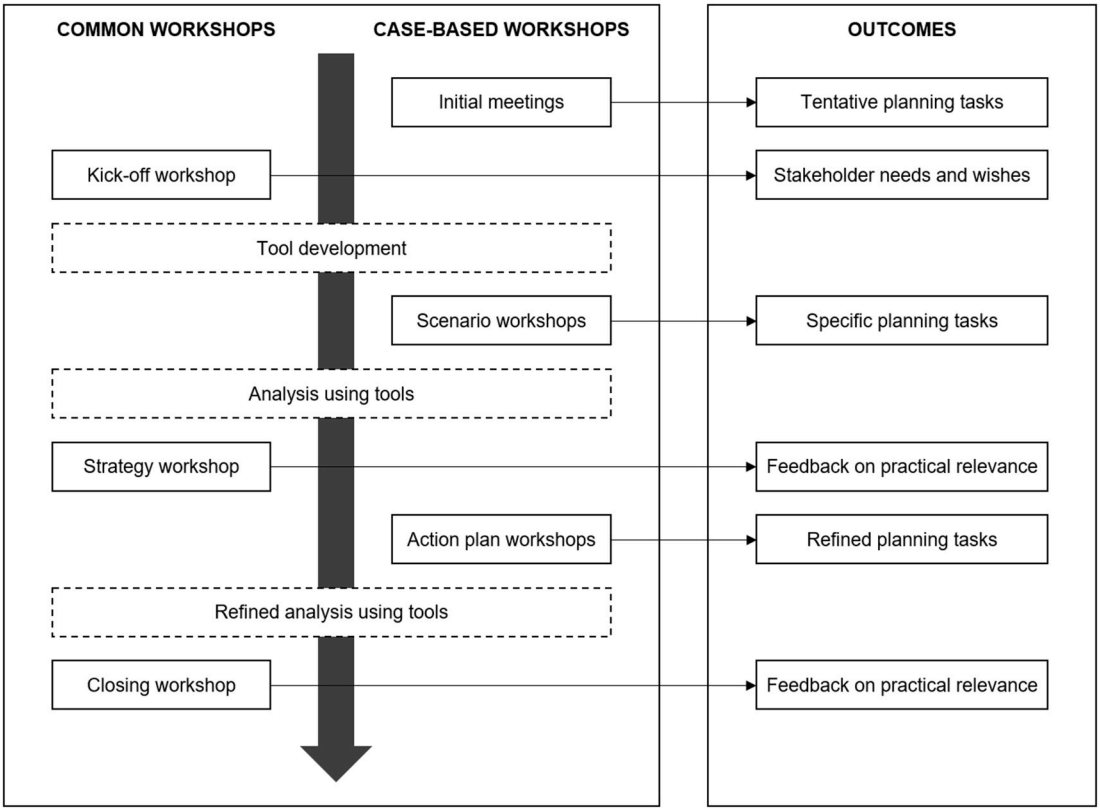

Fig. 1. Tool application and stakeholder engagement process implemented in the Munich region.

3.2. Applications

3.2.1. Mobility hubs

This application addresses the introduction of multimodal mobility hubs in the county of Fürstenfeldbruck, located to the west of the city of Munich. Mobility hubs, integrating bike sharing, car sharing, public transport, and other services, are recognized for contributing to sustainable mobility by fostering intermodal and active mobility, strengthening the public transport system, and providing alternatives to a privately owned car (Miramontes et al., 2017). Similar goals were pursued in the case of Fürstenfeldbruck, in particular, fostering multi-modality, encouraging modal shift, and reducing car ownership, thus contributing to the overall objective of reducing transport-related CO_2 emissions. The task assigned to the county's transport planners was to develop a comprehensive concept specifying the number and location of mobility hubs. Starting point was the definition of criteria for suitable locations. Firstly, mobility hubs should complement the existing public transport system in a meaningful way. Secondly, there should be a certain number of points of interest located within the walking catchment area of a mobility hub. Regarding the first criterion, multiple public transport stops were preselected and their priority was rated as high or low, depending on the types of lines, number of lines, service frequency, and passenger volumes. Distance-based accessibility turned out to be a useful method to address the second criterion.

After the presentation of the analysis results during the strategy workshop, the county's responsible transport planner matured the preliminary concept by introducing further conceptual considerations. While the refined concept foresees an even denser network of mobility hubs than the preliminary concept, some candidate locations might eventually be eliminated, depending on land availability and ownership as well as financial costs and resources.

Based on these experiences, two development paths to further enhance the application potential of accessibility instruments for this type of planning task were identified. The first path emerged from the difficulties reported by the practitioner to select locations based on a quantitative procedure due to a lack of relevant data and a lack of reference values regarding the number of destination potentials that should be within the station catchment. A second development path was linked to the fact that an ex-ante evaluation of the project's contribution to CO_2 emission reductions was required in order to receive financial support from the German climate protection initiative for the implementation of mobility hubs.

3.2.2. Urban planning

This application uses accessibility instruments to analyze urban development options in Haar, a municipality with around 20,000 inhabitants, bordering the city of Munich to the east. The municipality's building authority had predetermined a number of development areas for different types of urban functions, including housing, education, and commerce. The aim of the accessibility analysis was to determine the extent to which the intended development areas provide travelers with low carbon mobility options, also compared to other locations within the territory. Together with the head of the municipality's building authority, a combined index of carbon-based accessibility and density was chosen to be a suitable implementation for the planning task at hand (compare Yigitcanlar et al., 2007). For each spatial unit within the study area, both accessibility and density levels are calculated and assigned to five ascending categories, depending on their values. The two dimensions are combined for recommendations according to the following rules:

- Improve accessibility where density is two or more categories above accessibility
- Increase density where accessibility is two or more categories above density
- All other combinations correspond to a comparative mix of accessibility and density

In this particular application, the level of spatial detail corresponded to census grid cells, sized 100 by 100 m. For the preliminary analysis, a gravity-based accessibility indicator using a negative linear decay function was employed, following a logic of "the more emissions, the worse". Due to the lack of standards for defining absolute thresholds, accessibility and density levels were categorized according to their relative position within the entire value set, with each category containing 20% of all values (quintiles). Given the diversity of urban functions under consideration, the focus was set on the key area of interest, namely the distribution of jobs and housing. Still, multiple combinations of transport modes, destination potentials and densities were tested, as summarized in Table 1.

The intermediate evaluation revealed several issues with the preliminary analysis and yielded important conclusions for the refined analysis. Firstly, the negative linear decay function turned out to be too complex to make the municipality's urban planner fully understand that accessibility is an indicator of the joint characteristics of the land use and transport systems. In order to ensure better understanding of how accessibility is measured, a simpler accessibility indicator, namely cumulative opportunities, was used in the refined analysis. Secondly, the different combinations of modes, destination potentials, and densities led to further confusion. For the refined analysis, these were reduced to carbon-based public transport accessibility to jobs versus population density. Thirdly, the maps were not capable of "speaking for themselves", because the aggregation of several layers increased abstractness and opaqueness and the actual meaning of the output categories was not clear due to the absence of meaningful labels.

3.2.3. Express bus lines

This application concerns express bus services around the city of Munich, a major infrastructure project under discussion in the region. Munich has a purely radial suburban railway network, which is unattractive for tangential trips due to detours and the need to change in the city center. Orbital bus express lines are seen as an option to provide direct connections between regional hubs. Naturally, the analyses related to this planning issue were conducted in close cooperation with representatives from the Munich Transport and Tariff Association. Practitioners from regional public transport planning authorities were also involved in the process relating to this application.

The key strategic goal of the intervention was to increase the attractiveness and competitiveness of public transport compared to the car in order to encourage a mode shift, thus reducing emissions. Two main risks of the project were identified: the loss of political support and poor utilization of the new services by travelers. Following these clarifications, the purpose of applying accessibility instruments was not so much an assessment of the accessibility impacts of this transport infrastructure investment, but rather the communication of the benefits of public transport compared to cars, serving as argumentation support towards politicians and citizens. For this purpose, carbon catchment areas by car and public transport were visualized for main regional hubs along the orbital bus express lines. An analysis done with the regional travel demand model showed that public transport demand decreases on radial railway lines and increases on orbital bus connections with the introduction of express services. Travel demand determines the per-passenger emissions in public transport via occupancy rates and is therefore essential for the calculation of carbon-based accessibility levels.

Table 1
Overview of accessibility and land use combinations for the preliminary analysis in the municipality of Haar.

Accessibility dimension		Land use dimension
Transport mode	Destination potential	
Public transport	Jobs	Density of workers
Public transport	Workers	Density of jobs
Car	Jobs	Density of workers
Car	Workers	Density of jobs

4. Practical relevance of accessibility instruments for low carbon mobility planning

In this section, the results of the planning practice applications in the Munich region are discussed with respect to the theoretical framework on usefulness of accessibility instruments for low carbon mobility planning (see section 2).

4.1. Identification

The value of accessibility instruments for identifying and localizing options or needs for strategic interventions in the land use and transport system was confirmed during the strategy workshop. This purpose was exploited in the urban planning application (3.2.2). Fig. 2 shows the refined analysis for the municipality of Haar, which was presented to political representatives during a municipality council meeting, resulting in interest and positive feedback. The maps visualize public transport accessibility to jobs within 1500 g of CO_{2e} (a normatively defined emission threshold), population density, and the combined index. The intended development areas coincide nicely with locations that feature low density levels in the current situation (Fig. 2a), high carbon-based public transport accessibility compared to other locations within the municipality's territory (Fig. 2b), and consequently an accessibility surplus, indicating a large potential for urban development (Fig. 2c).

The mobility hub application (3.2.1) relied on non-motorized accessibility analysis to count the points of interest within a network distance of 1000 m around the candidate hubs (Fig. 3). The considered destination potentials included population, number of workers, education facilities, gastronomy, shopping opportunities, and services. Accessibility analysis enabled a first estimation of the potential number of hub users.

Creating mobility hub networks turned out to be a pressing planning issue in the Munich region and planners are in need of tools that support the spatial allocation of mobility hubs. Accessibility instruments are an efficient method to analyze a large number of candidate locations in terms of characteristics that determine hub utilization, such as the number of workplaces or residents within the catchment area. While the initial analysis was limited to pre-selected locations, the refined method uses comprehensive heat maps to identify the most promising locations for mobility hubs within a given study area by analyzing the number of potential users on a grid cell level.

Accessibility instruments are suitable for identifying options or needs for interventions within mixed-methods approaches. Municipal planners are typically well acquainted with the specific land use and transport conditions within their territory, but qualitative approaches could be supplemented by quantitative accessibility analysis. Still, the need for qualitative work was evident in both the urban planning application and the mobility hubs application. Specific local circumstances, such as land availability and ownership, constitute central decision criteria that cannot be addressed by accessibility analysis.

4.2. Assessment

During the workshops, practitioners confirmed the potential usefulness of accessibility instruments for assessing alternative scenarios and evaluating impacts. In theory, different types and densities of potential land uses could have been tested in the urban planning application (3.2.2) to assess the extent to which they provide for low carbon mobility options. Also regional accessibility improvements due to public transport investments could have been assessed in the express bus lines application (3.2.3). However, accessibility-based impact evaluations were no main concern among practitioners and none of the applications turned out to assess the accessibility impacts of (alternative)

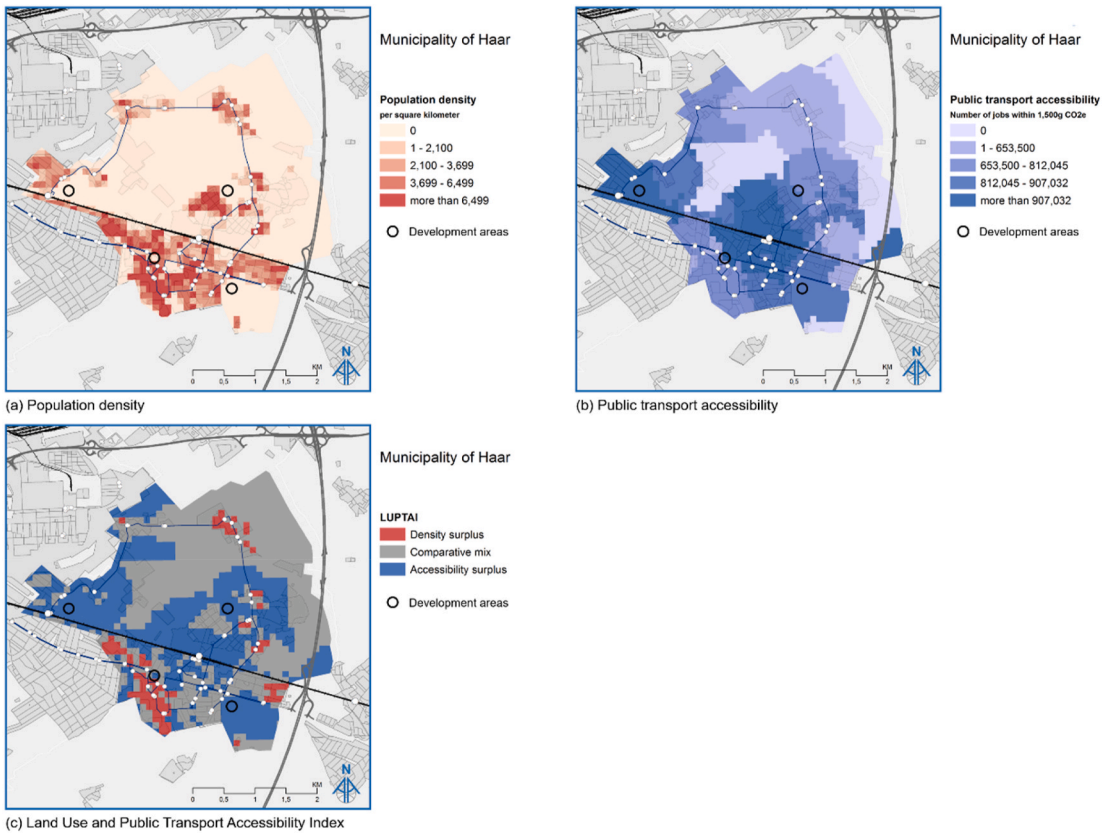

Fig. 2. Population density, public transport accessibility, and LUPTAI in the municipality of Haar.

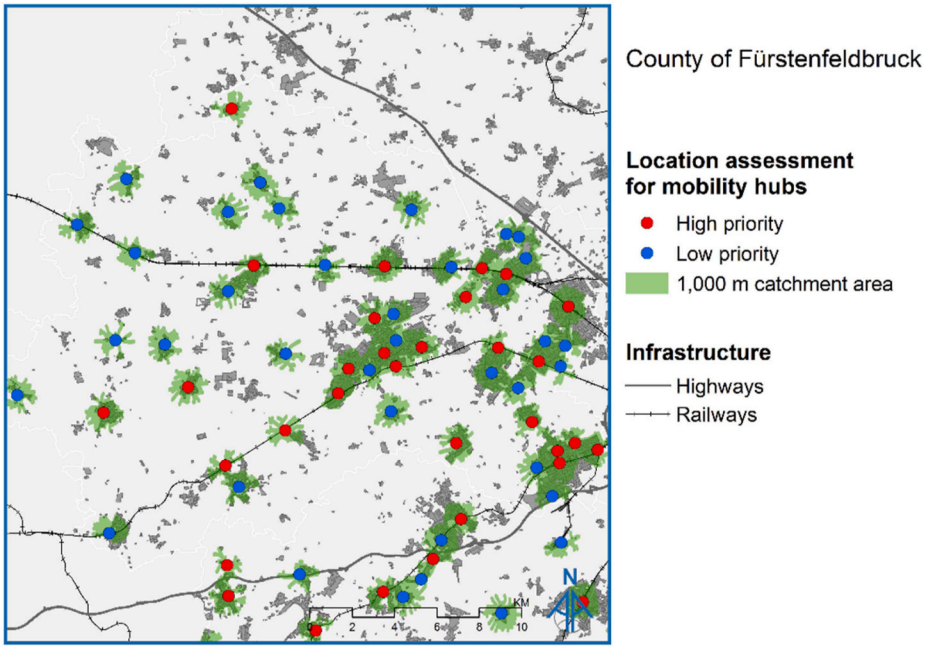

Fig. 3. Potential locations of mobility stations in the county of Fürstenfeldbruck.

interventions. The core reason of this observation might lie in the institutional isolation of land use and transport planning: In an environment where land use planners take care of land use planning and transport planners take care of transport planning, using an integrated performance indicator such as accessibility is not the norm. Planners are typically not acquainted with accessibility evaluations, since accessibility standards or reference values barely exist. These key implementation barriers of accessibility instruments have been reported in other contexts (Bertolini and Silva, 2019, Te Brömmelstroet et al., 2019b; Te Brömmelstroet, 2010) and were confirmed in this research.

While accessibility is not a formal performance indicator, CO_2 emission quantification clearly is. During the closing workshop, one

practitioner stated that ex-ante quantification of emission savings is intangible and does not have any real meaning, but is crucial for satisfying the requirements of funding schemes. In fact, an evaluation was only performed in the case of the mobility hubs application (3.2.1), where accessibility outcomes could be linked to emission savings. Based on the outputs of accessibility analysis and additional data from travel survey statistics, the spreadsheet developed within this application enables a rough estimation of emission savings (Fig. 4).

First, the number of potential customers is estimated based on the destination potentials within the catchment area of the mobility hub. Then, the reduction in vehicle mileage among these customers is estimated to yield the expected emission reductions. Despite limited scientific rigor, this approach enables practitioners to estimate emission savings in a transparent way, using basic data and assumptions. This combination of accessibility analysis and emission quantification is comparably easy to apply and understand, but a full evaluation (also with respect to other planning goals) certainly requires more sophisticated tools (Bertolini et al., 2005; Straatemeier, 2008; Hensher, 2008).

4.3. Communication

The value of accessibility outputs in supporting interaction between different stakeholders was recognized, although this ability might currently be underused due to the isolation of planning disciplines. Unilateral viewpoints became evident when, despite the use of accessibility as an integrative concept, practitioners still focused more on their respective planning discipline. In the express bus lines application (3.2.3), transport planners were mainly interested in the size and shape of the catchment area, not as much the number of accessible workers. In the urban planning application (3.2.2), the transport system's function as a connector between origins and destinations was difficult to discern for the involved land use planner. Nevertheless, the involved practitioners were more aware of the importance of integrating their projects into both the existing land use and transport systems after seeing the outputs of accessibility instruments. Such awareness represents a crucial first step towards integrated land use and transport planning.

A central focus that emerged early on in the process was the intermediary role of land use and transport planners, having to communicate with experts and professionals, politicians, and citizens. Specific communication needs in the context of planning for low carbon mobility options were gathered during the kick-off workshop. A first point was the need for argumentation support to promote and accelerate projects. Planners may recommend preferred solutions, but politicians decide about their realization. Moreover, while there is increasing willingness to spend money on climate change mitigation, decision-makers still need to hear good arguments and see potential benefits of a project to approve of investments. In this context, practitioners mentioned that simpler methods than traditional cost-benefit analyses are needed as argumentation support. Simplicity and understandability are also key for communicating the benefits of planned or implemented solutions to citizens as the potential users. It should be noted that all of these points were raised by transport planners, which can be explained by the fact that in transport planning, emission reductions are at the center of attention. On the contrary, in land use planning, the reduction of transport-related emissions is not a dedicated decision criterion per se, which makes the issue less relevant and concrete (this reasoning was confirmed in conversations with the practitioners).

Map-based outputs turned out to be particularly relevant for planners' communication needs in the context of planning for low carbon mobility options. Both during the strategy workshop and during the closing workshop, practitioners highly appreciated the power of maps in making planning issues understandable at a glance. The outputs of accessibility instruments might not always serve the specific information needs of planners, but they can be used to communicate the benefits of solutions towards non-expert decision-makers, be it politicians or citizens, once these benefits have been evaluated by other means. This was most evident in the express bus lines application (3.2.3), where the maps highlight striking differences in the shapes of catchment areas between car and public transport. Fig. 5 exemplifies this by showing the carbon catchment areas for the two cities of Dachau and Fürstenfeldbruck, using an emission budget of 1 kg of CO_{2e}. On average across all analyzed hubs, the number of accessible workers within the catchment is eight times higher by public transport than by car. However, highly occupied radial train services contribute more to this difference than orbital bus services. Occupancy rates on express bus lines were increased in two scenarios to 30% and 50%, respectively, above the modeled values. Increases in occupancy rate of such magnitude are indeed required in some areas to ensure the competiveness of public transport in terms of per-passenger emissions compared to the car. These findings highlight that public transport is not by default more carbon efficient than the car, which in turn reinforces the importance of making the offer attractive to citizens. Overall, the application showed that accessibility instruments can make the emission impacts of different transport modes tangible. At the same time, practitioners stressed that indicators of public transport

Basic data

	Residents	Employees	Customers and visitors
Number within catchment area of hubs	12,666	3,135	9,405
Trips per day	3.1	2.5	2
Projection coefficient [days/year]	365	249	365
Emission factor [grams/km]	182		

Scenario assumptions

	Residents	Employees	Customers and visitors
Share of bike sharing customers	7%	7%	7%
Relative reduction of car trips	-5%	-10%	-15%

Scenario without bike sharing

	Residents	Employees	Customers and visitors
Share of car trips	53%	60%	49%
Occupancy [passengers/car]	1.5	1.2	1.5
Average trip length [km]	17.9	20.5	18.2
Vehicle mileage [millions of km/year]	90.6	20.0	40.8
Emissions [tons/year]	16,497	3,641	7,429
Total emissions [tons/year]	27,567		

Scenario with bike sharing

	Residents	Employees	Customers and visitors
Share of car trips	52.8%	59.6%	48.5%
Occupancy [passengers/car]	1.5	1.2	1.5
Average trip length [km]	17.9	20.5	18.2
Vehicle mileage [millions of km/year]	90.3	19.9	40.4
Emissions [tons/year]	16,439	3,615	7,351
Total emissions [tons/year]	27,405		
Potential emission savings [tons/year]	161		

Fig. 4. Spreadsheet to calculate emission savings due to bike sharing services provided at a mobility hub (a similar spreadsheet is available for car sharing services).

Fig. 5. Carbon catchment areas by car (a–b) and transit (c–d) from Dachau and Fürstenfeldbruck.

service quality, affordability, and comfort, such as fares, travel time or number of transfers, need to be considered as well. These are particularly important from a user perspective and most likely more important than CO_2 emissions (Salonen et al., 2014). Thus, maps are a valuable, but not the only means of effective communication.

While the practitioners verified the understandability and interpretability of accessibility outputs, the calculations behind the outputs were not necessarily considered transparent. However, further discussions revealed that understanding the outputs and being able to explain them to others is more important than fully understanding the underlying input data, assumptions, and calculations (although both aspects are connected). Simple indicators are preferable to complex ones for communication with non-expert decision makers, which was most evident in the urban planning application (3.2.2). The involved practitioner rated the initially employed gravity-based indicator as too complex for effective communication with politicians, who typically have less expertise than planners.

5. Conclusions

5.1. Likeliness of implementation

The objective of this work was to shed light on the practical relevance of accessibility instruments for the policy and planning aim of reducing transport-related emissions. Accessibility instruments turned out to be applicable to a variety of low carbon planning issues in both land use and transport planning. Future potential use cases were identified during the closing workshop, including location allocation of public transport stops and retail, analysis of corridors for cycling highways, and emission budgeting for residents and businesses to increase transparency in terms of transport-related emissions.

Concerning the likeliness of future implementation of accessibility instruments for low carbon mobility planning, our findings reveal two main implementation barriers. The first is the already known institutional separation of land use and transport planning (Bertolini and Silva, 2019), which undermines the relevance of an integrated concept, such as accessibility. The second one is specific to the planning issue of low carbon mobility planning: Accessibility instruments cannot directly quantify CO_2 emissions, which is why these tools can be used to plan for low carbon mobility options, but cannot estimate emission reductions – a central performance indicator for evaluating the impacts of interventions.

Accessibility instruments offer a plethora of application purposes for low carbon planning, but the main challenge might lie in introducing accessibility to practitioners who are unfamiliar with the concept and its multi-dimensional nature. Joint policy design and planning also requires a corresponding institutional framework, equipping practitioners with the competences required for integrated planning and defining formal accessibility requirements (Silva et al., 2017; Bertolini and Silva, 2019). Even if practitioners are open to using planning support tools other than the established ones, they need to adhere to political guidelines. Consequently, a provocative question might be: Do accessibility instruments provide unsuitable outputs for low carbon mobility planning or are we using unsuitable processes and performance indicators? While there certainly is no clear answer to this question, accessibility tools and indicators need to be developed further in order to become an accepted standard, as recommended by one of the involved practitioners. However, institutionalization is not the only implementation path for accessibility instruments. Practitioners recognized the practical relevance and clear implementation potential of accessibility instruments within mixed-method approaches, for example in terms of communication (section 4.3). Moreover, reprioritization of political objectives as well as new mobility options and services require new planning approaches. Alternative tools, such as accessibility instruments, might fill the niches opening up. An important conclusion of the planning practice applications was that all practitioners are interested in using accessibility instruments in the future.

Two points are central for increasing the implementation potential of

accessibility instruments. Firstly, accessibility instruments need to be more accessible and provide key functionalities and data through interactive tools, possibly available online. Secondly, practitioners need not only formal, but also informal reference values as orientation. Examples include the minimum number of opportunities within the catchment area of mobility hubs to successfully operate the system or a reference value defining "good" accessibility conditions for urban development, beyond relative comparisons within the territory of one single municipality.

5.2. Needs for further research

Whether accessibility evaluations will be established in the future to assess the impacts of land use and transport interventions on environmental or other goals remains an open question. Future research exploring the practical relevance of accessibility instruments for low carbon mobility planning could focus on the following aspects:

1. One key advantage of accessibility instruments is their capability to integrate land use and transport planning, a crucial prerequisite for sustainable development in general and low carbon mobility in particular. Thus, future research should systematically explore if and how accessibility instruments can support the development of integrated transport and land use policies and plans, where the joint goal is to reduce transport-related emissions.
2. Another research path worth exploring concerns the usefulness of accessibility as an environmental indicator. Scholars have long demanded a shift from mobility-based to accessibility-based evaluations, but typically with a social rather than an environmental focus (Ferreira et al., 2012). Future research could compare and contrast the outcomes of carbon-based accessibility analysis, travel-time-based evaluations, and model-based emission savings.
3. There should be a more detailed evaluation of different ways to present accessibility outputs to politicians and citizens in order to determine which of these communication forms work best, for which purpose and under which conditions.
4. Finally, future research should further explore potential paths for implementing accessibility instruments to plan for low carbon mobility options. What are barriers and drivers? How do accessibility instruments fit into existing and emerging planning processes or institutions?

While the planning practice applications and conclusions presented in this paper refer to a particular spatial and institutional context, the applied research approach could be transferred elsewhere. Generally valid conclusions on the practical relevance of accessibility instruments for low carbon mobility planning need to rely on findings from a larger variety of applications, instruments, and planning contexts. In addition, qualitative methods, such as interviews and focus groups, might be suitable to gain a deeper understanding of the practitioners' perspective. A more diversified collection of experiences will enrich the knowledge on how to best employ accessibility instruments for low carbon mobility planning – an issue that is relevant all over the world.

Declaration of interest

None.

Author statement

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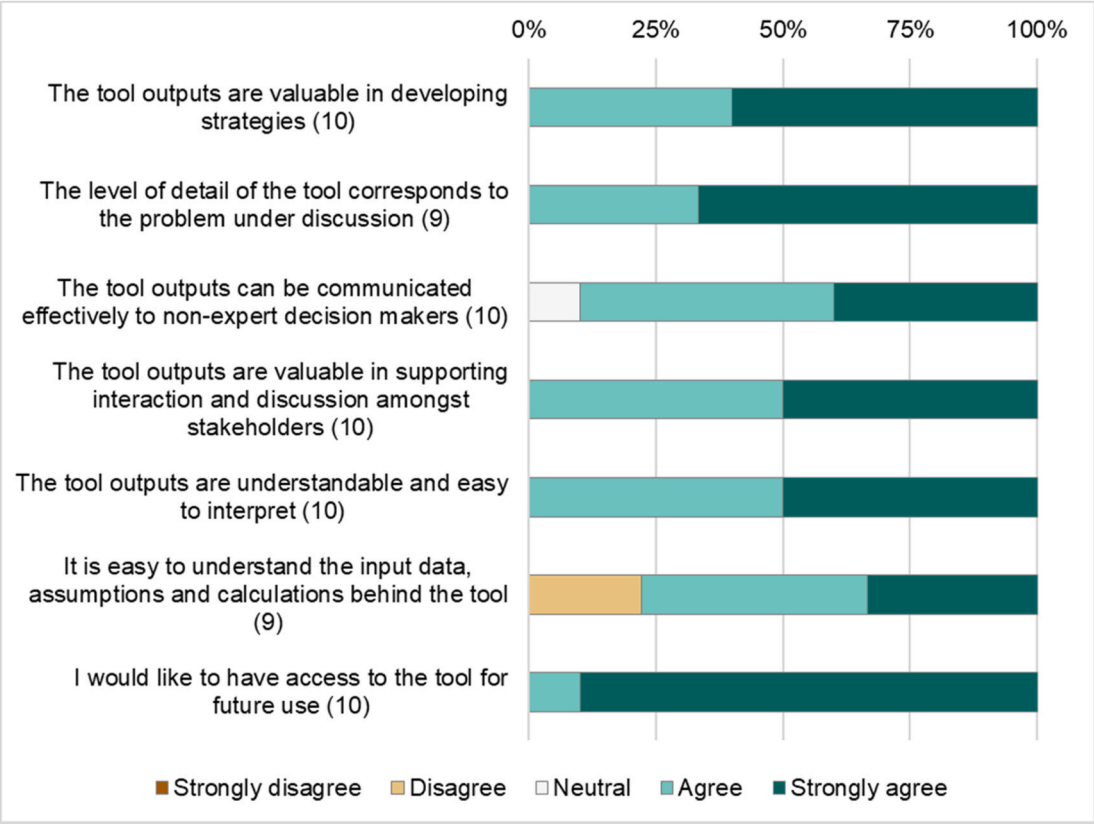
Appendix A. Selected statements from the user survey conducted during the strategy workshop (number of responses in parentheses)



References

Banister, D., 2008. The sustainable mobility paradigm. Transport Pol. 15, 73–80.

Banister, D., 2011. Cities, mobility and climate change. J. Transport Geogr. 19, 1538–1546.

Barla, P., Miranda-Moreno, L.F., Lee-Gosselin, M., 2011. Urban travel CO2 emissions and land use: a case study for Quebec City. Transport. Res. Transport Environ. 16, 423–428.

Bertolini, L., Le Clercq, F., Kapoen, L., 2005. Sustainable accessibility: a conceptual framework to integrate transport and land use plan-making. Two test-applications in The Netherlands and a reflection on the way forward. Transport Pol. 12, 207–220.

Bertolini, L., Silva, C., 2019. Bridging the implementation gap. In: Silva, C., Bertolini, L., Pinto, N. (Eds.), Designing Accessibility Instruments: Lessons on Their Usability for Integrated Land Use and Transport Planning Practices. Routledge, New York.

Cervero, R., Kockelman, K., 1997. Travel demand and the 3Ds: density, diversity, and design. Transport. Res. Part D: Transp. Environ. 2, 199–219.

Curtis, C., 2008. Planning for sustainable accessibility: the implementation challenge. Transport Pol. 15, 104–112.

Curtis, C., Scheurer, J., 2010. Planning for sustainable accessibility: developing tools to aid discussion and decision-making. Prog. Plann. 74, 53–106.

Ferreira, A., Beukers, E., Te Brömmelstroet, M., 2012. Accessibility is gold, mobility is not: a proposal for the improvement of Dutch transport-related cost–benefit analysis. Environ. Plann. Plann. Des. 39, 683–697.

Geels, F.W., 2012. A socio-technical analysis of low-carbon transitions: introducing the multi-level perspective into transport studies. J. Transport Geogr. 24, 471–482.

Geurs, K., Van Wee, B., 2004. Accessibility evaluation of land-use and transport strategies: review and research directions. J. Transport Geogr. 12, 127–140.

Geurs, K., Van Wee, B., 2006. Ex-post evaluation of thirty years of compact urban development in The Netherlands. Urban Stud. 43, 139–160.

Handy, S., Cao, X., Mokhtarian, P., 2005. Correlation or causality between the built environment and travel behavior? Evidence from Northern California. Transport. Res. Transport Environ. 10, 427–444.

Handy, S., Niemeier, D., 1997. Measuring accessibility: an exploration of issues and alternatives. Environ. Plann. 29, 1175–1194.

Hensher, D.A., 2008. Climate change, enhanced greenhouse gas emissions and passenger transport – what can we do to make a difference? Transport. Res. Transport Environ. 13, 95–111.

Hickman, R., Ashiru, O., Banister, D., 2010. Transport and climate change: Simulating the options for carbon reduction in London. Transport Pol. 17, 110–125.

Hull, A., Silva, C., Bertolini, L. (Eds.), 2012. Accessibility Instruments for Planning Practice. COST Office.

Kinigadner, J., Büttner, B., Wulfhorst, G., 2019. Beer versus bits: CO2-based accessibility analysis of firms' location choices and implications for low carbon workplace development. Appl. Mobil. 4, 200–218.

Kinigadner, Julia, Vale, David, Büttner, Benjamin, Wulfhorst, Gebhard, 2021. Shifting perspectives: A comparison of travel-time-based and carbon-based accessibility landscapes. J. Transport. Land Use 14, 345–365. https://doi.org/10.5198/jtlu.2021.1741.

Levine, J., Merlin, L., Grengs, J., 2017. Project-level accessibility analysis for land-use planning. Transport Pol. 53, 107–119.

Loo, B., Tsoi, K.H., 2018. The sustainable transport pathway: a holistic strategy of Five Transformations. J. Transp. Land Use 11.

Määttä-Juntunen, H., Antikainen, H., Kotavaara, O., Rusanen, J., 2011. Using GIS tools to estimate CO2 emissions related to the accessibility of large retail stores in the Oulu region, Finland. J. Transport Geogr. 19, 346–354.

Marsden, G., Ferreira, A., Bache, I., Flinders, M., Bartle, I., 2014. Muddling through with climate change targets: a multi-level governance perspective on the transport sector. Clim. Pol. 14, 617–636.

Merlin, L.A., Levine, J., Grengs, J., 2018. Accessibility analysis for transportation projects and plans. Transport Pol. 69, 35–48.

Miramontes, M., Pfertner, M., Rayaprolu, H.S., Schreiner, M., Wulfhorst, G., 2017. Impacts of a multimodal mobility service on travel behavior and preferences: user insights from Munich's first Mobility Station. Transportation 44, 1325–1342.

Næss, P., 2012. Urban form and travel behavior: experience from a Nordic context. J. Transp. Land Use 5.

Næss, P., Strand, A., Næss, T., Nicolaisen, M.S., 2011. On their road to sustainability? The challenge of sustainable mobility in urban planning and development in two Scandinavian capital regions. Town Plan. Rev. 82, 285–316.

Páez, A., Scott, D.M., Morency, C., 2012. Measuring accessibility: positive and normative implementations of various accessibility indicators. J. Transport Geogr. 25, 141–153.

Pajares, E., Büttner, B., Jehle, U., Nichols, A., Wulfhorst, G., 2021. Accessibility by proximity: Addressing the lack of interactive accessibility instruments for active mobility. J. Transport Geogr. 93.

Papa, E., Coppola, P., 2019. The learning process of accessibility instrument developers. In: Silva, C., Bertolini, L., Pinto, N. (Eds.), Designing Accessibility Instruments: Lessons on Their Usability for Integrated Land Use and Transport Planning Practices. Routledge, New York.

Papa, E., Coppola, P., Angiello, G., Carpentieri, G., 2017. The learning process of accessibility instrument developers: Testing the tools in planning practice. Transport. Res. Pol. Pract. 104, 108–120.
Papa, E., Silva, C., Te Brömmelstroet, M., Hull, A., 2016. Accessibility instruments for planning practice: a review of European experiences. J. Transp. Land Use 57–75.
Pelzer, P., 2017. Usefulness of planning support systems: a conceptual framework and an empirical illustration. Transport. Res. Pol. Pract. 104, 84–95.
Rode, P., Da Cruz, N.F., 2018. Governing urban accessibility: moving beyond transport and mobility. Appl. Mobil. 3, 8–33.
Salonen, M., Broberg, A., Kyttä, M., Toivonen, T., 2014. Do suburban residents prefer the fastest or low-carbon travel modes? Combining public participation GIS and multimodal travel time analysis for daily mobility research. Appl. Geogr. 53, 438–448.
Scarinci, R., Rast, F., Bierlaire, M., 2017. Needed reduction in mobility energy consumption to meet the goal of a 2000-watt society. Transport. Res. Pol. Pract. 101, 133–148.
Silva, C., Bertolini, L., Pinto, N. (Eds.), 2019. Designing Accessibility Instruments: Lessons on Their Usability for Integrated Land Use and Transport Planning Practices. Routledge, New York.
Silva, C., Bertolini, L., Te Brömmelstroet, M., Milakis, D., Papa, E., 2017. Accessibility instruments in planning practice: bridging the implementation gap. Transport Pol. 53, 135–145.
Stewart, A.F., 2017. Mapping transit accessibility: Possibilities for public participation. Transport. Res. Pol. Pract. 104, 150–166.
Straatemeier, T., 2008. How to plan for regional accessibility? Transport Pol. 15, 127–137.
Te Brömmelstroet, M., 2010. Equip the warrior instead of Manning the equipment. Land use and transport planning support in The Netherlands. J. Transp. Land Use 3, 25–41.
Te Brömmelstroet, M., Curtis, C., Larsson, A., Milakis, D., 2016. Strengths and weaknesses of accessibility instruments in planning practice: technological rules based on experiential workshops. Eur. Plann. Stud. 24, 1175–1196.
Te Brömmelstroet, M., Milakis, D., Curtis, C., 2019a. Mapping real experiences with accessibility instruments: a methodological approach to improve their design. In: Silva, C., Bertolini, L., Pinto, N. (Eds.), Designing Accessibility Instruments: Lessons on Their Usability for Integrated Land Use and Transport Planning Practices. Routledge, New York.
Te Brömmelstroet, M., Schrijnen, P.M., 2010. From planning support systems to mediated planning support: a structured dialogue to overcome the implementation gap. Environ. Plann. Plann. Des. 37, 3–20.
Te Brömmelstroet, M., Silva, C., Bertolini, L. (Eds.), 2014. Assessing Usability of Accessibility Instruments. COST Office, Amsterdam.
Te Brömmelstroet, M., Silva, C., Milakis, D., Papa, E., 2019b. Bottleneck blocking use of accessibility instruments - exploring usability, usefulness and institutional barriers. In: Silva, C., Bertolini, L., Pinto, N. (Eds.), Designing Accessibility Instruments: Lessons on Their Usability for Integrated Land Use and Transport Planning Practices. Routledge, New York.
Vasconcelos, A.S., Farias, T.L., 2012. Evaluation of urban accessibility indicators based on internal and external environmental costs. Transport. Res. Transport Environ. 17, 433–441.
Wulfhorst, G., Büttner, B., Ji, C., 2017. The TUM Accessibility Atlas as a tool for supporting policies of sustainable mobility in metropolitan regions. Transport. Res. Pol. Pract. 104, 121–136.
Yigitcanlar, T., Sipe, N., Evans, R., Pitot, M., 2007. A GIS-based land use and public transport accessibility indexing model. Aust. Plan. 44, 30–37.