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Carbon-based accessibility analysis
Characteristics, operationalization, theoretical basis, and practical relevance of a planning tool for low carbon mobility options

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Abstract

Climate change mitigation represents one of the main challenges of our time. The transport sector is among the largest contributors to continuously increasing greenhouse gas emissions worldwide. Consequently, decision-makers are obliged to find appropriate strategies to reduce transport-related emissions.

This thesis explores the benefits and limitations of carbon-based accessibility instruments as decision-making tools for low carbon mobility planning, with a focus on everyday passenger transportation. CO_2 emissions are considered as the relevant travel cost in location-based accessibility measures to operationalize the concept of carbon-based accessibility. Carbon-based accessibility instruments are expected to fulfill three criteria for low carbon mobility planning: focusing on emission impacts, integrating land use and transport, and addressing decision-makers. The implications in terms of advantages and disadvantages compared to other decision-making tools and methods are explored along four research questions, relating to tool characteristics, operationalization, theoretical basis, and practical relevance. A carbon-based accessibility instrument for the Munich region is developed and used in various experiential and planning practice applications in order to identify strengths and weaknesses for decision-making processes related to ambitious emission reduction targets.

Existing tools and methods in this context mainly focus on transport planning, whereas carbon-based accessibility analysis enables integrated land use and transport planning to provide for low carbon mobility options. While the method does not enable aggregated emission quantification, it is capable of visualizing catchment areas and accessibility levels based on emission budgets. The outputs reflect changes in the land use and transport systems, but cannot directly assess measures aimed at behavioral change, such as pricing strategies or awareness campaigns. However, the increased transparency, understandability, and communicability of carbon-based accessibility instruments counterbalance this limitation.

Carbon-based accessibility is more difficult to operationalize than traditional accessibility approaches, since CO_2 emissions need to be added to the transport network models. CO_2 emissions per passenger-km are influenced by three main parameters: energy consumption, emission factors, and occupancy rates, which feature large variations by spatial and temporal context. The chosen values significantly influence the analysis results, but they can also be freely changed based on assumptions or targets in order to assess a variety of scenarios.

Carbon-based accessibility is conceptually different from traditional accessibility approaches by focusing on external travel costs instead of internal user costs. This shift in perspectives accounts for a clear distinction from tools which have strong ties with travel behavior theory. Low carbon mobility options are an important prerequisite for low carbon mobility behavior. Nevertheless, acceptable travel costs from an individual perspective do not necessarily correspond with acceptable emissions from a collective perspective. This conflict emphasizes the importance of accompanying measures, such as pricing strategies, that ensure that travel demand, which is determined by internal travel costs, matches the boundaries set by the associated external travel costs.

There exists a variety of useful applications for carbon-based accessibility analysis in planning practice. These include the identification of intervention needs, the assessment of alternative land use and transport scenarios as well as communication purposes. In terms of analytical capabilities, carbon-based accessibility instruments are more useful in early planning phases to generate strategies and assess scenarios. Emission quantification is the key performance indicator for evaluating projects and measures, whereas accessibility is still facing the well-known implementation barrier. Furthermore, carbon-based accessibility instruments are sensitive to only a selection of interventions and impacts that are relevant for transport-related emissions. While these limitations restrain the relevance of carbon-based accessibility instruments as evaluation tools for project appraisal in later planning phases, their communicative skills are useful throughout the planning process. Carbon-based accessibility instruments can promote the implementation of solutions and has the potential to enhance the commitment of both public and private stakeholders.

Accessibility planning, both carbon-based and traditional, is a powerful method to plan for both low carbon mobility options by motorized modes on a regional scale and non-motorized mobility options on a local scale. Clearly, other approaches are still needed to develop and evaluate effective climate change mitigation measures, also with respect to wider sustainability goals. However, carbon-based accessibility instruments bring a unique set of characteristics into planning and decision-making, which warrant further exploration in future research.

Kurzfassung

Klimaschutz stellt eine der größten Herausforderungen unserer Zeit dar. Der Verkehrssektor trägt signifikant zu steigenden Treibhausgasemissionen weltweit bei. Entscheidungsträger müssen daher passende Lösungen zur Reduzierung der verkehrsbedingten CO_2-Emissionen finden.

Diese Dissertation untersucht die Stärken und Schwächen von CO_2-Erreichbarkeitstools als Entscheidungsinstrumente bei der Planung kohlenstoffarmer Mobilität. Der Fokus liegt dabei auf dem alltäglichen Personenverkehr. Die Operationalisierung von CO_2-Erreichbarkeit erfolgt mithilfe eines standortbasierten Erreichbarkeitsindikators, der Emissionen als Reisekosten berücksichtigt. Es wird davon ausgegangen, dass CO_2-Erreichbarkeit die folgenden drei Kriterien erfüllt: Fokus auf Emissionen, Integration von Siedlung und Verkehr und Unterstützung von Entscheidungsträgern. Welche Vor- und Nachteile dadurch bei der Planung kohlenstoffarmer Mobilität im Vergleich zu anderen Entscheidungsinstrumenten und -methoden entstehen, wird anhand von vier Forschungsfragen beleuchtet, die sich auf Eigenschaften, Operationalisierung, theoretische Grundlagen und Praxisrelevanz des Tools beziehen. Ein für die Region München entwickeltes CO_2-Erreichbarkeitstool wird in hypothetischen und realen Anwendungen erprobt, um Stärken und Schwächen bei der Unterstützung von Entscheidungsprozessen im Zusammenhang mit ambitionierten CO_2-Reduktionszielen zu identifizieren.

Bestehende Instrumente und Methoden in diesem Kontext dienen überwiegend der Verkehrsplanung, wohingegen CO_2-Erreichbarkeitsanalysen eine integrierte Siedlungs- und Verkehrsplanung für kohlenstoffarme Mobilitätsoptionen ermöglichen. Emissionsberechnungen auf aggregierter Ebene sind nicht möglich, allerdings können anhand von Emissionsbudgets Einzugsbereiche visualisiert und Erreichbarkeitsniveaus berechnet werden. Die Methode reagiert auf Änderungen der Siedlungsstruktur und des Verkehrsangebots, kann jedoch Maßnahmen wie Bepreisung oder Sensibilisierungskampagnen, die direkt auf das Mobilitätsverhalten abzielen, nicht unmittelbar abbilden. Im Gegenzug bieten CO_2-Erreichbarkeitstools bessere Transparenz, Verständlichkeit und Kommunizierbarkeit.

CO_2-Erreichbarkeit lässt sich im Vergleich zu traditionellen Erreichbarkeitskonzepten schwieriger operationalisieren, da Emissionen in den Modellen der Verkehrsnetze abgebildet werden müssen. Die CO_2-Emissionen pro Personenkilometer werden primär von drei Parametern beeinflusst: Verbrauch, Emissionsfaktor und Besetzungsgrad, welche

sowohl räumlich als auch zeitlich variieren. Die konkreten Werte bestimmen die Analyseergebnisse, können jedoch auch anhand von Annahmen oder Zielen gewählt werden, um verschiedene Szenarien zu testen.

Da CO_2-Erreichbarkeit durch externe Umweltkosten und nicht interne Nutzerkosten bestimmt wird, unterscheidet sie sich konzeptionell von traditioneller Erreichbarkeit. Durch diesen Perspektivwechsel weicht CO_2-Erreichbarkeit von Methoden ab, die stärker mit dem tatsächlichen Reiseverhalten verknüpft sind. Optionen für eine kohlenstoffarme Mobilität sind eine wichtige Voraussetzung für kohlenstoffarmes Mobilitätsverhalten. Die aus individueller Sicht annehmbaren Reisekosten entsprechen jedoch nicht unbedingt den aus kollektiver Sicht akzeptablen Emissionen. Begleitmaßnahmen wie Bepreisung sind daher wichtig, um sicherzustellen, dass die durch interne Kosten bestimmte Nachfrage innerhalb der durch externe Kosten gesetzten Grenzen liegt.

Für CO_2-Erreichbarkeitsanalysen gibt es zahlreiche Anwendungsmöglichkeiten in der Planungspraxis, unter anderem das Identifizieren von Interventionsmöglichkeiten, die Untersuchung alternativer Szenarien für Siedlungsstruktur und Verkehr sowie die Verbesserung der Kommunikation. Die analytischen Fähigkeiten von CO_2-Erreichbarkeit helfen in frühen Planungsphasen dabei, Strategien zu entwickeln und Szenarien zu analysieren. Emissionsberechnungen sind als Bewertungskriterium zentral für die Beurteilung von Projekten und Maßnahmen, wohingegen Erreichbarkeit nach wie vor einigen Hürden bei der Umsetzung gegenübersteht. CO_2-Erreichbarkeitstools können nur bestimmte emissionsrelevante Interventionen und Wirkungen abbilden. Aus diesen Gründen sind CO_2-Erreichbarkeitstools weniger geeignet für eine umfassende Projektbewertung in späteren Planungsphasen. Kommunikative Fähigkeiten sind jedoch während des gesamten Planungsprozesses hilfreich. CO_2-Erreichbarkeitstools bieten das Potenzial, die Realisierung von Maßnahmen zu beschleunigen und das Engagement öffentlicher und privater Akteure zu verbessern.

Erreichbarkeitsplanung (sowohl CO_2-basiert als auch traditionell) hilft dabei, kohlenstoffarme Optionen für motorisierte Mobilität auf regionaler Ebene sowie für nicht motorisierte Mobilität auf lokaler Ebene zu schaffen. Andere Methoden werden ergänzend benötigt, um effektive Maßnahmenpakete für den Klimaschutz oder auch andere Nachhaltigkeitsziele zu entwickeln und zu bewerten. Dennoch verfügen CO_2-Erreichbarkeitstools über für Planungs- und Entscheidungsprozesse wertvolle Eigenschaften, die in Zukunft weiter erforscht werden sollten.

Table of contents

List of abbreviations

A

ASTUS	*Alpine Smart Transport and Urbanism Strategies*

B

BMU	*Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (Bundesministerium für Umwelt, Naturschutz und nukleare Sicherheit)*

C

CBA	*Cost-benefit analysis*
CLC	*CORINE Land Cover*
CO_2	*Carbon dioxide*
CO_{2e}	*Carbon dioxide equivalents*

D

DB	*German Railways (Deutsche Bahn)*

E

EC	*European Commission*
EEA	*European Environment Agency*
EMM	*Munich Metropolitan Region (Europäische Metropolregion München)*
EU	*European Union*

G

GHG	*Greenhouse gas*
GIS	*Geographic information system*

H

HBEFA	*Handbook Emission Factors for Road Transport*

I

IPCC	*Intergovernmental Panel on Climate Change*

L

LHM	*City of Munich (Landeshauptstadt München)*
LVM-By	*Travel demand model of the State of Bavaria (Landesverkehrsmodell Bayern)*

M

MVG	*Munich public transport operator (Münchner Verkehrsgesellschaft)*
MVV	*Munich Transport and Tariff Association (Münchner Verkehrs- und Tarifverbund)*

O

OSM	*OpenStreetMap*

R

RQ	*Research question*

T

TAZ	*Transportation Analysis Zone*
TREMOD	*Transport Emission Model*
TUM	*Technical University of Munich*

U

UBA	*German Environment Agency (Umweltbundesamt)*
UNEP	*United Nations Environment Programme*
UNFCCC	*United Nations Framework Convention on Climate Change*

List of figures

List of tables

1. Introduction

1.1. Background

A large part of human activities is fueled by fossil energy, emitting carbon dioxide (CO_2) and other greenhouse gases (GHG), which contribute to a global rise in temperatures (Climate Transparency, 2018). In 1992, the United Nations Framework Convention on Climate Change (UNFCCC) was initiated, aiming to stabilize GHG concentrations in the atmosphere (United Nations, 1992). The convention, which entered into force in 1994, not only acknowledged the existence of climate change, but also the substantial contribution of human activities to its acceleration (UNFCCC, 2020c). Initially, emission limits were neither compulsory nor enforced, but the UNFCCC outlined potential pathways towards binding international agreements (United Nations, 1992). These were adopted with the Kyoto Protocol in 1997, which committed developed countries to binding emission targets, as defined in its Annex B (UNFCCC, 1997). The emission targets pursued during the first commitment period (2008-2012) correspond to an average of 5 % reduction compared to 1990 levels (UNFCCC, 2020a) and were revised in the Doha Amendment for a second commitment period (2013-2020), aiming for emission reductions of at least 18 % (UNFCCC, 2012). In 2015, the UNFCCC parties reached the Paris Agreement as a follow-up to the Kyoto Protocol in the quest for climate protection (UNFCCC, 2020b). The primary objective of the Paris Agreement is to keep the global temperature increase below 2° Celsius or even below a more ambitious limit of 1.5° Celsius (UNFCCC, 2015). A recent report by the Intergovernmental Panel on Climate Change (IPCC) emphasizes that the limit of 1.5° is in fact imperative if irreversible negative consequences of global warming are to be avoided (IPCC, 2018). Against this background, climate change emerges as central within the global discourse and political agenda. Civil initiatives like “Fridays for Future” urge for fulfillment of the Paris Agreement, thus giving further momentum to the topic (Fridays For Future). Governments are under growing pressure, since ambitious and comprehensive action is required to reduce and manage the risks related to climate change (IPCC, 2014a; IPCC, 2014b).

The dilemma of climate protection and the role of the transport sector

In line with international agreements, GHG emission reduction targets are anchored in legislations throughout the world. The European Commission (EC) defines a reduction target of 20 % compared to 1990 levels in its 2020 climate and energy package under the UNFCCC and the Kyoto Protocol (EC, 2020a). According to the 2019 inventory report of the European Environment Agency (EEA), GHG emissions in 2017 were already

23.5 % below 1990 levels (EEA, 2019a, p. iii). Looking further into the future, the 2030 target foresees GHG emissions to be 40 % below 1990 levels (EC, 2020b). While the European Union (EU) is on the way to reaching its 2020 target, projections are less positive regarding the 2030 target, which will likely be missed unless additional policies and measures are implemented by EU member states (EEA, 2019c). Not only the EU needs to enhance its efforts regarding climate protection: The Emissions Gap Report 2018, prepared by the United Nations Environment Programme (UNEP), highlights the struggle of countries worldwide to reduce emissions in the dimensions necessary to keep global warming within acceptable thresholds (UNEP, 2018).

Why is the limitation of anthropogenic GHG emissions so difficult? The answer lies in the major dilemma that climate change mitigation entails: The magnitude of required emission reductions is large, but so are the difficulties of decoupling energy consumption from economic prosperity (International Energy Agency, 2019) as well as the risks of jeopardizing social wellbeing (Markkanen and Anger-Kraavi, 2019). The negative socio-economic impacts of climate change will unquestionably be much graver than those of climate change mitigation policies (EEA, 2017b). Nevertheless, short-term local costs are difficult to associate with long-term global benefits, which makes climate protection inconvenient. This dilemma concerns the transport sector in particular, since travel is linked to a wide range of social and economic benefits (Banister, 2011; Banister et al., 2011; Chapman, 2007; Bertolini, 2017). While other sectors have succeeded in reducing emissions, transport-related CO_2 emissions in the EU have actually increased since 1990 (see Figure 1).

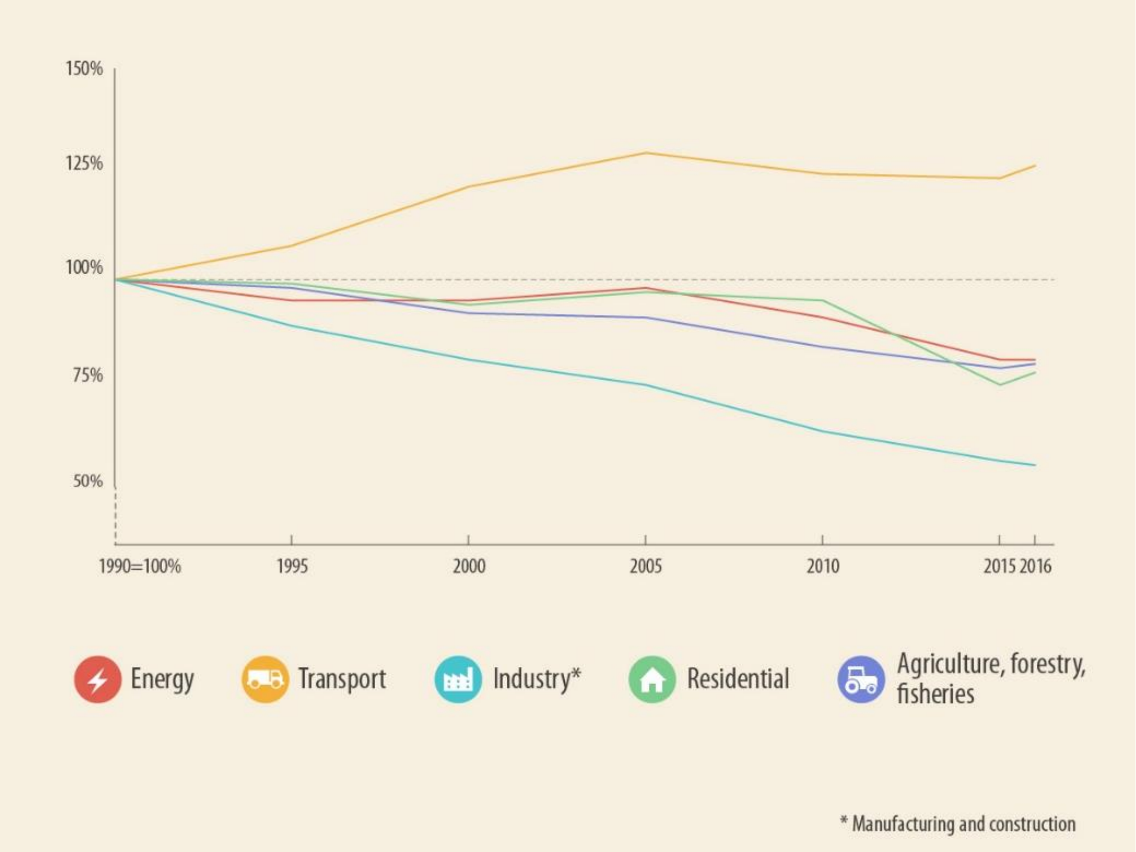

Figure 1. Evolution of CO_2 emissions in the EU by sector (1990-2016). Source: European Parliament (2019) based on data from the EEA.

The transport sector, which includes road and rail transport, aviation, and shipping, is responsible for one quarter of GHG emissions in the EU and the share continues to grow (EEA, 2019a; EEA, 2020). Road transportation alone, which includes both passenger and freight transport, accounts for 72 % of total transport-related GHG emissions (see Figure 2).

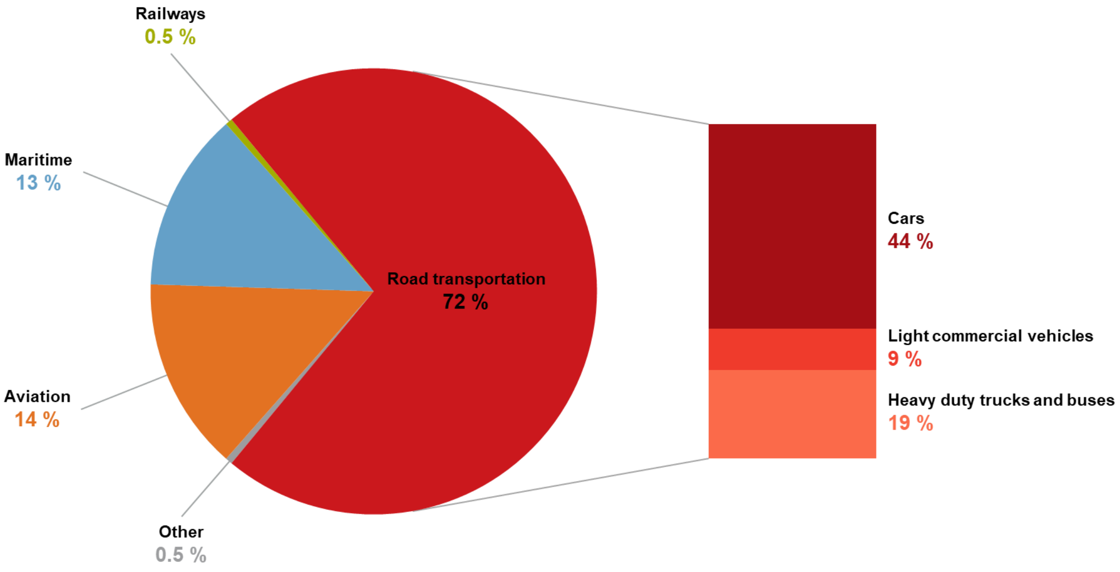

Figure 2. GHG emissions from transport in the EU by mode (2017). Source: Own illustration based on data from the EEA (2019b).

Given these dimensions, the transport sector clearly needs to contribute its share if ambitious emission reduction targets are to be met. The 2011 Transport White Paper targets a 60 % emission cut by 2050, compared to 1990 levels (EU, 2011). In light of the fact that transport-related GHG emissions have actually increased by nearly 30 % since 1990 (including international aviation, excluding international shipping, EEA, 2019b), radical policies and measures are needed to reach this objective (EEA, 2020).

The Climate Action Plan 2050, elaborated by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU), sets medium- and long-term national emission reduction targets in line with agreements on the European level (BMU, 2016). The transport sector is intended to contribute a minimum relative reduction of 40 % to the overall 2030 emission reduction target of 55 % (see Figure 3). However, transport-related emissions in Germany (including road transportation, diesel railways, domestic aviation, and inland shipping) are still on 1990 levels (BMU, 2019a).

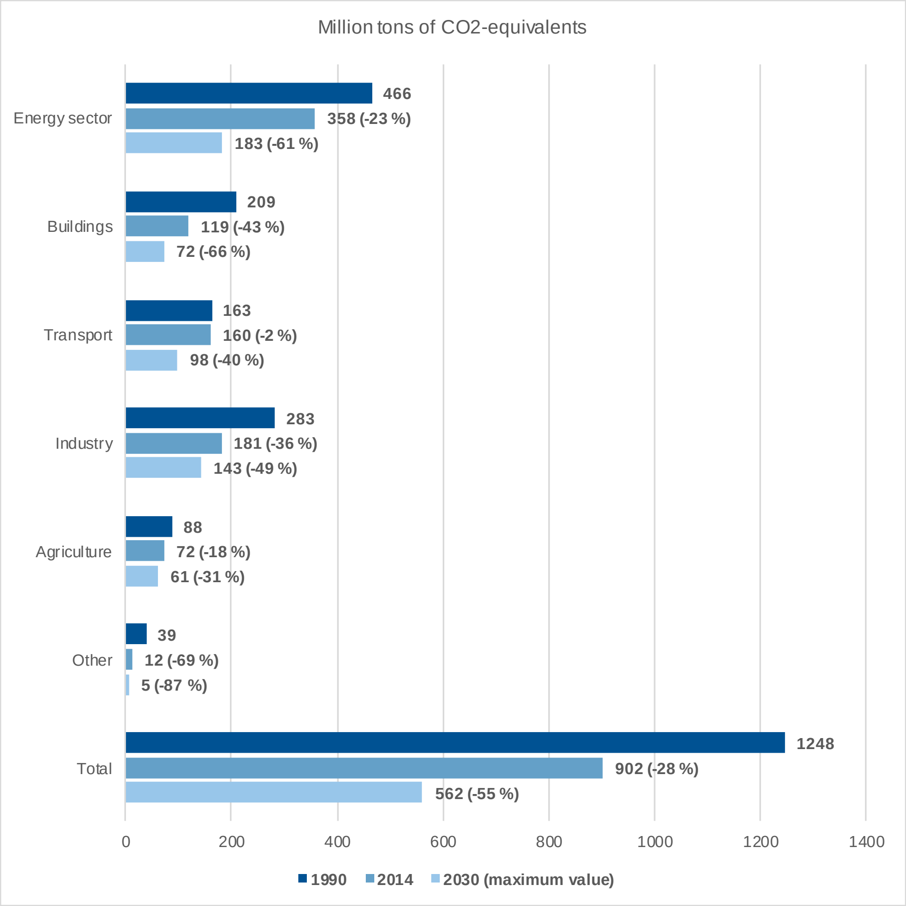

Figure 3. GHG emissions and targets by sector according to the Climate Action Plan 2050 of the German Federal Government. Source: Own illustration based on data from BMU (2016, p. 33).

According to a recent inventory of the German Environment Agency (UBA), GHG emissions from the transport sector have even increased by 0.7 % between 2018 and 2019 (UBA and BMU, 2020). While other sectors, such as the energy sector, contribute their shares to both the 2030 reduction target and the aim of GHG neutrality by 2050, the transport sector remains a huge challenge (UBA and BMU, 2020).

1.2. Motivation and objectives

As outlined in section 1.1, transport-related GHG emissions need to be reduced while economic and social sustainability shall be maintained. The realization that access to opportunities – not transport per se – is the basis of economic development and social wellbeing (Rode and da Cruz, 2018; Ferreira et al., 2012; Handy, 2005) opens up a pathway towards achieving a compromise between economic, social, and environmental goals. Such a compromise requires mobility options that enable linkages between the supply and demand for opportunities while minimizing the negative impacts of transport (Crozet and Wulfhorst, 2010). The extent to which these options are available depends on the characteristics of both the transport system and the land use system. Spatial patterns determine the distribution of residences, jobs, leisure activities, and other locations. Transport networks help to overcome spatial separation by different modes of travel. The accessibility concept describes the joint outcome of the land use and transport systems, thus providing a suitable framework for integrated land use and transport planning (see section 2.2 for further details on the concept and its operationalization). While accessibility planning is widely recognized for contributing to sustainable development in general (Bertolini et al., 2005; Straatemeier, 2008; Curtis, 2008; Banister, 1999), its potential to support low carbon mobility planning deserves particular focus. Accessibility is typically operationalized from a user perspective, where travel time and money are important travel costs (Handy and Niemeier, 1997; Büttner, 2017). The environmental impacts of transport could be catered for in accessibility analysis and planning by focusing on GHG emissions as the relevant travel costs. Within this research, an accessibility instrument tailored to the task of planning for low carbon mobility options is developed and applied in order to:

- Explore the benefits and uncover the limitations of carbon-based accessibility instruments regarding low carbon mobility planning
- Formulate recommendations for researchers, planners, and others who intend to reproduce the method in different political and spatial contexts
- Contribute to the much needed low carbon transition in the transport sector

Project context

This research is embedded in the framework of the project *Alpine Smart Transport and Urbanism Strategies* (ASTUS), which was conducted at the Technical University of Munich (TUM) in cooperation with local and international project partners between November 2016 and December 2019. The project ASTUS was co-financed by the European Regional Development Fund through the program Interreg Alpine Space under Priority 1: Low Carbon Alpine Space, aiming to establish transnationally integrated low carbon policy instruments and to increase options for low carbon mobility and transport (Interreg Alpine Space). ASTUS in particular was designed to support public authorities in identifying and implementing land use and transport planning solutions to reduce CO_2 emissions linked to people's everyday mobility. Hence, while acknowledging the contribution of other transport activities to GHG emissions (compare section 1.1), this research focuses on passenger land travel. Options for extending the proposed method beyond this focus are presented in section 9.2. Local and regional practitioners from Austria, France, Germany, Italy, and Slovenia were involved in the project. The experiences addressed in the remainder of this thesis are linked to the activities in the Munich region with the following pilot sites (see Figure 4): county of Fürstenfeldbruck, county of Starnberg, county of Ebersberg, and county of Munich (including the municipalities of Haar and Neubiberg). All pilot sites are located within the service area of the Munich Transport and Tariff Association (MVV).

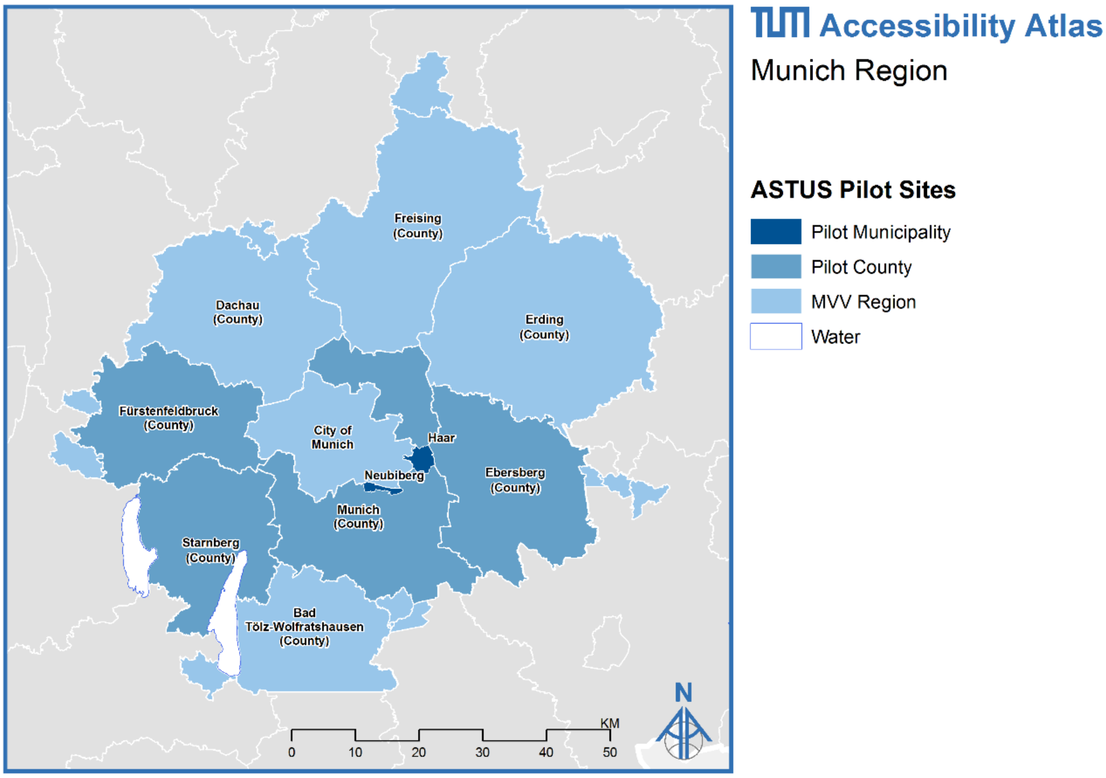

Figure 4. ASTUS pilot sites in the Munich region.

A core task within the project was to develop and test decision-making tools for the generation and assessment of low carbon scenarios. One of these tools was the TUM Accessibility Atlas, an accessibility instrument for the Munich Metropolitan Region (EMM) under development at the TUM Chair of Urban Structure and Transport Planning since 2009 (Büttner et al., 2018; Büttner et al., 2010). It is based on a geographic information system (GIS), containing a multi-modal transport network as well as structural land use data. The instrument aims to inform decision-making in the context of integrated land use and transport planning through map-based outputs. More specifically, it is able to visualize accessibility levels within the EMM by mapping travel cost catchments (see Figure 5), summing up the number of opportunities within a given travel cost threshold or weighting opportunities according to a function of spatial impedance.

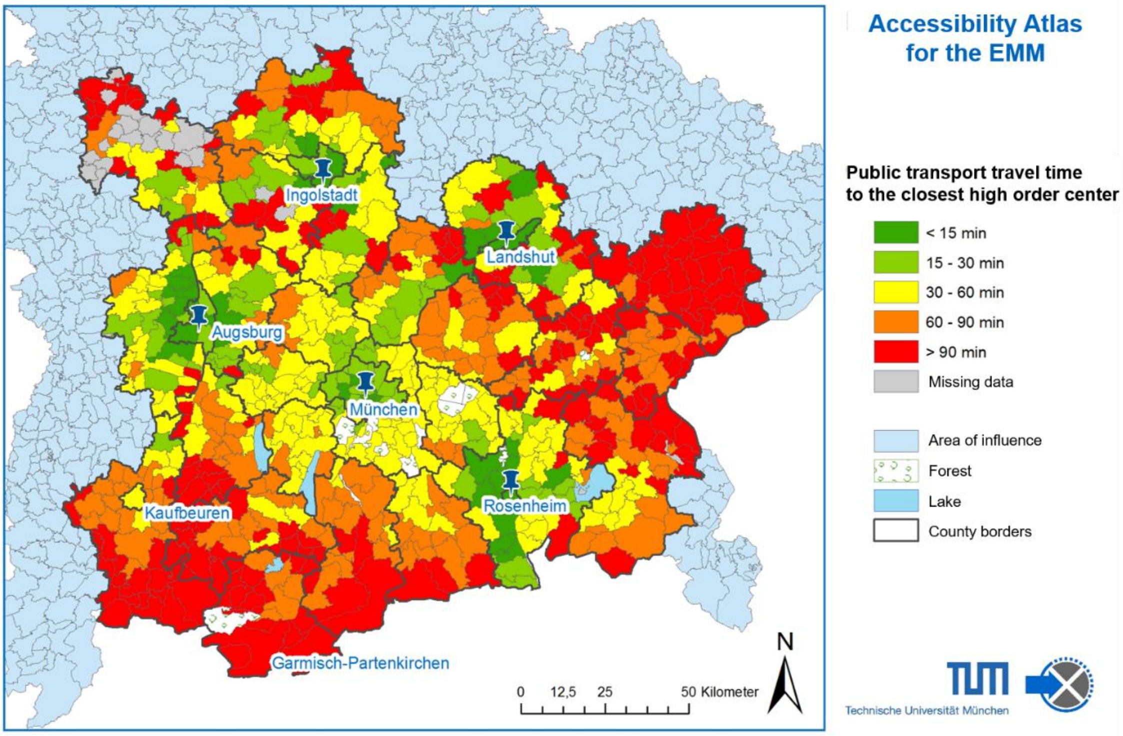

Figure 5. Travel time by public transport to the closest high order center. Source: Büttner et al. (2010, p. 26, translated).

The potential usefulness of the TUM Accessibility Atlas for decision-making was verified in workshops with practitioners (Wulfhorst et al., 2017; Büttner et al., 2019). Previous applications of the TUM Accessibility Atlas used time, distance, and financial expense as travel costs (Büttner et al., 2018). Within ASTUS, the tool was adapted to measure CO_2 emissions by car and public transport as an additional travel cost. The project provided the overall framework for the development of the carbon-based accessibility instrument and its application to real-world planning issues. This setting made it possible to explore the perspectives of both the developer and practitioners on the tool’s benefits and limitations regarding low carbon mobility planning.

1.3. Thesis structure

This thesis consists of nine chapters. Following the introduction to the background, motivation, and objectives in chapter 1, chapter 2 emphasizes the academic and practical importance of the research topic by providing an overview of the context in which this thesis is embedded. Based on the state of the art, carbon-based accessibility instruments are expected to fulfill the following requirements for low carbon mobility planning: focusing on emission impacts, integrating land use and transport, and addressing decision-makers. Chapter 2 also introduces the four research questions (RQ), related to the characteristics, operationalization, theoretical basis, and practical relevance of a carbon-based accessibility instrument. The three-step methodology to address these questions is presented in chapter 3. More precisely, the research design comprises the tool development as well as experiential and planning practice applications of carbon-based accessibility analysis. The implementation of this methodology is linked to four scientific papers (chapters 4 to 7):

Paper I:	Planning for low carbon mobility: Impacts of transport interventions and location on carbon-based accessibility
Paper II:	Beer versus bits: CO_2-based accessibility analysis of firms' location choices and implications for low carbon workplace development
Paper III:	Shifting perspectives: a comparison of travel-time-based and carbon-based accessibility landscapes
Paper IV:	How accessibility instruments contribute to a low carbon mobility transition: Lessons from planning practice in the Munich region

The synthesis and discussion of the findings follow in chapter 8, structured by RQ. This thesis concludes with a reflection on the hypotheses in chapter 9. In addition, future research paths and potential advancements of the method are outlined. An overview of all elements within this thesis, indicating how they build upon and link to each other, is provided in Figure 6.

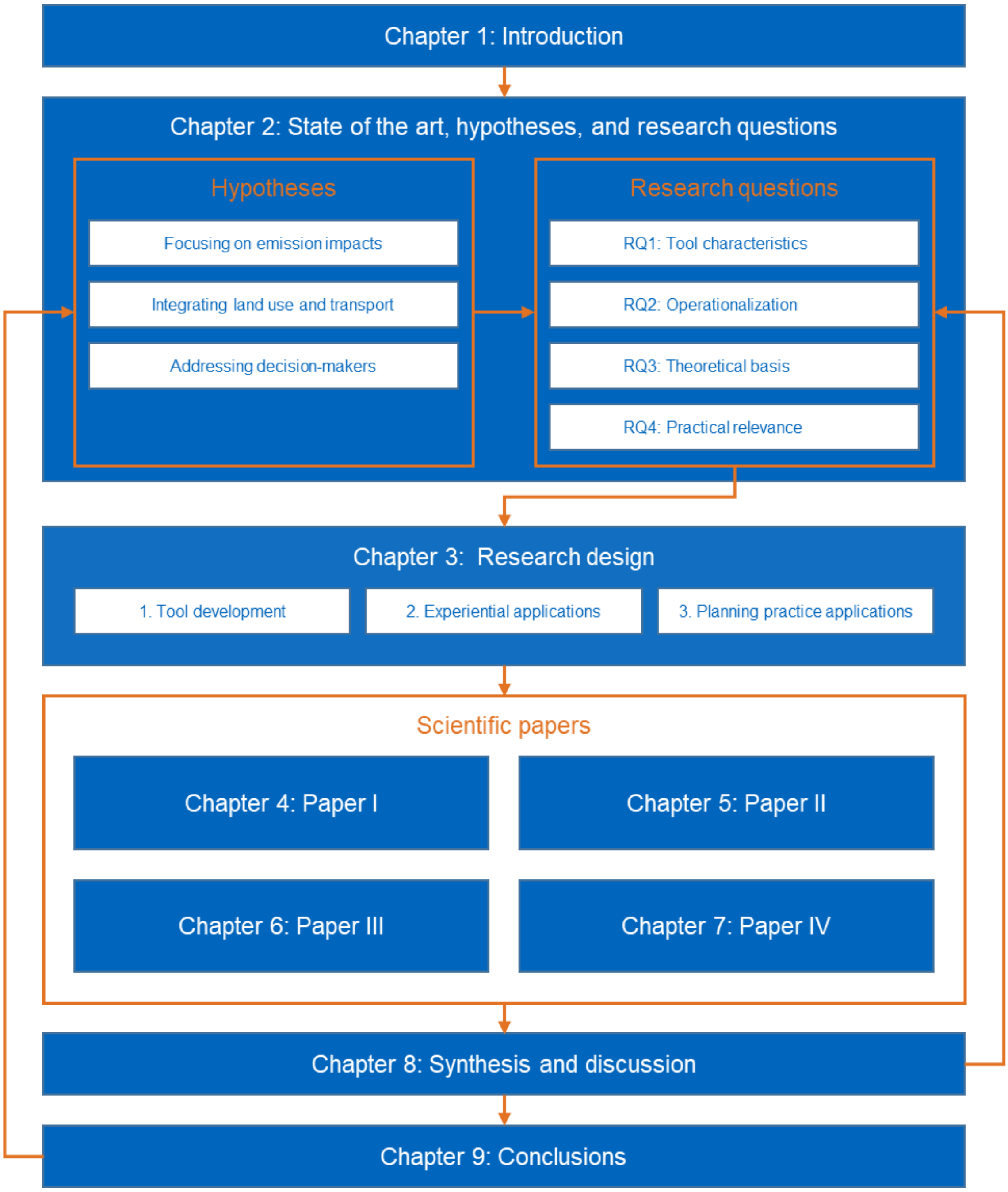

Figure 6. Thesis structure.

2. State of the art, hypotheses, and research questions

This chapter presents the overarching research context of this thesis. Section 2.1 introduces three criteria pertaining to decision-making tools for low carbon mobility planning. This set of requirements is not to be understood as absolute, but hypothesized to represent an important, yet unoccupied tool profile. Section 2.2 provides the theoretical background on accessibility and summarizes previous experiences with accessibility analysis and planning in research and practice. Finally, section 2.3 outlines how accessibility instruments, adapted to plan for low carbon mobility options, are expected to comply with the previously defined criteria. The chapter closes with presenting the research questions linked to the development and application of a carbon-based accessibility instrument.

2.1. Planning for low carbon mobility

2.1.1. Focusing on emission impacts

The threats posed by climate change demand rearrangements in the prioritization of planning and policy objectives (see section 1.1). Public authorities need to identify and implement solutions addressing the particular goal of reducing transport-related emissions. However, existing decision-making instruments are not necessarily a good fit for environmental and climate concerns. Many planning support methods and tools focus on economic efficiency by means of cost-benefit analysis (CBA), where the costs and benefits for society due to public interventions are evaluated in monetary terms (Boardman, 2015). Environmental impacts are typically included, but might be masked within aggregate outputs, which are based on a large number and variety of cost-benefit categories (Pearce et al., 2006).

CBA has been widely used for the ex-ante evaluation of major transport investments (Bristow and Nellthorp, 2000), but has also been widely criticized due to technical and process-related limitations (Beukers et al., 2012). In fact, this type of analysis is based on models, data, and assumptions that may lead to a neglect of long-term environmental consequences and negative impacts on social equity (Næss, 2006). Especially the importance attributed to travel time savings is considered a problematic element of CBA (Martens and Di Ciommo, 2017; Ferreira et al., 2012). Reflecting on the theory of constant travel time budgets (Mokhtarian and Chen, 2004), assessment methods focusing on travel time savings might negatively affect transport-related emissions by promoting projects that encourage people to travel more frequently and across larger distances

(Metz, 2008). Privately funded projects, such as small-scale commercial, office or residential developments, do not have to undergo CBA, but require a traffic impact analysis to prove that the existing transport infrastructure will not be overloaded due to the structural intervention (Levine et al., 2017; Lin and Yang, 2019). However, also the fact that urban development decisions have implications for the transport-related emissions caused by residents, employees, and visitors, should be taken into account (the links between land use planning and transport-related emissions will be deepened in section 2.1.2).

In order to enable emission reductions in the transport sector, it is essential that environmental aspects play a central role in decision-making as part of sustainability and livability objectives (Hickman and Banister, 2007). Consequently, decision-making tools, methods, and processes are needed, which reflect the increased importance of emission impacts by making them a particular focus rather than considering them in aggregate and insufficient ways. This not only applies to the examples outlined above, but is valid for all planning phases (from strategic to project level), spatial scales (from supranational to local), and stakeholders (including both public and private actors).

2.1.2. Integrating land use and transport

Transport-related emissions are directly related to the number of trips, trip distance, mode share, occupancy rate, and emission factor per distance unit (compare Becker et al., 2009). All of these parameters are levers that can be addressed by decision-makers to reduce the negative externalities of transport activities. Climate change mitigation efforts in the transport sector have long focused on technological solutions targeting the reduction in specific vehicle emissions (Chapman, 2007). However, changes in the other parameters of the equation have led to increasing travel volumes, which counteract emission reductions through efficiency gains (UBA, 2020b; EC, 2016).

Spatial patterns play a central role in these dynamics. Although land use characteristics are far from being able to fully explain complex travel behavior (Maat et al., 2005), the built environment has an impact on transport-related energy consumption and emissions by influencing trip lengths, the availability of trip chaining options, and the attractiveness of different mobility options (Handy et al., 2005; Barla et al., 2011; Zahabi et al., 2012; Næss, 2012). Thus, urban development can be a lever in tackling climate change, but can also contribute to its aggravation (Ewing et al., 2007). Separation of urban functions and dispersion of activities through sprawled development result in car dependence and increased travel distances, which correspond to increased energy consumption and transport-related emissions (Ewing, 1997; VandeWeghe and Kennedy, 2007). On the contrary, compact, mixed-use, and multi-modal urban environments ensure proximity to various urban functions and enable people to use public transport, walk or cycle (Geurs and Van Wee, 2006; Banister, 2011; Cervero and Kockelman, 1997; Scarinci et al., 2017). Thus, land use policies could either reinforce or undermine the effects of other measures seeking to decarbonize the transport sector (Loo and Tsoi, 2018; Price, 2020). What is more, compact development not only saves emissions with respect to travel behavior, but also in terms of infrastructure requirements and building energy use (Litman, 2020, p. 31). Although non-transport-related emissions are not the focus of this research, this fact corroborates the importance of land use planning for emission reductions.

In light of these insights, efforts aimed at sustainable mobility should not only target the transport sector, but need to address transport and land use planning in an integrated way (Banister, 1999; Van Wee and Handy, 2016; Leibowicz, 2020). However, existing climate change mitigation strategies and measures underline the high hopes attributed to technological innovation, with some additional focus on economic measures and mode shifts. For example, the EU's strategy for low emission mobility contains three main elements: (1) increased efficiency of the transport system (digital solutions, pricing strategies, mode shifts), (2) low emission alternative energy for transport, and (3) zero emission vehicles (EC, 2016). The guiding principles of Germany's Climate Action Plan 2050 mention integrated urban development as a lever to reduce trip lengths (BMU, 2016, p. 50), but the Climate Action Program 2030, which specifies measures to achieve the 2030 targets, does not include a dedicated measure on integrated land use and transport planning (BMU, 2019b). The overall six fields of action relate to mode shifts (two fields of action), alternative fuels, change to alternative drives for cars and commercial vehicles (two fields of action), and digitalization (BMU, 2019b, p. 65). The introduction of CO_2 emission pricing is an overarching measure within the Climate Action Program, affecting energy and fuel trade companies (BMU, 2019b, p. 24).

The effects of land use policies only become visible in the long-term, which might be a barrier regarding their alignment with emission reduction goals. Pricing policies and technological innovation may significantly reduce emissions from the transport sector before alternative land use configurations take hold on an appreciable scale. Nevertheless, there is consensus that relying solely on technology or pricing will not be sufficient (Åkerman and Höjer, 2006; Boarnet, 2010; Moriarty and Honnery, 2013). Sustainable mobility in general and low carbon mobility in particular can only be achieved if multiple levers are mobilized (Banister et al., 2011; Sheller and Urry, 2016; Banister, 2011; Schwanen et al., 2011; Yang et al., 2009; Litman and Burwell, 2006; Stanley et al., 2011). Against this background, integrated land use and transport planning represents a relevant field of action that receives limited attention compared to other interventions.

2.1.3. Addressing decision-makers

While climate change mitigation targets and programs are formulated on national or supranational government levels, local and regional authorities need to ensure the implementation of specific planning solutions (EC, 2016, pp. 11-12; Marsden et al., 2014; Stead, 2018). They are responsible for urban development and transport investments on local and regional scales, thus acting as integrators between the land use and transport systems (Rode and da Cruz, 2018). However, lack of coordination between different sectors, levels, and administrative territories might hamper the realization of sustainable mobility solutions (Næss et al., 2011). Various actors on multiple scales need to be involved, interact, and take decisions (Geels, 2012; Ostrom, 2010; Marsden et al., 2014). Acceptance and active support of the identified strategies and actions is required to facilitate and accelerate implementation – an essential step that should not be neglected (Banister, 2008; Sheller and Urry, 2016; Hickman et al., 2011; Lewis et al., 2018).

Especially early planning phases are dynamic and interactive due to a large number and variety of potential solutions and involved stakeholders – thus, they are likely to benefit from planning support systems that stimulate the discussion (Te Brömmelstroet, 2010). Political decision-makers need to position themselves in terms of a planning issue and set the framework for low carbon mobility behavior, but typically do not have expert knowledge. Thus, potential planning and policy options and their emission impacts (see section 2.1.1) need to be highlighted in a transparent and understandable way. Clarity regarding the implications of land use and transport decisions across spatial scales and beyond an elected official's own territorial responsibility can improve cooperation across institutional boundaries (Price, 2020).

Setting the framework in terms of low carbon mobility options is not sufficient: Citizens need to embrace these options and realize low carbon mobility behavior. Behavioral change towards low carbon mobility can surely be encouraged by economic measures, but also by communicative tools aimed at increasing awareness, acceptance, and commitment among citizens (Banister, 2008; Hickman et al., 2010; Brazil et al., 2013).

2.1.4. Summary: Planning for low carbon mobility

Three aspects are introduced, which are expected to be important for low carbon mobility planning, but not well addressed by existing decision-making tools. The first aspect is focusing on emission impacts: Due to an increasing relevance of environmental and climate objectives in policy and planning, decision-making processes need to put particular emphasis on the emission impacts of potential interventions. The second aspect is integrating land use and transport planning: Technological innovation, economic measures, and investments in infrastructure for alternative modes cannot be effective without compact, mixed used urban development oriented towards low carbon transport networks. The third aspect is addressing decision-makers: Emission impacts need to be transparent and understandable for both public and private decision-makers in order to support engagement efforts and promote the successful implementation of low carbon mobility solutions. These aspects are referred to below as criteria that carbon-based accessibility instruments are expected to comply with.

2.2. Planning for accessibility

2.2.1. Concept

Changing places is an essential part of people's everyday life. Different locations provide different opportunities and activities that people want to or need to pursue. These destinations may include work, shopping, education, leisure, and other activities. Even in the digital age, physical presence at these locations is typically required, which in turn demands physical movement through space, from one place to another, from a previous activity to the next. The opportunities available to individuals in space and time and the means available to move between locations are captured by the concept of accessibility. Many definitions describe accessibility as the potential, ability or ease to reach spatially distributed opportunities (Hansen, 1959; Koenig, 1980; Páez et al., 2012; Vale and Pereira, 2016). Opportunities are associated with social and economic benefits (Handy and Niemeier, 1997; Geurs and Ritsema van Eck, 2001), but realizing these opportunities also entails costs (Batty, 2009). The accessibility concept is directly linked to both people and places and thus can be understood as a property of either a person or a place (Farrington, 2007; Neutens et al., 2010). In the first case, accessibility describes how easily an individual can reach activity locations (Kwan, 1998). In the second case, it describes the potential to reach either a place as a destination or opportunities from a place as an origin (Cascetta, 2001).

Regardless of perspective, the key elements in these dynamics are the spatial distribution and attractiveness of opportunities, the location and characteristics of the users of these opportunities, and the spatial impedance between origins and destinations that needs to be overcome to reconcile supply and demand (Handy and Niemeier, 1997). In essence, accessibility depends on (1) the urban patterns determined by the land use system and (2) the travel options provided by the transport system. Transport supply may include various means of travel, such as car, public transport, walking, cycling or a combination of transport modes (Geurs and Van Wee, 2004).

Land use and transport can be seen as the basic geographical components of accessibility (Haugen, 2012). Nevertheless, there are further aspects of accessibility, which are determined by attitudes, resources, and restrictions. When seen from the perspective of a person, accessibility is influenced by individual characteristics, perceptions, and abilities (Geurs and Östh, 2016; Páez et al., 2012; Kwan, 1998; Farrington, 2007). For example, driving is not an option for people without a car or license, just as access to schools is typically not relevant for senior citizens. Accessibility also changes throughout the day, for example because of varying service levels of the transport system or because of limited opening hours of shops and services (Farber et al., 2014; Moya-Gómez et al., 2018; El-Geneidy and Levinson, 2007; Boisjoly and El-Geneidy, 2016). The combined geographical, temporal, and individual framework results in accessibility constraints. The fact that one day has 24 hours clearly limits the number of activities that can be pursued, not only because of the time spent for the activities themselves, but also because of the time spent in transport while moving from one activity to the next. Furthermore, people are not free to use their time as they desire, but typically depend on activity schedules, be it their own or those of others they need to accompany. These schedules contain activities that are fixed in space and time, which introduce spatial-temporal constraints to accessibility (Neutens et al., 2008; Hägerstrand, 1970). All of these aspects are summarized by Geurs and Van Wee (2004) as the four components of accessibility: land use, transport, individual, and temporal.

Due to this variety of aspects and manifestations, accessibility clearly is a multi-faceted concept. The myriad of notions and understandings make it difficult to find a universal definition. Within this thesis, accessibility is seen from the perspective of locations and determined by the joint characteristics of the land use and transport systems. Thus, while acknowledging the existence of non-spatial factors, this research focuses on the geographical aspects of accessibility.

Accessibility, mobility options, and travel behavior

As a potential, accessibility is conceptually different from realized travel behavior, but nevertheless has a behavioral basis (Koenig, 1980). The land use and transport systems, as key dimensions of accessibility, dictate the mobility options available to realize opportunities. Accessibility planning can help to create environments where availability of sustainable transport systems and proximity to opportunities provide for sustainable mobility options (Silva et al., 2017; Bertolini et al., 2005). Thus, accessibility affects the realized mobility behavior by influencing destination choice and travel mode choice (as well as location choice in the long-term). While mobility options from an objective point of view are determined by the geographical aspects of accessibility, individual factors, such as lifestyles, preferences, and sociodemographic properties, have an impact on travel behavior as well (Scheiner and Holz-Rau, 2007; Bagley and Mokhtarian, 2002).

Traveling to desired or required destinations is linked to internal and external costs, which makes accessibility relevant at both the individual and the societal level. Implementations of accessibility are typically informed by travel behavior. In this context, Páez et al. (2012) distinguish between accessibility implementations based on how people actually travel and accessibility implementations based on how people ought to travel. Either approach can be applied to measure accessibility and generate solutions for shaping the land use and transport systems towards desired accessibility outcomes, as specified by the planning goals. Changes in accessibility have an impact on the mobility options available, which in turn play a role for realized travel behavior. These interactions are illustrated in Figure 7.

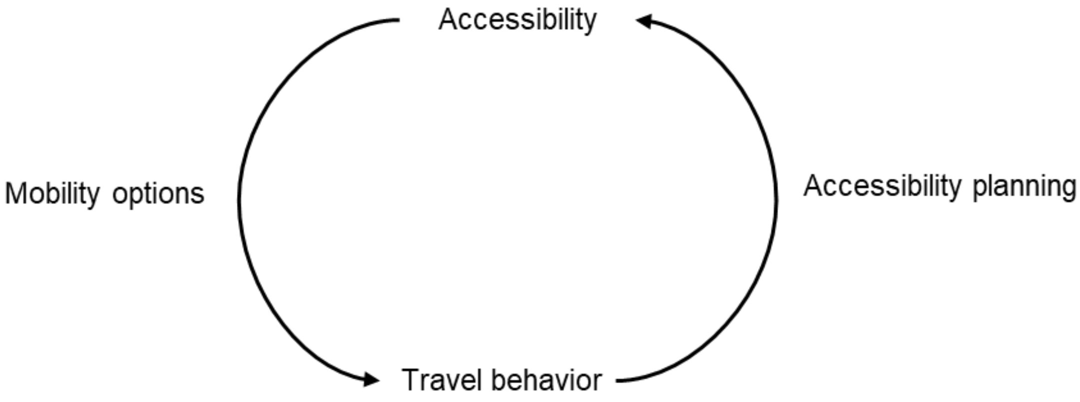

Figure 7. Relation between accessibility and travel behavior.

Access to social and economic needs can be provided in different ways, since both the land use system and the transport system, including multiple transport modes, influence accessibility. Depending on the options available to access opportunities, the outcome may be more or less sustainable. The overarching aim of accessibility planning is thus to plan for land use and transport systems that enable the realization of opportunities at low costs from both an individual and a collective perspective. An increasing body of literature focuses on the social aspects of accessibility (see for example Gil Solá et al., 2018), often with particular emphasis on the individual component. This thesis however shifts the focus from the internal travel costs of individuals to the negative externalities of travel activities.

2.2.2. Applications

Accessibility is an important concept in research as well as urban and transport planning (Geurs and Östh, 2016). Sensitivity to improvements in both proximity and transport supply quality ensures the suitability of the concept for integrated planning, which distinguishes accessibility from traditional transport planning approaches, mainly focusing on improvements in speed and traffic flow (Levine et al., 2012). Just like there is a variety of understandings of accessibility, there is also a variety of ways to measure it. Accessibility indicators vary in terms of complexity and the extent to which they take the four components of accessibility into account. The accessibility concept is flexible, which makes it applicable to a large variety of tasks, various spatial scales, and different phases of the planning process, depending on the accessibility indicator and specification employed. For example, accessibility analysis has been used for strategic policy design (Bertolini et al., 2005; Straatemeier, 2008), appraisal of integrated land use and transport strategies (Geurs et al., 2006; Geurs et al., 2010), and project level evaluations (Levine et al., 2017; Merlin et al., 2018).

The chosen accessibility measure and its specification determine the sensitivity (or insensitivity) to certain aspects of the land use and transport systems. This in turn has implications for both the outcomes and the conclusions of the accessibility analysis (Handy and Niemeier, 1997). There is no single best way to operationalize accessibility: Both practical and theoretical considerations determine the choice of indicator (Pirie, 1979) and its form should correspond to the context, purpose, and objective of the analysis (Silva et al., 2017). Several authors have identified requirements for accessibility indicators (Geurs and Van Wee, 2004; Pirie, 1979; Handy and Niemeier, 1997; Morris et al., 1979), which can be summarized as follows:

- The accessibility indicator should be sensitive to (changes in) the characteristics of the land use and transport systems that are relevant for the goal of the analysis.
- The accessibility indicator should be easy to handle in terms of resources and effort required for its application.
- The accessibility indicator should be consistent with reality in order to be meaningful.
- The accessibility indicator should be useful for decision-making, which is not only linked to analytical skills, but also transparency and understandability.

In practice, it is not possible to fully satisfy all of these requirements. The issue of finding a suitable compromise between scientific rigor and practical applicability has become evident in applications of accessibility instruments (Silva et al., 2019). In general, accessibility instruments are a type of planning support system enabling the design, evaluation, and implementation of integrated land use and transport policies, but they vary in terms of indicators, outputs, and data requirements (Papa et al., 2016). Within the COST Action TU1002 “Accessibility Instruments for Planning Practice” (Hull et al., 2012; Te Brömmelstroet et al., 2014), various accessibility instruments were applied to test their practical relevance. A key strength of accessibility instruments is their capability to integrate perspectives and enable stakeholder involvement across different levels and sectors (Te Brömmelstroet et al., 2016). These traits help to overcome institutional barriers and lack of interdisciplinary coordination impeding the implementation of sustainable land use and transport solutions (Næss et al., 2011; Rode and da Cruz, 2018). If appropriately implemented, accessibility instruments can act as communication tools and enhance the understanding of the interactions between land use and transport among a wide range of stakeholders (Curtis and Scheurer, 2010). For example, these tools can be helpful in raising awareness among elected officials and citizens for the threats that fuel price increases pose to transport affordability if the private car is the only option to reach activity destinations (Büttner, 2017). Map-based results and simple indicators are beneficial in terms of communication value and transparency (Wulfhorst et al., 2017; Te Brömmelstroet et al., 2014; Hull et al., 2012). More sophisticated tools deliver theoretically sound results, but are poorly understood by politicians and citizens (Te Brömmelstroet et al., 2016; Silva et al., 2017). In fact, researchers’ efforts to increase the theoretical soundness of planning support systems through sophisticated modeling techniques conflict with the need for transparency and high communication value (Te Brömmelstroet, 2010; Te Brömmelstroet et al., 2017).

2.2.3. Summary: Planning for accessibility

Accessibility describes the potential to reach spatially distributed opportunities and is influenced by both the transport system and the land use system. The concept is linked to travel behavior, since accessibility determines the mobility options available to reach opportunities. There are multiple ways to operationalize accessibility and the choice of an accessibility measure should be informed by considerations regarding the objectives of the analysis, operationalization, theoretical basis, and practical relevance. Practical applications of accessibility instruments show that simple tools providing visual outputs are particularly suitable for integrating perspectives and enabling communication across different disciplines, institutions, and levels of expertise.

2.3. Planning for carbon-based accessibility

2.3.1. Operationalizing carbon-based accessibility

Many implementations of accessibility are based on the idea that accessibility increases with the size or attractiveness of an opportunity and decreases with the cost of realizing that opportunity (Batty, 2009). Spatial impedance is frequently measured in travel time or other internal costs from the user perspective (Handy and Niemeier, 1997; Cui and Levinson, 2018). Such implementations are useful to shape land use and transport conditions to foster walking, cycling, and public transport, but lack a focus on emission impacts. So far there have been limited efforts to more directly incorporate external travel costs, such as CO_2 emissions, into accessibility analysis. Määttä-Juntunen et al. (2011) assess retail store locations based on the CO_2 emissions generated when potential customers drive to these stores by car. They conclude that compact urban patterns can help to reduce CO_2 emissions by decreasing trip lengths. Cui and Levinson (2019) incorporate both internal and external travel costs into their assessment of full cost accessibility by car. When converted to monetary terms, emissions only have a minor share of the full costs compared to time and money (Cui and Levinson, 2019, p. 655). Given the increasing importance of climate objectives in planning and decision-making (section 2.1.1), CO_2 emissions should be considered a relevant travel cost in accessibility measurement.

Location-based or place-based accessibility indicators are frequently used accessibility measures, which operationalize accessibility as the property of a place by considering the number of destinations accessible from a given origin location (Geurs and Van Wee, 2004). The following mathematical expression represents the basic form of location-based accessibility measures:

$$A_i = \sum_j D_j \, f(c_{ij})$$

A_i represents the accessibility at location i, D_j the destination potential at location j, and $f(c_{ij})$ a function of the travel costs between locations i and j. Two commonly known subtypes of location-based accessibility measures are cumulative opportunities measures, which sum up the number of opportunities within a given travel cost threshold (e.g. the number of jobs within 30 minutes by public transport from a residential location), and gravity-based measures, which weight opportunities by a continuous function of the travel costs (El-Geneidy and Levinson, 2006). Within this thesis, the cost component c_{ij} is represented by the GHG emission costs generated while traveling from origin i to destinations j. Reflecting on the criteria for low carbon mobility planning (section 2.1) and the state of the art on accessibility (section 2.2), a location-based accessibility instrument is expected to be a good fit for the intended purpose of accessibility analysis within this thesis. Location-based accessibility measures include both the land use and transport components, which are key prerequisites to enable integrated land use and transport planning. The level of complexity is low compared to other accessibility measures. Furthermore, location-based tools are capable of producing visual outputs in map format, which have proven useful in addressing decision-makers.

2.3.2. Hypotheses

The three criteria introduced in section 2.1 are expected to be essential for low carbon mobility planning, while existing decision-making tools are expected to be incapable of fulfilling this set of requirements entirely. On the contrary, carbon-based accessibility instruments are hypothesized to fill this gap by complying with the three criteria, as detailed in the following.

- *Focusing on emission impacts:* The increasing importance of emission reductions implies a need to tailor accessibility instruments to the specific objective of low carbon mobility planning. CO_2 emissions are incorporated as the relevant travel cost in location-based accessibility measures, which introduces an explicit focus on emission impacts into accessibility analysis and planning.

- *Integrating land use and transport:* The accessibility concept acts as integrator of the land use and transport systems. Thus, carbon-based accessibility planning can help to activate integrated land use and transport planning as a field of action for tackling climate change.

- *Addressing decision-makers:* Accessibility instruments are recognized for their communicative capabilities. Carbon-based accessibility instruments can make emission impacts tangible in order to create awareness, enhance engagement efforts, and increase acceptance for low carbon mobility solutions among both public and private decision-makers.

Figure 8 summarizes these hypotheses by highlighting how carbon-based accessibility instruments could build upon the known benefits of accessibility instruments to comply with the outlined criteria.

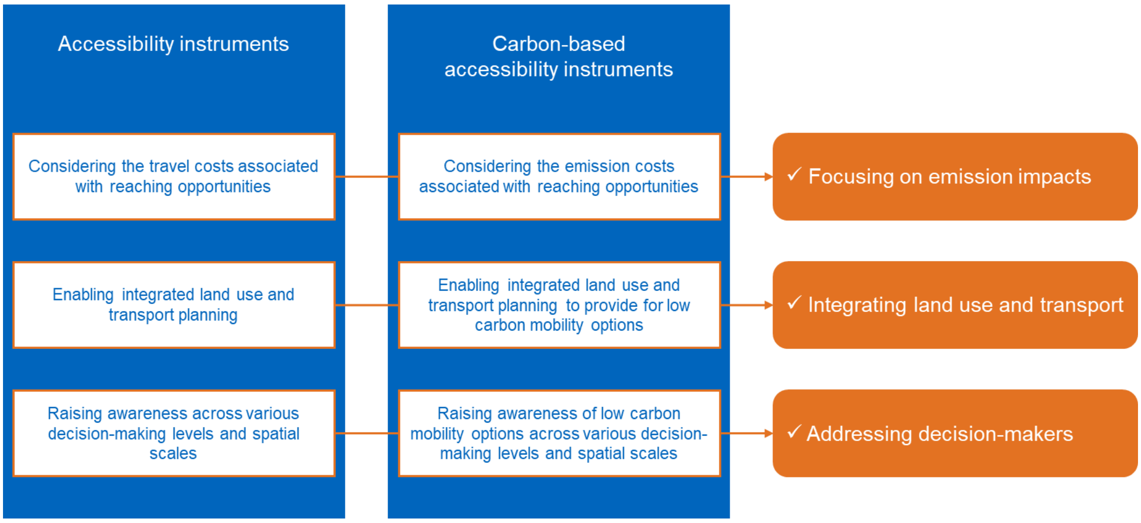

Figure 8. Expected benefits of carbon-based accessibility instruments for low carbon mobility planning.

2.3.3. Research questions

The application of accessibility instruments for low carbon mobility planning is promising, but also entails the need to explore the benefits and limitations of carbon-based accessibility analysis as a novel method, which is the central aim of this thesis (section 1.2). Regarding the hypotheses, this research aims to reveal how well carbon-based accessibility instruments comply with the three defined criteria (section 2.3.2) and to uncover the implications in terms of advantages and disadvantages as a decision-making tool. Merging these themes with the requirements for operationalizing accessibility (section 2.2.2) yields a total of four RQ, relating to the characteristics, operationalization, theoretical basis, and practical relevance of carbon-based accessibility instruments. The RQ do not address the hypotheses in a linear, but cross-cutting manner.

RQ1: Tool characteristics

What are the distinctive characteristics of a carbon-based accessibility instrument in comparison with other decision-making tools for low carbon mobility planning?

In order to reveal the extent to which carbon-based accessibility instruments comply with the three criteria of focusing on emission impacts, integrating land use and transport, and addressing decision-makers (section 2.3.2), their characteristics need to be investigated in a systematic way. This RQ focuses on similarities and differences compared to existing tools and methods that are able to support decision-making towards reducing transport-related emissions. Different approaches are compared in terms of inputs, outputs, and workings in order to enable better understanding of the strengths and weaknesses of carbon-based accessibility instruments for low carbon mobility planning.

RQ2: Operationalization

Which kind of data and software is required to operationalize carbon-based accessibility?

Ease of operationalization is an important requirement for planning tools in general and accessibility instruments in particular (section 2.2.2). Carbon-based accessibility analysis demands transport network models that are able to estimate the amount of CO_2 emissions generated when traveling over network links. CO_2 emission modeling is not necessary for traditional travel-time-based accessibility analysis and thus an additional task for carbon-based accessibility analysis. This RQ aims to shed light on the implications of software environment and data for development effort and model accuracy.

RQ3: Theoretical basis

Can carbon-based accessibility be conceptualized and operationalized in a theoretically sound way?

Carbon-based accessibility analysis is intended to serve as a useful reference for planning and decision-making. For this purpose, the tool results should be scientifically sound and consistent with reality (section 2.2.2). Theoretical shortcomings must be recognized and their consequences must be described. This RQ has multiple dimensions: the position of carbon-based accessibility within existing understandings of the accessibility concept, the operationalization of carbon-based accessibility in the form of accessibility measures, and the effects of carbon-based accessibility on low carbon mobility behavior.

RQ4: Practical relevance

What is the practical relevance of a carbon-based accessibility instrument for real-world decision-making processes?

Practical relevance is directly linked to the characteristics, ease of operationalization, and theoretical basis of decision-making tools. The set of requirements that carbon-based accessibility instruments are expected to fulfill (section 2.3.2) could bring added value to real-world decision-making processes. This RQ focuses on the specific application potential of carbon-based accessibility instruments: For which planning issues could these tools be useful? What are the benefits and limitations according to practitioners? How could or should carbon-based accessibility instruments be combined with existing planning tools, methods, and processes?

2.3.4. Summary: Planning for carbon-based accessibility

CO_2 emissions can be directly incorporated into accessibility analysis by using them as the relevant travel costs in location-based accessibility measures. Carbon-based accessibility instruments are expected to comply with the three criteria of focusing on emission impacts, integrating land use and transport, and addressing decision-makers. Consequently, these tools could bring a useful set of requirements into the realm of low carbon mobility planning. The extent to which carbon-based accessibility instruments actually fulfill these criteria and the corresponding implications for decision-making are explored across four questions, focusing on tool characteristics, operationalization, theoretical basis, and practical relevance.

3. Research design

The research design enables reflections on tool characteristics, operationalization, theoretical basis, and practical relevance through the following activities:

1. By determining and processing the underlying data and software to produce a functional carbon-based accessibility instrument, the *tool development* is the underlying requirement for the applications within the following activities 2 and 3. Furthermore, this step contains the elaboration of a tool typology to compare the characteristics of carbon-based accessibility instruments and existing decision-making tools for low carbon mobility planning.

2. The tool is tested in *experiential applications* by applying it to a variety of hypothetical planning issues. The test applications serve to gather experiences with the tool, test its capabilities, and gain insights into the evolving accessibility landscapes and impacts when adapting the parameters of the accessibility analysis in different scenarios.

3. The purpose of the *planning practice applications* is to obtain a picture of the practical relevance of a carbon-based accessibility instrument for real-world planning issues. These applications show how well the tool responds to what is actually important in planning practice from the practitioners' perspective regardless of the potential capabilities of the tool.

Figure 9 gives an overview of the links between research design, research questions, and hypotheses. The viewpoint of the developer is shaped by all three steps of the research design, whereas the practitioners gain insights into selected applications only, which are related to their everyday planning practice. Similarly, the developer is able to reflect on the entire set of research questions, while the viewpoint of the practitioners mainly feeds into RQ4 (although additional reflections on the other research questions based on the practitioners' input are intended). RQ1 and RQ4 enable direct conclusions on the hypotheses and the corresponding implications regarding strengths and weaknesses of carbon-based accessibility instruments for low carbon mobility planning. RQ2 and RQ3, which represent general prerequisites for decision-making tools, help to uncover the benefits and limitations of carbon-based accessibility instruments at a fundamental level.

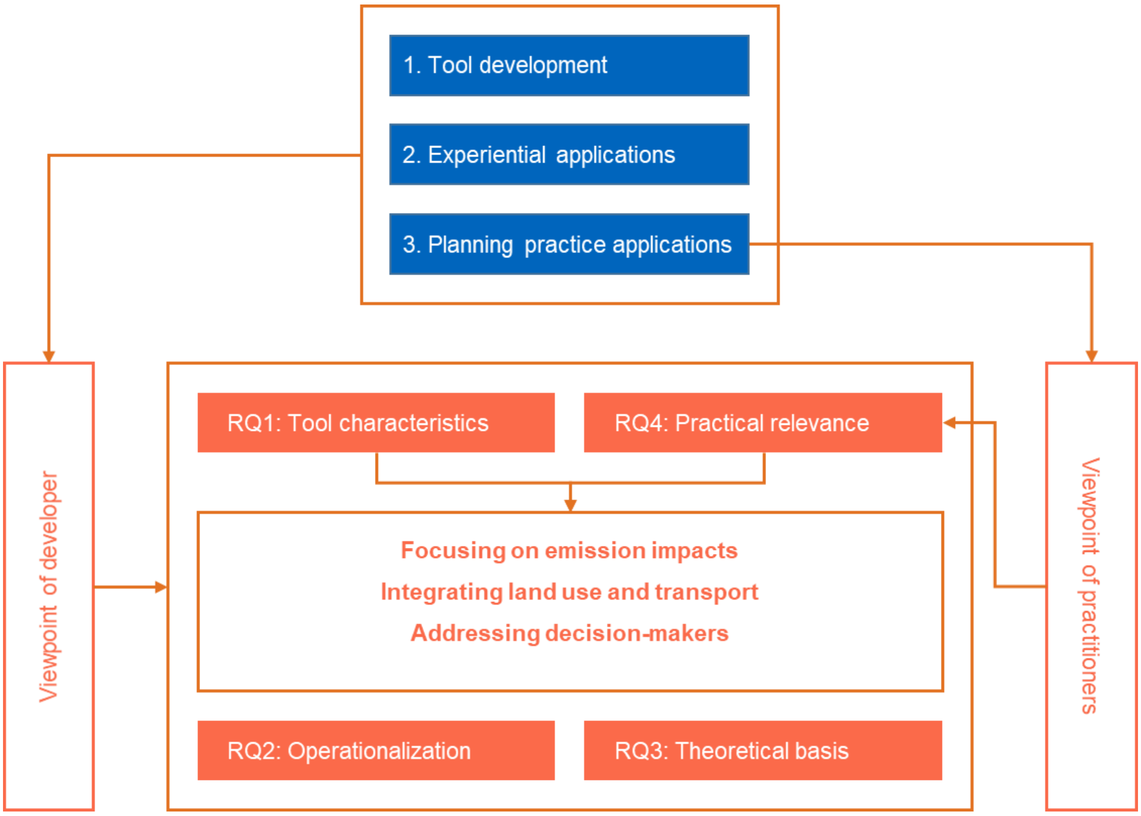

Figure 9. Links between research design, research questions, and hypotheses.

Sections 3.1 to 3.4 explain in more detail how the three-step research design was conducted and how it is linked to the four scientific papers. Due to the ASTUS project context as well as the availability of data and resources, the Munich region serves as study area. Nevertheless, the findings regarding tool characteristics, operationalization, theoretical basis, and practical relevance are not necessarily limited to the Munich region. The transferability of the method and generalizability of the results are discussed in chapter 9.

3.1. Tool development

3.1.1. Tool typology and assessment with respect to the criteria

The characteristics of carbon-based accessibility instruments were systematically analyzed in order to understand the implications regarding strengths and weaknesses for low carbon mobility planning, also in comparison with other tools and methods. This step focuses on RQ1, but also lays the foundation for reflections in terms of operationalization, theoretical basis, and practical relevance.

Starting point was a review of international tools that enable public or private decision-making related to low carbon mobility. The aim was not to have a complete collection, but rather a saturated typology of tools. Different tool types were distinguished based on their general scope of decision-making. Variations among tools within the same category in terms of certain non-distinctive characteristics are possible. In addition, the research on existing decision-making tools served as inspiration and data source for the emission modeling (section 3.1.2).

Following the tool review, a framework was developed to assess all tool types, including carbon-based accessibility instruments, in terms of compliance with the criteria for low carbon mobility planning (section 2.3.2). The assessment framework includes the following key characteristics: land use component, spatial dimension, scenario building capabilities, and communicability. For detailed explanation on why these attributes are important to satisfy the identified criteria for low carbon mobility planning see Paper I and section 8.1.

3.1.2. Modeling transport networks for CO_2 emission estimation

The development of a carbon-based accessibility instrument within this thesis builds upon existing data and experiences related to the TUM Accessibility Atlas (section 1.2). While the land use component is unchanged compared to traditional accessibility analysis, adding CO_2 emissions to the car and public transport networks as an additional travel cost was a challenge. Several steps were required for the CO_2 emission estimation: modeling the topological network, assigning relative energy consumption (per distance unit) to network links based on their characteristics, converting relative energy consumption to absolute emissions based on link length and emission factors, and converting per-vehicle emissions to per-passenger emissions based on occupancy rates (see Figure 10).

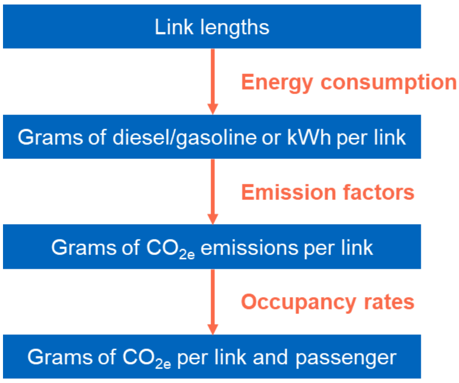

Figure 10. Overview of the emission modeling process.

Table 1 provides an overview of all data sources tested or used within this research. The specific process, software environment, and data varied by application and are described in the respective papers (chapters 4 to 7).

Table 1. Overview of data and sources used in the emission modeling.

Source	**Data**
Travel demand model of the Munich region developed and owned by the City of Munich (LHM), MVV and the Munich public transport operator (MVG), reference year 2015	- Topology of public transport network including route type
Travel demand model of the State of Bavaria (LVM-By) developed and owned by the Motorway Directorate (Maget et al., 2019), reference year 2014	- Topology of public transport network including route type - Daily demand in public transport on link level - Topology of car network including road type and speed limit - Daily demand in private transport on link level
Google Maps API	- Travel distances for selected origin-destination relations
OpenStreetMap (OSM)	- Topology of public transport network including route type - Topology of walking network (access/egress) - Topology of car network including road type and speed limit
Transport Emission Model (TREMOD) (Knörr et al., 2016; UBA, 2020c)	- GHG emissions per passenger-km - Average occupancy rates for Germany
Germany Railways (DB) Mobility Check (DB, 2019)	- Diesel and electricity consumption for buses, tramways, subways, and trains - Occupancy rates for buses, tramways, subways, and trains [passenger-km/seat-km] - Emission factors for electricity
MVV internal data	- Diesel consumption of regional buses by county - Occupancy rates in regional buses by location, differentiated by weekdays/weekend [passenger-km/vehicle-km]
Handbook Emission Factors for Road Transport (HBEFA), version 3.3 (INFRAS, 2017)	- Diesel and gasoline consumption of cars by traffic situation in Germany for the year 2018 [g/km] - Share of diesel and gasoline vehicles of the total vehicle fleet in Germany for the year 2018
CORINE Land Cover (CLC)	- Shape and location of urban areas
Helms et al. (2016)	- Electricity consumption of electric cars within/outside of urban areas and on motorways [kWh/km]
Schmied and Mottschall (2014)	- Emission factors for diesel and gasoline [CO_{2e}/gram]

Source	Data
Knote et al. (2015)	- Electricity consumption of electric buses [kWh/km]
UBA (2016b)	- Occupancy rates in cars by trip purpose

3.1.3. Feedback loops

The development process ran in parallel with the experiential applications (section 3.2) and the planning practice applications (section 3.3), which served as feedback loops for the development process. The tool was constantly refined based on the gathered experiences.

3.2. Experiential applications

3.2.1. Impacts of transport on carbon-based accessibility

The first experiential application focused on the impacts of changes in the transport system on carbon-based accessibility levels. Carbon-based accessibility by car and public transport was measured for a selected workplace location, the business park Gilching in the county of Starnberg. The application employed a cumulative opportunities indicator and visualized catchment areas for two different CO_2 emission budgets. Different scenarios with changed occupancy rates and emission factors were compared in order to understand how carbon-based accessibility would respond to changes in the underlying parameters. Furthermore, this application highlighted carbon-based accessibility differences by transport mode under various assumptions and gave first insights into the impacts of location – a question to be deepened in the second experiential application.

3.2.2. Impacts of location on carbon-based accessibility

The second experiential application uncovered the potential consequences of different firm location choice strategies in terms of transport-related emissions. Firm locations have an impact on carbon-based accessibility levels, the availability of low carbon mobility options, and ultimately the energy use of commuting (Næss and Sandberg, 1996). The relocations of two companies in the Munich region, namely Paulaner Brewery and Microsoft, served as study case. Carbon-based accessibility by car and public transport was analyzed for a total of four heterogeneous locations, using a cumulative opportunities indicator. Additionally, different emission budgets were applied in order to visualize the implications of ambitious emission reduction targets for carbon-based accessibility levels.

3.2.3. Comparison of carbon-based and travel-time-based accessibility

While the first and second experiential applications focused on the visualization of catchments for single locations, the third application covered the entire area of the EMM. This application focused on the differences between travel-time-based (user or individual perspective) and carbon-based (environmental or collective perspective) accessibility levels by location and transport mode, employing different CO_2 emission budgets. Cumulative opportunities indicators were used to analyze accessibility for all municipalities within the EMM. The emerging accessibility patterns helped to understand which areas feature the largest discrepancies between travel-time-based and carbon-based accessibility levels and which areas are most vulnerable to the introduction of emission reduction targets.

3.3. Planning practice applications

3.3.1. Stakeholder involvement

Decision-making tools need to be well aligned with the intended purposes and targeted users, which requires engagement with real-world policy and planning (Marsden and Reardon, 2017). In order to better understand the needs of practitioners, relevant stakeholders were involved in the process of developing and applying a carbon-based accessibility instrument from the very beginning. Numerous common and individual meetings with pilot site representatives were conducted within the ASTUS project. Additional stakeholders included the MVV, as core project partner, as well as representatives from the regional planning authority and the EMM. This context made it possible to apply the carbon-based accessibility instrument not only to hypothetical, but also to real-world planning issues and evaluate the tool from the practitioners' perspective. A timeline of the stakeholder involvement activities that are relevant for this thesis is shown in Figure 11. More details on the process can be found in Paper IV and in the documentations of the common stakeholder workshops in Annexes A, B, and C.

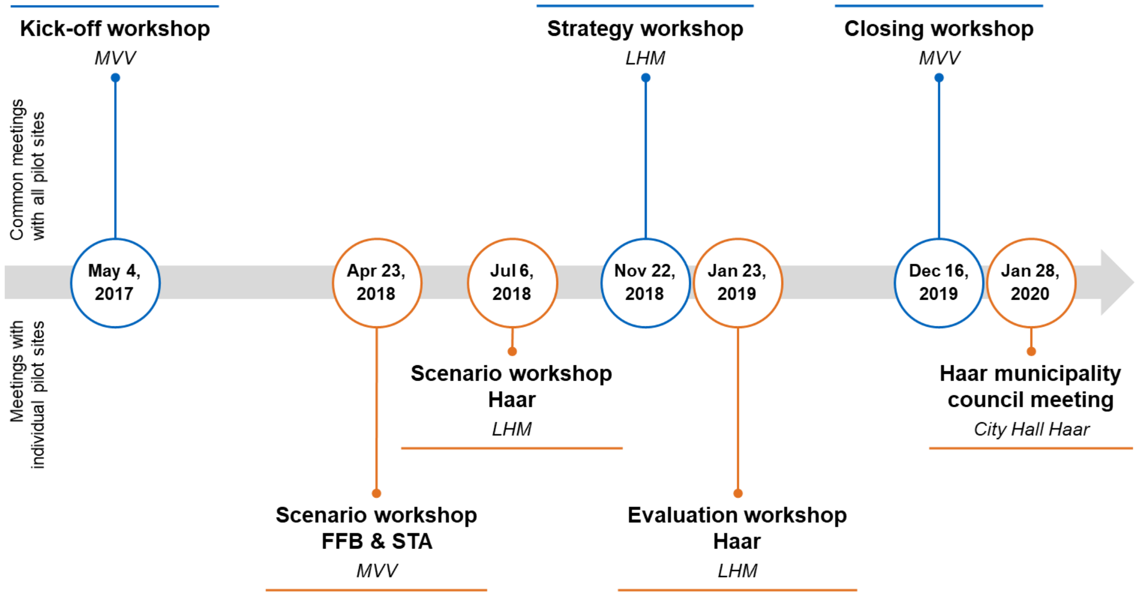

Figure 11. Timeline of selected stakeholder workshops and meetings within the ASTUS project.

3.3.2. Carbon-based accessibility analysis for real-world planning issues

Real-world planning issues had to be defined in cooperation with the practitioners. A number of decision-making tools, including the carbon-based accessibility instrument, were presented during the kick-off workshop (see Figure 11) to show practitioners the capabilities of the tools. Then, practitioners were asked to state their needs and wishes regarding planning support (see workshop documentation in Annex A). Specific planning issues and applications were specified during the scenario workshops (see Figure 11). Carbon-based accessibility analysis was applied to the following planning issues:

- The first one is a transport planning issue, relating to the introduction of orbital express bus services around the city of Munich and the benefits of this investment for low carbon mobility.

- The second one is a land use planning issue in the municipality of Haar, dealing with the question of how different urban development options contribute to low carbon mobility.

The accessibility analyses conducted for these planning issues can be found in Paper IV. All decisions pertaining to the specification of the accessibility analysis, such as level of detail and type of indicator, were taken by the developer based on discussions with the practitioners and in line with the planning issue at hand. The analyses had to be done in the back office, but intermediate meetings and discussions with the practitioners served to refine the results.

3.3.3. Discussion of the results and tool evaluation

A comprehensive evaluation of the practical relevance of carbon-based accessibility was beyond the scope of this work and needs to be addressed in future research. However, the planning practice applications helped to gain first insights into the practical relevance of carbon-based accessibility instruments from the practitioners' perspective. The key evaluation formats were the strategy workshop (see Figure 11 and documentation in Annex B) and the closing workshop (see Figure 11 and documentation in Annex C), which included a user survey, interactive formats, and discussions with practitioners. Since no representatives from the municipality of Haar were present at the strategy workshop, an individual evaluation meeting was scheduled at a later point in time (see Figure 11). More details on methods and findings can be found in Paper IV, which not only addresses carbon-based accessibility instruments, but reflects on the practical relevance of accessibility instruments in general for low carbon mobility planning.

3.4. Linking research design and papers

Each of the four scientific papers following in chapters 4 to 7 entails its own literature review, methodology, results, discussion, and conclusions sections. At the same time, the papers are embedded in the overarching framework and research design of this thesis. Table 2 indicates the relation between the individual papers and the overall research design.

Table 2. Relation between research steps and scientific papers.

	Paper I (chapter 4)	**Paper II (chapter 5)**	**Paper III (chapter 6)**	**Paper IV (chapter 7)**
1. Tool development				
1.1. Tool typology and assessment with respect to the criteria	X			
1.2. Modeling transport networks for CO_2 emission estimation	X	X	X	
1.3. Feedback loops	X	X	X	X
2. Experiential applications				
2.1. Impacts of transport on carbon-based accessibility	X			
2.2. Impacts of location on carbon-based accessibility	X	X		
2.3. Comparison of carbon-based and travel-time-based accessibility			X	
3. Planning practice applications				
3.1. Stakeholder involvement				X
3.2 Carbon-based accessibility analysis for real-world planning issues				X
3.3. Discussion of the results and tool evaluation				X

4. Planning for low carbon mobility: Impacts of transport interventions and location on carbon-based accessibility

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Kinigadner, J., Büttner, B., Wulfhorst, G., Vale, D., 2020. Planning for low carbon mobility: Impacts of transport interventions and location on carbon-based accessibility. Journal of Transport Geography 87.

Available online: https://www.sciencedirect.com/science/article/pii/S0966692319309780

Abstract

Accessibility has been conceptualized and applied in different ways, depending on the underlying political objectives. In the context of climate change and ambitious emission reduction targets, environmental concerns have risen high on the political agenda. Existing methods for assessing transport-related environmental impacts typically depend on realized or modeled travel behavior. Many of them do not entail a spatial dimension, ignore the importance of the land use component, lack scenario building capabilities or have limited communication value. Consequently, accessibility analysis and planning could make a valuable contribution towards a low carbon transition, but needs to attune to the specific objective of reducing transport-related greenhouse gas emissions. This paper introduces a novel conceptualization of location-based accessibility, where CO_2 emissions are used as a travel cost in place of time or monetary costs. By identifying and assessing options for interventions in the land use and transport system, carbon-based accessibility instruments might serve a number of potential decision-making purposes related to low carbon mobility planning. Carbon-based accessibility of a business park in the Munich region is analyzed in multiple scenarios to demonstrate the application potential of the method. The experiential application focuses on the effects of changes in vehicle efficiency and occupancy rates of both car and transit, but also compares the resulting carbon-based accessibility levels to alternative sites with the transport system unchanged. Applying carbon-based accessibility instruments to real-world planning issues could enhance strategic decision-making processes in the context of climate change mitigation.

4.1. Introduction

Impacts from transport activities have become part of the political agenda due to an increasing awareness of their negative consequences for many sustainability goals (Bertolini, 2017; Litman and Burwell, 2006). Transport-related GHG emissions, in particular CO_2 emissions, are among the most pressing concerns in the context of global warming and climate change. While total CO_2 emissions in the EU were 21 % below 1990 levels in 2017 (EEA, 2019a, p. vii), road transportation is the only source category where emissions have not been reduced (EEA, 2019a, p. 90). Road transportation is the second largest key source category after public electricity and heat production, accounting for 25 % of total CO_2 emissions in the EU (EEA, 2019a, p. 71). Despite these concerning facts, decision-makers are hesitant to restrict transport activities due to social protest or fear of economic losses (Banister, 2011; Geels, 2014). However, it seems that the relation between increased motor vehicle travel and greater economic benefits is limited (Litman and Burwell, 2006) and that the basis of economic development is in fact access to people, goods, and services rather than mobility itself (Rode and da Cruz, 2018).

This finding contradicts with the nature of traditional transport planning focused on promoting mobility (Ferreira et al., 2012). Accessibility subsumes both mobility and proximity, thus not only reflecting the characteristics of the transport system, but also the characteristics of the land use system (Cervero, 2005; Bertolini, 2017). The concept provides a suitable framework for integrated land use and transport planning, which can support the achievement of economic, social, and environmental sustainability goals (Bertolini et al., 2005). Travel impedance in accessibility analysis is usually measured in distance, time or monetary costs (Handy and Niemeier, 1997). However, in light of the challenges outlined above, the environmental costs of travel – which have rarely been directly included in accessibility measures so far – need to be considered (for examples see Määttä-Juntunen et al., 2011; Vasconcelos and Farias, 2012).

This paper introduces an accessibility-based method for assessing the potential environmental impact of locations as a consequence of urban form, transport supply or changes to these systems. CO_2 emissions are used as a travel cost indicator for car and transit in place of time or monetary costs. The first part of the paper builds a theoretical framework for the applicability of carbon-based accessibility analysis. Existing decision-making tools and methods linked to transport-related emissions are reviewed in order to highlight the particularities and added value of carbon-based accessibility analysis. The second part of the paper illustrates decision-making purposes for which the method could be useful.

More specifically, the experiential application uses scenario analysis to assess the impacts of a number of potential transport interventions on the carbon-based accessibility of a workplace location and compares the resulting accessibility levels to alternative sites. The paper closes with a reflection on the benefits and limitations of carbon-based accessibility measures in section 4.5.

4.2. Supporting decision-making in the context of transport-related greenhouse gas emissions

4.2.1. Key characteristics of low carbon mobility planning tools

Four key characteristics of tools and methods for low carbon mobility planning are introduced in this section. While full compliance with these characteristics is not necessarily imperative for a decision-making tool to be useful, they are expected to bring added value to the realm of low carbon mobility planning and serve as criteria to compare existing tools and methods (section 4.2.2) with carbon-based accessibility instruments (section 4.2.3).

The first characteristic is the consideration of the *land use component*. Climate change mitigation in the transport sector has a strong focus on technological innovation and associated reductions in specific vehicle emissions (Schwanen et al., 2011). However, the availability of low emission transport modes is not sufficient if spatial patterns do not enable low carbon mobility. Urban form influences trip lengths and mode choice, which in turn have an impact on transport-related energy consumption and emissions. Various studies focus on the relationship between the built environment at the neighborhood level and travel behavior or GHG emissions (see for example Cervero and Kockelman, 1997; VandeWeghe and Kennedy, 2007; Barla et al., 2011). The findings point towards higher emissions in low density areas compared to central locations, since the lack of proximity to activities and services demands more extensive use of the private car. Likewise, density and the distribution of residences, workplaces, and other urban functions influence travel behavior at the city and metropolitan level (Næss, 2012). Newman and Kenworthy (1989) found a negative correlation between residential urban density and energy consumption per capita. However, this relation is also influenced by fuel prices and individual travel costs (Wegener, 1996). Economic growth and changes in lifestyles might counteract efforts to achieve emission reductions in the transport sector through integrated land use and transport planning (Greene and Wegener, 1997; Holz-Rau and Scheiner, 2019). Nevertheless, low carbon mobility options are an essential prerequisite for low carbon mobility behavior. The absence of compact urban development policies would likely result in sprawl, more car use, and higher emissions (Geurs and Van Wee, 2006; Ewing, 1997). Density and functional mix of uses as well as the integration of urban areas with existing urban patterns and the public transport system are acknowledged as important levers to reduce travel distances and car dependence (Banister, 2011). Consequently, sustainable transport and reductions in transport-related emissions depend on land use policies (Loo and Tsoi, 2018). Integrated planning approaches are required in order to link the land use and transport systems in an intelligent and efficient way. Additional measures, such as travel demand management and pricing strategies, need to ensure that the provided low carbon mobility options are realized. Strategies in the context of carbon pricing, budgeting, and trading could eventually prove effective in further incentivizing compact urban development.

A second characteristic is the presence of a *spatial dimension*, which determines if a tool or method is based on a model of the land use and transport system, featuring its specific characteristics. Georeferenced data on both systems facilitates integrated land use and transport planning as well as the generation of visual outputs in map format. While numerical outputs are typically useful to assess interventions, maps make it possible to not only assess, but also identify needs for intervention that are specific in nature, dimension, and geographic terms. Abstract issues can be made tangible under the conditions given in a specific context. This is especially helpful for decision-making on local, regional, and metropolitan scales.

A third aspect refers to *scenario building capabilities*, describing a tool's capability to react to interventions in the land use and/or transport system. Scenarios help to understand the consequences of decisions or the effects of strategies and measures, thus serving as a valuable basis for discussion on low carbon transport futures (Hickman et al., 2011). Tools with scenario building capabilities are especially important for decision-making of politicians and planners, who are able to intervene in the land use and transport system.

The last key characteristic is a high *communication value*, which enables discussion, understanding, and cooperation across disciplines and decision-making levels. Transitions require commitment and action of multiple stakeholders, including politicians, planners, corporations, and citizens (Geels, 2012). Consequently, decision-making instruments need to encourage action by making problems and potential solutions related to low carbon mobility options understandable for a variety of stakeholders.

4.2.2. Existing tools and methods

Multiple tools and methods exist to identify strategies and measures for reducing transport-related emissions. They range from simple online calculators for public use to complex models for expert use. This section presents an inventory of decision-making instruments and reflects on their characteristics with respect to the criteria identified in section 4.2.1.

Microscopic emission quantification focuses on the technological aspects of transport-related emissions. The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Model calculates energy use and emission impacts of different fuel and vehicle types in a life-cycle approach (Wang et al., 2017). Other tools determine energy use, fuel consumption or tailpipe emissions of a given vehicle fleet for a variety of operation modes. The distinction between different operation modes can be rather general, as in the HBEFA (INFRAS, 2017) or modeled on a more disaggregate scale, as in the Comprehensive Modal Emission Model (Barth et al., 2000). While such tools are helpful in assessing the impacts of technological innovation, intelligent transport systems or ecological driving, they do not capture mobility behavior on a comprehensive level. The absence of a land use component or spatial dimension makes them applicable to decision-making related to vehicle efficiency only.

Macroscopic emission quantification addresses the level beyond individual vehicles or vehicle fleets, such as trips, households or even countries. Transport mode analysis tools enable the user to compare a number of transport alternatives with respect to costs or emissions. Transport choices can be related to passenger trips (DB, 2019; Knörr and Hüttermann, 2016) or freight trips (EcoTransIT World, 2020). Emission calculation tools are also available on analysis scales beyond single trips, focusing on the mobility patterns of individuals, households or firms (Carbon Footprint Ltd, 2020; UBA, 2020a). The information needed for emission quantification, such as trip length, mode choice, emission factors, and occupancy rates, is based on user input or default values. Many of these tools are implemented as online calculators, aiming to enhance individual awareness and decision-making.

Calculations on household or vehicle level can be aggregated on a higher level based on knowledge about vehicle fleets or sociodemographic structure within a given administrative unit (Knörr et al., 2016). The outputs are especially relevant for monitoring environmental performance. Some tools and methods are not limited to transport-related emissions, but support GHG inventories, energy and CO_2 balancing and benchmarking across different sectors (IPCC, 2006; ECOSPEED Climate Software Solutions, 2020).

Especially when intended for political decision-making on aggregated scales, macroscopic emission quantification tools often have scenario building capabilities to assess general strategies or policies. Since they do not entail a spatial dimension, the impacts of specific interventions in the land use and/or transport system can only be assessed with the help of other tools providing knowledge about how these interventions affect the input parameters used for emission quantification.

Residential location choice tools highlight the financial costs of different residential location alternatives and are also able to estimate the mobility-related carbon footprint linked to these choices (Housing and Transportation Affordability Index, 2020; NaWo, 2020). Transport-related emissions are calculated based on statistical data or user input. Typically, such tools are intended for use by individuals or households, but they could also be useful for planners who are interested in comparing multiple locations on a local or regional scale. In terms of key characteristics, both a spatial dimension and the land use component are present. The communication value is high due to easily understandable and visual outputs. However, these tools do not enable an assessment of system-wide land use and transport interventions, resulting in limited scenario building capabilities. Furthermore, the focus is on residential locations only.

Travel demand models focus on traffic generation and distribution (Te Brömmelstroet et al., 2016), as well as mode choice and route choice. Travel demand models provide essential input data for emission estimation, potentially integrated in sophisticated decision-making tools (Szimba et al., 2018). However, they are generally not suitable for mutually assessing interventions in the transport and land use system due to limited consideration of the land use component (Geurs and Van Wee, 2004). The focus on transport-related aspects on different aggregation levels reduces their applicability to transport decision-making only.

Integrated land use/transport models not only consider the impacts of land use on transport, but are also capable of predicting urban development based on a complete feedback cycle between the land use and transport systems. Such models are able to assess a large variety of policy interventions and provide information about CO_2 emissions or changes in CO_2 emissions as an output (Hensher, 2008; Schwarze et al., 2017; Ford et al., 2018). While scientifically sound, the complexity and data requirements of these models as well as their limited transparency and understandability for decision-makers (Waddell, 2011) reduce their communication value.

One common feature of all reviewed tools and methods is the quantification of transport-related emissions as an output, albeit on different aggregation scales. This is a key difference compared to the method proposed in this paper, which produces accessibility levels as an output, based on CO_2 emissions as an input. Figure 12 illustrates the workings of all tools and methods in a schematic way. A more detailed description of carbon-based accessibility instruments follows in section 4.2.3.

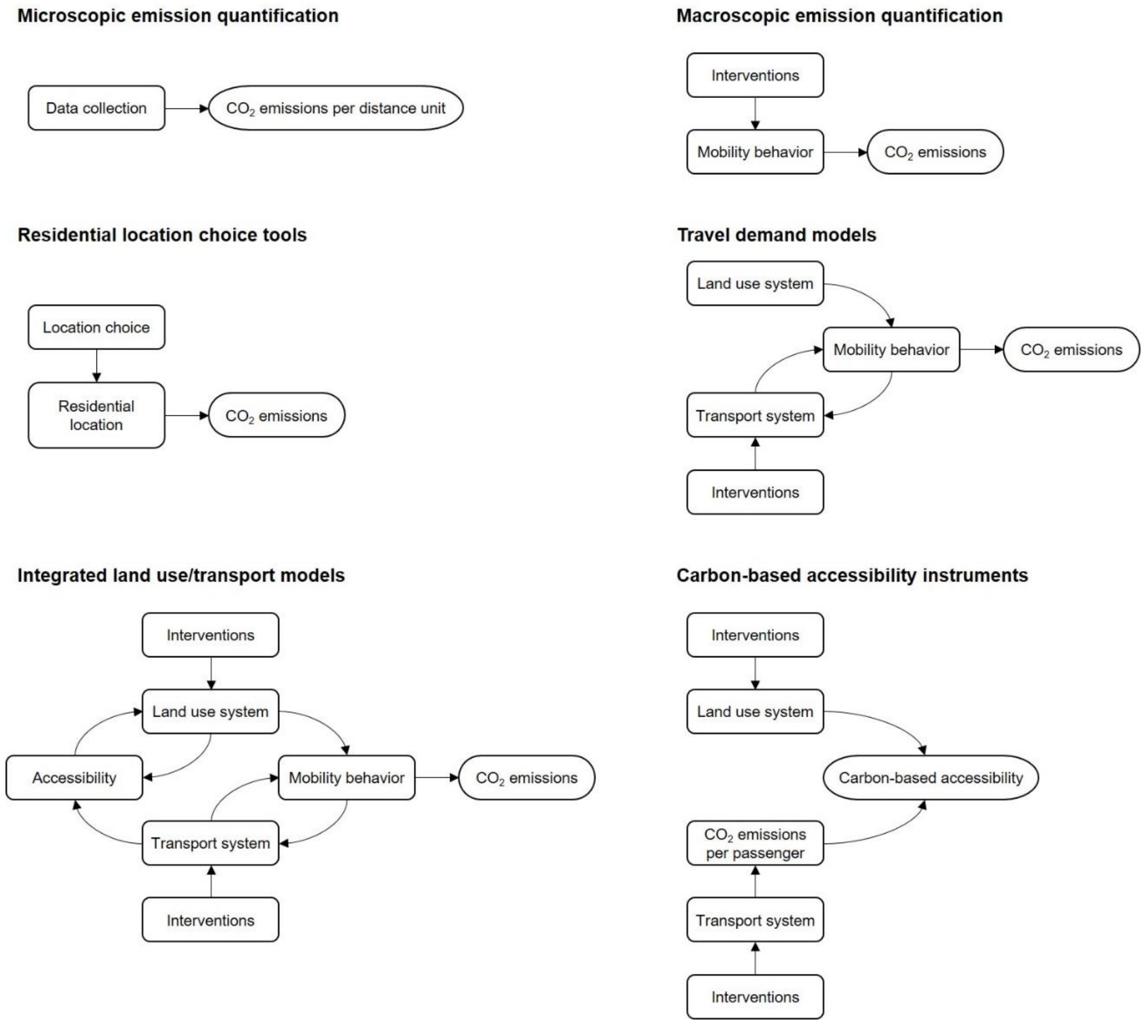


Figure 12. Overview of the basic workings of the different tool types.

The tools presented so far might be useful for a number of decision-making purposes in the context of low carbon mobility, such as assessing the impacts of climate change mitigation measures. However, in terms of the criteria defined in section 4.2.1, all of them hold limitations: Some of them lack a land use component or spatial dimension, others do not enable scenario building, and still others have limited communication value due to their large complexity. By uniting all of these characteristics, carbon-based accessibility instruments could represent a valuable addition to existing decision-making tools aiming to reduce transport-related emissions.

4.2.3. Applicability of carbon-based accessibility instruments

The type of decision-making instrument proposed in this work relies on location-based accessibility measures, which describe the ease of reaching spatially distributed activities from a given location (Geurs and Van Wee, 2004). The general formula of location-based accessibility has the following form:

$$A_i = \sum_j D_j \, f(c_{ij})$$

A_i is the accessibility at origin location i, D_j represents the activities at destinations j, and $f(c_{ij})$ is a function of the travel impedance c_{ij}. Traditionally, accessibility is conceptualized in line with the travelers' perceptions, using time or monetary costs as travel impedance (Handy and Niemeier, 1997). In contrast, viewing CO_2 emissions as a travel cost in accessibility analysis might be a suitable conceptualization to cater for political objectives related to climate change mitigation instead. CO_2 emissions are viewed as a constraint on reaching activity destinations, rather than an output of travel activities. This perspective is especially relevant in light of the emerging discussions on carbon pricing and emission limits, which will affect the accessibility of both locations and individuals.

In terms of the key characteristics introduced in section 4.2.1, carbon-based accessibility promises to bring added value compared to other tool and methods. Location-based accessibility measures require data on the land use and transport system. Consequently, accessibility instruments typically entail a spatial dimension and are able to produce visual outputs in map format. The land use component is represented at both origins i and destinations j. While some accessibility measures, such as utility-based or person-based models, are rather complex, location-based measures are much easier to understand and use (Bertolini et al., 2005; Geurs and Van Wee, 2004). Finally, accessibility instruments enable scenario building, thus highlighting potential impacts of decisions. Based on experiences with existing accessibility instruments (Te Brömmelstroet et al., 2016; Papa et al., 2016; Silva et al., 2017; Büttner et al., 2018), carbon-based accessibility could be useful for a number of potential decision-making purposes:

- Comparing carbon-based accessibility levels across different urban structures
- Assessing the impact on carbon-based accessibility of land use development targeting increases in density and diversity
- Comparing carbon-based accessibility levels using different transport modes

- Assessing the impact on carbon-based accessibility of transport interventions aiming to reduce specific emissions

A selection of these potential decision-making purposes is showcased in the experiential application following in sections 4.3 and 4.4.

4.3. Experiential application: scope, method and data

4.3.1. Carbon-based accessibility of a workplace location

Carbon-based accessibility analysis is tested in an exemplary case study in order to demonstrate its application potential and highlight its particularities compared to existing tools and methods. In this paper, scenario analysis is used to show the impacts of interventions in the transport system on the carbon-based accessibility of a business park. The question of employment accessibility is a relevant planning issue that has found particular attention in the past (Cheng and Bertolini, 2013). The campus under consideration is located in Gilching, situated to the west of the city of Munich (see Figure 13). The business park is frequently mentioned by local transport planners as one of the main traffic generators in the region due to its prominent role as a workplace location. The campus is located close to a motorway as well as a suburban railway line. Two recently introduced express bus lines connect the business park to the main hubs of the region, the cities of Fürstenfeldbruck and Starnberg, as well as further public transport supply, including suburban trains and subway. Compared to regular bus lines, the express services have fewer stops and more direct routes.

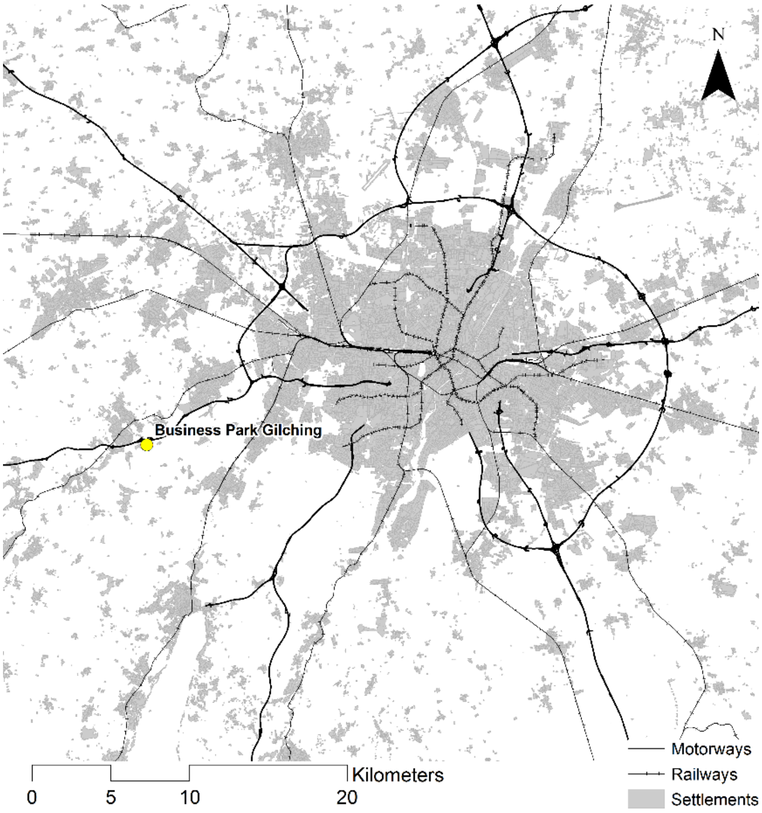


Figure 13. Location of the business park Gilching in the Munich region.

A location-based accessibility measure according is used to calculate carbon-based car and transit accessibility of the business park under changing transport conditions. Contour measures are the simplest type of location-based accessibility measures, simply summing up the number of opportunities that can be reached within a given travel cost threshold (Bertolini et al., 2005). Since the analysis is focused on a business park, the opportunities D_j are represented by the number of accessible workers. Data on the number of workers is available on municipality level from the Bavarian State Office for Statistics and was disaggregated into smaller spatial units based on the ATKIS dataset (Bayerische Vermessungsverwaltung, 2014). Travel costs c_{ij} are measured in carbon dioxide equivalents (CO_{2e}), a common unit to quantify the global warming potential of human activities. Emission costs, which are not directly perceptible by travelers, play a minor role in travel decisions, since individuals typically try to optimize travel time (Vale, 2013). Consequently, the travel cost threshold is independent of how long people are willing to travel, but represents the political target for the maximum CO_2 emissions of one trip. The emission budget can be chosen according to any low carbon policy goal or emission reduction scenario. It is represented by the emissions ε in the following equation:

$$f(c_{ij}) = \begin{cases} 1 \; if \; c_{ij} \leq \varepsilon \\ 0 \; if \; c_{ij} > \varepsilon \end{cases}$$

It should be noted that people might be willing to travel further than the defined CO_2 budget. The original definition of accessibility as a potential (Hansen, 1959) is even more relevant in this case: Without any options for reaching important destinations with low emissions, low carbon mobility cannot be realized. High accessibility of a location indicates that many workers are located within the defined budget. As a result, the probability increases that workers commute from within the catchment area. However, this does not allow final conclusions regarding the realized mobility behavior of individual workers.

Before describing the selected accessibility scenarios and chosen cutoff values in section 4.3.3, section 4.3.2 explains the process of modeling the emission costs c_{ij} for car and transit.

4.3.2. Modeling CO_2 emissions as a travel cost

The emission modeling consisted of multiple steps, as shown in Figure 14. The process started with preparing models of the network topologies of car and transit in the Munich region. The next step was to assign values for the energy consumption of different transport modes to all network links based on their characteristics. Absolute consumption on link level was converted to emissions based on the corresponding emission factors. Finally, occupancy rates were used to break down emissions per vehicle to emissions per passenger.

The data used in the emission models stems from different sources and years, but discrepancies between data sets and points in time are expected to be negligible. Nevertheless, both temporal and spatial dynamics, such as time of the day and precise location within the network, certainly influence the results and might require more detailed data depending on the purpose of the analysis. The default values can be adapted to assess any desired scenario, as done in the experiential application.

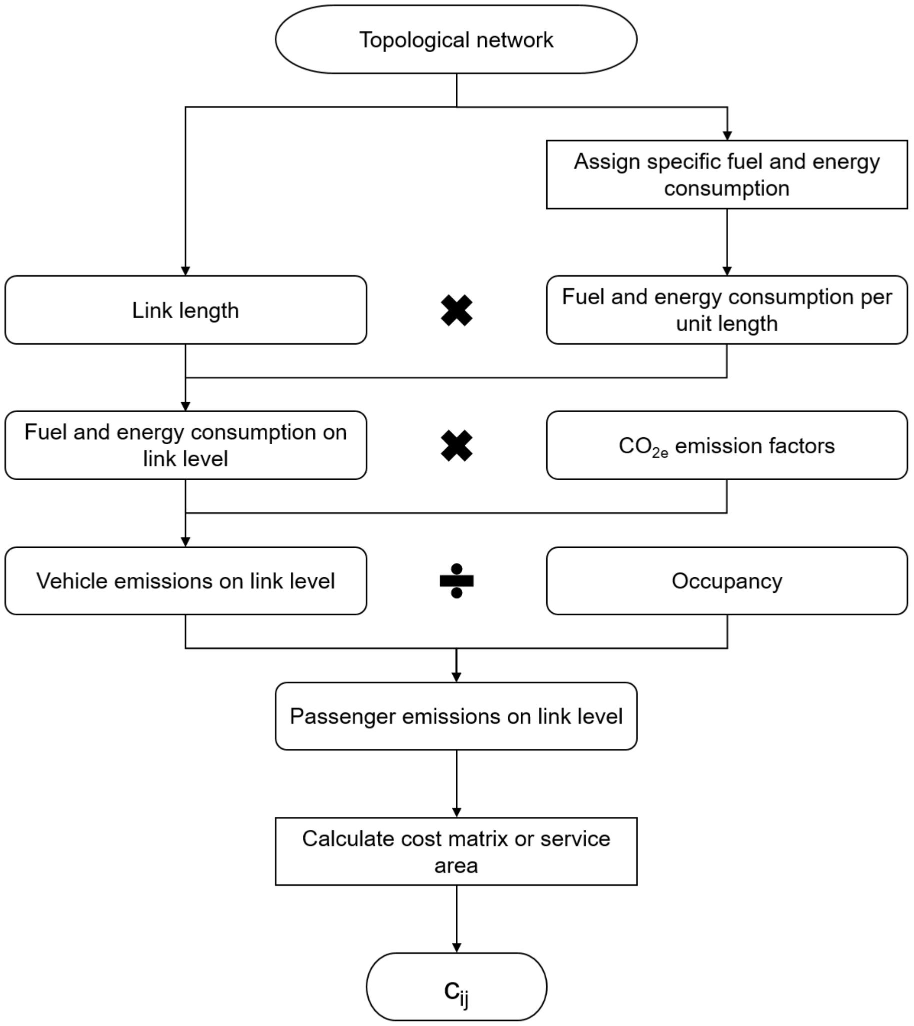


Figure 14. Process of emission modeling.

Transport networks

Different software environments were applied, depending on the available data. The car emission model was implemented in ArcGIS, whereas the transit emission model was implemented in the transport modeling software PTV Visum. The network links for the car model, including road types and speed limits, were retrieved from OSM.

OSM data also served to model pedestrian access and egress to and from transit stops. A catchment of 600 meters around transit stops was used to ensure spatial coverage. Other means of access to transit, like park and ride or bike and ride, were not considered. However, they could be added in the future to analyze intermodal carbon-based accessibility.

Fuel and energy consumption

HBEFA (INFRAS, 2017) is a database providing information on fuel consumption and emission factors for a number of vehicle categories like passenger cars, trucks and buses. The aggregation level for the car emission model is fuel type, based on the 2018 fleet composition in Germany. Fuel consumption information in grams per kilometer for diesel and gasoline cars is available for a number of traffic situations. Traffic situations in HBEFA are determined by location of the road (urban or rural area), road type, speed limit and level of service (free flow, heavy, saturated and stop and go). Due to lack of data on road congestion, we determined the level of service to be saturated in urban areas and free flow in rural areas, respectively. The network model can be updated if more detailed data is available or adapted to compare different congestion scenarios. CLC was used to differentiate between urban and rural areas. Specific fuel consumption values were assigned to the network segments according to their characteristics in terms of location, road type, and speed limit. The multiplication of link length and specific fuel consumption yielded the absolute amount of diesel or gasoline consumed by a passenger car on each OSM link.

HBEFA version 3.3 does not provide emission factors or energy consumption data for electric vehicles. While information about the average consumption of electric vehicles can be found easily, detailed consumption values by road type or travel speed still require more research and testing (Braun et al., 2014). Consequently, the consumption model for electric vehicles is simplified compared to the consumption model for conventional passenger cars. The model for electric vehicles distinguishes between traveling on highways, traveling within urban areas and traveling outside of urban areas.

Public transport features large variations in vehicle types. Buses are usually diesel fueled, whereas most rail-bound transit in the Munich region runs on electricity. Thus, units and quantities of energy consumption vary depending on the route type. Table 3 provides an overview of the units and sources of fuel and energy consumption used in the emission models of car and transit.

Table 3. Fuel and energy consumption used in the emission model.

Vehicle type	**Fuel and energy consumption**	**Source**
Gasoline car	40.462 - 73.441 grams/km by urban environment, road type and speed limit	INFRAS (2017)
Diesel car	35.401 - 66.846 grams/km by urban environment, road type and speed limit	INFRAS (2017)
Electric car	0.199 - 0.271 kWh/km by urban environment and road type	Helms et al. (2016)
Regional bus	235 - 371 grams of diesel/km by county and urban environment	Data provided by the Munich Transport and Tariff Association
Regular bus	4.4 grams of diesel/seat-km	DB (2019)

Vehicle type	Fuel and energy consumption	Source
Electric bus	1.5 kWh/km in light urban traffic by vehicle type	Study by Knote et al. (2015) conducted for the County of Munich
Tramway/Subway	0.023 kWh/seat-km	DB (2019)
Suburban train	0.018 kWh/seat-km	DB (2019)
Regional train	0.021 kWh/seat-km	DB (2019)
Intercity train	0.022 kWh/seat-km	DB (2019)

Emission factors

As opposed to other pollutants, GHGs do not have a local impact, emphasizing the importance of considering the entire energy chain. A well-to-wheels approach, considering emissions generated during upstream processes, is more comprehensive, especially when jointly considering electric and conventional vehicles (Moro and Lonza, 2018).

In order to determine the emissions generated while traveling across a network segment, the absolute fuel and energy consumption was multiplied by the specific emission factors. The emission factors used in the network model are presented in Table 4. In order to calculate average emissions for a conventional car, the emissions of diesel and gasoline were weighted by their share of the German fleet composition, as given in HBEFA.

Table 4. Emission factors used in the emission model.

Fuel and energy type	Emission factor	Source
Gasoline (well-to-wheels)	3.86 grams of CO_{2e}/gram	Schmied and Mottschall (2014)
Diesel (well-to-wheels)	3.9 grams of CO_{2e}/gram	Schmied and Mottschall (2014)
Electricity (well-to-tank)	580 grams of CO_{2e}/kWh	DB (2019)

Occupancy rates

Information about the number of passengers per vehicle is required to break down the total emissions per vehicle to emissions per individual passenger. Occupancy can be based on either actual data or assumptions in order to analyze different scenarios.

Occupancy is easy to model in the case of car travel, typically remaining the same throughout the trip. On the contrary, occupancy rates of transit vehicles vary widely in space and time. Average occupancy rates might deviate a lot from the actual occupancy on a specific line segment at a specific point in time. In this particular emission model, spatial variations in occupancy were considered, whereas temporal variations were not. This means that emissions generated on a line segment are equally distributed among all passengers using this link, independent of when they are traveling. Table 5 gives an overview of the different occupancy rates implemented in the network model.

Table 5. Occupancy rates used in the emission model.

Vehicle type	Occupancy rate	Source
Car	1.2 passenger-km/vehicle-km	UBA (2016b)
Regional bus	7.7-13.6 passenger-km/vehicle-km by county on a working day	Data provided by the Munich Transport and Tariff Association for the year 2015
Bus/Tramway/Subway	0.21 passenger-km/seat-km	DB (2019)
Suburban train	0.29 passenger-km/seat-km	DB (2019)
Regional train	0.25 passenger-km/seat-km	DB (2019)
Intercity train	0.48 passenger-km/seat-km	DB (2019)
All public transport modes	daily number of passengers/link	Travel demand model of the State of Bavaria for the reference year 2014

4.3.3. Selected scenarios

The carbon-based accessibility of the business park Gilching is analyzed in 14 scenarios assuming different transport conditions. Table 6 shows the selected scenarios for transit (scenarios 1a-g) and car (scenarios 2a-g). Each mode features a default scenario based on today’s carbon footprint related to work trips. The emission cutoff was derived from information of the German Environment Agency (UBA, 2017b). The total GHG emissions in Germany in 2016 were broken down to the share of one commuting trip, which yielded a default budget of 1,500 grams of CO_{2e}. Targets for 2030 require a reduction in transport-related GHG emissions by at least 40 % (BMU, 2016). An ambitious emission budget of 750 grams of CO_{2e} was selected as cutoff value for the remaining accessibility analyses (1b-g and 2b-g, respectively). These scenarios feature variations in the parameters of the emission model, namely fuel and energy consumption, emission factors, and occupancy rates.

Table 6. Overview of selected scenarios.

No.	**Transport mode**	**Scenario title**	
1a	Public transport	Default	1500 g
1b	Public transport	Reduced carbon budget	750 g
1c	Public transport	Increased occupancy rate	750 g
1d	Public transport	Electrification	750 g
1e	Public transport	Electrification and improved electricity generation mix	750 g
1f	Public transport	Relocation 1	750 g
1g	Public transport	Relocation 2	750 g
2a	Car	Default	1500 g
2b	Car	Reduced carbon budget	750 g
2c	Car	Increased occupancy rate	750 g
2d	Car	Electrification	750 g
2e	Car	Electrification and improved electricity generation mix	750 g
2f	Car	Relocation 1	750 g
2g	Car	Relocation 2	750 g

Scenarios 1c and 2c consider the accessibility impacts of changes in occupancy rate. The transit scenario presumes an increase in occupancy rates of the two express bus lines serving the business park to 25 % average occupancy throughout the day. The occupancy rates of all other transit lines remain unchanged. The assumed increase is realistic considering the average occupancy rate of public transport in Germany (21 %, DB, 2019) as well as the overall rising passenger numbers in the Munich region (MVV, 2015). The car scenario assesses the impacts of carpooling, which increases the occupancy rate from 1.2, the average value for work trips in Germany (UBA, 2016b), to 2 persons.

Electric vehicles are expected to contribute to emission savings, but the emission reduction potential clearly depends on the carbon intensity of electricity (Moro and Lonza, 2018). Even though electric vehicles do not cause any local GHG emissions, they are not emission-free, which highlights the importance of a well-to-wheels approach. The coal combustion in a power plant might even cause more emissions than the fuel combustion in a conventional car or bus. Scenarios 1d-e and 2d-e feed this discussion by analyzing the impacts of electrification on carbon-based accessibility. Scenario 1d analyzes the carbon-based accessibility impacts of replacing diesel buses with battery-powered buses on the two express bus lines serving the business park. Scenario 2d focuses on the question of how many workers could access the campus within the defined emission budget if they were using battery electric vehicles. Both scenarios were revisited in scenarios 1e and 2e, assuming an improved electricity generation mix. In recent years, the CO_2 emissions from electricity generation have constantly decreased in Germany (Icha and Kuhs, 2016). Here, the assumption was a 20 % reduction, resulting in an emission factor of 464 instead of 580 grams per kWh. It should also be noted that the manufacturing process of electric vehicles causes more GHG emissions than the production of conventional vehicles due to the battery (Helms et al., 2016). Emission impacts related to manufacturing were not considered in this exercise, but should be included in a complete life-cycle analysis.

Accessibility can be useful to compare alternative locations and inform location choices. While efficiency improvements and occupancy increases may benefit the carbon-based accessibility of a given location, other locations may still feature higher accessibility levels under the given emission constraints. Scenarios 1f-g and 2f-g focus on urban development options by assessing two alternative business park sites under unchanged transport conditions. A complementary application of carbon-based accessibility deepening the land use aspect can be found in Kinigadner et al. (2019). The study identifies differences in carbon-based accessibility of various spatial typologies, such as urban and suburban.

4.4. Results and discussion

Figure 15 presents both transit and car accessibility of the business park based on the default emission budget of 1,500 grams CO_{2e} and the reduced emission budget of 750 grams CO_{2e}, respectively.

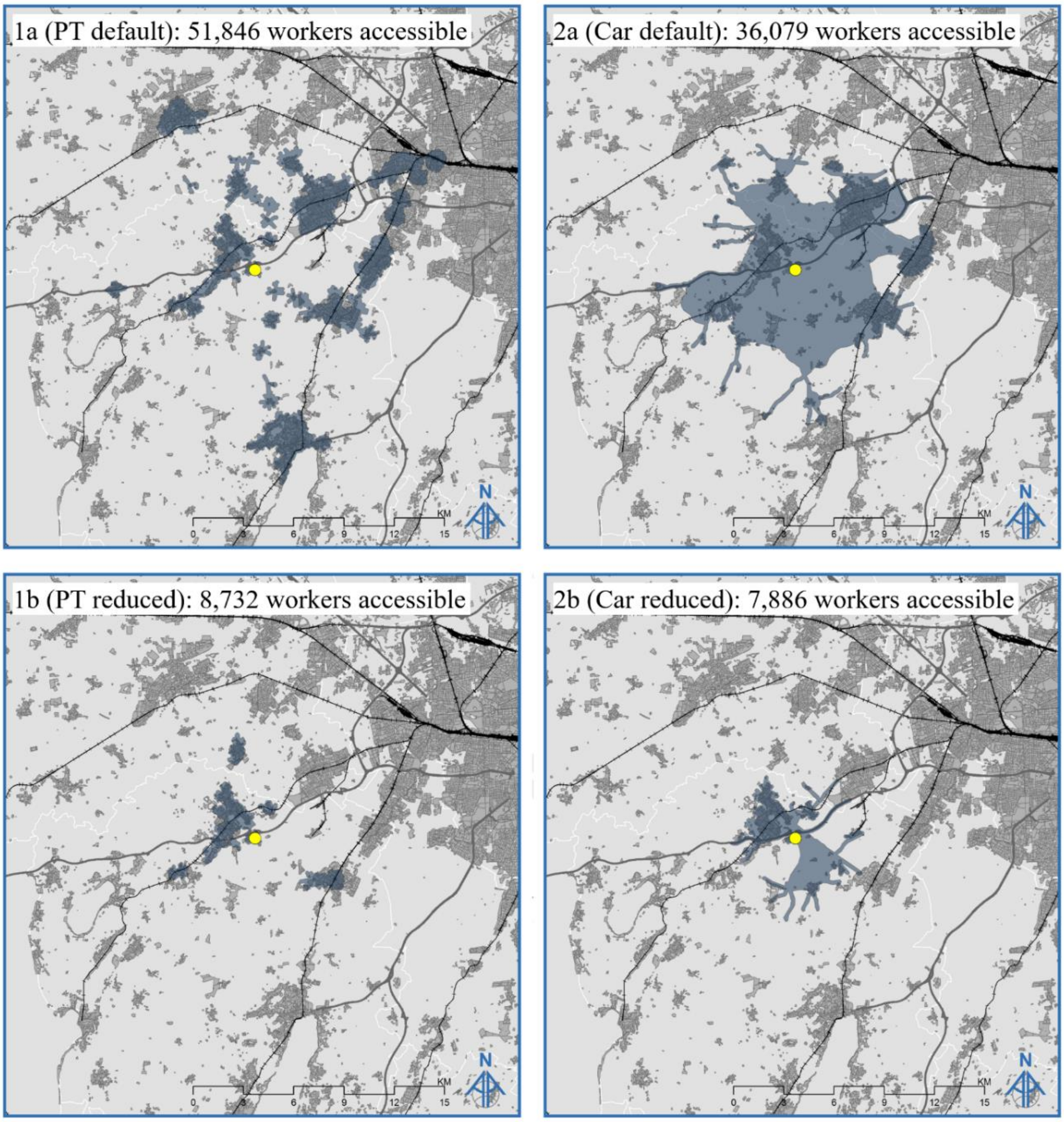


Figure 15. Carbon-based accessibility maps for scenarios 1a-b and 2a-b.

In the default scenario, carbon-based transit accessibility surpasses car accessibility by a factor of almost 1.5. Using public transport, workers from more densely populated areas in the cities of Fürstenfeldbruck in the north, Starnberg in the south, and Munich in the east are able to access the campus with a budget of 1,500 grams of CO_{2e}. Cutting the emission budget by half reduces carbon-based accessibility levels to roughly one fifth of the original values for both modes. Public transport suffers from larger reductions, but still provides higher accessibility levels than the private car. The large vulnerability to a reduced emission budget can be explained by the isolated location of the business park. Larger urban areas are accessible with the default budget, but not with the reduced budget. This observation emphasizes the importance of not only the transport system, but also the land use system if emission limits are implemented. Decreases in catchment size might decrease accessibility by a larger factor in case of an unfavorable urban form.

Scenarios 1c-d and 2c-d analyze to what extent interventions in the transport system, targeting emission reductions, can make up for limited density and contribute to recovering accessibility levels. Figure 16 shows the two options considered: increases in occupancy rates (c) and electrification (d).

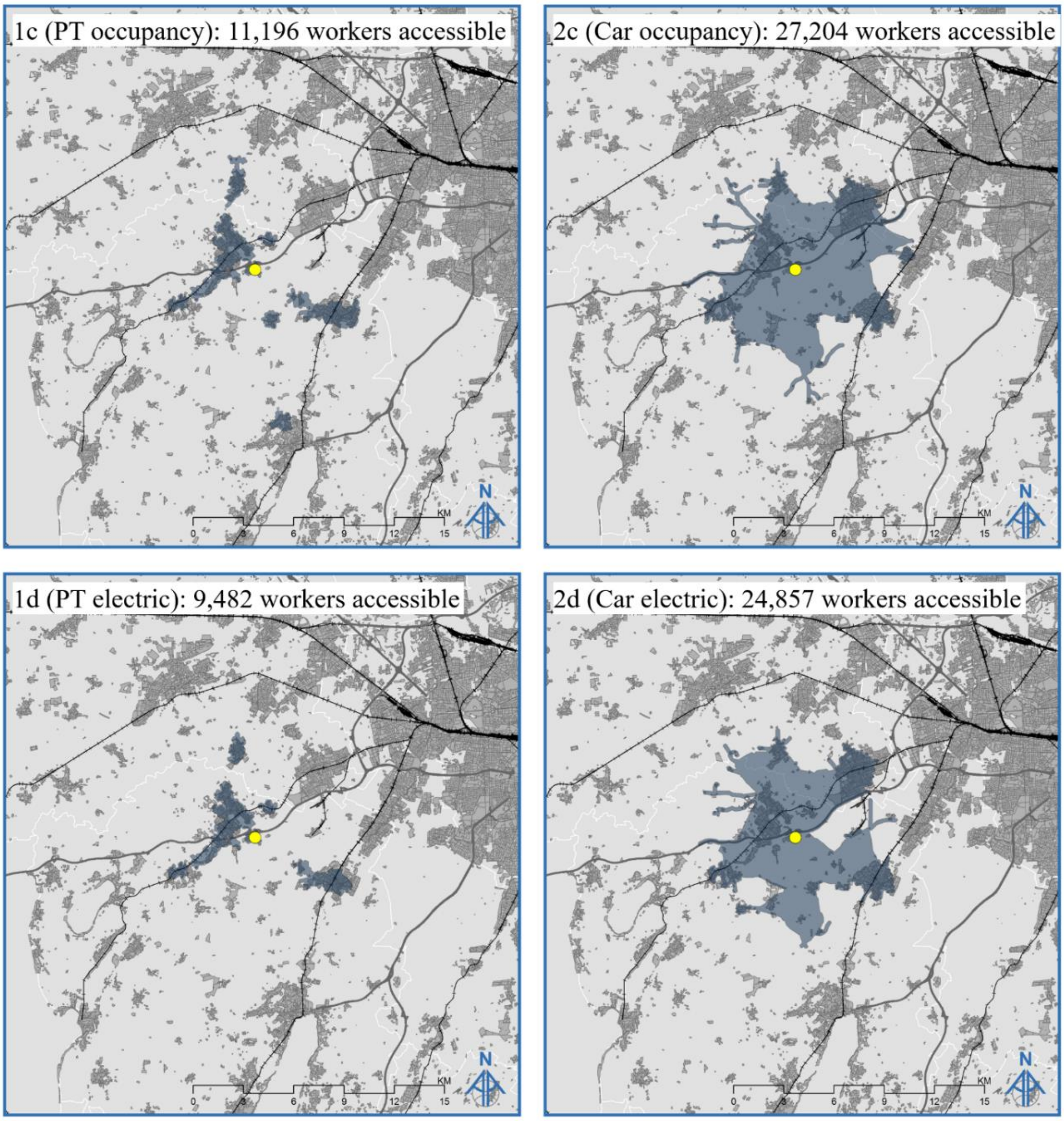


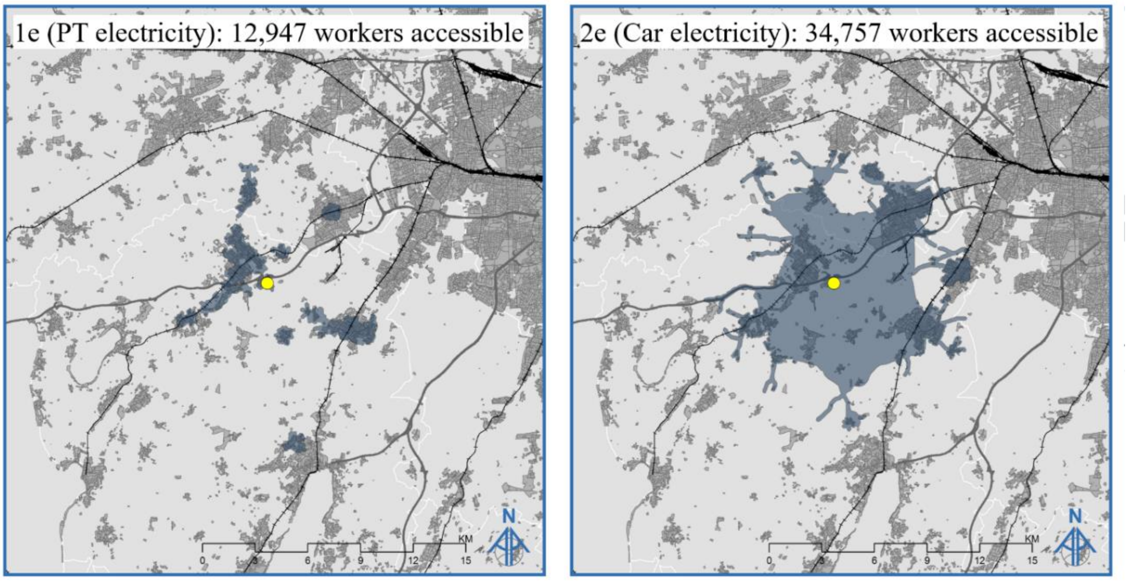
Figure 16. Carbon-based accessibility maps for scenarios 1c-d and 2c-d.

The impacts on carbon-based accessibility of increased occupancy rates and electrification are comparable. For both modes, the occupancy scenarios perform just slightly better than the electrification scenarios. An increase from 1.2 to 2 persons increases carbon-based accessibility levels by a factor of almost 3.5 in the car scenario. Carbon-based accessibility triples when replacing a conventional car by an electric car. The underlying efficiency gains vary by road type. Electric cars produce 25 % less emissions on highways and almost 50 % less within urban areas, where recuperation is possible.

Car accessibility benefits from larger increases than transit accessibility. Higher occupancy rates increase carbon-based transit accessibility by about 30 %, whereas electrification results in accessibility gains of almost 10 %. However, also the relative changes in the input parameters, namely occupancy rates and energy consumption, are not as large in the case of public transport. According to the assumptions underlying scenario 1d, battery-powered buses produce only 15 % less CO_{2e} per kilometer compared to diesel buses. Furthermore, the intervention in the public transport system was rather small, since only two express bus lines were adapted in terms of occupancy and consumption values. Efficient, high occupancy vehicles are clearly needed throughout the entire transport system in order to significantly increase carbon-based accessibility.

The travel cost threshold plays a major role when using contour measures, since all destination potentials located outside the catchment area do not contribute to accessibility. In public transport, travelers can only access or exit the transport system at stops. Consequently, accessibility levels increase in jumps. Especially in the case of long distances between stops, which is true for both express bus lines and suburban train lines, the emission budget might be exhausted before another stop is reached.

Scenarios 1e and 2e explore the benefits of improving the electricity generation mix. The corresponding accessibility maps are shown in Figure 17.


1e (PT electricity): 12,947 workers accessible

2e (Car electricity): 34,757 workers accessible

Figure 17. Carbon-based accessibility maps for scenarios 1e and 2e.

The number of accessible workers by public transport is 12,947. This accessibility level is slightly higher than in scenario 1c, where occupancy was increased. The improved electricity generation mix does not only impact the emissions of buses, but also the emissions of rail-bound transit, causing the catchment area to increase. Car accessibility to workers is 34,757. Compared to scenario 2d, this corresponds to an accessibility gain of another 40 %. Some of the larger settlements in the vicinity of the business park are now completely covered by the catchment area of 750 grams of CO_{2e}. Accessibility levels by car are unmatched by public transport in scenarios c, d, and e. These results represent a basis for discussion on the environmental competitiveness of cars in suburban or rural areas, where occupancy rates in public transport tend to be lower than in highly urbanized areas.

Accessibility levels may differ significantly within a region, emphasizing the importance of land use and location choices. Figure 18 illustrates the impacts of relocating the business park from its peripheral location to a different site instead of improving vehicle efficiency or increasing occupancy rates. The first alternative (scenarios 1f and 2f) is near the original site, but located within the existing agglomeration of Gilching. Such a relocation would bring the business park closer to the suburban railway line, but further away from the motorway. The second alternative (scenarios 1g and 2g) is an undeveloped plot next to the suburban railway stop in the city of Fürstenfeldbruck, a larger agglomeration to the north of the original site.

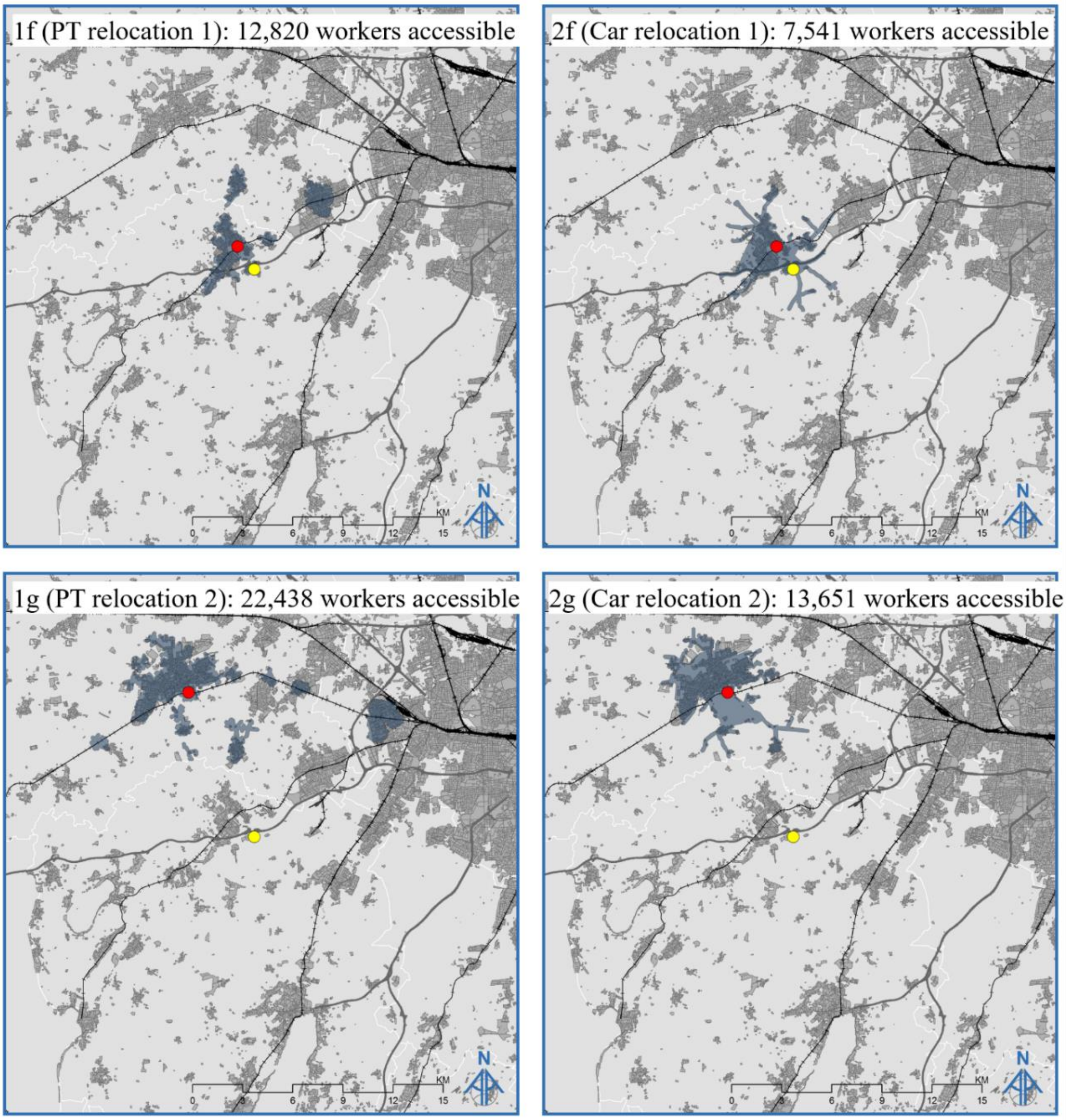


Figure 18. Carbon-based accessibility maps for scenarios 1f-g and 2f-g.

In terms of carbon-based accessibility by car, scenario 2f does not result in an improvement compared to scenario 2b. In both cases, Gilching is located within the emission budget of 750 grams and cumulative opportunities indicators do not account for the fact that these settlements are accessible with less CO_2 emissions from alternative 1. Moreover, the original site's car-oriented and intermediate location benefits its carbon-based accessibility, since some of the built-up areas to the south-east can be reached within the given budget as well. These findings point towards the need to also include accessibility by non-motorized modes in evaluations of location alternatives. Public transport shows a different picture: Scenario 1f results in a 50 % increase in accessibility levels compared to scenario 1b, since alternative 1 is close to the suburban railway line, which enables low carbon transport to neighboring agglomerations. Likewise, scenario 1g more than doubles carbon-based accessibility compared to scenario 1b. The second location alternative also results in an improvement in accessibility by car, which almost doubles in scenario 2g compared to scenario 2b. Reasons include the larger size and higher density of the city of Fürstenfeldbruck, where alternative 2 is located. Electrification and occupancy increases still have a larger impact on accessibility by car than the relocation. Figure 19 provides an overview of all scenario results.

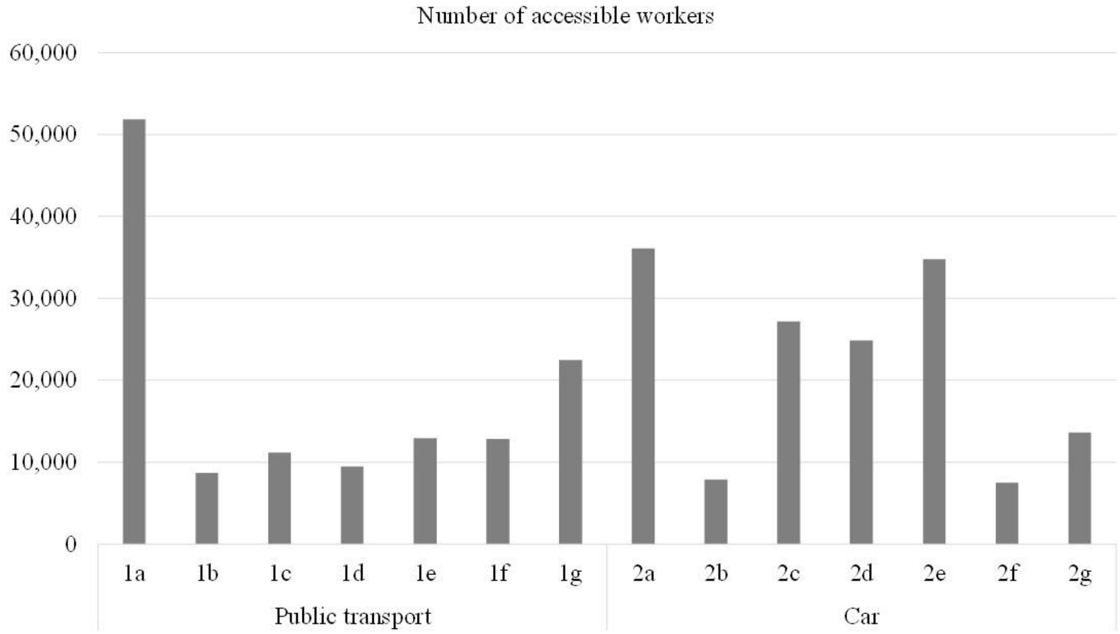


Figure 19. Overview of scenarios 1a-g and 2a-g.

Our results show that by using a carbon-based accessibility measure, car accessibility is smaller than public transport accessibility. However, for our particular case study, increased car occupancy, electrification, and the alteration of the electricity generation mix significantly increase the carbon-based accessibility by car to values greater than the carbon-based accessibility by public transport. This highlights three main important features with significant impact on carbon-based accessibility. First, occupancy rates might exert an important role, either for public transport or for car accessibility. This gives support to carpooling initiatives to increase car occupancy and simultaneously to eventual fare policies to increase the number of transit passengers. Second, the generation of electricity will also have an impact at a local scale, revealing that carbon-based accessibility can reflect structural issues of national scale. Finally, the number of electric cars in operation will also have an impact, once their CO_2 emissions are significantly smaller than internal combustion engines. This electrification of the fleet will also have an impact on public transport accessibility, as buses still run on diesel in the majority of cities. However, the experiential application has shown that minor interventions in the public transport system might not be able to significantly improve carbon-based transit accessibility. It should be noted that individual carbon footprints might be lower by car than by public transport, but from a system perspective, the electrification of buses could be a better solution than the electrification of cars, given their higher capacity and associated occupancy rate. Efficiency improvements and occupancy increases have a large positive impact on carbon-based accessibility by car, but might only be valid for individual vehicles and do not necessarily represent a system improvement. Changing the entire private vehicle fleet is difficult to realize, whereas interventions in the public transport system have a direct impact on all users.

In addition to the transport interventions presented in this paper, the carbon-based accessibility impacts of multiple other options could be explored in scenarios. High demand corridors in suburban areas might offer the potential for a bus rapid transit system. If operated with trolley buses, such a system is expected to outperform not only diesel buses, but also battery-powered buses in terms of energy efficiency and consequently carbon-based accessibility. Furthermore, on-demand services might be a better form of public transport in rural areas than large diesel buses. Not only could such services be an attractive option for passengers, but they might also perform better in terms of carbon-based accessibility by operating smaller shared vehicles.

Regarding implications for land use planning, the reduced emission budget has clearly shown the vulnerability of peripheral workplace locations in terms of carbon-based accessibility. New developments should be located in dense urban environments and oriented towards high quality public transport axes. The application highlights that deliberate location choices and reasonable land use policies could be more useful to reduce transport-related emissions than the electrification of suburban bus lines or potentially unsuccessful carpooling initiatives.

4.5. Conclusions

The experiential application allows for general reflections on the benefits and limitations of incorporating CO_2 emissions as a travel cost in a location-based accessibility framework with respect to decision-making processes. Typical for an accessibility-based approach, the instrument is sensitive to spatial as well as transport-related changes and disparities. The possibility to visualize emission-related aspects adds a new perspective compared to traditional, travel-time-based accessibility analysis, thus enabling joint transport and land use planning from a low carbon perspective. Carbon-based accessibility instruments are able to translate abstract discussions on emission budgeting, carbon taxes, and emission trading into tangible spatial constraints considering local conditions. Even though the output is not quantifiable in terms of emission savings, the visualization in maps might be a main strength in terms of decision-making processes. The results highlight options or needs for interventions in the land use and transport system, which are easily understandable and can serve as a basis for common discussion.

Not all types of interventions aimed at reducing transport-related emissions can be examined with the instrument presented in this paper. The fact that past gains in vehicle efficiency have been annihilated by a growth in travel demand emphasizes the importance of a suitable economic and political framework for decarbonizing the transport sector (Banister et al., 2011; Schwanen et al., 2011). Policies affecting individual travel costs (e.g. pricing strategies) cannot directly be assessed by means of this particular accessibility analysis. Prediction of behavioral change requires knowledge about the travel cost elasticity of mobility choices, which adds complexity to the task at hand. Consequently, a location-based accessibility analysis is too simple to provide a full evaluation of the desirability of a particular emissions mitigation strategy. More technical methods based on intensive data input and modeling could enable a more precise assessment of the costs and benefits of various measures. Thus, the collection of existing tools and methods (section 4.2.2) is not replaced, but supplemented by carbon-based accessibility instruments to provide a useful toolbox for decision-making.

The exemplary application was intended as a demonstration of application potential rather than a solution-finding process for real-world planning issues. Local stakeholders should be involved in the future in order to assess the instrument’s practical relevance for the development of specific low carbon strategies. The analysis could also be extended to a location assessment on a more comprehensive scale, identifying spatial development options with minimum climate impact. Further development and application of the carbon-based accessibility instrument will demonstrate whether the tool continues on its promising path of enhancing decision-making processes related to climate change mitigation in transport. While the underlying spatial data limits the applicability of the instrument to the Munich region, the concept of a carbon-based accessibility instrument could easily be transferred to any other context. Climate change mitigation is a global challenge, making the addressed planning issues and the presented method relevant all over the world.

5. Beer versus bits: CO_2-based accessibility analysis of firms' location choices and implications for low carbon workplace development

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Abstract

Firm locations are a determining factor in shaping low carbon transport futures due to their influence on mobility practices. This paper proposes a methodology for assessing workplace locations based on commuting-related CO_2 emissions. The approach relies on accessibility in order to compromise validity and ease of use. Accessibility planning is increasingly acknowledged for enabling the development of sustainable land use and transport strategies, but has not been tailored to address the challenges of climate change so far. This application substitutes CO_2 emissions from car and public transport for travel time, the traditionally used indicator of travel impedance in accessibility analysis. The methodology is applied to the recent relocations of a brewery and a tech company in the Munich region. Opposing relocation directions emphasize that different firms have different requirements regarding their location, where employee mobility might not be a determining factor. Four different spatial typologies are compared in terms of CO_2-based accessibility: urban central, urban, urban fringe and suburban. The question of how these different workplace locations can cope with strict emission reduction targets and carbon budgeting is one special focus. The analysis reveals significant differences in the carbon footprints of central and peripheral workplace locations. In light of the urgent need to reduce negative impacts from transport activities, such an assessment could be useful for strategic decision-making in the fields of land use and transport planning.

5.1. Introduction

Applied research on low carbon transitions in the transport sector has gained increasing importance in the context of climate change (Banister, 2011) and the new mobilities paradigm (Sheller and Urry, 2006; Sheller and Urry, 2016). A consensus has emerged that micro-level solutions, like technological fixes, will not be sufficient to significantly reduce GHG emissions (Schwanen et al., 2011). Instead, climate change mitigation needs to take place on a macro level, incorporating not only technological innovation, but also economic measures, behavioral change as well as new forms of urban and transport planning (Sheller and Urry, 2016; Banister, 2011).

Workplace locations deserve particular attention in this context because of their constraining nature and their considerable impact on everyday mobility behavior (Bertolini et al., 2005). However, the CO_2 emissions related to commuting most likely play a minor role in the location choice process, which differs among industry sectors. Space intensive production and logistics firms tend to locate in more peripheral areas, where affordable land and suitable freight infrastructure are available (Paulaner Brauerei, 2012). Knowledge intensive firms, on the contrary, are in search of highly educated young talents, who can mainly be found in urban centers (Florida, 2002). Even if other decision factors prevail, both corporate and political decision-makers need to be aware of the environmental impacts of firm locations. In the context of an urgent need to decarbonize transport (Banister et al., 2011), firms should strive towards minimizing their carbon footprint. Emission impacts are traditionally analyzed through empirical surveys or models of travel behavior (Schwanen et al., 2011). However, these methods are data-intensive and not necessarily suitable for supporting the decision-making process related to alternative workplace locations. The concept of accessibility enables an assessment of locations by representing the number of opportunities reachable from a given point in space, independent of realized or modelled travel demand. Travel time is traditionally used as travel impedance, but might as well be exchanged for other indicators. Thus, the concept of accessibility could be applied to answer the question of how many workers can reach a workplace location with a given CO_2 budget. The goal of this paper is to apply such a CO_2-based accessibility analysis to a case study and assess its potential usefulness for corporate and municipal decision-making. The analysis aims to highlight spatial disparities regarding the CO_2 footprint of workplace locations in order to uncover the potential consequences of different location choice strategies for commuting-induced GHG emissions. The recent relocations of two heterogeneous companies in the Munich metropolitan region are considered as an example and their location choice strategies are discussed from an environmental perspective.

This paper is structured as follows: Section 5.2 sheds light on the links connecting workplace accessibility with corporate mobility and provides an overview of existing methods for the assessment of workplace locations. The following two sections are dedicated to the methodological basis of the CO_2-based accessibility analysis and its application in the case study. The paper ends with a discussion about the potentials and challenges related to the applicability of the methodology in planning practice.

5.2. Accessibility of workplace locations

5.2.1. Workplace locations and mobilities

“Social practices and institutions are mobility dependent” (Sheller and Urry, 2016, p. 21). This statement is especially true for work routines. The journey to work represents only a fraction of total mobility. In Germany, for example, 22 % of all passenger-kilometers travelled are due to work and education trips (UBA, 2017a). Nevertheless, commuting has been able to attract the interest of researchers for a long time. Work trips take place frequently, impose spatial constraints, peak within a short time frame and are traditionally car-dominated (Cass and Faulconbridge, 2016; Bertolini et al., 2005; Næss and Sandberg, 1996). For all these reasons, work routines significantly contribute to social, economic, and environmental impacts from transport activities. Despite a trend towards more flexible, digital, and mobile work routines (Kesselring, 2015), workplace locations shape short-term, mid-term, and long-term mobility decisions and practices (Abreu e Silva et al., 2006; Vale et al., 2018). Studies of revealed travel behavior provide findings on two main spatial levels: a macro level, focusing on urban form, and a micro level, focusing on specific workplace locations.

Much research on the relation between urban form and commuting has been conducted in the context of the jobs-housing balance. This strategy aims to reduce travel times and distances by improving the land use mix of residences and employment. Decentralization is one option to bring jobs and workers closer together (Levine, 1998). However, if co-location of workers and firms does not take place, the effects will be minor (Giuliano and Small, 1993; Aguilera, 2005). Even if trip lengths and travel times can be decreased, the car is likely to be the dominant transport mode (Levinson, 1998; Cervero and Wu, 1997). Thus, a good land use mix is not sufficient to bring about sustainable commuting patterns. Without compact development, neither active modes nor public transport will be efficient and attractive alternatives (Levine, 1998; Schwanen et al., 2004). In order to be able to fully assess the environmental impacts of commuting, mode choice needs to be considered in addition to trip length (Boussauw et al., 2012). With this in mind, the characteristics of both the transport system and the land use system are determinant on the regional level.

Another body of literature investigates the impacts of the characteristics of specific workplace locations on commuting. Traditionally, research has focused on the impacts of the built environment at origins or residences (Ding et al., 2016; Cervero and Kockelman, 1997). However, the equal importance of destinations, e.g. workplace locations, for travel behavior is increasingly recognized (Vale et al., 2018; Abreu e Silva et al., 2006). Longitudinal studies of firm relocations and related mobility impacts essentially confirm the findings on the macro level outlined above. Central, high-density workplace locations are favorable in terms of reducing car travel and energy use (Næss and Sandberg, 1996). Suburbanization of workplaces results in shorter or stable travel times in connection with increased car use and potentially increasing commuting distances (Bell, 1991; Vale, 2013). Again, the importance of not only land use, but also transport related characteristics of the immediate surroundings is highlighted. Closeness to railway stations increases commuting shares by public transport compared to private car (Van Wee and Van der Hoorn, 1996; Schwanen et al., 2004). Mobility management measures or policies, in particular reduced parking availability, can contribute further towards achieving a desired mobility behavior within a given built environment (Vale, 2013; Van Wee and Van der Hoorn, 1996).

Since the micro scale focuses on specific workplace locations, it enables more in-depth analysis of the characteristics of a company and its employees. Socio-economic traits, preferences, attitudes, and lifestyles have an impact on mobility behavior, attaching some importance to industry sector and employee structure (Scheiner and Holz-Rau, 2007; Van Wee, 2002). Even though location is not the only factor influencing commuting patterns, it seems to be decisive (Zhao et al., 2017; Thierstein et al., 2016). However, the role of accessibility in shaping employee mobility might be larger than its role in shaping firm mobility. While Giuliano et al. (2012) found that both labor force and network accessibility are significantly related to the growth of employment centers, De Bok and Sanders (2005) state that accessibility barely influences location preferences of firms. The previous location has a major impact, as firms tend to stay within the same corridor in order to maintain existing links (De Bok and Sanders, 2005). In light of the direct relationship between the geographical location of the workplace and the energy use of the journey to work (Næss and Sandberg, 1996), the mobility impacts of firm locations cannot be neglected when striving for sustainable, low carbon transport (section 5.1). Not only firms should include such considerations in their decision-making process related to short-term location choices, but also planning institutions should focus their strategies related to long-term employment development accordingly.

5.2.2. Assessment of workplace locations

Studies of revealed travel behavior provide in-depth knowledge about the mobility impacts of employment locations. Information about mode choice and travel distance enables an assessment of the environmental impacts of commuting, including emissions. However, the fact that surveys can only be conducted after a decision has already been made represents a major drawback. In order to support the decision-making process, an ex-ante assessment of the consequences of corporate location choice is required. Such an approach can build upon the findings of existing travel behavior studies in order to ensure low carbon land use and transport planning.

Existing assessment methods include databases and models (Hensher, 2008; Geurs et al., 2010). While these methods enable a more detailed prognosis of travel impacts, the amount of data and effort required is immense. Location-based accessibility analysis provides a suitable compromise, as location influences travel behavior via accessibility in addition to a complex and wide range of other factors (section 5.2.1). Accessibility incorporates characteristics of both the land use and the transport system, thus describing a potential for reaching destinations (Geurs and Van Wee, 2004; Geurs et al., 2016). Where traditionally, land use planning focuses on proximity and transport planning focuses on mobility, accessibility planning unites both approaches. Accessibility can be measured in different ways and for different purposes (Geurs and Van Wee, 2004; Handy and Niemeier, 1997). Employment accessibility is among the most frequent types of accessibility analysis. In this context, it is important to distinguish between active and passive accessibility (Cascetta, 2001). Active accessibility describes the accessibility to jobs from the workers' perspective. In analogy to studies of revealed commuting behavior, studies of employment accessibility typically deal with this perspective (see for example Cheng and Bertolini, 2013; Shen, 1998). Studies covering the passive accessibility, i.e. the workplaces' perspective, are much rarer. Some studies investigate the relation between accessibility to the labor force and employment development (De Bok and Sanders, 2005; Giuliano et al., 2012). Martín-Barroso et al. (2017) highlight how accessibility needs vary by industry sector, where knowledge intensive firms require better accessibility to the labor market than other sectors. Accessibility analysis from a corporate perspective mainly focuses on economic aspects rather than on environmental aspects related to employee mobility. One exception that is directly tied to planning practice is the Dutch ABC location policy. The policy categorizes workplace locations based on their accessibility by car and public transport (Van Wee and Van der Hoorn, 1996). However, while one important aim is to reduce car use, there is no particular emphasis on the climate impacts of corporate location choice. The approach and application presented in the remainder of this paper address precisely this issue. It thus combines the plea for decarbonizing transport (Banister et al., 2011) and the plea for integrating land use and transport planning via accessibility (Rode & da Cruz 2018).

5.3. Research framework and methodology

5.3.1. Introduction to the study area

The accessibility-based approach for assessing the environmental impact of workplace locations is applied in the Munich metropolitan region. This study area is chosen due to the availability of an existing accessibility instrument that can be adapted to incorporate CO_2 emissions as travel impedance. The tool is described in more detail in section 5.3.2.

The Munich metropolitan region, situated in southern Germany, covers close to 30,000 square kilometers and is home to six million inhabitants. The city of Munich represents the heart of the region with a population of 1.5 million. Despite some polycentric tendencies, flows are mainly oriented towards the region’s core (Kinigadner et al., 2015). Economic prosperity has increased in recent years and a break in this trend is not foreseeable, as both employment and population growth are predicted to continue (Schlitte et al., 2013). The region’s rapid growth has made the negative externalities of transport activities increasingly evident (Büttner et al., 2014). Housing development, employment development and commuting count among the most pressing concerns (Thierstein et al., 2016).

Firms and their geographical locations play a major role within these dynamics (section 5.2.1). In order to link corporate mobility to the challenges of climate change (section 5.1), two large companies in the Munich region are considered in a case study: the Paulaner brewery and the Munich branch of Microsoft. As one of the major breweries in Munich, Paulaner is part of the consumer goods industry. Microsoft is a well-known software and hardware producer. Both companies changed their location within the previous years. However, their highly different foci reflect in opposing relocation strategies and motivations. Increased attractiveness and better accessibility to knowledge workers were among the location choice factors for Microsoft (Microsoft Deutschland GmbH, 2016). Paulaner, on the other hand, wanted to gain larger areas for production and logistics activities (Paulaner Brauerei, 2012). Table 7 provides an overview of the previous and current firm locations.

Table 7. Information about the previous and current locations of Paulaner and Microsoft.

Company	**Location**	**Spatial typology**	**Employees**	**Status**
Paulaner	Nockherberg	Central urban	900[a]	Previous
Paulaner	Langwied	Urban fringe	550[a]	Since 2015[b]
Microsoft	Unterschleißheim	Suburban	1,900[c]	Previous
Microsoft	Schwabing	Urban	1,900[c]	Since 2016[c]

Sources:

Becker et al. (2011)

Paulaner Brauerei (2012)

Microsoft Deutschland GmbH (2016)

The new locations are optimized with respect to the firms' individual needs and preferences. Figure 20 shows the four different geographical locations. Paulaner relocated from a central inner city location to the urban fringe. The new grounds are still situated within the boundaries of the city of Munich. However, they are directly located next to a highway interchange, which is favorable for heavy vehicles and logistics. At the same time, the brewery is located at a distance from main railway axes. Microsoft relocated from a suburban location to a relatively new mixed-use area within the outer core of Munich. Both locations are accessible by highways and rail-bound public transport. However, the current location is embedded in a much denser environment.

Figure 20. Overview of the previous and current locations of Paulaner and Microsoft.

The location choice strategies of both companies are comprehensible from an economic perspective. However, the environmental impacts related to GHG emissions from commuting are opaque at this point. The general objective of this research is to propose a methodology to assess the CO_2 footprint of (potential) workplace locations using accessibility metrics. The case study application particularly aims to answer the following questions:

1. How do workplace locations situated within various spatial typologies differ in terms of their CO_2 footprint related to commuting?

2. How resilient are different workplace locations if strict emission reduction targets are to be realized for the journey to work?

5.3.2. CO_2 emissions as travel cost in the transport network

Accessibility instruments are designed to support the decision-making process related to integrated land use and transport planning (Papa et al., 2016). Even though these tools are hardly used in planning practice so far, they provide the potential to enhance policy outcomes by enabling multi-level stakeholder involvement across different sectors (Te Brömmelstroet et al., 2016). The TUM Accessibility Atlas is such a planning support system, aiming to foster sustainable land use and transport planning in the Munich metropolitan region (Wulfhorst et al., 2017). The instrument is designed as a GIS-based tool, containing a multi-modal transport network as well as structural land use data. Various types of land use data are available at different spatial resolutions. Transport networks are available for public transport, private motorized transport and active modes. Time, distance, and financial expense have been used as travel cost indicators in previous applications of the instrument (Büttner et al., 2018). The database is continually updated in response to current planning issues.

As outlined in section 5.2.2, accessibility planning has the potential to support the development of low carbon land use and transport strategies for workplace locations. The transport networks of the TUM Accessibility Atlas need to be modified for the specific purpose of enabling CO_2-based accessibility analysis. CO_2 is included as a travel cost indicator based on the distances covered by car and public transport, respectively. Non-motorized transport modes like walking and cycling are considered emission-free, which makes editing the respective networks irrelevant. Määttä-Juntunen et al. (2011) have realized a comparable network model to account for transport-related CO_2 emissions, but their study was limited to car travel and did not include public transport.

Within the TUM Accessibility Atlas, the private transport network is based on OSM, which provides information about the location, length, type and speed limit of road segments. Emission factors within various settings (road type, environment, speed limit etc.) can be retrieved from HBEFA. The emission factors from HBEFA are assigned to the corresponding types of OSM road segments. Following this procedure, the amount of CO_2 generated by an average gasoline car on each link can be used as a travel cost attribute. From the perspective of an individual traveler, not the emissions per vehicle-kilometer, but the emissions per passenger-kilometer are relevant. Different occupancy rates can be considered by adding a parameter to account for the number of people sharing the car. The average occupancy rate for work trips in Germany is 1.2, the lowest among all trip purposes (UBA, 2016b). This occupancy rate is used to convert the emissions from CO_2 per vehicle-kilometer to CO_2 per passenger-kilometer.

Creating a sound CO_2 network model for public transport is more challenging than for cars, due to larger variations in emission factors and occupancy rates. The public transport system in the Munich region includes busses, tramways, metro lines, suburban trains and long distance trains. TREMOD from the German Environment Agency provides emission factors for a number of public transport modes (UBA, 2016a). Underlying occupancy rates range from 19 % for metro, tram, and other urban rail systems to 50 % for long distance trains. Data from the transport model for the Munich region serves as a basis to calculate the in-vehicle travel distance by public transport mode for every stop-to-stop connection. The distance per public transport mode is multiplied by the corresponding emission factor and summed up over all public transport modes used for each stop-to-stop connection. The resulting emissions are given in CO_2 per passenger-kilometer. Emissions per seat-kilometer can be deduced as well, based on the emission factors and corresponding occupancy rates from TREMOD. Thus, the public transport network model could be adapted to any desired occupancy rate. In order to ensure area coverage, walking catchments need to be added around public transport stops. An OSM pedestrian network was used for this purpose, where acceptable walking distances to and from public transport stops can be freely chosen.

5.3.3. CO_2-based accessibility indicator

The intent of the workplace assessment method presented in this paper is to inform both corporate and municipal decision-making. In order to be useful for planning practice, accessibility measures need to be empirically sound and sufficiently plain at the same time (Bertolini et al., 2005; Wulfhorst et al., 2017). Location-based accessibility measures are frequently used in urban planning, as they provide a way of achieving such a compromise (Geurs and Van Wee, 2004). Typically, location-based accessibility measures have the following form:

$$A_i = \sum_j D_j \, f\left(c_{ij}\right)$$

In the case of the assessment method proposed in this paper, A_i represents the CO_2-based accessibility of the respective workplace location. D_j is the number of workers residing within a spatial unit. Only workers with social insurance are included in the official German statistics. Self-employed persons and public officials, for example, are not included. Nevertheless, the distribution of the workers with social insurance can be considered representative, as they account for 75 to 80 % of the entire labor force (Statistisches Bundesamt, 2018). The Federal Statistical Office provides data on municipality level. For this reason, the structural data has to be disaggregated to smaller spatial units based on polygons specifying the location and function of the built-up area. The cost function $f(c_{ij})$ can have different forms of varying complexity (Geurs and Van Wee, 2004). A simple cumulative opportunities indicator is chosen for this case study application. The function equals 1 if the considered spatial unit is located within a defined budget and 0 if the considered spatial unit is located outside a defined budget. Travel costs c_{ij} are measured in CO_2 emissions per passenger-kilometer. Typically, commuters do not consider CO_2 emissions when making a travel choice, but try to optimize travel time instead (Vale, 2013). Therefore, in terms of scientific soundness, it might be the better choice to accumulate CO_2 emissions along the road network, while choosing the route based on the shortest travel time (Määttä-Juntunen et al., 2011). However, for calculating CO_2 catchments that show a potential coverage, as done in this application, the logic of minimizing emissions irrespective of travel time seems reasonable. Another particularity worth mentioning is that in travel time based analysis, car accessibility is usually higher than public transport accessibility (Benenson et al., 2011). Depending on vehicle occupancy rates, the CO_2-based accessibility analysis might show a reverse picture. The analysis uses the occupancy rates as described in section 5.3.2. The walking buffer around public transport stops is 400 meters.

With reference to the first research question, the cumulative opportunities indicator is used to compare the four workplace locations with a CO_2 budget of 1 kg. The CO_2 budget of 1 kg roughly corresponds to the average emissions of an individual employee on a one-way work trip in Germany. This value was derived based on the current average CO_2 emissions in Germany: Out of 9 tons of CO_2 emitted per person per year, 23 % result from road transportation (assumptions based on EEA, 2017a; UBA, 2017b). The share of work trips is estimated based on the fact that 22 % of all vehicle kilometers travelled are for work (UBA, 2017a). An average of 210 work days per year yields a budget of about 2 kg per day, which corresponds to 1 kg per one-way trip. This simplified approach is ignoring some influencing factors like mode share and business trips, but is considered sufficient for an exemplary application.

In order to address the second research question, a reduced budget of 0.25 kg is introduced. Many European countries, including Germany, have set ambitious emission reduction targets. GHG emissions are supposed to be reduced to about two tons per person per year by 2050 (UBA, 2017b). This target reduces the cut-off value for the CO_2 catchments from 1 kg to about 0.25 kg per one-way work trip. The previous analysis is repeated with the lower budget and unchanged occupancy rates for car and public transport. The 0.25 kg scenario showcases the potential consequences of more restrictive emission budgets. The CO_2-based accessibility is expected to decrease for all workplace locations, however, by a different factor, depending on the spatial typology of the respective geographical location. The following section presents the results of the location assessment for both budgets, both firms and both transport modes.

5.4. Results

The number of workers accessible with the given CO_2 budgets are evaluated for the previous and current locations of Paulaner and Microsoft, respectively. Figure 21 shows the 1 kg CO_2 catchment areas of the previous and the current location of Paulaner for car and public transport.

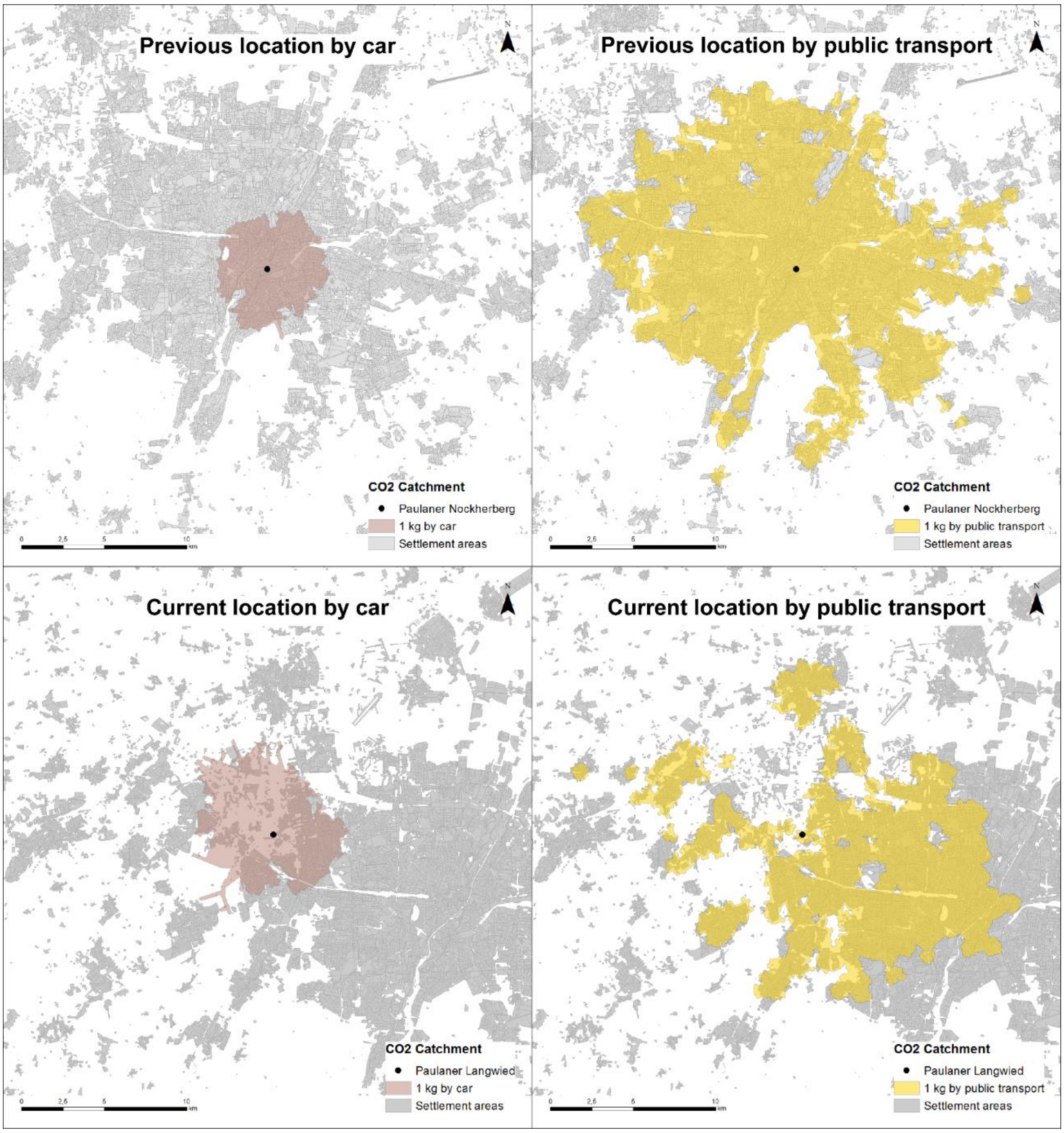

Figure 21. CO_2 catchments of Paulaner with a 1 kg budget.

The maps highlight the differences in CO_2 catchments between the central urban location and the urban fringe location. The size of the catchment area by car is comparable for both locations. It is slightly larger in the urban fringe area due to wide roads that enable constant speeds with less stop and go travel. The public transport catchment covers almost the entire city in the case of the previous location, which is located close to the geographical center of Munich. However, in the case of the urban fringe location, the surrounding built up area is not as dense. Also, due to a less dense public transport network with fewer lines and stops, large portions of the areas to the west cannot be covered. In order to be able to compare all four workplace locations with respect to their carbon footprint, the analysis is repeated for Microsoft and presented in Figure 22.

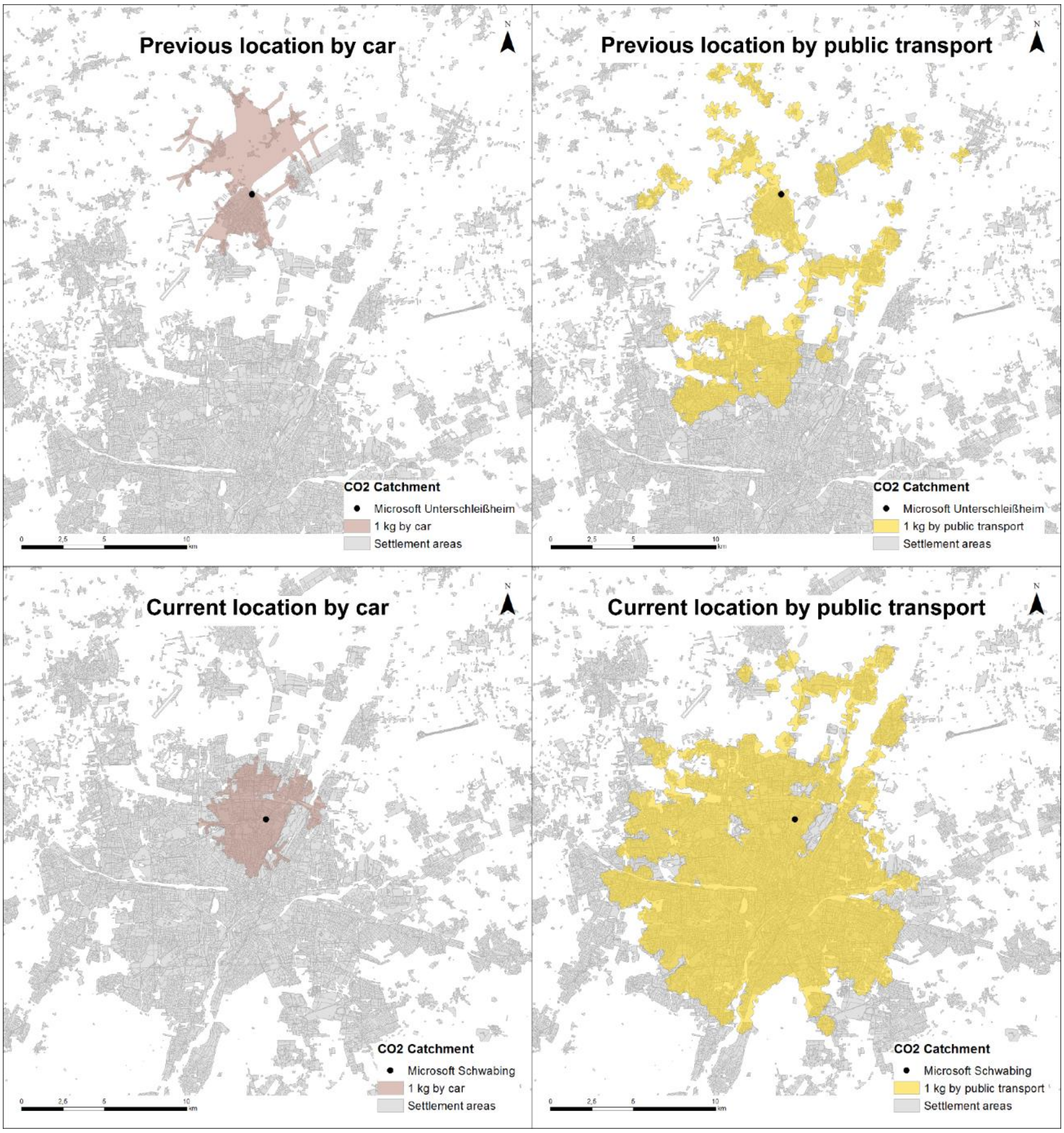

Figure 22. CO_2 catchments of Microsoft with a 1 kg budget.

The suburban location Unterschleißheim has a significantly less dense private transport network than the urban fringe location Langwied. Closeness to the motorway enables fast and smooth travels, but flexibility is limited. Unterschleißheim is served by a suburban railway line running along a north-south axis. The areas to the east and west of the firm location are served by bus lines. Even though the catchment extends to the northern parts of the city of Munich, the dispersed settlements in the suburban area are expected to reduce the overall number of accessible workers.

The catchment area by car of the current, urban office location in Schwabing is not large, but it covers densely populated areas. The English Garden, a large green area with few crossings, acts as a barrier towards the eastern part of the city. The public transport catchment of Schwabing is comparable to the public transport catchment of the previous location of Paulaner. Nearly the entire city can be covered with a 1 kg CO_2 budget by public transport. Due to a larger distance to the geographical center of the city, the catchment is shifted towards the northern parts. Table 8 summarizes the results of the cumulative opportunities accessibility measure with a 1 kg CO_2 budget. The number of workers accessible by car and public transport are presented for each of the four workplace locations.

Table 8. Number of accessible workers with a CO_2 budget of 1 kg.

1 kg	**Car**	**Public transport**
Nockherberg	125,746	628,253
Langwied	46,726	399,634
Unterschleißheim	15,105	104,457
Schwabing	68,968	545,660

Due to the firms' contrary location choice strategies, the accessibility outcome changes into opposite directions from previous to current location. The accessibility of Paulaner reduces by a factor of 0.4 for car and by a factor of 0.6 for public transport due to the relocation. On the contrary, the accessibility of Microsoft's current location is about five times higher than the accessibility of the previous location for both modes. In answering the first research question, the differences between spatial typologies are obvious and as expected. The central urban location is by far the most accessible one, followed by the urban location, the urban fringe location and finally, the suburban location.

The accessibility analysis of the previous and current locations of Paulaner and Microsoft is repeated with a CO_2 budget of 0.25 kg. The following maps illustrate the effect of such a drastic reduction in the maximum CO_2 emissions per employee and direction. The 0.25 kg scenario gives a good idea of a workplace location's vulnerability in the case of stricter emissions reduction targets and thus lower emission budgets. Figure 23 presents the results for the two different locations of Paulaner.

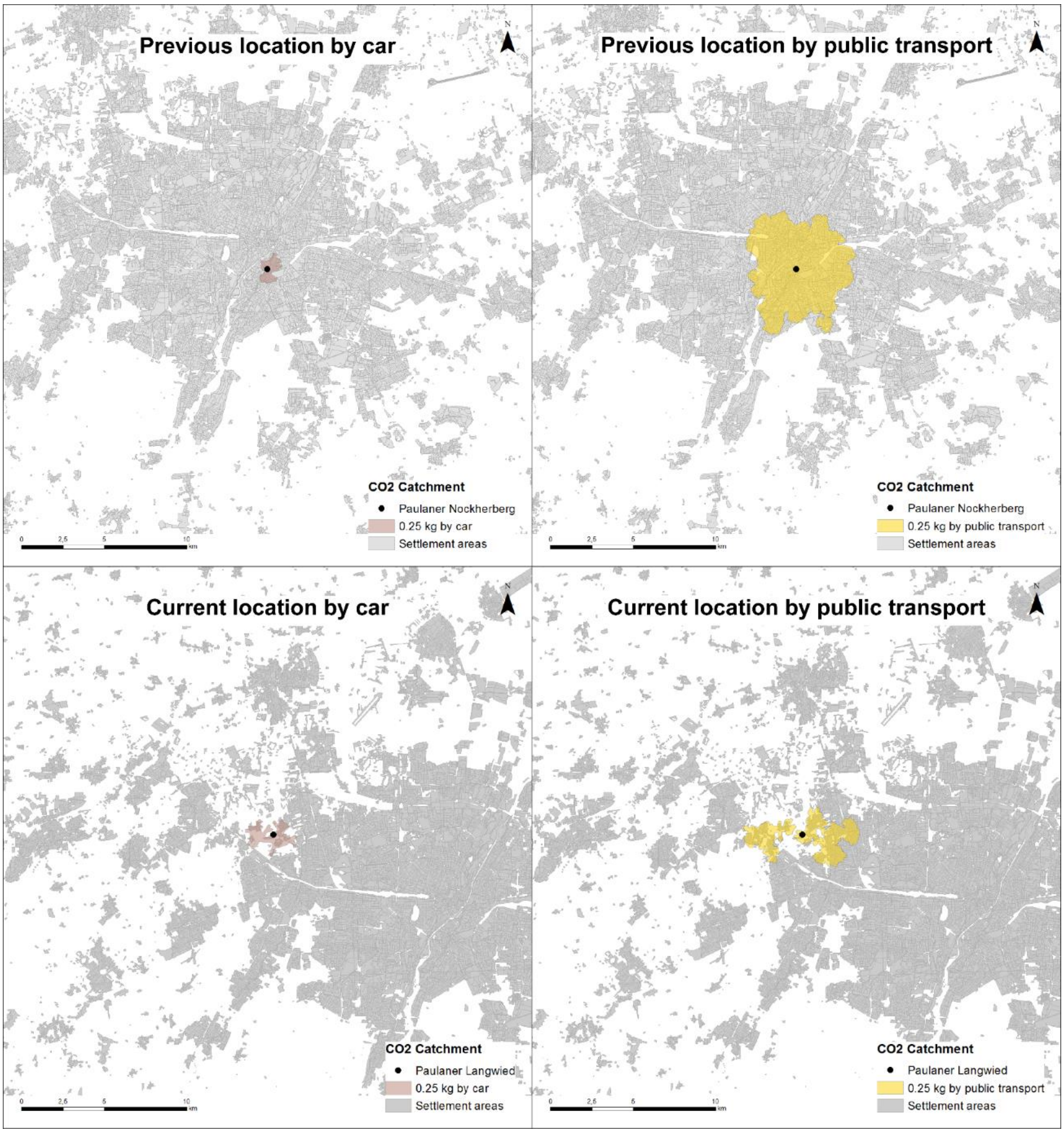

Figure 23. CO_2 catchments of Paulaner with a 0.25 kg budget.

The catchment areas are significantly smaller than before. The same effect is visible in the maps for the workplace locations of Microsoft, as presented in Figure 24.

Figure 24. CO_2 catchments of Microsoft with a 0.25 kg budget.

The urban location is comparable to the central urban location, while the suburban location is comparable to the urban fringe location. The catchment areas by car are similar in size for all four locations due to the ubiquitous road infrastructure, but the surrounding land use makes a difference. The effect of the transport network is more obvious in the case of public transport. Due to a less fine grained network in the more peripheral areas, the areas that can be covered are more dispersed and disconnected. Table 9 gives an overview of the results of the CO_2-based accessibility measure for the reduced budget scenario.

Table 9. Number of accessible workers with a CO_2 budget of 0.25 kg.

0.25 kg	**Car**	**Public transport**
Nockherberg	7,632	129,182
Langwied	1,496	12,339
Unterschleißheim	583	11,677
Schwabing	1,456	60,722

Cutting the available CO_2 budget by 75 %, from 1 kg to 0.25 kg, reduces the number of workers accessible by an even larger factor. Assuming equal propagation in all directions and a homogeneous land use distribution, the catchment area corresponds to a circle with an area of $\pi * r^2$. Reducing the radius to 1/4 of the original radius implies an expected reduction in the number of accessible workers by 1/16 in case of a homogenous distribution of workers across space. Table 10 shows the ratio between the number of workers accessible in the 0.25 kg scenario and the number of workers accessible in the 1 kg scenario.

Table 10. Ratio of accessible workers with a CO_2 budget of 1 kg and 0.25 kg.

0.25 kg / 1 kg	**Car**	**Public transport**
Nockherberg	1/16	1/5
Langwied	1/31	1/32
Unterschleißheim	1/26	1/9
Schwabing	1/47	1/9

The urban fringe location is most affected by a reduction in the CO_2 budget, as the high density areas of the city of Munich cannot be reached anymore. The central location on the other hand is least affected. Public transport accessibility tends to be less affected by the reduced budget than car accessibility. The large differences in accessibility ratios can be explained by the heterogeneous land use surrounding the firm locations under consideration. Low density areas separating the respective firm location from more densely populated areas cause drastic reductions in accessibility. This is especially true for the car, whereas denser areas are still accessible by public transport in most cases. To summarize, the accessibility analysis for car and public transport shows large differences in CO_2-based accessibility depending on spatial typology and CO_2 budget. The differences between spatial typologies regarding the number of accessible workers highlights the role of both high density urban structures and the availability of low carbon mobility options. Due to the favorable assumptions for public transport occupancy, public transport accessibility in the 0.25 kg scenario is comparable to car accessibility in the 1 kg scenario. The differences between the standard and the reduced budget emphasize that ambitious emission reduction targets will be difficult to achieve without appropriate employment development. Therefore, consequences of the location choices of companies should be considered in a holistic decision-making process. Nevertheless, the special requirements of diverse companies cannot be ignored.

5.5. Discussion and conclusions

The analysis of the relocations of the Paulaner brewery (beer) and Microsoft (bits) presented in the previous sections clearly highlights differences in accessibility requirements. Beyond location, the physical nature of work, such as the possibility of telecommuting (Microsoft) versus shift work (Paulaner), creates disparities that relate to commuting practices. Production companies, often located in the periphery, are associated with lower income groups. Remote locations not only make longer commutes necessary, but are also worse off in terms of public transport service, causing car dependence of low income employees (Hu, 2016). Such interrelations challenge firms' location choices not only from an environmental, but also from a social perspective. In fact, land use policies – both on the corporate and municipal level – should not limit their focus to one aspect, but need to consider a broad range of factors (Van Wee, 2002). Hence, a multi-criteria decision-making process taking into account diverse perspectives will help to make more consolidated location choices. Sector-specific requirements as well as environmental and social consequences of companies' location choices could be included in such a process.

In terms of spatial coverage, a regionally coordinated approach is expected to be most successful (Moeckel, 2009). The CO_2-based assessment method could be extended to cover a larger area rather than just focusing on individual workplace locations. Thus, regional scans will highlight more comprehensive development options. Two directions for action can be deduced: On the one hand, firms should preferably settle at locations with good accessibility. On the other hand, existing workplace locations with a large carbon footprint require accessibility improvements by either providing low carbon transport infrastructure or creating additional housing in close vicinity to the firm location. In this context, non-motorized accessibility or further intermodal options need to be included in the analysis (Van Wee, 2016). Walking and cycling are especially important, as they have the smallest carbon footprint among all modes.

Institutional barriers and lack of coordination between different planning disciplines might impede the implementation of sustainable land use and transport solutions (Næss et al., 2011; Rode and da Cruz, 2018). Even though there seems to be a transition away from car dominated transport and the predict and provide ideology (Bertolini, 2017; Sheller and Urry, 2016), political decision-makers might be hesitant to break “transport taboos” (Gössling and Cohen, 2014). The commitment of all stakeholders is imperative in order to strengthen the role of climate change in decision-making and bring about low carbon transitions in the transport sector (Banister, 2011). Also society needs to be included, as government initiatives will only be successful if they manage to encourage a change in mobility practices (Cass and Faulconbridge, 2016; Schwanen et al., 2011). If a suitable way can be found for the implementation in planning practice, CO_2-based location assessment has the potential to support decision-making processes of both municipalities and companies.

The CO_2-based accessibility instrument presented in this paper certainly requires further refinement, but seems to be an effective tool to assess the environmental impact of workplace locations. Replacing the commonly used travel time with emissions as travel impedance opens up new perspectives. “Low emission is best” rather than “faster is best” becomes visual with the application of CO_2-based accessibility analysis and the corresponding catchment maps. Further research should involve practitioners and their real-world planning issues in order to verify the theoretical usefulness of this tool for planning practice.

6. Shifting perspectives: a comparison of travel-time-based and carbon-based accessibility landscapes

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Kinigadner, J., Vale, D., Büttner, B., Wulfhorst, G. Shifting perspectives: A comparison of travel-time-based and carbon-based accessibility landscapes. Journal of Transport and Land Use.

Abstract

Undoubtedly, climate change and its mitigation have emerged as main topics in public discourse. While accessibility planning is recognized for supporting sustainable urban and transport development in general, the specific challenge of reducing transport-related greenhouse gas emissions has rarely been directly addressed. Traditionally, accessibility is operationalized in line with the user perception of the transport system. Travel-time-based measures are considered to be closely linked with travel behavior theory, whereas CO_2 emissions are not necessarily a major determinant of travel decisions. Given the changed prioritization of objectives, additional emphasis should be placed on the environmental costs of travel rather than solely the user costs. Accessibility analysis could account for this shift in perspectives by using CO_2 emissions instead of travel time in the underlying cost function. While losing predictive power in terms of travel behavior compared to other implementations of accessibility, carbon-based accessibility analysis enables a normative understanding of travel behavior as it ought to be. An application in the Munich region visualizes the differences between travel-time-based and carbon-based accessibility by location, transport mode, and specification of the accessibility measure. The emerging accessibility landscapes illustrate the ability of carbon-based accessibility analysis to provide new insights into land use and transport systems from a different perspective. Based on this exercise, several use cases in the context of low carbon mobility planning are discussed and pathways to further develop and test the method in cooperation with decision-makers are outlined.

6.1. Introduction

Increasing awareness of the negative and potentially irreversible consequences of global warming have caused the hierarchy of planning objectives to be reconsidered. Emission reductions in all sectors have become a top priority for governments around the globe (UNFCCC, 2015). The transport sector struggles most to achieve emission reduction targets and – in contrast to other sectors – has not succeeded in decreasing emissions (United States Environmental Protection Agency, 2019; EEA, 2019a). Environmental objectives seem to be in conflict with the social and economic benefits linked to mobility (Banister, 2011). Accessibility, determined by the joint characteristics of the land use and transport systems, could be a suitable concept to address this challenge.

The first reason for employing accessibility to plan for low carbon mobility options is its intrinsic capability to integrate land use and transport planning. Dense and mixed use urban development can contribute to the goal of GHG emission reductions, especially if oriented towards public transport systems (Banister, 2011; Schwanen et al., 2011). Thus, consideration of land use configurations and policies is indispensable in promoting sustainable transport (Loo and Tsoi, 2018). Increased vehicle efficiency will not solve the issue of transport-related emissions if separation of urban functions, suburbanization, and car dependence prevail (Chapman, 2007). Multimodal mobility behavior, increasingly enabled by innovative mobility services, will not suffice if the level of travel activity, in particular trip distance, continues to grow (Heinen and Mattioli, 2019). Through the introduction of a land use dimension, accessibility helps to distinguish between the need to reach opportunities as an end and the need to travel as a means.

Tackling climate change requires efforts on multiple scales, from local to global (Ostrom, 2010; Marsden et al., 2014), and depends on the involvement and interaction of multiple actors (Geels, 2012). In order to reduce transport-related emissions, not only the impacts of potential interventions and policies need to be assessed, but also the issue of implementation needs to be addressed (Lewis et al., 2018). Even if political decision-makers have succeeded in defining a suitable framework for low carbon mobility, public awareness, acceptance, and commitment are equally important (Banister, 2008). Against this background, the second reason for exploring accessibility-based planning approaches to address climate change is their ability to support decision-making on multiple levels, both spatially and institutionally. Firstly, accessibility analysis is applicable on various geographical planning scales (Papa et al., 2016). Secondly, accessibility can – given an appropriate implementation – contribute to enhancing discussion and decision-making of stakeholders across different institutions, disciplines, and levels of expertise (Te

Brömmelstroet et al., 2016; Wulfhorst et al., 2017). Complex tools might be needed for further in-depth analysis, but simpler tools, featuring high transparency and communication value, are most suitable to explore alternative scenarios in strategic planning (Te Brömmelstroet, 2010; Ford et al., 2018). While the underlying accessibility metrics might be of varying complexity, accessibility instruments often produce visual outputs in map format (Papa et al., 2016), which tend to improve understandability and communicability (Curtis and Scheurer, 2010; Büttner et al., 2019).

This potential is not yet fully exploited, since emissions are seldom explicitly considered in accessibility analysis and planning. Environmental objectives are often addressed indirectly, for example when trying to minimize the gap between accessibility by car and accessibility by other modes considered to be more sustainable (Salonen and Toivonen, 2013). Accessibility measures in these and many other applications are based on the uses and perceptions of the people. Consequently, travel costs are operationalized as internal user costs, typically represented by travel time (Cui and Levinson, 2018). In contrast, emissions are not necessarily a major determinant of individual travel decisions, but represent a normative, politically defined constraint to travel activities. The plea for reinventing seemingly invariable concepts, thus enabling new rather than habitual ways of thinking in the context of climate change (Schwanen, 2019), might as well be transferred to the accessibility concept. In this paper, we propose an alternative conceptualization of accessibility, dominated by an environmental perspective instead of a user perspective. More precisely, travel time is replaced by CO_2 emissions as the relevant travel cost. Multiple studies have compared accessibility implementations based on different cost components (El-Geneidy et al., 2016; Cui and Levinson, 2018; Büttner, 2017), impedance functions (Vale and Pereira, 2016; Higgins, 2019), behavioral foundations (Páez et al., 2012) or indicator types (Kwan, 1998). However, to the best of our knowledge, the partially conflicting perspectives of the user and the environment have never been directly compared. In order to determine whether this reinvention provides new insights compared to traditional implementations, both approaches are compared and contrasted using the Munich region as a case study. A review of the theoretical considerations underlying the accessibility concept and its operationalization follows in section 6.2, the presentation of the implementations in section 6.3, and a discussion of the application potential of carbon-based accessibility in section 6.4. Conclusions and future research paths are outlined in section 6.5.

6.2. Perspectives on accessibility

In this paper, accessibility is defined as the number of opportunities within acceptable reach of a given place (Te Brömmelstroet et al., 2016), where acceptable could refer to either a user perspective (section 6.2.1) or an environmental perspective (section 6.2.2). The objective of the analysis determines the relevant perspective as well as the appropriate operationalization of accessibility.

6.2.1. The user perspective

The user perspective is centered on how (potential) travelers experience accessibility. There are different manifestations of this viewpoint in how accessibility is conceptualized and measured. In fact, it can be related to all four components of accessibility, as defined by Geurs and Van Wee (2004): the land use, transportation, temporal, and individual component.

One central aspect of the land use component is the spatial distribution of destinations, representing relevant activities or opportunities (Handy and Niemeier, 1997; Páez et al., 2012). Different types of opportunities can be analyzed, most of which are assumed to provide some benefit to individuals (e.g. job opportunities). Destination potentials can be weighted by their attractiveness or value for the user and classified according to their characteristics, which make them particularly relevant (or irrelevant) for a specific group of travelers.

Much-cited papers describe the transportation component as determining the effort (Geurs and Van Wee, 2004) or ease (Handy and Niemeier, 1997) of traveling for an individual. Consequently, travel costs in accessibility measures are often purely internal, typically measured in travel time or generalized costs, as experienced by the traveler (Cheng and Bertolini, 2013). Such implementations are useful to analyze the attractiveness and affordability of different transport modes for the user (El-Geneidy et al., 2016).

A person’s range of accessible opportunities might be reduced due to the limited time available in between activities that are fixed in space and time. The temporal component of accessibility represents these individual spatial-temporal constraints (Geurs and Van Wee, 2004).

Handy and Niemeier (1997) criticize loose consideration of the user perspective, arguing that accessibility measures should be determined by the uses and perceptions of the travelers, rather than the assumptions of the analyst. This comes along with a need for more disaggregate measures, focusing on (groups of) individuals as the unit of analysis. The individual component of accessibility acknowledges that persons have different characteristics, capabilities, and preferences (Geurs and Van Wee, 2004), enabling a more accurate depiction of the travelers' viewpoint. However, even in aggregate implementations, accessibility is typically operationalized from a user perspective, albeit based on what the analyst assumes reasonable rather than on the users' actual perceptions and preferences (Páez et al., 2012). Clearly, the user perspective is particularly suitable for social evaluations, whereas its applicability for environmental evaluations is limited. In order to build upon accessibility analysis for a much-needed reduction in transport-related emissions, a shift in perspectives is required.

6.2.2. The environmental perspective

Especially in recent years, objectives related to climate change and emission reductions have been given high political priority. This shift in priorities needs to reflect in methods aimed at supporting decision-making, such as accessibility analysis (Kinigadner et al., 2019). Contrary to the user perspective, which focuses on internal costs and benefits of individuals, the environmental perspective focuses on the external costs of travel to be borne by the environment and society in general. The environmental perspective is often treated implicitly in accessibility analysis. For example, if accessibility levels by carbon-efficient modes match the accessibility levels by carbon-intensive modes from a user perspective, this is associated with more sustainable travel options (Salonen and Toivonen, 2013; Benenson et al., 2011; Bertolini et al., 2005). However, such implementations are not tailored to GHG emission reduction objectives and do not explicitly consider the environmental costs of travel activities. In the following, two options for more directly introducing an environmental perspective into accessibility analysis are outlined.

The first option is to quantify environmental impacts as an outcome of accessibility analysis. The user perspective determines the relevant opportunities based on their attraction factor and the individual costs involved in reaching them. The environmental perspective evaluates the external costs associated with traveling to these opportunities. However, GHG emissions are not only influenced by characteristics of the land use and transport systems, but also by individual characteristics, such as gender, age or income (Barla et al., 2011). Consequently, a more solid and disaggregate behavioral basis is required for more accurate quantification of emissions or emission savings. Data requirements and complexity are clearly a downside of this approach, especially with increasing consideration of the individual component.

The second option for incorporating environmental impacts, in particular CO_2 emissions, into accessibility analysis is to weight opportunities based on the environmental costs of travel. In other words, environmental impacts serve as an input for the calculation of accessibility levels rather than an output of user-based accessibility measures. Referring back to the four components of accessibility addressed in section 6.2.1, the shift in perspectives from the user to the environment occurs with respect to the transportation component. A user viewpoint might still be applied to the land use component in order to select relevant origins and destinations.

Even though CO_2 emissions might to some extent influence travel choices (Salonen et al., 2014), the environmental impacts of travel are not necessarily evident to the users and expected to be much less determining than internal costs, such as travel time. Clearly, this results in a loss of behavioral basis with respect to the operationalization of accessibility. However, the proposed approach makes it possible to define normative accessibility standards and compare these standards with the actual situation. In this paper, we distinguish between “descriptive” and “prescriptive” accessibility measures (Páez et al., 2012). In the first case, the analysis is based on realized or assumed travel behavior, typically informed by travel behavior statistics and surveys. In the second case, the implementation is based on normative definitions of how people should (be able to) travel, which is decoupled from observed behavior.

Instead of finding or assessing intervention options with respect to individual user benefits, accessibility indicators using emissions as the underlying travel costs help to explore climate impacts, thus serving the common good. Cui and Levinson (2018) demonstrate how accessibility-based approaches, which are not limited to internal travel costs but also include external travel costs, might affect the ranking of potential interventions in the land use and transport system. However, their results also show that a full cost assessment is still dominated by monetary costs and travel times, which might underestimate the value of emission savings. For this reason, we opted for a clear distinction between accessibility analysis based on user costs and accessibility analysis based on environmental costs. The following section illustrates the accessibility impacts of such a shift in perspectives, where travel time is used as a proxy for the user perspective and CO_2 emissions represent the environmental perspective.

6.3. Comparing carbon-based and travel-time-based accessibility

6.3.1. Study area and data

Travel-time-based and carbon-based accessibility levels by car and transit are compared using the Munich region (EMM) in southern Germany as a study area. The EMM is an alliance of multiple institutional entities, ranging from public bodies to industry and academia, who collaborate to address common issues such as mobility (Metropolregion München, 2020). Of around six million inhabitants, 1.5 million live in the city of Munich, which acts as geographical and functional core of the region. A map of the region, presenting the density of workers at their residential location, is shown in Figure 25.

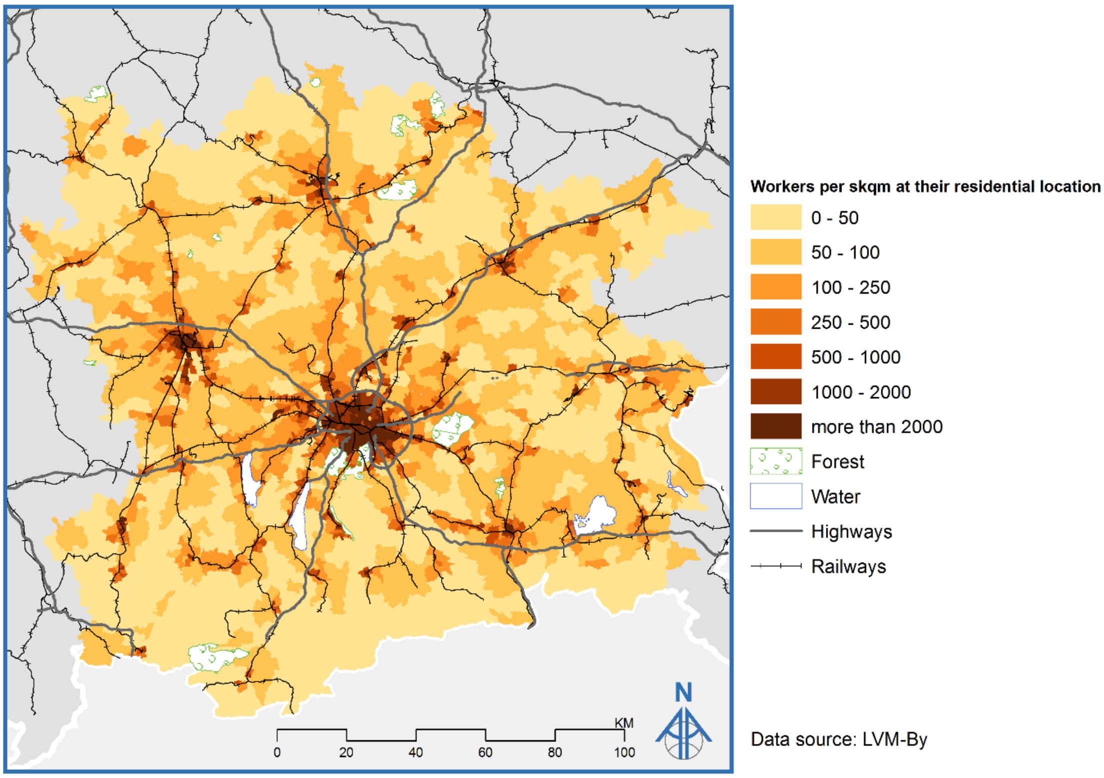
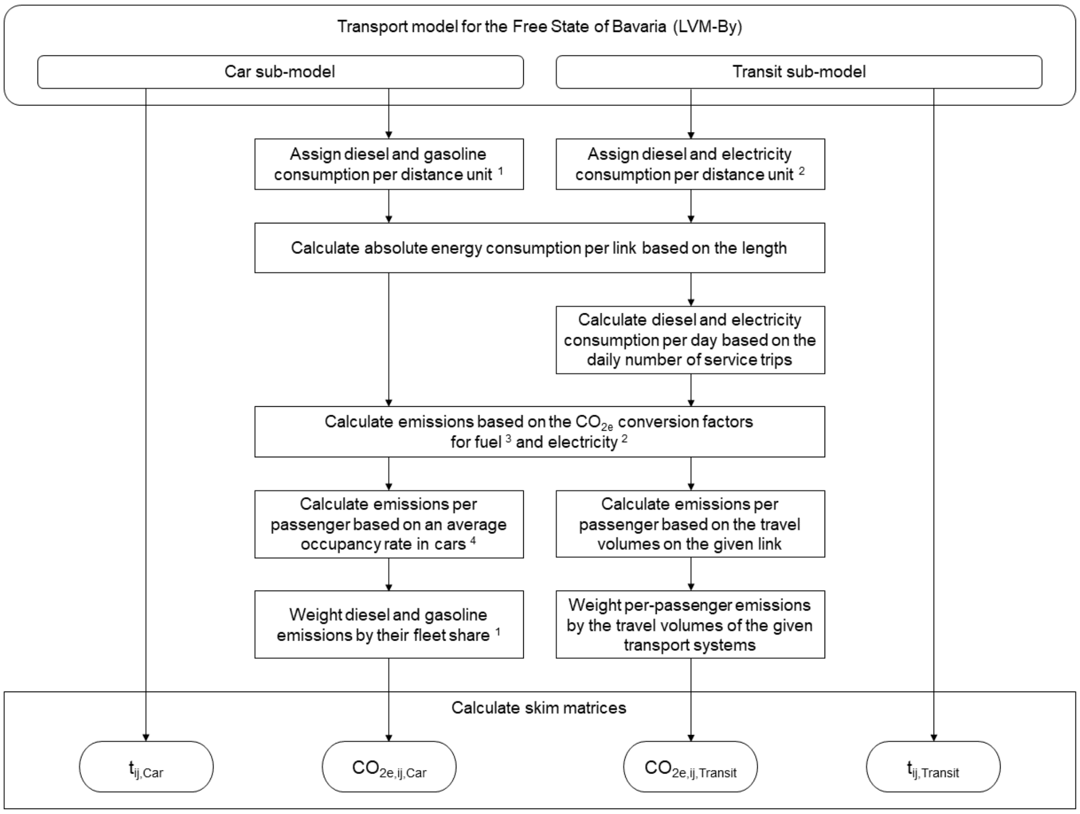


Figure 25. Density of workers in the EMM.

Accessibility is analyzed on the spatial level of transportation analysis zones (TAZ). The main data source of the analysis is the official travel demand model of the state of Bavaria (LVM-By). The model is available in the transport modeling software PTV Visum and provides not only structural data on the TAZ level, but also transport networks as well as travel demand for both car and transit (Maget et al., 2019). Out of 6,659 TAZs in total, 1,918 are located within the EMM. Figure 26 provides an overview of the data, sources, and process used to calculate zone-to-zone travel times and emissions.



Data sources:
[1] INFRAS (2017)
[2] DB (2019)
[3] Schmied and Mottschall (2014)
[4] Umweltbundesamt (2016b)

Figure 26. Process for calculating zone-to-zone travel time and emissions in the EMM.

Zone-to-zone travel times by car and transit were directly calculated using a built-in procedure of PTV Visum. The retrieval of zone-to-zone CO_2 emissions required editing of the networks as well as manipulation of the built-in skim matrix calculation. Different values for energy consumption per distance unit were assigned to all links in the car and transit networks, based on link characteristics which influence energy consumption. In transit, energy consumption varies by vehicle type and is given in liters of diesel for buses and kilowatt hours of electricity for trains, tramways, and subways. Since information on the precise vehicles in operation was unavailable, average energy consumption values for transit in Germany (DB, 2019) were assigned according to the transit route types given in the LVM-By. The relative fuel consumption of cars (in grams of diesel and gasoline per km) was retrieved from version 3.3 of HBEFA (INFRAS, 2017). HBEFA is a comprehensive database which provides information on fuel consumption for different fuel types, years, and countries – in our case for the German fleet composition in 2018. Fuel consumption values per distance unit are available by traffic situation, which is determined by a combination of the following parameters: location (urban or rural), road type (e.g. national motorway or residential road), speed limit, and traffic state (free flow, dense, saturated, stop+go). Road type and speed limit are link attributes in the LVM-By car network. CLC, a dataset providing the shape and location of urban areas, was used to differentiate between urban and rural links. The traffic state was assumed to be saturated in urban areas and free flow in rural areas. Further analysis of the dynamics of carbon-based accessibility levels due to detailed spatial and temporal variations of traffic states represents an interesting perspective for future research, but requires high-quality congestion data.

Relative values per kilometer were converted to absolute values based on the respective link lengths. Energy and fuel consumption were converted to CO_{2e} using the corresponding conversion factors. For reasons of simplicity, we use the term CO_2 in this paper, except for when we are speaking of mathematical units. For the car network, an average of diesel and gasoline emissions was calculated based on the German fleet composition in 2018. Since emission budgets would be assigned on a per-person basis, vehicle emissions were broken down to individual passengers based on occupancy rates. Occupancy rates in transit are derived from the LVM-By, which is capable of modeling daily passenger volumes by transit link and route. The occupancy rate of cars was uniformly set to 1.2, which represents a reasonable value for commutes (UBA, 2016b). The emissions generated per person when traveling across the network links are used as travel cost attribute in the carbon-based accessibility analysis.

Four zone-to-zone matrices were calculated: travel time by car, travel time by transit, CO_2 emissions by car, and CO_2 emissions by transit. It should be noted that all calculations are based on an average of best paths between zones, as defined in the parameters of the LVM-By. Travel resistance in the car model is calculated based on travel time, including walking time and parking search time, as well as fuel costs. In transit, the relevant route choice parameters include travel time as the sum of walking, waiting, and in-vehicle travel time, as well as number of changes, fare, and service frequency. Travel time and CO_2 emissions were accumulated along these best paths during the calculation. The resulting cost matrices were exported from the transport model in list format to be used for the accessibility measurement.

6.3.2. Accessibility measures

Independent of the underlying travel costs, there are numerous ways to operationalize accessibility. For the implementations presented in this paper, we selected a cumulative opportunities measure (Geurs and Van Wee, 2004). The accessibility level is equal to the number of opportunities within a given travel cost threshold, in our case measured in terms of travel time and emissions, respectively. The following equations express this relation in mathematical terms:

$$A_i = \sum_j D_j \, f(c_{ij})$$

$$f(c_{ij}) = \begin{cases} 1, if \; c_{ij} \leq cutoff \\ 0, if \; c_{ij} > cutoff \end{cases}$$

The term c_{ij} represents the travel costs that are generated when traveling from origin *i* to destination *j*. Time and emission costs for all relevant zone-to-zone relations in the Munich metropolitan region are retrieved from the LVM-By. The term D_j represents the destination potential at location *j*, in our case the number of workers at their residential location in each TAZ.

Cumulative opportunities measures are the simplest type of location-based accessibility indicators (Handy and Niemeier, 1997; Bertolini et al., 2005). Nevertheless, this type of indicator offers an intuitively understandable approach to comparing travel-time-based and carbon-based accessibility levels by car and transit using the same unit, namely the number of workers within the given time and emission thresholds. The objective of the applications is not so much to deduce concrete recommendations for regional planning based on the analysis outcomes, but rather to illustrate the relative differences between the user perspective and the environmental perspective on accessibility. Further deliberation on the most suitable form of operationalization would certainly be necessary for real world applications.

Selecting an appropriate cutoff value represents the key calibration issue with cumulative opportunities measures (Handy and Niemeier, 1997). In the following, we explain the reasoning behind our choice of threshold values for the comparison of travel-time-based and carbon-based accessibility landscapes. Three different specifications are used: a descriptive travel time budget based on current travel behavior, a descriptive CO_2 emission budget based on current travel behavior, and a prescriptive CO_2 emission budget if emission reduction targets are to become a reality.

1. *Descriptive implementation from a user perspective*: Travel time serves as the relevant travel cost in the accessibility analysis. Reasonable time thresholds are typically informed by travel survey statistics (Bertolini et al., 2005). The cutoff travel time in this application was chosen to be 28.6 minutes, which is the average travel time for a commuting trip in Germany (Follmer and Gruschwitz, 2019).

2. *Descriptive implementation from an environmental perspective*: CO_2 emissions serve as the relevant travel cost in the accessibility analysis. Similar to the travel time cutoff, the reasonable emission limit is based on current travel behavior.

Commuting-related CO_2 emissions can easily be estimated based on trip length and specific emission factors. Both of these parameters, and consequently emissions, are expected to be more heterogeneous across transport modes than travel times (even though transit users might also accept longer travel times than car drivers). Since the analysis is conducted for two motorized means of travel, namely car and transit, an average commuting trip by car was chosen as the benchmark. Specific emission factors in transit tend to be lower, but are more difficult to determine due to variations in occupancy rates. At the same time, trip lengths in transit tend to be longer, which counteracts the effect of lower per-passenger emissions to some extent. The starting point for estimating the CO_2 cutoff value was the average trip length of a work trip by car in Germany, which is 18.4 km (Bundesministerium für Verkehr und digitale Infrastruktur, 2017). Based on average fuel consumption (INFRAS, 2017), the well-to-wheels emission factors of gasoline and diesel (Schmied and Mottschall, 2014), as well as information on the German fleet composition (INFRAS, 2017), we deduced an average emission factor of around 190 grams of CO_{2e} per vehicle kilometer. Multiplying the emission factor by the trip length and dividing by the average occupancy yields a reasonable emission threshold of around 3,000 grams of CO_{2e}. We acknowledge that the average CO_2 emissions across all commuting trips in Germany are certainly lower due to the share of less carbon intensive modes.

3. *Prescriptive implementation from an environmental perspective*: Again, CO_2 emissions serve as the relevant travel cost in the accessibility analysis. The cutoff value is normatively defined and derived from emission reduction targets. Germany aims to reduce transport-related GHG emissions by at least 40 % compared to 1990 levels (BMU, 2016). Since the transport sector has not achieved any emission reductions so far, this percentage is still valid today (BMU, 2019a). Applying this percentage to a one-way commute reduces the emission budget from 3,000 grams to 1,800 grams of CO_{2e}. Emission budgets could also be derived from more nuanced considerations, for example in terms of the specific shares of the overall emission reductions to be borne by car users in particular. Car drivers will likely need to contribute more to the overall emission reductions than the users of other transport modes, because of their larger contribution to overall emissions. The CO_2 emission budget used in this paper serves as a proxy and could be substituted by any normatively defined value. Besides the lower emission budget, all other parameters in the land use and transport system remain unchanged in the 2030 scenario. We acknowledge that by 2030, certain development, such as changed land use configurations, infrastructure changes,

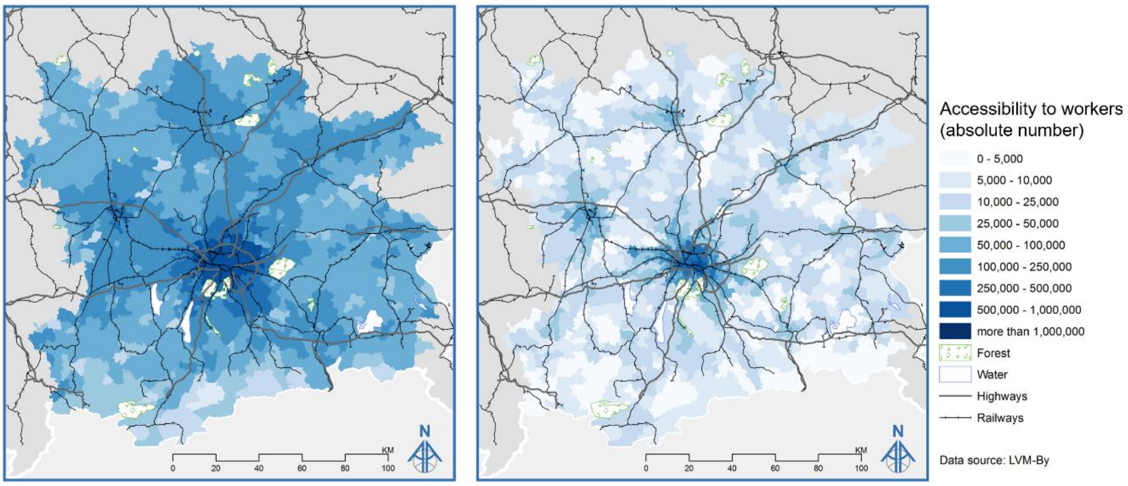
> and changes in vehicle efficiency or fleet composition, will likely have taken place. The 2030 scenario is purely illustrative, intended to highlight needs for active intervention under current conditions, without taking any trends or actions as given.

Accessibility by car and transit is analyzed for each of the three implementations, resulting in a total of six accessibility landscapes. For reasons of comparability, the same thresholds were used for car and transit. Accessibility measures based on the given specifications were calculated using python scripts (Vale, 2019) and visualized in ArcGIS. The resulting accessibility landscapes in the Munich metropolitan region are presented in the following section.

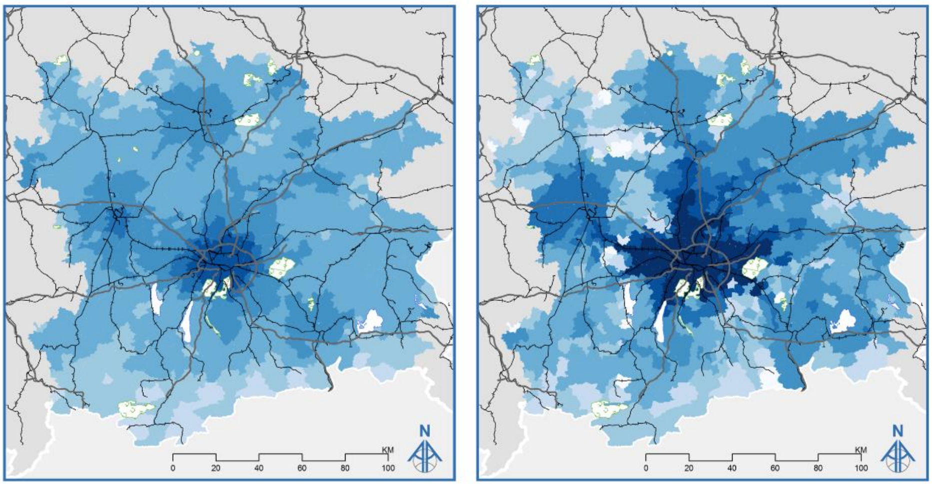
6.3.3. Accessibility landscapes

Spatial patterns

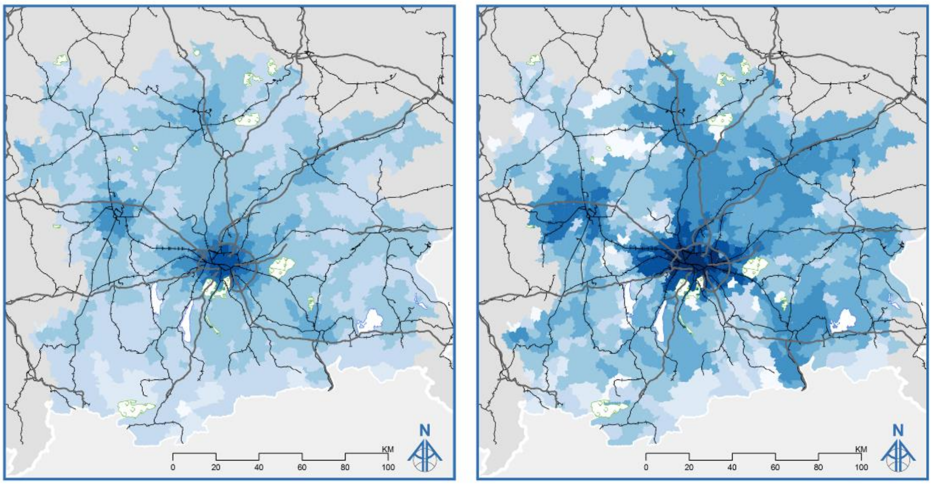
The maps in Figure 27 show the results of the accessibility analysis. The same quantity classes were used for all implementations in order to be able to compare accessibility levels across maps. The spatial patterns in all maps have several commonalities. The larger cities feature high accessibility levels, whereas the peripheral areas in between the transport axes have lower accessibility to workers. Rural and mountainous areas, which can for example be found towards the alps in the south, show the lowest accessibility levels overall. Most workers can be reached by potential employers in dark colored TAZs, which are mainly found in the city of Munich. These general patterns are not surprising, as they match the population distribution and the radial transport network structure in the Munich metropolitan region. One noticeable particularity of the spatial patterns stems from the influence of occupancy rates on carbon-based accessibility by transit. According to the LVM-By, the northwest-southeast railway axis and the railway lines leading northwards have the largest passenger loads. This fact is evident in the maps as well, since Figure 27d and Figure 27f have high carbon-based accessibility in the areas adjacent to these railway axes.



(a) Car travel time (threshold: 28.6 min) (b) Transit travel time (threshold: 28.6 min)



(c) Car CO_2 2019 (threshold: 3,000 grams) (d) Transit CO_2 2019 (threshold: 3,000 grams)



(e) Car CO_2 2030 (threshold: 1,800 grams) (f) Transit CO_2 2030 (threshold: 1,800 grams)

Figure 27. Travel-time-based and carbon-based accessibility by car and transit.

Despite some similarities in terms of relative spatial patterns, absolute accessibility levels are clearly different across maps, epitomized by the variations in color. The map for travel-time-based accessibility by transit is dominated by pale color shades, featuring the lowest accessibility levels among all implementations. Consequently, the visual difference between transit and car is dramatic when comparing the accessibility maps using the same travel time cutoff. Interestingly, this picture is reversed when focusing on carbon-based accessibility. Applying an emission budget rather than a time budget substantially increases transit accessibility. Transit outperforms car accessibility with both the 2019 and the 2030 CO_2 emission cutoff. The highest overall accessibility levels, with more than one million workers within reach, are achieved in these two implementations. There is a striking difference between the transit accessibility maps using 28.6 minutes and 3,000 grams of CO_2 as threshold values. Conversely, the two car accessibility maps based on these thresholds are nearly identical. This analogy in terms of absolute accessibility levels is excepted, since the 2019 emission budget is based on an average commuting trip by car. Consequently, the range is comparable to the average travel time per commuting trip. Carbon-based accessibility by car with the 2030 threshold (Figure 27e) performs just slightly better than travel-time-based accessibility by transit, with significant accessibility losses compared to the other two car accessibility implementations. Contrary to transit, occupancy rates in cars are generally independent of the spatial context, thus not reflecting in terms of spatial accessibility patterns. The carbon-based accessibility by car has a more polycentric pattern compared to travel-time-based accessibility, where urban cores stand out as high-accessibility islands.

Cumulative distribution of accessibility values

The visual trends observed in the previous section are underpinned by the empirical cumulative distribution function in Figure 28. Each accessibility implementation corresponds to one line, where the curve represents the share of accessibility values below the percentage of the overall maximum accessibility given on the horizontal axis. The cumulative percentage of travel-time-based accessibility by transit rises quickly at comparably low accessibility values. Carbon-based accessibility by car with the 2030 threshold has a similar curve, with slightly higher accessibility levels. The two remaining car accessibility implementations, namely travel-time-based accessibility and carbon-based accessibility with the 2019 limit, have almost identical curves. Carbon-based accessibility by transit with the more ambitious 2030 budget provides accessibility levels similar to these two implementations. However, the maximum accessibility values are even higher, resulting in a more moderate rise in the cumulative percentage towards higher accessibility levels. Carbon-based accessibility by transit with the 2019 limit clearly features the highest accessibility levels overall, with a particularly flat curve for the upper 25 to 50 % of accessibility values.

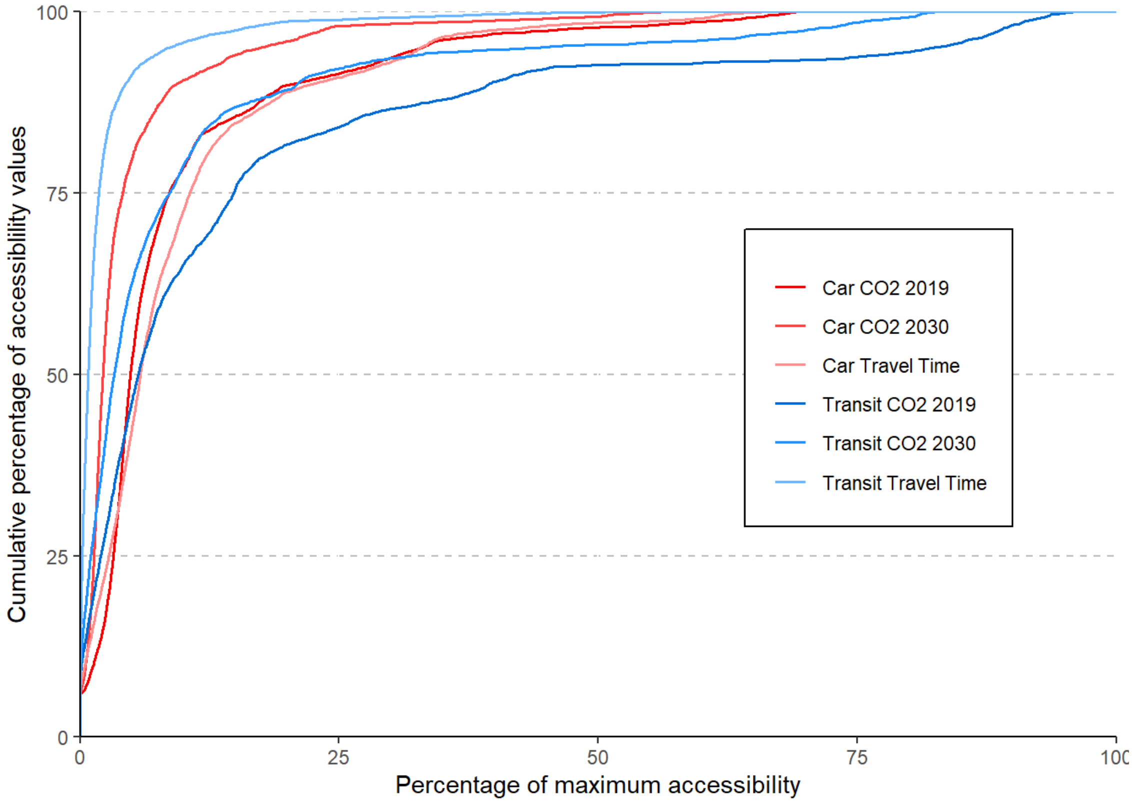
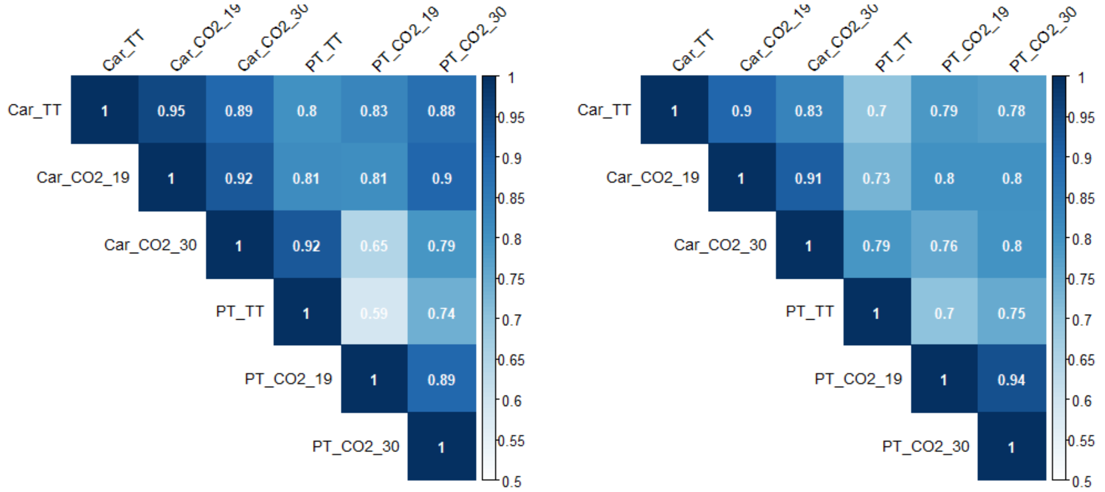


Figure 28. Cumulative distribution function of accessibility values.

Correlations between accessibility implementations

Correlation matrices help to understand the relationship between two variables. Correlations between different implementations of accessibility in the same study area are typically high (Higgins, 2019). Figure 29 shows the correlations between number of workers accessible in the six different implementations for two different methods. The Pearson method (a) analyzes the linear relationship between two variables based on their values. The Spearman method (b) uses ranks instead and examines whether two variables increase or decrease together, independent of the rate of change. A correlation value close to 1 indicates that high values in the first array correspond to high values in the second array and vice versa. All correlations were found to be significant. Correlations are generally high (around 90 %) between the accessibility levels by car, independent of the specific travel cost used as threshold. This is not true for accessibility by transit, where only the measures using CO_2 emissions as a travel cost have a correlation value above 90 %. The lowest correlation can be found between travel-time-based accessibility by transit and carbon-based accessibility by transit (2019), with a value of 59 % for the Pearson method.



	Car_TT	Car_CO2_19	Car_CO2_30	PT_TT	PT_CO2_19	PT_CO2_30
Car_TT	1	0.95	0.89	0.8	0.83	0.88
Car_CO2_19		1	0.92	0.81	0.81	0.9
Car_CO2_30			1	0.92	0.65	0.79
PT_TT				1	0.59	0.74
PT_CO2_19					1	0.89
PT_CO2_30						1

	Car_TT	Car_CO2_19	Car_CO2_30	PT_TT	PT_CO2_19	PT_CO2_30
Car_TT	1	0.9	0.83	0.7	0.79	0.78
Car_CO2_19		1	0.91	0.73	0.8	0.8
Car_CO2_30			1	0.79	0.76	0.8
PT_TT				1	0.7	0.75
PT_CO2_19					1	0.94
PT_CO2_30						1

(a) Pearson

(b) Spearman

Figure 29. Correlations between accessibility levels.

A corresponding scatter plot revealed that low values in terms of travel-time-based accessibility mainly correspond to low values in terms of carbon-based accessibility, but might also be paired with rather high carbon-based accessibility levels. This underlines the disconnect between travel-time-based and carbon-based accessibility by transit, as highlighted in the visual accessibility landscapes. Despite strong correlations of more than 70 % for most variable pairs, there clearly seem to be dissimilarities pointing towards the fact that carbon-based accessibility highlights different aspects of the land use and transport system compared to travel-time-based accessibility.

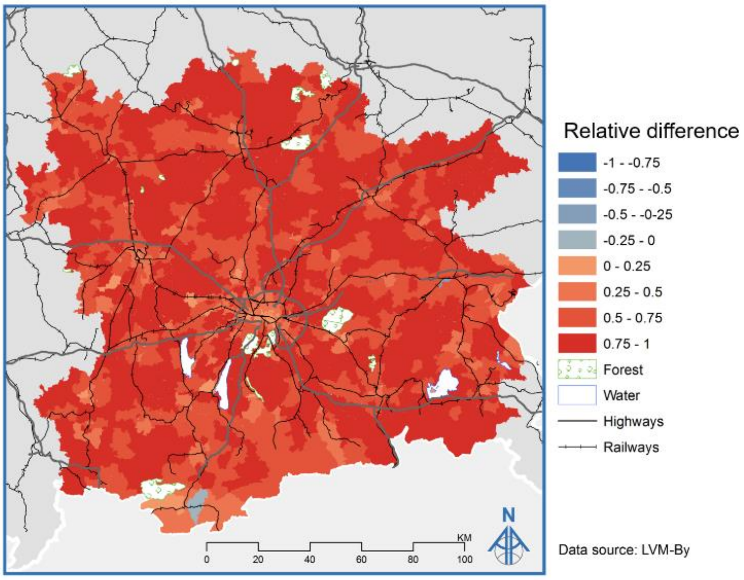
Relative difference between car and transit

Relative differences can be used to analyze the spatial disparities between two accessibility implementations rather than their relationship, as done in the correlation analysis. In this section, relative differences are calculated and mapped in order to compare the accessibility by car and transit for the different travel costs and thresholds. The relative difference (RD) for TAZ *i* is calculated according to the following equation:

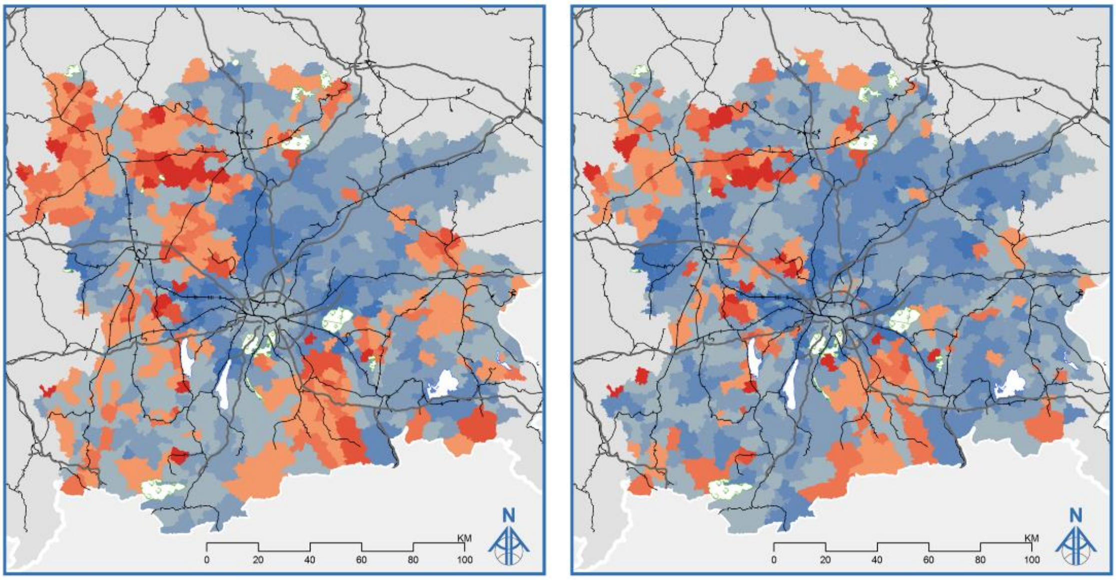
$$RD_i = \frac{A_{i,a} - A_{i,b}}{A_{i,a} + A_{i,b}}$$

The subscripts *a* and *b* indicate different accessibility implementations, for example travel-time-based accessibility by car and travel-time-based accessibility by transit. If both values are balanced, the relative difference is close to 0. It approaches +1 if $A_{i,a}$ is large compared to $A_{i,b}$ and -1 if $A_{i,a}$ is small compared to $A_{i,b}$.

The relative differences between accessibility by car and transit on travel-time-based and carbon-based accessibility measures are shown in Figure 30. Throughout the region, the car enables access to a larger number of workers than transit when using time as the relevant travel cost (Figure 30a). This situation is reversed in the case of carbon-based accessibility, with nearly identical spatial patterns for the 2019 and 2030 thresholds (Figure 30b and Figure 30c). In both cases, transit performs better, especially in proximity to railway lines and the areas surrounding larger cities.



(a) Travel time: Car - transit



(b) CO_2 2019: Car - transit

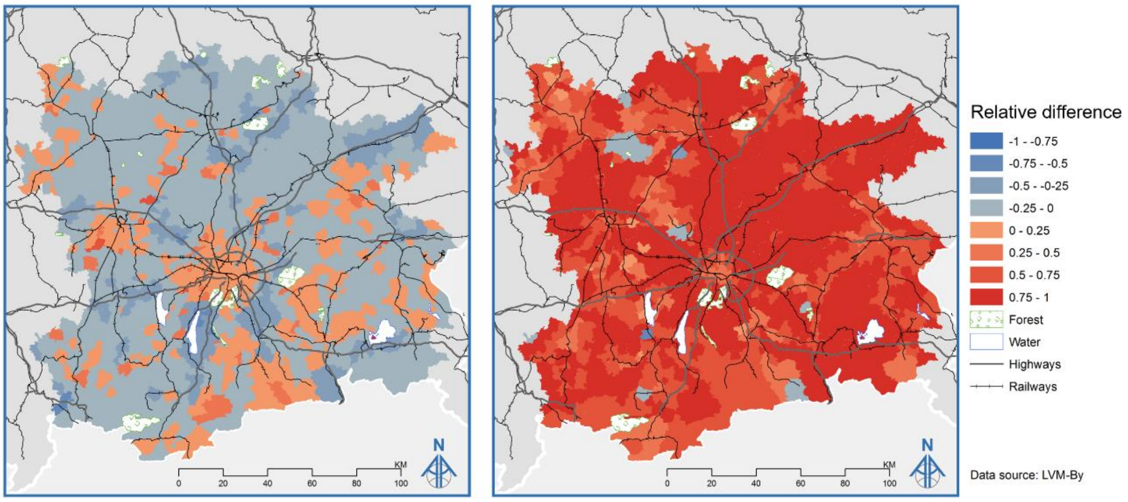
(c) CO_2 2030: Car - transit

Figure 30. Relative differences: (Car – Transit) / (Car + Transit).

The northeastern part of the region, where carbon-based transit accessibility is generally high, stands out with primarily blue areas. Clearly, occupancy is a crucial determinant of how well transit performs against the car. The areas where the LVM-By indicates high occupancy rates, resulting in low carbon mobility options by transit, are concurrent with negative relative differences. At the same time, low occupancy areas correspond to positive relative differences, which implies that transit performs worse than the car in terms of emissions. While the possibility of relating this generally known fact to specific spatial contexts is valuable, the implications might be misinterpreted. For example, the maps could be used to argue for the abolishment of transit in rural areas for environmental reasons. If implemented, such policies will result in car dependence and social exclusion of citizens without the ability to drive. Transit lines in rural areas might also serve as feeder services towards main lines, enabling high occupancy transit in the first place. Similarly, increases in service frequency – per se an improvement in terms of the quality of the transit system – might negatively affect carbon-based accessibility if passenger numbers do not increase accordingly. Nevertheless, the analyses might also help to develop and assess alternative solutions in low-density spaces, such as smaller, electrified vehicles instead of diesel buses, and demand-sensitive solutions instead of traditional bus services with fixed routes and schedules.

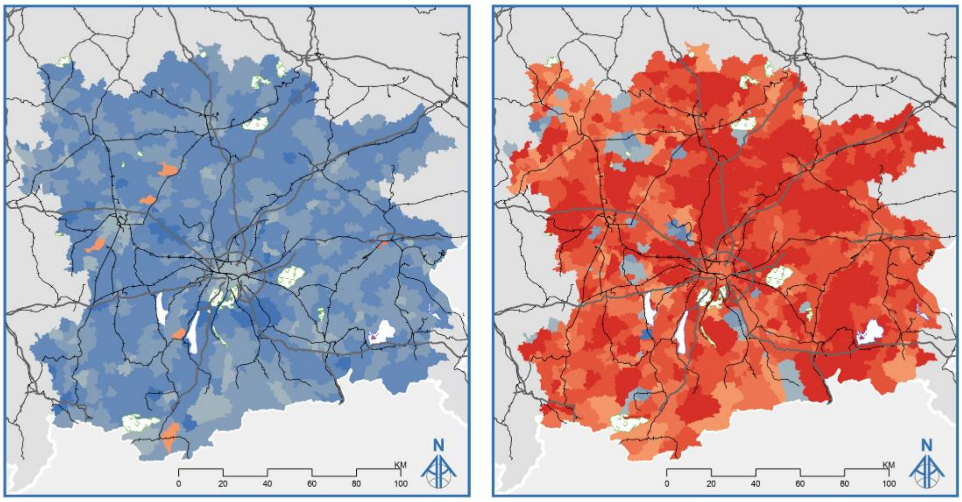
Relative difference between emissions and travel time

The previously introduced equation was used to calculate relative differences between carbon-based and travel-time-based accessibility by car and transit, respectively. The results are visualized in Figure 31. The relative differences between travel-time-based and carbon-based accessibility with the 2019 threshold are moderate in the case of the car, with the majority of values slightly above or below 0. In contrast, the majority of TAZs experience a decrease in the number of accessible workers when CO_2 emissions with the 2030 cutoff are used as travel cost instead of time. These results are expected, since the 2019 CO_2 emission budget is based on current travel behavior, just like travel time, whereas the 2030 cutoff limits the travelers' range based on the 40 % reduction objective. If emission reduction targets were to be proportionally applied to individual travel activities, commuters' emission budgets will be exhausted before their time budgets are. Carbon-based accessibility surpasses travel-time-based accessibility by transit for both the 2019 and the 2030 emission cutoff. The largest increases can be observed in the areas that feature high absolute carbon-based accessibility levels. The immediate city centers are an exception, since many workers can be reached within the given travel time threshold, as well.



(a) Car: CO_2 2019 - Travel time

(b) Transit: CO_2 2019 - Travel time



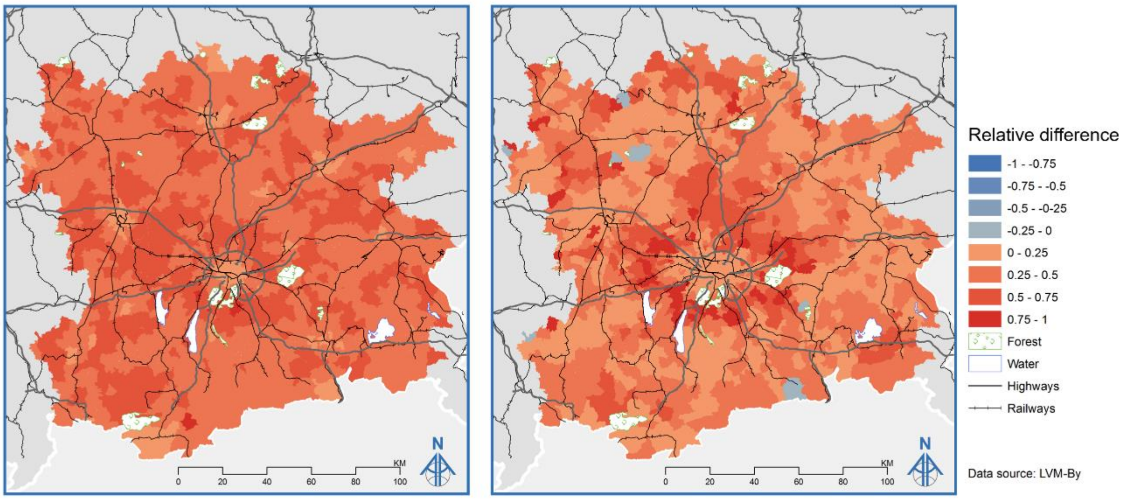
(c) Car: CO_2 2030 - Travel time

(d) Transit: CO_2 2030 - Travel time

Figure 31. Relative differences: (CO_2 – Time) / (CO_2 + Time).

Relative difference between emission cutoffs in 2019 and 2030

A final useful application of relative differences is the comparison between the carbon-based accessibility landscapes with the 2019 and the 2030 budget. This analysis helps to identify areas that are most or least vulnerable to emission budgeting. Figure 32 highlights that accessibility losses are smallest in the cities, which is true for both car and transit. The effect on many peripheral regions in between the transport axes is small to moderate. This can be explained by generally low carbon-based accessibility levels with large distances to dense urban areas. Suburban areas are most affected by stricter emission limits, since the city cores are out of reach when reducing the emission budget. Dark shaded areas, indicating large accessibility losses, form a belt around the city of Munich in Figure 32b. As a consequence, decision-makers might need to focus their efforts for low carbon land use and transport interventions in these areas.



Data source: LVM-By

(a) Car: CO_2 2019 - CO_2 2030

(b) Transit: CO_2 2019 - CO_2 2030

Figure 32. Relative differences: (CO_2 2019 – CO_2 2030) / (CO_2 2019 + CO_2 2030).

While the planning implications of presented results are purely illustrative, carbon-based accessibility analysis might contribute to real-world planning issues. Potential applications, strengths and limitations are discussed in the following section.

6.4. Carbon-based accessibility: a valuable contribution?

This section discusses potential decision-making purposes for which carbon-based accessibility analysis could be useful. Particular focus is put on the added value compared to traditional accessibility analysis, which applies a user perspective on travel costs rather than an environmental perspective. Carbon-based and travel-time-based accessibility landscapes show different patterns, which supports the claim that they prioritize different planning goals.

In general, accessibility analysis serves two types of planning purposes (compare Bertolini, 2017). Firstly, it helps to analyze the current land use and transport situation in order to identify accessibility deficits or highlight development potentials. Secondly, it enables an assessment of the impacts of potential interventions in the land use and transport system in order to prioritize, select or validate solutions. Carbon-based accessibility analysis in particular could thus help to identify and assess interventions related to the provision of low carbon mobility options. The following list of potential use cases is not necessarily exhaustive, but alludes to the variety of increasingly relevant planning questions, which could be addressed by carbon-based accessibility analysis.

- *Identify intervention needs to provide for low carbon mobility options:* The analysis in section 6.3 highlights large gaps between descriptive and prescriptive accessibility levels. Some areas stand out with particularly low carbon-based accessibility or high vulnerability to the introduction of emission budgets. Consequently, such analyses could be a starting point to identify and prioritize intervention needs, ensuring low carbon mobility options at existing settlements. On a more general level, the analysis highlights the dissimilarities between personal travel time budgets and per-capita emission budgets in a striking way. Consequently, planners need to identify and implement solutions that are able to align the environmental perspective and the user perspective on acceptable travel costs.

- *Guide land use development based on the potential carbon footprint:* Investment decisions might increasingly be determined by the potential carbon footprint of transport activities related to the location under consideration for development. Carbon-based accessibility analysis enables a comparison across urban structures, where locations could be classified based on the extent to which they provide low carbon mobility options. While these considerations help to guide urban development, other factors, such as the capacity of the existing transport system, need to be considered as well. For example, solely investing in locations with the highest carbon-based accessibility levels might lead to uneven utilization and overcrowding of the transit system.

- *Strengthen environmental objectives in transport investment decisions:* Environmental impacts should be explicitly considered in decision-making, as to not mask their importance. Travel-time-based evaluations suggest that time is the key optimization criterion. Efficiency improvements do not reflect in a corresponding accessibility map. On the contrary, carbon-based accessibility is sensitive to changes in occupancy or vehicle efficiency due to the underlying transport system parameters. Furthermore, whereas the car typically performs better than transit in terms of travel time, the picture is reversed when considering emissions. Investments in the transit system are expected to have a much larger positive impact on carbon-based accessibility than road extensions, depending on the spatial context and the efficiency of the vehicle fleet. Thus, this type of analysis could be useful for transit operators in order to argue for or assess the benefits of transit improvements in line with the existing urban patterns. Even though project appraisal certainly needs to consider multiple dimensions, the option to build a variety of low carbon mobility scenarios is expected to be a major strength of carbon-based accessibility planning.

- *Support policies related to carbon pricing and budgeting:* Emission pricing and carbon taxes are repeatedly discussed in the context of climate change mitigation. Carbon-based accessibility could easily be extended to address these topics. For example, taxes to be paid by land developers might depend on carbon-based accessibility. It is also likely that the users themselves will be charged for the emissions linked to their travel behavior. The analysis can be adapted to highlight the minimum price for reaching a fixed number of opportunities or the closest facility of a given kind. This in turn could directly be linked to social considerations and transport affordability. In the future, strict emission caps might not only apply to firms, but also individuals, introducing restrictions with regards to opportunity choices and transport mode choice. Consequently, frequent travelers would need to buy emission allowances from fellow residents with less carbon-intensive mobility behavior. The visualization of emission catchments would add transparency in terms of people's spatial range with a given CO_2 budget. Interactive tools utilizing carbon-based accessibility could help citizens to plan for their individual radius of movement. In theory, the concept enables inclusion of longer leisure or business trips, but this requires an extension to supra-regional scales.

Despite a clear application potential of carbon-based accessibility, there are also limitations. Carbon-based accessibility only helps to plan for low carbon mobility options, whereas transport-related emissions are directly linked to realized mobility behavior. Traditional accessibility measures, focusing on the user view of the transport component, are more suitable to predict emission-relevant characteristics of this behavior, such as trip length or mode choice (Barla et al., 2011). Even if in theory the land use and transport conditions enable low carbon mobility, the realized behavior is not necessarily the same as the required behavior. Individuals need to embrace the low carbon mobility options provided through land use and transport planning by changing their attitudes and behavior. Carbon-based accessibility is unable to either assess strategies targeted at behavioral change or reflect the environmental impacts of behavioral change. Thus, the level of goal achievement related to emission reductions in the transport sector cannot be evaluated. Some hope in this regard lies in the communicative power attributed to accessibility instruments. The ability of carbon-based accessibility to visualize the impacts of transport-related emissions in a specific spatial context could be a basis for the development of tools aimed at raising awareness among citizens. However, the verification of this and other hypotheses related to the practical relevance of carbon-based accessibility, which were raised in this section, is beyond the scope of this paper and needs to be addressed in future work.

6.5. Conclusions and research perspectives

In this paper, we compared accessibility implementations based on different perspectives on the transport component of accessibility. Travel costs from the user perspective were represented by travel time, whereas travel costs from the environmental perspective were represented by CO_2 emissions. The emission thresholds of the cumulative opportunities indicator were based on both descriptive and prescriptive travel cost budgets. In light of the need to reduce transport-related GHG emissions, the latter, purely normative approach to implementing carbon-based accessibility might serve as an important indicator for decision-making. Carbon-based accessibility implementations are able to project CO_2 emissions, a hardly tangible and barely perceptible global issue, onto specific local contexts in a visually striking way. The presented accessibility landscapes highlight disparities between locations, transport modes, and travel cost budgets. The results emphasize the magnitude of change needed and give support to the assumption that carbon-based accessibility brings added value to decision-making processes. Clearly, the selected emission budget determines the results of carbon-based accessibility analysis, where a more ambitious emission reduction target will cause accessibility losses, unless there are counteracting interventions in the land use and/or transport system. This trait is considered a major strength of the method and despite missing links with actual travel behavior, the concept offers a clear application potential in the context of planning for low carbon mobility options.

Carbon-based accessibility analysis and planning opens up multiple research paths to further explore, improve, and expand the method. Scenario-building capabilities were not tested in this paper, but represent an interesting starting point for future work. Carbon-based accessibility landscapes do not only change depending on the emission budget, but also react to interventions in both the land use and transport systems. The presented method can be used to assess the impacts of different urban development options on carbon-based accessibility. Structural interventions in the transport system, such as network extensions, will also reflect in the results of carbon-based accessibility analysis, possibly providing new insights from a low carbon perspective. Furthermore, carbon-based accessibility analysis is sensitive to changes in occupancy rates or vehicle efficiency, e.g. due to electrification of cars and buses, which distinguishes the approach from travel-time-based accessibility. A comparison of different evaluation methods promises to be highly interesting. For example, transit investments and road infrastructure investments could be analyzed by means of carbon-based accessibility, travel-time based accessibility, and standard evaluation methods in transport planning. The outcomes would likely be different and certainly provide a useful basis for further discussion.

Besides applying the method to a number of different planning purposes, alternative ways of operationalizing carbon-based accessibility should be explored. These could be different types of location-based accessibility indicators, such as distance-decay measures, or implementations uniting the user perspective and the environmental perspective. Emissions could be incorporated into implementations entailing the individual component of accessibility in order to determine the necessary magnitude of change in terms of perceptions, carbon price or willingness to pay for emission reductions, so that emission outcomes would be in line with normatively defined thresholds. Approaches considering the individual component of accessibility also enable social evaluations related to carbon pricing. For example, the inclusion of CO_2 emissions as a travel cost component could be used to compare the accessibility impacts for high-income and low-income persons under different carbon price scenarios. Furthermore, the carbon-based approach might be extended to conceptually different types of accessibility indicators. For example, person-based accessibility indicators could consider emission constraints instead of or in addition to time constraints. Emissions would act as an authority constraint, limiting the freedom of movement and activity participation of people (Hägerstrand, 1970).

Even though climate change mitigation is a central theme around the globe, travel activities cause other environmental impacts besides GHG emissions. Negative externalities include congestion, noise, and a number of different pollutants, such as nitrogen oxides. Expanding the method to include other impacts enables a more comprehensive analysis of environmental accessibility. Opening up the method for the integration of multiple perspectives also makes it possible to apply accessibility analysis to other objectives besides environmental ones. Accessibility approaches based on generalized costs, both internal and external, could present an alternative to classical cost-benefit-analysis (Cui and Levinson, 2018; Cui and Levinson, 2019). Such holistic approaches help to combine economic, social, and environmental goals. This type of analysis could even consider wellbeing as a combination of these dimensions on the individual level, with a particular focus on mobility-impaired people, children or the elderly. Short-term individual user needs might to some extent be in conflict with the long-term common good. Carbon-based accessibility planning, if properly implemented, can contribute to linking both objectives. However, if environmental objectives shall be the focus, as argued earlier in this paper, the analysis of CO_2 emissions in an isolated manner might be valid and necessary by itself.

Efforts to enhance the method need to be in parallel with the involvement of potential users in order to ensure two interconnected aspects: Firstly, fulfillment of the information needs of decision-makers and secondly, proper embedding into decision-making processes. Specific requirements will likely differ by spatial context, institutional arrangements, and application purposes. The outcomes could be contrary: A very simple method might be sufficient or a more multifaceted method might be necessary. The involvement of potential users is crucial in order to determine the added value of the method compared to, but also in addition to, existing decision-making tools and planning support systems. Further exploration of carbon-based accessibility is certainly worthwhile and decision-making tools based on this concept might help to better plan for low carbon mobility in the future.

7. 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, focusing on three aspects: analytical capabilities, communicative capabilities, and likeliness of future implementation. Accessibility analysis is applied to three real-world planning issues in the Munich region, with the overarching goal of reducing transport-related emissions. 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 providing for low carbon mobility options. 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.

7.1. 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). Accessibility instruments are acknowledged for helping practitioners to gain new insights or to develop common understanding across various disciplines and levels of expertise (Te Brömmelstroet et al., 2016; Silva et al., 2017; Wulfhorst et al., 2017). Despite these positive experiences, accessibility instruments are rarely employed in real-world planning practice beyond experiential applications for research purposes (Bertolini and Silva, 2019). Main implementation barriers include the separation of land use and transport planning, lack of familiarity with the accessibility concept, limited resources, and a mismatch between political goals and the goals implied by accessibility instruments (Bertolini and Silva, 2019; Te Brömmelstroet et al., 2019b; Te Brömmelstroet, 2010).

This paper presents three real-world planning issues in the Munich region where accessibility instruments were employed. The objective of this research was to explore the practical relevance of accessibility instruments for the particular planning goal of reducing transport-related CO_2 emissions. In this context, practical relevance is defined as the extent to which the functionality of an instrument can be used for the purposes needed in a specific policy and planning context. 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 political 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., 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.

Our assessment of the practical relevance of accessibility instruments for low carbon mobility planning focuses on three aspects: analytical capabilities, communicative capabilities, and likeliness of implementation. The analytical and communicative capabilities of planning support systems are identified by Pelzer (2017) as two key factors determining usefulness related to the tool-task-match. The usefulness in terms of analytical capabilities goes beyond the mere question of whether a tool is applicable to the planning task at hand: Tools need to serve the specific information needs linked to the underlying planning tasks and policy goals (Silva et al., 2017; Bertolini and Silva, 2019). They should be able to analyze the impacts of proposed interventions with respect to the planning goal (Pelzer, 2017), in this case reducing transport-related emissions. The communicative capabilities of accessibility instruments are recognized as decisive for their usefulness in terms of enabling understanding, participation, interaction, and integration across disciplines and levels of expertise (Curtis and Scheurer, 2010; Stewart, 2017; Papa and Coppola, 2019). Communication is of particular importance in the context of reducing transport-related emissions, since identification and implementation of solutions require the awareness and commitment of multiple stakeholders, including politicians, planners, and citizens (Hickman et al., 2010; Banister, 2011; Banister, 2008; Geels, 2012). Concerning the likeliness of future implementation, the question is whether accessibility instruments could be established as tools addressing planning issues linked to emission reductions in the transport sector. If so, under which conditions and for which particular purpose? Clearly, the answer depends on the usefulness of accessibility instruments in terms of analytical and communicative capabilities. Some general implementation barriers of accessibility instruments might still apply, but there could be both additional barriers and additional opportunities in the context of low carbon mobility planning.

Before discussing the practical relevance of accessibility instruments with respect to these three aspects in section 7.4, we present the methodological process in section 7.2 and the planning practice applications forming the basis of our research in section 7.3.

7.2. Research design

7.2.1. Project context and study area

The work presented in this paper is related to the Interreg Alpine Space project ASTUS[1]. Within ASTUS, partners from Austria, France, Germany, Italy, and Slovenia supported local and regional authorities in identifying and implementing land use and transport planning solutions to reduce CO_2 emissions. The general methodology employed in the project's 17 pilot sites consisted of three steps: (1) building low carbon scenarios, (2) formulating appropriate strategies, and (3) preparing action plans. Multiple decision-making tools were developed and applied to support this process (Kinigadner and Büttner, 2019). In this paper, we focus on the specific process, planning issues, and decision-making tools in the region of Munich. The MVV, responsible for coordinating public transport (an essential ingredient of low carbon mobility) in the Munich region, was a key project partner. MVV representatives not only accompanied and supported the entire process, but also ensured the contact and close cooperation with the practitioners (section 7.2.2). The interdisciplinary group of stakeholders involved in the process included both land use and transport planners on municipality and county level as well as representatives from other institutions, such as the regional planning authority. The study region is equivalent to the operation area of the MVV, as shown in Figure 33.

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[1] Project website: https://www.alpine-space.eu/projects/astus/en/home

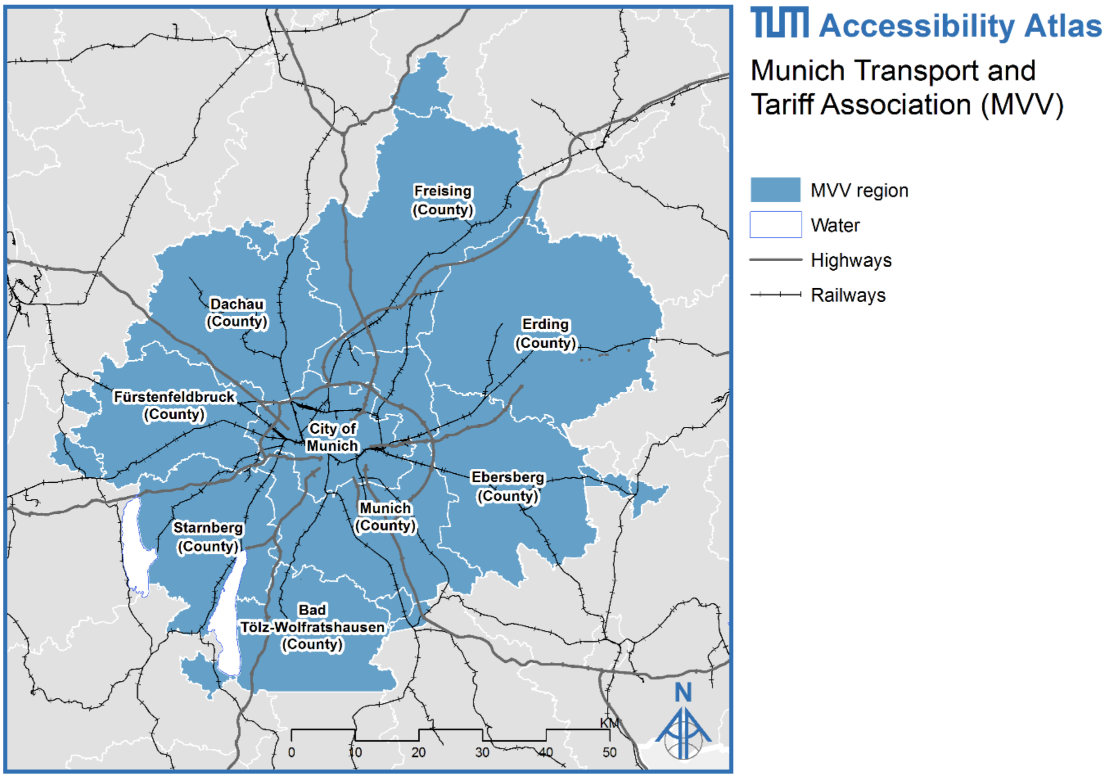


Figure 33. Operation area of the Munich Transport and Tariff Association.

Two types of tools were developed and applied in the Munich region: (1) accessibility instruments and (2) a spreadsheet to quantify and compare emissions in different scenarios. Regarding the former, this research builds on existing knowledge and previous experiences with the TUM Accessibility Atlas, a GIS-based accessibility instrument for the Munich region (Büttner et al., 2018).

7.2.2. Process description

An overview of the individual steps implemented in the Munich region and their outcomes is provided in Figure 34. The process followed the general three-step methodology within ASTUS (section 7.2.1). Since there was particular interest in the practical relevance of accessibility instruments for the identification and implementation of low carbon solutions in land use and transport planning, the process also entailed elements of the workshop procedure applied within the COST Action “Accessibility Instruments for Planning Practice” (Hull et al., 2012; Te Brömmelstroet et al., 2014). The guideline consists of four steps: (1) formulate planning goals and define criteria or outcome, (2) analyze the current situation, (3) develop intervention strategies, and (4) scan and evaluate effects on pre-defined criteria (Te Brömmelstroet et al., 2014, p. 17, developed by Goudappel Coffeng).

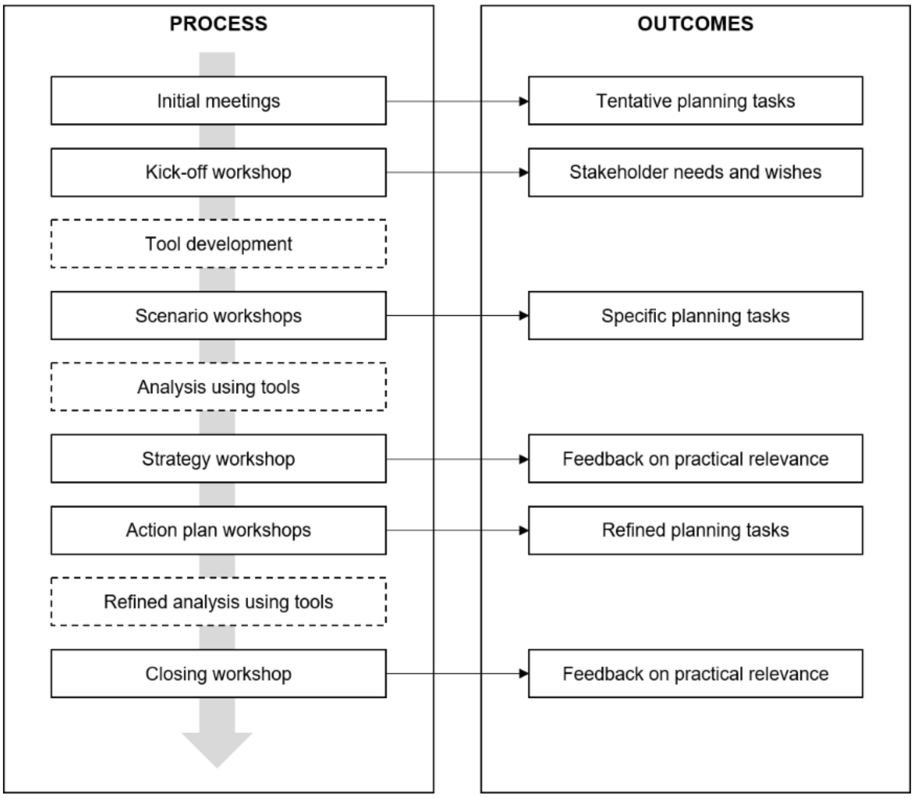


Figure 34. Tool application and stakeholder engagement process implemented in the Munich region.

The participatory workshop settings alternated with back office work, serving to conduct the analysis and improve the analytical abilities of the tools. Regarding the detailed process, the first step was to identify current planning issues in the context of transport-related CO_2 emissions during *initial meetings* with individual practitioners. The planning issues were specified during the scenario building phase following later on in the process.

All stakeholders gathered for a common *kick-off workshop* to collect ideas for the development and application of tools to support the identification and/or implementation of low carbon solutions in land use and transport planning. Several potentially relevant tools, including accessibility instruments, were presented to inform, sensitize, and inspire the workshop participants. Subsequently, the practitioners' ideas, needs, and expectations regarding relevant (and currently missing) planning tools were collected. The benefits of the kick-off workshop were twofold: Firstly, it helped the developers to understand the practitioners' 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. These realizations provided the basis for the following development and application of the tools.

Conclusions on the practical relevance of planning support systems cannot solely be based on hypothetical statements of practitioners, but require actual implementation (Te

Brömmelstroet et al., 2019a). With this in mind, the planning issues were specified during *scenario workshops* with smaller groups of practitioners, depending on their territorial responsibility. Three of these planning issues are presented in this paper: urban planning towards low carbon mobility (section 7.3.1), carbon-based accessibility benefits of public transport compared to the car (section 7.3.2), and location allocation and emission impacts of mobility hubs (section 7.3.3). After the specification of planning tasks, we could move on to conduct preliminary analyses with the tools.

All stakeholders came together once again during the *strategy workshop*, which served two objectives: (1) to develop strategies in order to realize the desired scenarios and (2) to evaluate the tools' practical relevance based on the preliminary analysis results. Regarding the second objective, the workshop participants were asked to rate a number of statements related to the tools' 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). Table 11 presents selected statements of the user survey and relates them to the three practical relevance aspects introduced in section 7.1. This quantitative evaluation supplemented the qualitative evaluation in the form of observations and discussions during the various workshops and meetings with practitioners (Figure 34).

Table 11. Statements in the user survey relating to analytical capabilities, communicative capabilities, and likeliness of implementation.

Practical relevance aspect	**Statements**
Analytical capabilities	*The tool outputs are valuable in developing strategies.* *The level of detail of the tool corresponds to the problem under discussion.*
Communicative capabilities	*It is easy to understand the input data, assumptions, and calculations behind the tool.* *The tool outputs are understandable and easy to interpret.* *The tool outputs are valuable in supporting interaction and discussion amongst stakeholders.* *The tool outputs can be communicated effectively to non-expert decision-makers.*
Likeliness of implementation	*I would like to have access to the tool for future use.*

The process continued with individual *action plan workshops*, aiming to specify the steps needed to implement the developed strategies. Both the strategy and action plan workshops 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 multidisciplinary 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 in terms of all three practical relevance aspects. Before presenting and discussing these insights in sections 7.3 and 7.4, respectively, we shed light on the accessibility measures used in the planning practice applications.

7.2.3. Accessibility measures

There exist multiple types of accessibility measures (Geurs and Van Wee, 2004) and instruments (Papa et al., 2016). The reasoning behind our choice of accessibility implementation was the intention to maximize practical relevance with respect to the aspects introduced in section 7.1. Regarding communicative capabilities, we set two preconditions: (1) the tool should be simple enough to enable transparency and understandability and (2) the tool should produce visual outputs in map format to enhance interpretability of the outputs. These requirements generally match the type of accessibility instrument used in previous applications in the Munich region (Büttner et al., 2019; Büttner et al., 2018; Wulfhorst et al., 2017), employing location-based accessibility measures according to the following equation:

$$A_i = \sum_j D_j \, f\left(c_{ij}\right)$$

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). Regarding the purpose of planning for low carbon mobility options, two specifications proved most fitting. The first one uses per-passenger emissions by car and transit, measured in grams of CO_{2e}, as travel cost in the accessibility analysis. The second one uses network distance to measure accessibility by non-motorized (hence emission-free) modes in a more traditional way. 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).

7.3. Applications of accessibility for low carbon mobility planning

Accessibility analysis was applied to the identified planning issues, which varied in terms of scope and scale. Three of these applications, relating to urban planning, public transport investment, and multimodal mobility hubs, respectively, are presented in this section. Practitioners were invited to react on the accessibility outputs during individual meetings, focusing on specific territorial responsibilities and issues, as well as during common workshops, uniting all practitioners from different disciplines and institutions (section 7.2.2).

7.3.1. Urban planning towards low carbon mobility

In the first planning practice application, accessibility instruments were used 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:

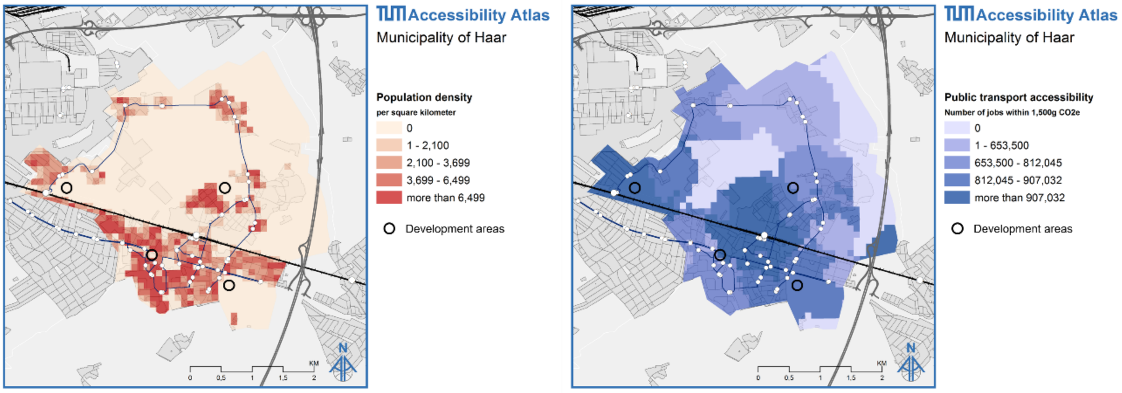
- Improve accessibility where density is two or more categories above accessibility
- Increase density where accessibility is two or more categories above density
- All other combinations correspond to a comparative mix of accessibility and density

In this particular application, the level of spatial detail corresponded to census grid cells, sized 100 by 100 meters. 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 12.

Table 12. Overview of accessibility and land use combinations for the preliminary analysis in the municipality of Haar.

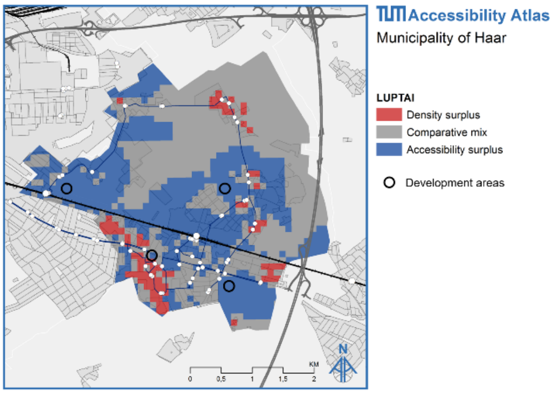
Accessibility dimension		**Land use dimension**
Transport mode	Destination potential	
Public transport	Jobs	Density of workers
Public transport	Workers	Density of jobs
Car	Jobs	Density of workers
Car	Workers	Density of jobs

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. From his viewpoint, accessibility refers to the availability of transport infrastructure, such as proximity to a public transport stop or the mere existence of a road. Once introduced to the fact that accessibility entails a land use component, he was not able to immediately comprehend how undeveloped grid cells could have high accessibility levels (which is due to low emission connections to developed cells). In order to ensure better understanding of how accessibility is measured, a simpler accessibility indicator, namely cumulative opportunities, was used in the refined analysis to introduce the practitioner to a different understanding of accessibility than his own. 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. The main conclusion was not to oversimplify legend items, since practitioners might prefer to look at a map and try to understand on their own, without additional explanation. The outcomes of the refined analysis were presented to political representatives during a municipality council meeting, resulting in interest and positive feedback. Figure 35 shows the final maps for the municipality of Haar: public transport accessibility to jobs within 1,500 grams 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 (Figure 35a), high carbon-based public transport accessibility compared to other locations within the municipality's territory (Figure 35b), and consequently an accessibility surplus, indicating a large potential for urban development (Figure 35c).



(a) Population density

(b) Public transport accessibility



(c) Land Use and Public Transport Accessibility Index

Figure 35. Population density, public transport accessibility, and LUPTAI in the municipality of Haar.

Accessibility instruments have the potential to support low carbon urban planning beyond merely substantiating decisions already taken. Although accessibility analysis generally allows project-level evaluations of urban development options (Levine et al., 2017), the largest application potential of accessibility instruments in this context lies in strategic planning. Different types and densities of potential urban functions could be tested in scenarios, assessing the extent to which they provide for low carbon mobility options, also by means of non-motorized modes. Planners on the municipality level are typically well acquainted with the specific land use and transport conditions, but qualitative approaches could be supplemented by quantitative accessibility analysis. The type of accessibility analysis implemented in this application does not enable impact evaluation in terms of transport-related emissions, which might not be as relevant on the scenario level, but increasingly important on the project level (compare sections 7.3.3 and 7.4.1).

7.3.2. Carbon-based accessibility benefits of public transport compared to the car

The second application concerns orbital express bus lines around the city of Munich, a major infrastructure project under discussion in the MVV 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 express services 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 MVV representatives, who employed a regional travel demand model to investigate the changes in travel demand on public transport lines due to the orbital express services. The analysis showed that public transport demand is reduced on radial railway lines and increased on orbital bus connections (Figure 36). 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.

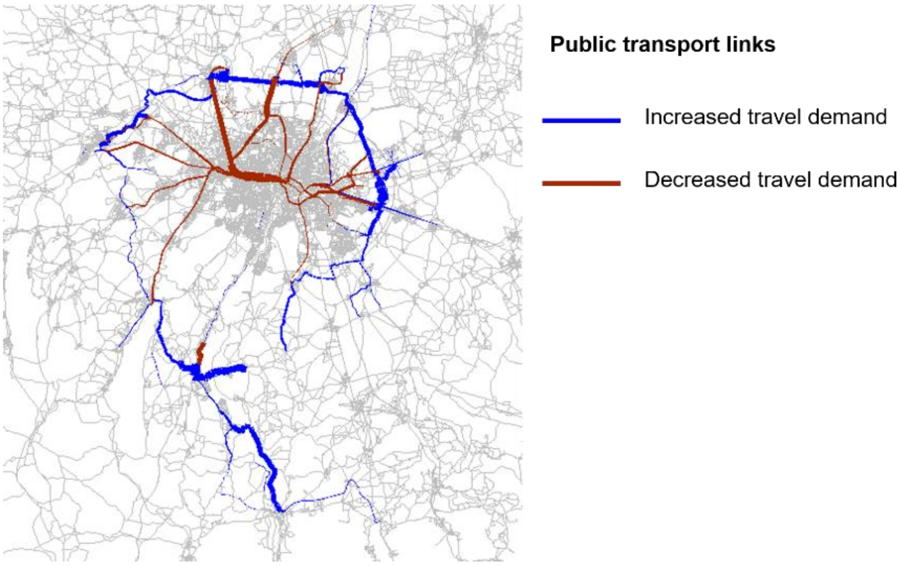
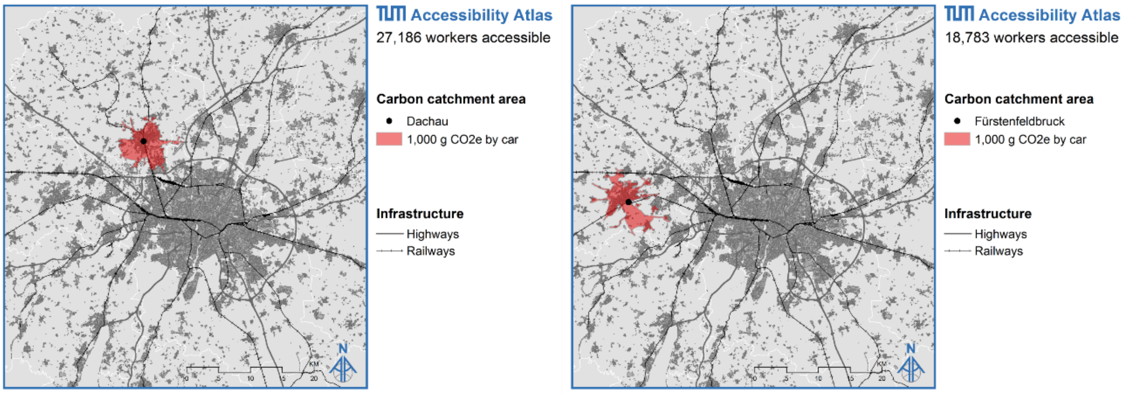


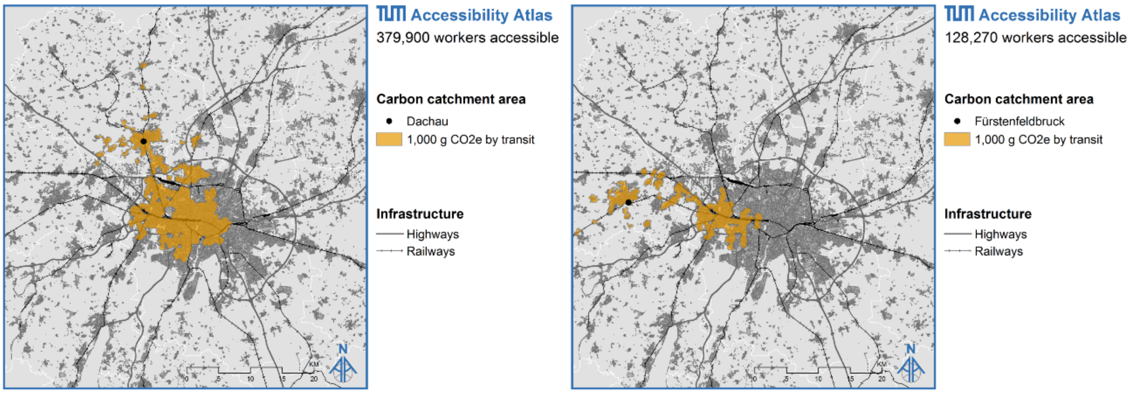
Figure 36. Screenshot from the regional travel demand model, showing changes in traffic loads on public transport lines due to orbital bus express lines.

Practitioners from the pilot counties' transport planning authorities, responsible for public transport supply within their territory, were involved in the process relating to this application. The main strategic goal of the intervention is to increase the attractiveness and competitiveness of public transport compared to the car in order to encourage a mode shift, thus reducing emissions. Further aims are to ensure regional cohesion through connectivity, to strengthen the economic position of the region, and to reduce traffic loads on the existing transport infrastructure. 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 major transport intervention, 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 bus express ring. Figure 37 exemplifies this for the two cities of Dachau and Fürstenfeldbruck, using an emission budget of 1 kilogram of CO_{2e}. The maps highlight striking differences in the shapes of catchment areas between car and public transport. 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.



(a) CO_2 catchment area by car from Dachau

(b) CO_2 catchment area by car from Fürstenfeldbruck



(c) CO_2 catchment area by transit from Dachau

(d) CO_2 catchment area by transit from Fürstenfeldbruck

Figure 37. Carbon catchment areas by car (a-b) and transit (c-d) from Dachau and Fürstenfeldbruck.

In addition to accessibility maps, other methods emerged as being relevant for the planning issue under discussion. The first method was telling individual storylines, where potential time, money, and emission savings due to the orbital bus services are highlighted on the scale of trips, persons and households. The second method was calculating the number of transfers and travel time ratios (public transport versus car) with and without the new services for selected origin-destination connections. Results were presented in matrices, where improvements were highlighted in color, for example by changing from red to green. Improvements of these indicators are implicitly linked to emission reductions by increasing the attractiveness of public transport.

This application showed that accessibility instruments can make the emission impacts of different transport modes tangible. At the same time, indicators of public transport 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). In consequence, these indicators influence realized CO_2 emissions via travel behavior, in particular mode choice.

7.3.3. Location allocation and emission impacts of mobility hubs

The third 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 stations.

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 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. Accessibility analysis turned out to be a useful method to address the second criterion. A cumulative opportunities indicator was applied, counting the points of interest within a network distance of 1,000 meters around the candidate hubs (Figure 38). The considered destination potentials included population, number of workers, education facilities, gastronomy, shopping opportunities, and services.

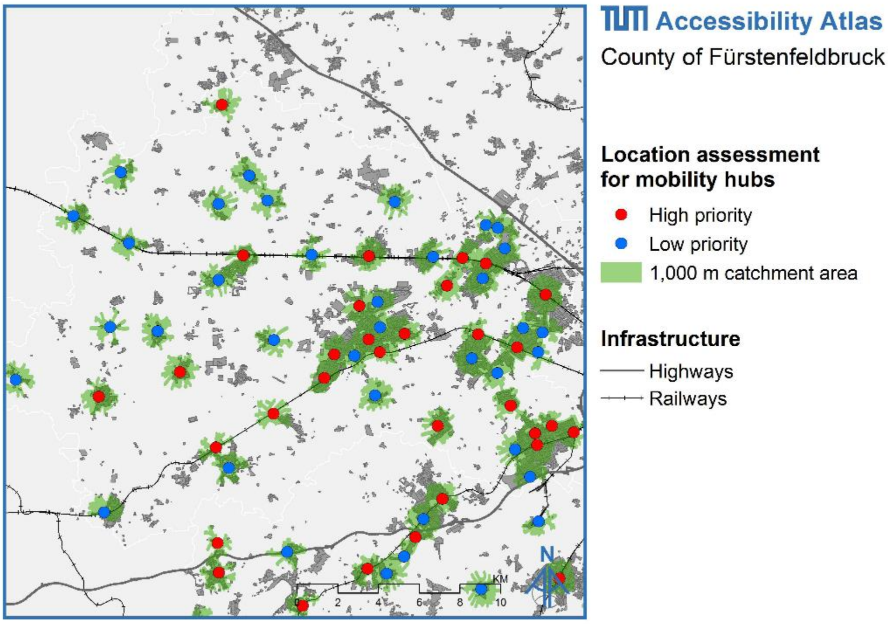


Figure 38. Potential locations of mobility stations in the county of Fürstenfeldbruck.

After the presentation of the analysis results during the strategy workshop (Figure 34), the county's responsible transport planner matured the preliminary concept by introducing further conceptual considerations. Firstly, also locations not coinciding with public transport stops should be taken into account in order to integrate agglomerations into the network that previously did not have any publicly available transport supply. Secondly, there should be a minimum distance between neighboring mobility hubs. Thirdly, mobility hubs should be categorized according to the services they provide, which entails implications in terms of the relevant catchment radius and destination potentials. For example, high residential population densities are important in the case of car sharing, because the vehicles are intended as a substitute for private cars and typically used in round trips starting from home. Bike sharing, on the contrary, could be used for intermodal or one-way trips, thus increasing the significance of other points of interest. The refined concept foresees an even denser network of mobility hubs than the preliminary concept. However, 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. To address this concern, an accessibility-based method was developed to identify the most promising locations for mobility hubs within a given study area. The method analyzes the number of potential users on a grid cell level and was implemented as an additional feature of the interactive accessibility instrument Geo Open Accessibility Tool (Pajares, 2020). A second development path was linked to the fact that the German climate protection initiative was foreseen in the action plan as a potential funding source for the implementation of mobility hubs. In order to receive financial support, an ex-ante evaluation of the project's contribution to CO_2 emission savings is required. For this purpose, we developed a simple spreadsheet, which calculates emission savings using the outputs of accessibility analysis and additional data from travel survey statistics. First, the number of potential customers is estimated based on the destination potentials within the catchment area of the mobility hub locations. 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. Both the location allocation method and the emission estimation method were presented during the closing workshop (Figure 34) to stimulate the debate.

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

Accessibility instruments were applied to planning issues in the Munich region with a focus on reducing transport-related emissions. This section discusses the implications of these experiences in terms of the three practical relevance aspects introduced in section 7.1: analytical capabilities, communicative capabilities, and likeliness of implementation.

7.4.1. Analytical capabilities

Accessibility instruments turned out to be applicable to all planning issues under discussion, for a variety of tasks and purposes 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. The user survey (section 7.2.2) was answered by a total of ten practitioners, from both urban and transport planning and ranging from the municipality to the regional level. Overall, the practitioners were pleased with the flexibility of accessibility instruments in terms of serving various spatial scales, from local to regional, depending on the respective planning issue (Figure 39).

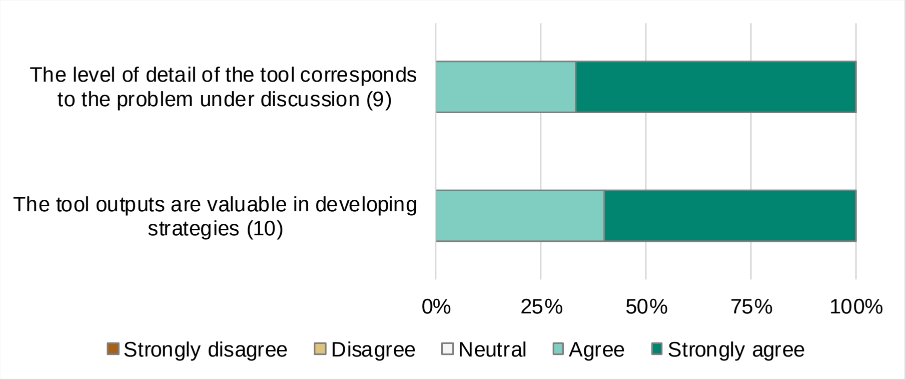


Figure 39. Survey responses on analytical capabilities (number of responses in parentheses).

Regarding tool outputs, practitioners identified two general requirements during the kick-off workshop (Figure 34). Tools should be able to (1) identify and/or localize options or needs for intervention and (2) assess the impacts of interventions in the land use and transport system. While both of these requirements are unspecific in terms of application purposes, they generally match the capabilities of accessibility instruments. This claim was confirmed during the strategy workshop (Figure 34), where all practitioners agreed on the added value of accessibility instruments for strategy-making (Figure 39). However, while accessibility instruments were indeed used to localize options for interventions, as demonstrated in section 7.3.1, none of the applications employed them to actually assess the impacts of (alternative) interventions. In theory, this would have been possible, for example by analyzing the accessibility impacts of land development choices in the municipality of Haar or assessing the regional accessibility improvements due to orbital express services compared to the status quo. Nevertheless, accessibility-based impact evaluations were no main concern among practitioners. The core reason of this observation lies 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 (section 7.3.1). This key implementation barrier of accessibility instruments has been reported in other contexts (Bertolini and Silva, 2019) and will be revisited in section 7.4.3.

While accessibility is not a formal performance indicator, CO_2 emission quantification clearly is. In fact, an evaluation was only performed in the case of mobility hubs (section 7.3.3), where accessibility outcomes could be linked to emission savings. The developed spreadsheet enables a rough estimation of emission savings based on the number of opportunities located within the catchment area of the mobility hubs. This combination of accessibility analysis and emission quantification is comparably easy to apply and understand, but a full ex-ante evaluation (also with respect to other planning goals) requires more sophisticated tools (Bertolini et al., 2005; Straatemeier, 2008; Hensher, 2008).

The planning practice applications showed that despite lacking institutionalization, accessibility instruments are suitable for various tasks within mixed-methods approaches, which not only entail quantitative evaluations, but also more qualitative methods. The need for qualitative work was evident in the case of urban development on the municipality level (section 7.3.1) and the precise determination of mobility hub locations (section 7.3.3). Specific local circumstances, such as land availability and ownership, constitute central decision criteria that cannot be addressed by accessibility analysis.

7.4.2. Communicative capabilities

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 analysis 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 (section 7.3.2). 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).

Based on previous findings on the communication value of accessibility instruments in general (Curtis and Scheurer, 2010; Stewart, 2017), there was hope that visual outputs in map format could fulfill planners' communication needs in the context of planning for low carbon mobility options. Figure 40 shows the survey results for the selected questions concerning communicative capabilities. While the practitioners verified the understandability and interpretability of the outputs, the accessibility instruments performed worse in terms of transparency. 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 (section 7.3.1). 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.

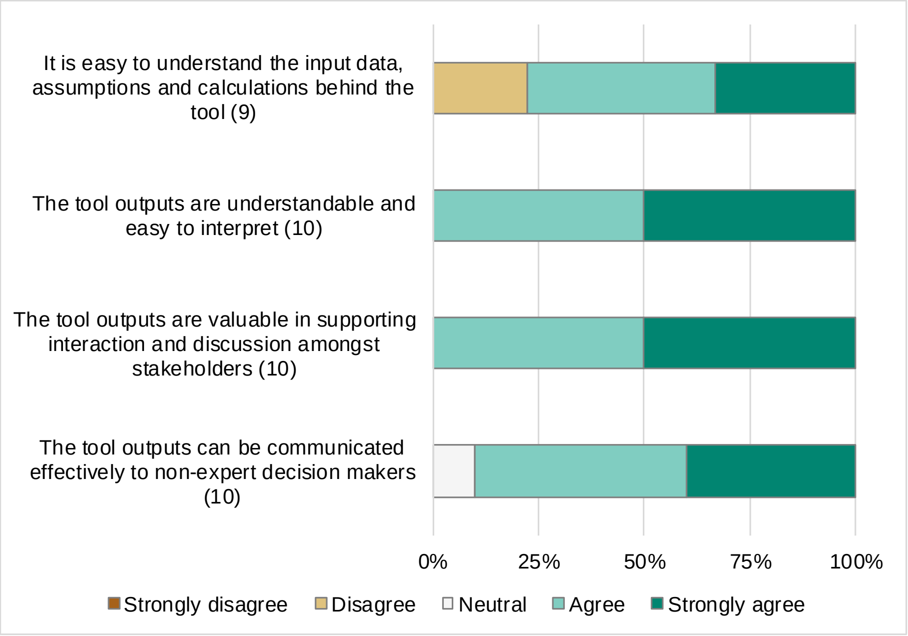


Figure 40. Survey responses on communicative capabilities (number of responses in parentheses).

Both during the strategy workshop and during the closing workshop (Figure 34), 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 (section 7.3.2). Additionally, the value of accessibility outputs in supporting interaction between different stakeholders was recognized (Figure 40), albeit this ability might currently be underused due to the isolation of planning disciplines. In line with the previous recognition that accessibility is not the decisive performance indicator, there is a particular need for understandable communication of emission savings, for example by highlighting relative changes due to the implementation of a project. Furthermore, maps are not the only means of effective communication. Other suitable options include individual storylines and colored origin-destination matrices (section 7.3.2).

7.4.3. Likeliness of implementation

The findings on analytical capabilities (section 7.4.1) revealed two main implementation barriers. The first is the already known institutional separation of land use and transport planning, 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: emission reductions are the central performance indicator for evaluating the impacts of interventions. Unilateral perspectives became evident when, despite the use of accessibility as an integrative concept, practitioners still focused more on their respective planning discipline. In the case of urban development (section 7.3.1), the transport system's function as a connector between origins and destinations was difficult to discern for the involved land use planner. In the case of express bus lines (section 7.3.2), transport planners were mainly interested in the size and shape of the catchment area, not as much the number of accessible workers. In the case of mobility hubs (section 7.3.3), the analysis did not focus on accessibility to activities, but on accessibility to transport supply. A conclusion is that finding potential applications of accessibility instruments in low carbon planning is not necessarily difficult. Instead, the main challenge might lie in introducing accessibility to practitioners who are unfamiliar with the concept and its multi-dimensional nature. In the end, the involved practitioners were more aware of the importance of integrating their projects into both the existing land use and transport systems. Such awareness represents a crucial first step towards integrating land use and transport policies and planning. However, 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. During the closing workshop (Figure 34), a 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. 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. Despite lacking institutionalization of accessibility, practitioners see a clear implementation potential, for example in terms of communication (section 7.4.2). 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 (Figure 41).

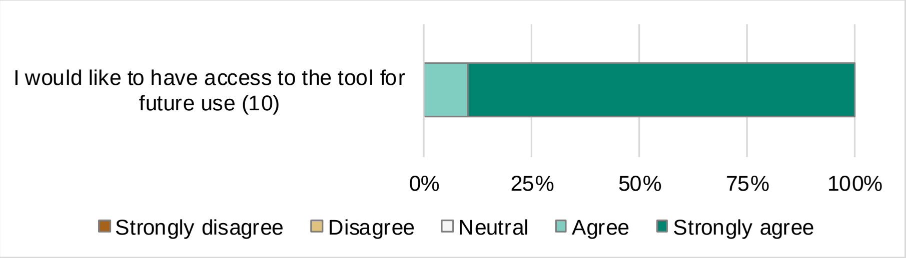


Figure 41. Survey responses on implementation prospects (number of responses in parentheses).

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.

7.5. Conclusions and needs for further research

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. The application of comparably simple location-based accessibility instruments providing visual outputs in map format turned out to be beneficial in terms of communication value. A limitation is their inability to quantify CO_2 emissions, which is why these tools can be used to plan for low carbon mobility options, but cannot assess actual expected emission reductions – a key assessment criterion. 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. However, institutionalization is not the only implementation path for accessibility instruments. Practitioners recognized an already existing practical relevance of accessibility instruments within mixed-method approaches. Overall, this paper brings up more new research questions than it answers. 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 (Banister, 2008; Curtis, 2008;

Bertolini et al., 2005). 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?

The planning practice applications and conclusions presented in this paper refer to a particular spatial and institutional context. 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, other, more 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.

8. Synthesis and discussion

8.1. RQ1: Tool characteristics

The characteristics of carbon-based accessibility instruments are expected to ensure compliance with the three criteria of focusing on emission impacts, integrating land use and transport, and addressing decision-makers (section 2.3.2). This section focuses on differences and similarities compared to existing decision-making tools and the corresponding implications regarding strengths and weaknesses for low carbon mobility planning. A typology of tools and methods as well as four key characteristics that should be present in order to comply with the stated criteria are introduced. All tools are assessed with respect to these key characteristics, with a particular focus on carbon-based accessibility instruments.

8.1.1. Typology of tools and methods

The main types of tools and methods supporting decision-making in the context of low carbon mobility planning are presented in this section (see also Paper I). The tool types differ in their scope of decision-making, mainly regarding the targeted decision-maker (political or individual, public or private) and the extent to which they include mobility behavior. There can be variations within the tool types in terms of characteristics that are considered to be non-distinctive, such as the specific study area (e.g. Germany or another country), the considered transport modes (e.g. single mode or across modes), the availability of other source categories besides transportation (for a complete emission inventory), and the precise emission factors considered (e.g. life cycle approach, well-to-wheels emissions or tank-to-wheels emissions). The following tool types were identified in addition to carbon-based accessibility instruments:

- *Microscopic emission quantification:* These tools provide information on emission factors (per distance unit) of motorized vehicles under different conditions. There are no links with the actual mobility behavior of people. Nevertheless, microscopic emission quantification is an important source of information for other tools and methods. A typical example is HBEFA (INFRAS, 2017), which is also used in this research as a basis for the emission model of the car network.

- *Macroscopic emission quantification:* This category represents a large group of tools that are capable of quantifying emissions based on mobility behavior. In addition to emission factors (by either vehicle-km or passenger-km), these tools consider information about trip lengths and possibly trip frequency. The spatial unit of analysis may vary: Some tools focus on the trip level, such as the DB Mobility Check (DB, 2019), comparing emissions of different transport options on a given origin-destination relation. Other tools focus on the household or firm level, helping private stakeholders understand their carbon footprint (UBA, 2020a). Another set of macroscopic emission quantification tools refers to entire territories, from municipalities to countries, thus mainly addressing public decision-makers. A typical example is ECOSPEED Region (ECOSPEED Climate Software Solutions, 2020), which enables GHG emission inventories for various sectors, including transportation.

- *Residential location choice tools:* These tools enable the evaluation of (mainly residential) locations in terms of their associated carbon footprint. Emission calculations are based on built-in parameters and user input. The central aim is to raise awareness and support the decision-making process of households and individuals. In principle, these tools could also be used to inform political and corporate decision-making. They are typically available online and embedded in a map-based environment. For example, the MORECO Household Calculator, which was developed further by Austrian project partners within the ASTUS project (Kinigadner and Büttner, 2019, pp. 30-37), combines an assessment of time, money, and emission costs for alternative location choice candidates.

- *Travel demand models* use data of the land use and transport systems and further parameters to model travel demand from origins to destinations and on network links for a specific region. The key elements of the modeling process are trip generation, trip distribution, mode choice, and route choice. Travel demand models may vary in scope and detail. Traditional 4-step models aggregate trips at the level of traffic analysis zones. Activity-based models are disaggregated on the person level and based on individual travel decisions (Bowman and Ben-Akiva, 2001). Thus, they are capable of considering characteristics, spatial-temporal constraints, and activity-coupling of persons and households (Castiglione et al., 2015, p. 6). Travel demand models can be linked to an emission model in order to calculate environmental impacts based on the outputs of the travel demand model (Schwanen et al., 2011).

- *Integrated land use/transport models* expand on the capabilities of travel demand models: They not only model the links from land use to transport, but can also predict land use development, thus representing the full feedback cycle of spatial development (Wegener and Fürst, 1999). Just like travel demand models, they can be aggregate or disaggregate, which in turn impacts model complexity

(Moeckel et al., 2018). Integrated land use/transport models can help to assess a large variety of policies in terms of their environmental impacts by linking them with GHG emission models (Hensher, 2008; Ford et al., 2018; Wegener et al., 2019). With advances in data availability and software capabilities, integrated land use/transport models have established strong theoretical foundations, but are still difficult to operationalize and use, which hampers their practical relevance for planning processes (Miller, 2018).

8.1.2. Key characteristics to meet criteria

Four key characteristics are identified (Paper I), which determine whether a decision-making tool is capable of fulfilling the three criteria of focusing on emission impacts, integrating land use and transport, and addressing decision-makers:

- *Land use component:* Does the tool enable decision-making related to land use policies and/or location choices?
- *Spatial dimension:* Does the tool contain a model of the characteristics of the land use and transport systems?
- *Scenario building capabilities:* Does the tool respond to policy interventions in the land use and/or transport systems?
- *Communicability:* Does the tool feature easily understandable outputs and transparent workings?

Table 13 shows how each of these key characteristics contributes to fulfilling the three criteria for low carbon mobility planning.

Table 13. Matrix of key characteristics and criteria for low carbon mobility planning.

	Focusing on emission impacts	**Integrating land use and transport**	**Addressing decision-makers**
Land use component	Emphasize the emission impacts of the land use system	Enable joint analysis of the land use and transport systems	Highlight land use policy and location choice options
Spatial dimension	Translate emission impacts to a specific spatial context	Analyze specific land use and transport conditions	Make intervention options and impacts tangible in local and individual contexts
Scenario building capabilities	Assess interventions in terms of emission impacts	Assess interventions in both systems	Highlight potential impacts of decisions

	Focusing on emission impacts	**Integrating land use and transport**	**Addressing decision-makers**
Communicability	Create particular awareness for emission impacts	Translate across disciplines and institutions	Provide understandable and transparent outputs

8.1.3. Assessment in terms of criteria

The tools and methods (section 8.1.1) are assessed with respect to the key characteristics (section 8.1.2.). Table 14 presents an overview of all tool types and their performance. Carbon-based accessibility instruments, as operationalized within this research, are compared to the state of the art based on the four key characteristics.

Table 14. Summary of methods and tools enabling low carbon decision-making.

	Land use component	**Spatial dimension**	**Scenario building capabilities**	**Communicability**
Microscopic emission quantification	-	-	-	-
Macroscopic emission quantification				
Trip level	-	-	-	+
Household/firm level	-	-	-	+
Territory level	-	-	±	±
Residential location choice tools	+	+	-	+
Travel demand models	±	+	+	-
Integrated land use/transport models	+	+	+	-
Carbon-based accessibility instruments	+	+	+	+
Symbols: + Characteristic met - Characteristic not met ± Characteristic partially met				

Land use component

While microscopic emission quantification tools only provide emission factors of vehicles or vehicle fleets, macroscopic emission quantification tools rely on actual travel demand and mobility behavior data. However, land use is at best indirectly addressed by using destination choice and trip lengths as input for the calculation. The four remaining tool types are to some extent capable of analyzing location choice and land use policies.

Travel demand models are sensitive to land use changes affecting the structural properties of a zone. However, outputs are provided on the level of the transport infrastructure, not on the level of spatial zones. Consequently, travel demand models cannot highlight needs or options for interventions in the land use system, which in turn is a major strength of location-based accessibility analysis (Paper III). At the same time, accessibility instruments are able to compare alternative locations in terms of potential emission impacts (Paper II) – a property they share with residential location choice tools. The land use dimension is essential for the joint analysis of land use and transport systems in order to design integrated transport and land use policies and plans. This capability is intrinsic to both accessibility instruments and integrated land use/transport models.

Spatial dimension

In general, emission quantification tools do not have a spatial dimension and the actual characteristics of the land use and transport systems are unknown. Consequently, these tools cannot identify specific intervention options or assess related impacts independently. External input data from surveys or models is required to calculate emissions or emission savings on various aggregation scales. All remaining tools and methods feature a spatial dimension, which generally enables them to analyze and assess the given land use and transport conditions. A spatial dimension is required for a tool to be able to not only identify, but also localize options for intervention. Depending on the unit of analysis and the extent to which the land use component is considered, tools could focus on land use decision-making (residential location choice tools), transport decision-making (travel demand models) or integrated land use and transport decision-making (integrated land use/transport models and accessibility instruments). Tools might also differ in terms of spatial detail and the overall size of the study area. Accessibility instruments are quite flexible in this regard: The applications within this research show that carbon-based accessibility analysis is applicable on local (Paper IV), regional (Paper I, Paper II), and metropolitan scales (Paper III), while analyzing specific locations (Paper I, Paper II), grid cells (Paper IV) or institutional units (Paper III).

Scenario building capabilities

Not all tools and methods are usable for emission evaluations, since they do not enable scenario analysis to assess the impacts of changes in the land use and transport systems. Typically, tools that are aimed at awareness raising (macroscopic emission quantification on trip, household or firm level and residential location choice tools) do not enable scenario building, but only provide insights into the consequences of alternative decisions under existing land use and transport conditions. Scenario-building capabilities are a crucial criterion to support planners and politicians in decision-making processes that have an impact on the commons. Even if tools are sensitive to transport and land use policies and plans, their scenario building capabilities may differ.

There are clear variations in terms of the types of policy interventions that can be assessed. The absence of a specific spatial context means that editing the transport network and changing the distribution and intensity of urban functions is not possible. Thus, specific physical interventions in the land use and transport systems, such as the construction of new infrastructure or urban development cannot be assessed. Macroscopic emission quantification tools on the territory level can only capture these changes if they are linked to a land use and transport model. Alternatively, emission impacts of a general concept or strategy could be estimated based on assumed changes in the input parameters, possibly supported by mobility statistics and data.

While carbon-based accessibility instruments are capable of reacting to changes in transport supply or spatial patterns, they are not sensitive to policies directly acting on travel behavior without changing the physical layout of the transport and land use systems (compare Paper III). Carbon-based accessibility analysis does not model travel behavior and is thus not sensitive to changes in travel behavior, for example due to measures affecting the price and comfort of travel options or people's attitudes and preferences in terms of mobility. Several climate change mitigation measures try to encourage behavioral change (compare Schwanen et al., 2011), but these do not necessarily entail changes in the built environment. Methods to effectively model the types of policy interventions which might reduce emissions via travel behavior changes, such as travel demand models and integrated land use/transport models, need to contain data and parameters about the travel cost elasticity of mobility choices, which makes them more technical and complex.

Similar to emission quantification tools, carbon-based accessibility could to some extent react indirectly. For example, the impacts on public transport ridership due to changed pricing schemes or other measures targeting increased attractiveness could be estimated based on models or assumptions. Changes in occupancy rates will in turn have an effect on carbon-based accessibility levels. Thus, carbon-based accessibility is more suitable to assess a variety of potential scenarios, such as occupancy or efficiency increases. By visualizing the benefits of various scenarios in terms of carbon-based accessibility, the tool might give impulses towards the development and implementation of measures that encourage such change (Paper IV).

Since carbon-based accessibility instruments are not capable of modeling travel behavior, they cannot produce emissions as an output. Instead, they provide accessibility levels as an output, based on emission constraints as an input. This is a major distinctive characteristic compared to other tools. However, using CO_2 emissions as travel impedance in an accessibility analysis is only applicable for motorized modes that actually generate emissions. The carbon-based accessibility by non-motorized modes, such as walking and cycling, is infinitely large. Consequently, strategies to improve conditions for walking and cycling cannot be analyzed by means of carbon-based accessibility analysis (see section 8.4.3 for options to compensate this limitation).

Decision-making tools can be used in different phases of the planning process, to assess system-wide scenarios or to evaluate specific projects (Levine et al., 2017). In general, accessibility analysis is applicable to both strategic planning and project appraisal (section 2.2.2). However, in terms of impact evaluation, the specific type of instrument developed and applied within this thesis is more suitable for strategic planning. Carbon-based accessibility analysis is only sensitive to broad interventions in the land use and transport systems and provides accessibility outputs instead of emission reductions – the key criterion for evaluating the impacts of climate change mitigation measures (Paper IV). These traits might not be a limitation for the identification of intervention options or assessment of broad alternatives in strategic planning, but other/additional capabilities are certainly needed during the project appraisal phase. The assessment of measures requires sophisticated tools to capture more measures and details, emission quantification as an indicator, and evaluation with respect to other sustainability goals. Thus, the characteristics of carbon-based accessibility instruments limit their ability to conclusively determine the desirability a particular emission mitigation strategy. Disaggregate models are more sensitive to policy measures and interventions than aggregate models (Schwanen et al., 2011), which makes activity-based travel demand models or integrated land use/transport models most suitable to analyze the detailed impacts of measures.

Communicability

A tool’s communicability is determined by interpretability and understandability of the outputs and transparency in terms of the tool’s workings. Regarding outputs, two main types can be determined: numerical outputs (emissions) and visual outputs (maps). Carbon-based accessibility instruments produce visualizations in map format, which clearly is an advantage in terms of communicability (compare section 2.2.2). However, map-based outputs do not automatically entail high communicability (Paper IV). Firstly, it is important to use simple accessibility indicators, where cumulative opportunities turned out to be most suitable in terms of communicability. Secondly, maps need clear legends to be self-explanatory. If properly implemented, carbon-based accessibility instruments promise to be useful for interdisciplinary communication, cooperation, and integration as well as communication with political decision-makers and the general public (Paper IV).

Modeling tools that enable sound and detailed evaluation of policy measures in terms of emission quantification are typically more difficult to operationalize and understand. This is in conflict with the requirements for integrated and participatory planning due to their large complexity, development effort, lack of transparency, and limited communication value (compare Banister, 2008; Sheller and Urry, 2016). Communicability turned out to be a valuable trait at multiple stages of the planning process: to develop shared perspectives among various stakeholders during strategic planning, to promote the implementation of measures with already known benefits, and to ensure commitment of citizens once the measures are already implemented (Paper IV). Carbon-based accessibility instruments have the potential to fulfill all of these communication tasks. This assumption was corroborated by practitioners during the planning practice applications (section 8.4.2), but a more comprehensive verification of this hypothesis needs to be the focus of future research.

8.1.4. Summary: Tool characteristics

Carbon-based accessibility instruments enable integrated land use and transport decision-making due to the presence of a land use dimension, which is absent from many other tools. Furthermore, they provide a specific spatial context, which enables them to analyze the current situation in order to identify specific intervention options and assess these strategies in scenarios. Options and impacts can be spatialized and visualized by means of map-based visual outputs. However, carbon-based accessibility instruments do not enable emission quantification and strategies or measures aimed at behavioral change cannot be assessed. At the same time, the lack of a travel behavior model makes the method simpler than more sophisticated land use and transport modeling methods, increasing its communicability.

8.2. RQ2: Operationalization

Carbon-based accessibility analysis requires transport networks that enable the measurement of per-passenger CO_2 emissions. This section sheds light on the data employed for the emission models of car and public transport within this thesis. The experiences gained during the development process serve to reflect on the ease of operationalization of carbon-based accessibility and the required quality and detail of data. Even though context and database are unique in each application, other developers could learn from these experiences in terms of software needs, data requirements, and potential issues.

8.2.1. Software environments

Different software environments were used to model the transport networks of car and public transport: (1) trip-based travel demand models available in PTV Visum (Paper I, Paper II, Paper III, Paper IV), (2) ArcGIS, a software specialized in the analysis, preparation, and presentation of spatial data (Paper I, Paper II, Paper IV), and (3) the trip planner Google Maps, using its API to request travel distances by mode for certain origin-destination connections (preliminary testing and analysis). Table 15 summarizes the experienced advantages and disadvantages of the tested approaches.

Table 15. Advantages and disadvantages of software environments.

	Advantages	**Disadvantages**
Travel demand model (PTV Visum)	• Relevant data (network topology, travel demand, public transport schedules…) is already included and ready to use	• Some editing might still be needed to make sure that the model is accurate and up to date • Transportation analysis zones are already fixed • Built-in calculation procedures need to be manipulated to fit analysis needs
GIS environment (ArcGIS)	• The increasing availability of free and open source data makes it possible to build a tailor-made model • Both service areas and origin-destination cost matrices can be calculated for any spatial analysis unit • Availability of multiple built-in data management methods • Appealing visual outputs	• Data needs to be gathered from multiple different sources, which entails a higher risk of lacking or erroneous data • Data processing is time-consuming (especially for large study areas) and error-prone (especially for public transport, which requires accurate modeling of connectivity and schedules)

	Advantages	Disadvantages
Trip planner (Google Maps)	• Quick and easy to implement solution, especially in smaller areas without large spatial variations of the parameters determining emissions	• Differentiation in terms of energy consumption or occupancy rates is only possible on the level of trip legs, not by spatial context • Transport network cannot be edited

CO_2 emission estimation requires information about link lengths. However, this information might be erroneous if network links are not represented true to shape. For example, the ArcGIS feature “Add GTFS to a Network Dataset” represents public transport routes as straight line connections between stops, since schedule-based analysis does not require detailed link shapes. Consequently, travel distances are underestimated when they are calculated based on the link length in the model. The same problem emerged with the LVM-By, which represents bus connections as straight lines. However, the error is smaller, since rail-based lines, which feature larger distances between stops, are modeled true to shape. Link lengths do not necessarily need to be calculated, but could be added as a link attribute. However, the true length needs to be known from other sources in this case.

Certainly, there are other software environment options than the ones used within this thesis. A multitude of factors might determine the most suitable approach in a given situation, such as purpose of the analysis, familiarity with the software, available budget or specific requirements on the software (e.g. open source products for easy manipulation).

8.2.2. Route choice: shortest time or lowest emission costs?

CO_2 emissions are used as a travel cost to weight the opportunities in the accessibility indicator. However, emissions should not be the travel cost used by the route choice algorithm, since it is not realistic to route along the most carbon efficient route. Travelers do not choose their route from an environmental perspective, but from a user perspective (a detailed discussion on the links between transport-related emissions and realized travel behavior follows in section 8.3). In other words, carbon-based accessibility analysis requires two different travel cost attributes: one for the route choice (e.g. time, fares, number of transfers) and one for the travel costs c_{ij} in the accessibility analysis (CO_2 emissions). This requirement entails two challenges: Firstly, there might be multiple best routes for any given origin-destination connection, which not only differ in terms of the parameters determining the route choice of travelers, but also in terms of emissions. The question whether these differences are significant or negligible was not explored in this thesis, but could be a future focus in order to better understand the magnitude of this effect. Within this thesis, a demand-weighted average of the emission costs of multiple possible routes throughout the day was calculated in the applications using PTV Visum. Another approach could be to opt for a single best route, e.g. the route with the fastest travel time at a given point in time. Secondly, catchment areas are more difficult to visualize if route choice attribute and cutoff attribute are two different parameters. Service area calculation in ArcGIS only allows a single travel cost attribute: it is not possible to use one attribute for the route choice and another one as the cutoff value. This is why the catchment areas serving the calculation of a cumulative opportunities measure might need to follow a lowest emission path (accessibility by car in Paper I and Paper II). Again, the extent to which the lowest emission path differs from the lowest cost path from a user perspective is a research question to be explored in the future. The problem can be avoided by using fixed origins and destinations and calculate cost matrices (which is typically the case in public transport due to the fixed number and location of stops). Both ArcGIS and PTV Visum allow to accumulate a link attribute, such as CO_2 emissions, along the best route for a given set of origins and destinations. For example, this approach was used in the zone-based application in Paper III.

8.2.3. Energy consumption: a matter of detail

Relative energy consumption per distance unit features large variations by vehicle type, traffic situation, and driving style. The variations in vehicle types are particularly large in public transport. While it is easy to distinguish between general vehicles types, such as buses and trains, detailed information about the specific vehicle types operating a given line and the associated energy consumption is more difficult to acquire. For example, HBEFA provides energy consumption values for different types of buses, but information about types and emissions classes of buses for all lines in the Munich region was unavailable. Operators might be willing to share this information upon request (Paper I), but when it comes to long-term strategic planning, specific operation concepts might not even exist, which requires assumptions in different scenarios.

Likewise, variations by traffic situation are difficult to model. According to HBEFA, the traffic situation is determined by location, road type, speed limit, and traffic state. The necessary information to differentiate by location, road type, and speed limit could be retrieved from OSM and CLC (see section 3.1.2). HBEFA 3.3 differentiates between four traffic states: free flow, heavy, saturated, and stop+go. The energy consumption of diesel (Figure 42) and gasoline cars (Figure 43) shows clear variations by traffic state, since energy consumption generally increases with increasing congestion or when driving at high speeds.

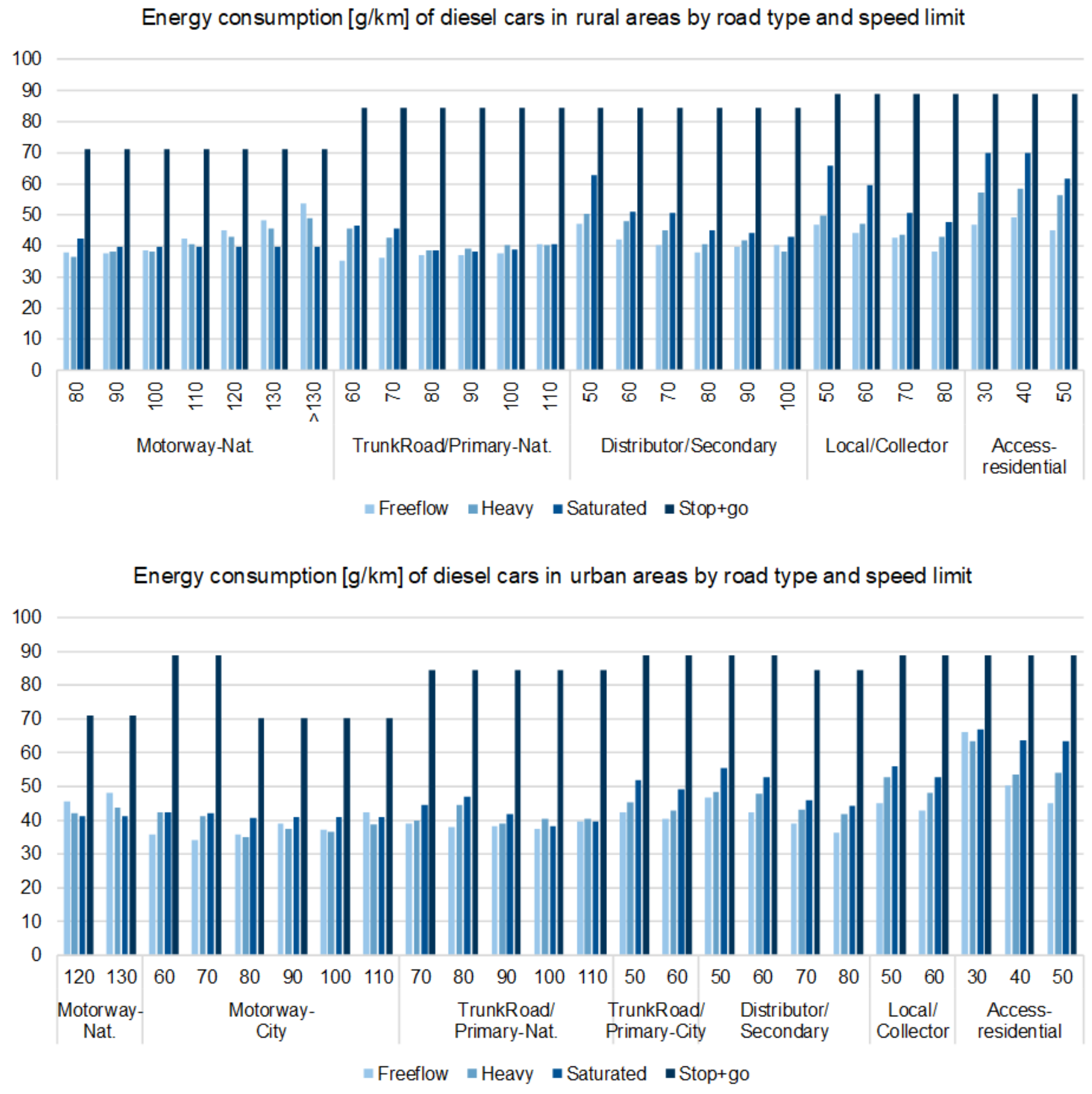


Figure 42. Variations in energy consumption of diesel cars by traffic state. Source: Own illustration based on data from HBEFA (INFRAS, 2017).

Traffic states vary in space (neighborhood streets versus urban ring roads) and time (off-peak versus rush hour). For the applications within this thesis, the traffic state was determined to be saturated in cities and free flow in rural areas. Based on the data from HBEFA, the absolute difference in energy consumption between saturated and free flow traffic is around 20 % across all traffic situations. The energy consumption in stop+go traffic is on average twice as high as in free flow traffic. TomTom or similar data on congestion levels could be used to determine traffic states detail by network location and time of the day. The traffic load from travel demand models could also be related to road capacity and linked to traffic states. However, depending on the aggregation level of the model, information on temporal variations might be missing.

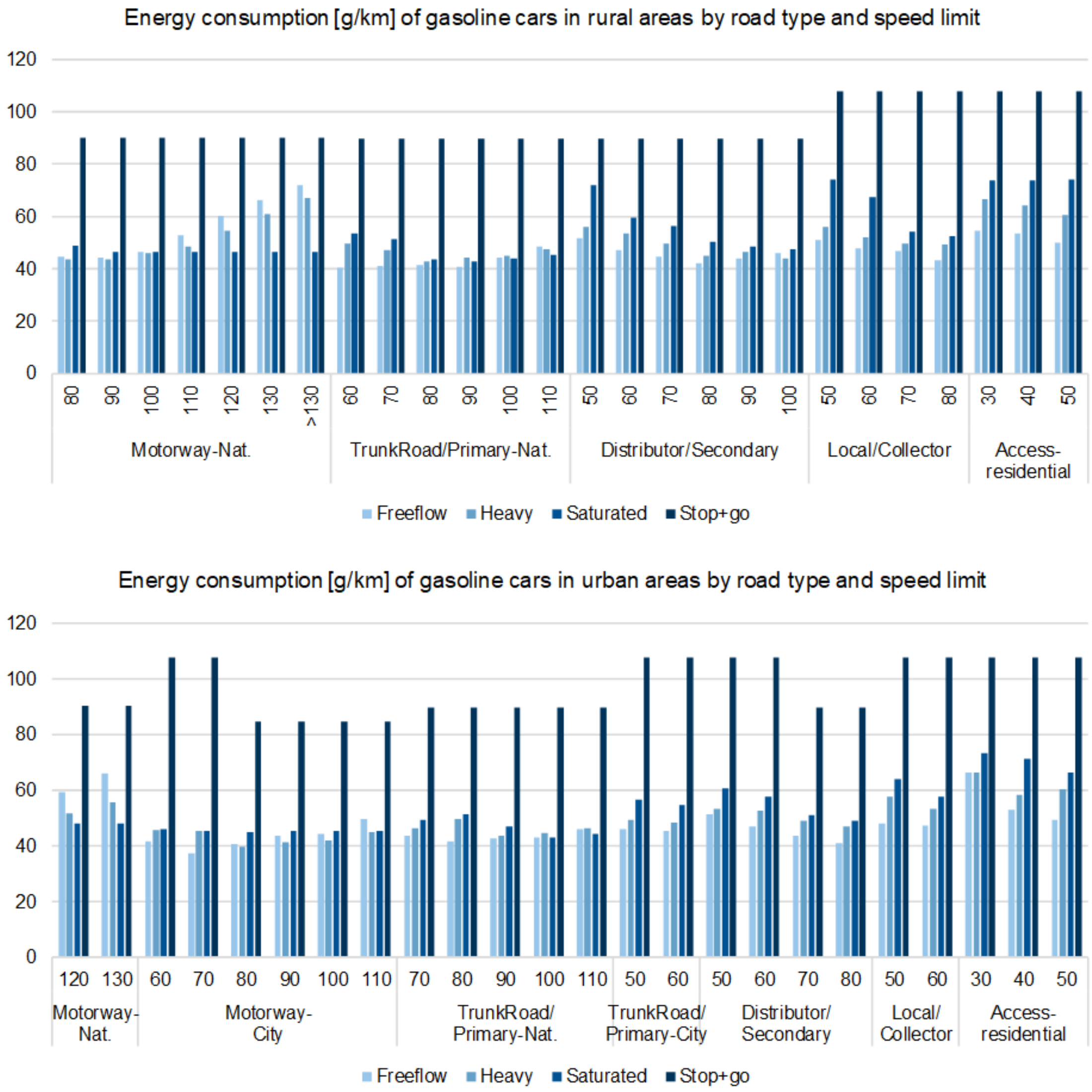


Figure 43. Variations in energy consumption of gasoline cars by traffic state. Source: Own illustration based on data from HBEFA (INFRAS, 2017).

Regarding public transport, traffic state is typically not an issue for rail-based systems, but more so for road-based systems. Buses have different driving pattern than cars (frequent stops and acceleration) and energy consumption in public transport might also be significantly influenced by the load factor. It was not possible to consider these impacts due to lack of data.

The energy consumption model for electric cars was simplified compared to the model for conventional cars (Paper I). Energy consumption values for electric vehicles were not available in HBEFA 3.3, which was used in this thesis. In August 2019, INFRAS published the most recent version HBEFA 4.1, which also contains information on electric vehicles and their (expected) share of the vehicle fleet until 2050. Based on this data, the emission model for electric cars could be refined to match the detail of the emission model for conventional cars.

HBEFA does not differentiate between different driving and acceleration styles. More detailed microscopic emission models could thus improve the energy consumption model. However, extremely disaggregated emission models based on microscopic data entail a larger development effort and such detail is likely unnecessary to analyze carbon-based accessibility on the regional level.

8.2.4. Emission factors: more than a triviality

Using energy consumption (in grams of diesel or gasoline per km and kWh per km) as an intermediate variable makes the model more flexible, since emissions are directly related to energy consumption and any given emission factor can easily be exchanged for another. The specific emission type (e.g. pure CO_2, CO_{2e} or other consumption-dependent pollutants such as NO_X) and the extent to which upstream processes are included (e.g. tank-to-wheels or well-to-wheels) can be adapted or updated without having to reassign these values based on the different link attributes. Well-to-wheels emission factors, which are widely used in policy making to assess emissions and emission savings (Moro and Lonza, 2018), were applied to the analyses in this thesis. A well-to-wheels approach makes it possible to compare electric vehicles and combustion engine vehicles, which is not possible when using a tank-to-wheels approach (since no emissions are generated during the actual operation of electric vehicles).

The electricity generation mix is the main determining factor in making electric vehicles a low carbon transport mode. Paper I shows that electric cars could even compete with public transport in rural areas. An increasing number of electric vehicles, fueled by carbon efficient electricity, will change the average emission factor of the car fleet. However, it should be noted that an electric car produces more GHG emissions during the manufacturing process than a conventional car, mainly because of the battery (see Figure 44).

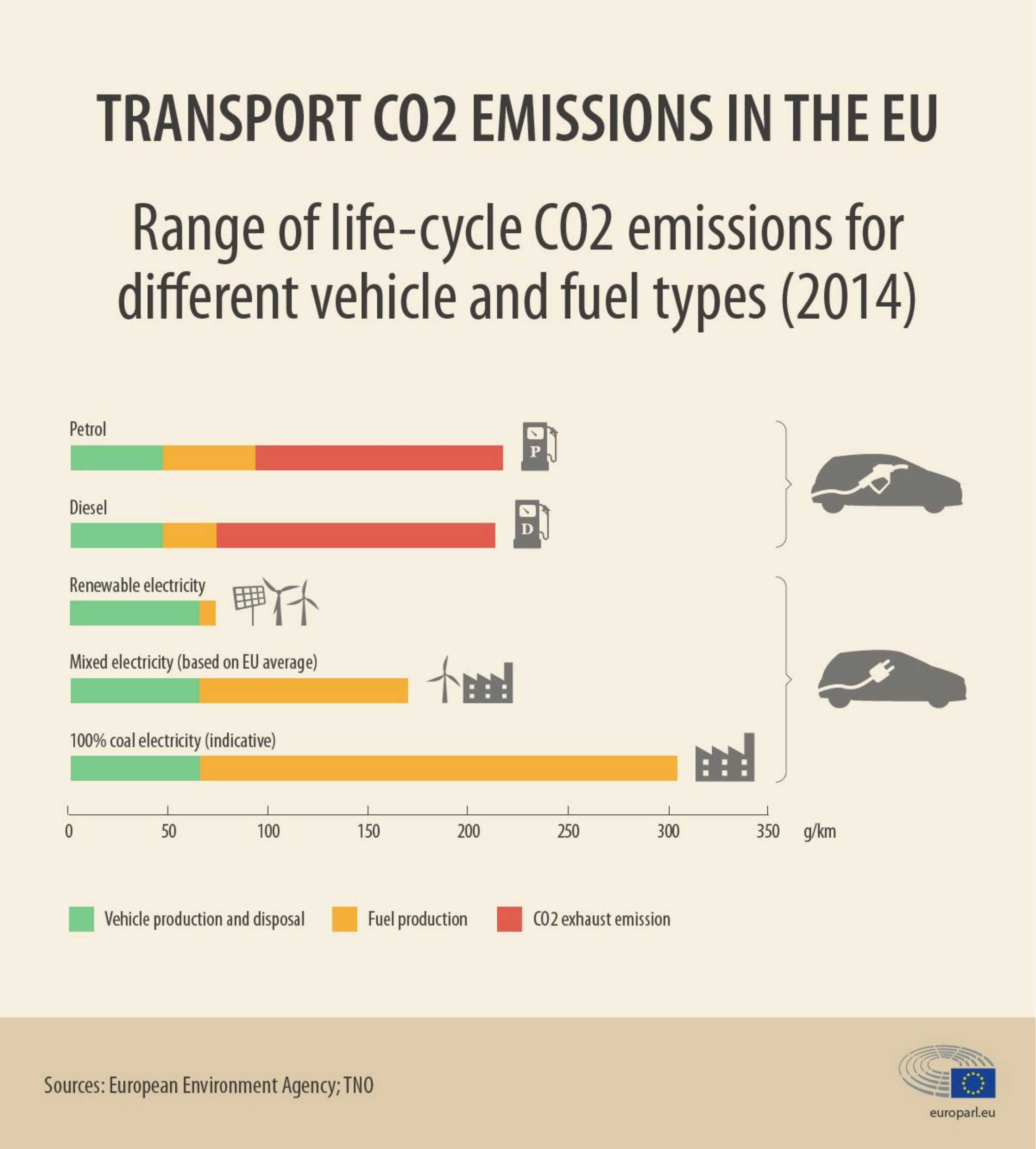


Figure 44. Life-cycle CO_2 emissions of conventional and electric vehicles. Source: European Parliament (2019).

Emissions generated during vehicle production and disposal could theoretically be included in the model by breaking the total lifecycle emission costs down to a per-kilometer level. However, this approach would demand even more assumptions, such as the expected mileage of a vehicle during its lifetime. A full life cycle assessment, considering not only the use phase, but also the production and disposal phases, would make carbon-based accessibility analysis more complex and data intensive. Nevertheless, life cycle analysis (which could also be detached from carbon-based accessibility analysis) needs to prove that electric vehicles are in fact more sustainable than conventional ones, not just in terms of operational environmental costs.

8.2.5. Occupancy rates: variations in space and time

Occupancy can feature large variations and turned out to play a major role for the analysis results (see Paper I). In cars, the occupancy rate typically remains the same throughout the trip. This might change with on-demand services, shared taxis or other ride pooling services, which frequently pick up and drop off passengers. Already today, occupancy rates in cars vary by trip purpose: Work trips feature low occupancy rates, whereas leisure activities typically feature high occupancy rates (UBA, 2016b). In public transport, occupancy rates vary by line, line section, and throughout the day. Public transport is generally designed for high travel loads. However, during off-peak times or at remote locations, it might have very low occupancy rates due to limited service quality and attractiveness. This undermines the assumption that public transport is by default more carbon-efficient than the car (Paper I, Paper IV).

Similar to energy consumption, occupancy rate is difficult to model in large spatial and temporal detail. Spatial variations in occupancy rates cannot be accounted for when implementing average occupancy rates in public transport. Consequently, such an approach may result in favorable assumptions for public transport in the outskirts and unfavorable assumptions within the city (Paper II). Also, average values on the national level might not necessarily be suitable for a specific local or regional context. Two alternatives can help to improve model accuracy: Firstly, more specific occupancy rates for a given territory or even line can be retrieved from transport operators if they are willing to share this data (Paper I). Secondly, occupancy rates can be deduced from a travel demand model (Paper III), which is typically calibrated based on counts and surveys. Within this thesis, a minor limitation remained regarding the PTV Visum travel demand model: The occupancy rates of lines serving the same link could only be differentiated in the case of path searches between selected origins and destinations, but not in the (more efficient) skim matrix calculation procedure. In other words, occupancy rates are not considered individually by line, but are aggregated on the link level.

8.2.6. Scenario building: infinite opportunities

It is important to select the right level of detail, but aggregation is needed in order to make the model easy to handle. The disaggregation level should be chosen based on data availability, size of the study area, and analysis purpose. Regarding spatial detail, it is acceptable to opt for a more aggregated approach. However, spatial differences, such as the variation in occupancy rates in public transport within and outside of urban areas do make a difference for the assessment of locations in terms of their carbon-based accessibility. Sound comparison of carbon-based accessibility by public transport and by car requires a sound database (Paper III). All parameters can be adapted if more recent or detailed data becomes available. Lack of accuracy due to missing data is a limitation of the analyses conducted within this research, but not of the methodology per se.

While the models of energy consumption and occupancy rates could surely be improved by incorporating higher quality data, all default values can be adapted for scenario building purposes in order to test policies or future developments. This applies for example to increases in occupancy rates through pricing in public transport or pooling initiatives for cars. Scenarios can even be based on assumptions in order to analyze what-if-situations. Based on more detailed data or realistic assumptions, a comparison between car and public transport at different times of the day would be an interesting perspective for further investigation. Public transport is expected to perform better during peak hours due to high occupancy rates, whereas the car is expected to perform worse due to congestion. Furthermore, diesel buses can be substituted by electric buses or any other type of public transport system (trolley bus, on-demand services) to highlight the impacts of this type of investment on carbon-based accessibility levels (Paper I). Such scenarios could help to analyze the effectiveness of electrifying either public transport systems or the private vehicle fleet. To summarized, carbon-based accessibility analysis offers various opportunities for scenario building, even beyond these examples and beyond the applications done within this thesis.

8.2.7. Summary: Operationalization

Different environments can be used for the development of a carbon-based accessibility instrument. An existing travel demand model comes with essential data, such as network topology and traffic loads. But also building a model from scratch, e.g. within a GIS environment, is possible and facilitated by the increasing availability of open source data. CO_2 emissions are influenced by multiple parameters and feature large variations, depending on the specific context. The chosen values play an important role for the outcome of the analysis. Tool developers need to select an appropriate level of detail based on data availability and purpose of the analysis. Figure 45 presents the influencing factors and three main parameters for the emission models within this thesis: energy consumption, emission factors, and occupancy rates. Energy consumption of cars by traffic state and occupancy rates in public transport turned out to be key influencing factors, which are difficult to model due to the required amount and detail of data. However, carbon-based accessibility instruments enable the generation and analysis of various scenarios by freely changing the underlying parameters.

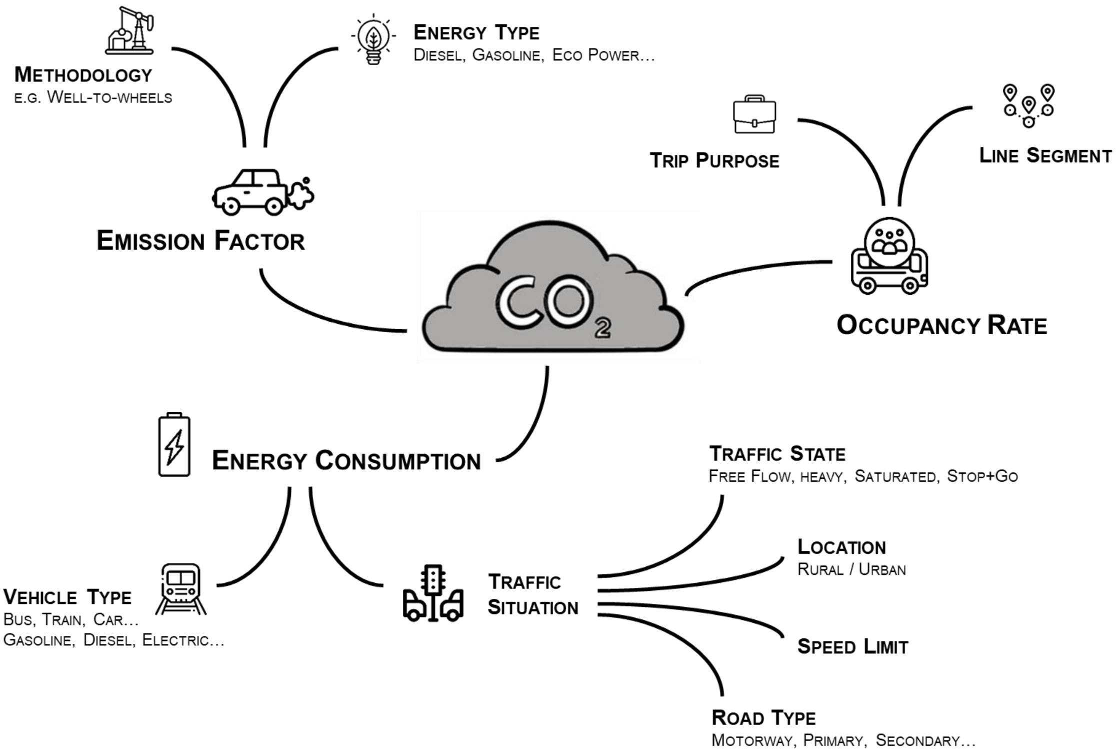


Figure 45. Parameters influencing the CO_2 emission model within this thesis.

8.3. RQ3: Theoretical basis

Like any other decision-making tool, carbon-based accessibility instruments should have a sound theoretical foundation. Potential shortcomings do not necessarily make the tool useless, but must be made transparent. The fact that carbon-based accessibility analysis is conceptually different from existing understandings of accessibility requires more detailed investigation. Implications in terms of operationalization and low carbon mobility behavior are discussed in this section.

8.3.1. Aligning individual and societal needs

Traditionally, accessibility is conceptualized in line with the user perspective, as emphasized by Handy and Niemeier (1997, p. 1176):

> *"…an accessibility measure is only appropriate as a performance measure if it is consistent with how residents perceive and evaluate their community. In other words, a practical definition of accessibility must come from the residents themselves, rather than from researchers, and reflect those elements that matter most to residents."*

Viewing accessibility from the user perspective clearly has an impact on how to operationalize the concept. In this case, the definition of acceptable travel costs has to be in line with the travelers' perceptions and values. In another much cited paper, Geurs and Van Wee (2004, p. 130) state the following:

> *"…an accessibility measure should firstly be sensitive to changes in the transport system, i.e. the ease or disutility for an individual to cover the distance between an origin and a destination with a specific transport mode, including the amount of time, costs and effort."*

Carbon-based accessibility accounts for a shift in perspectives from the user perspective to the environmental perspective, which is radically different from traditional implementations of accessibility (compare Paper III). Internal user costs, affecting individuals or groups of individuals, are replaced with external environmental costs, borne by the society in general. A key question emerging from this shift in perspectives is where to position carbon-based accessibility within existing understandings of the accessibility concept (see section 2.2.1).

Using CO_2 emissions as travel costs directly acts on the transport component of accessibility. More specifically, the environmental perspective determines how the transport system is measured and evaluated. Emission budgets limit travel distances and/or the choice of transport modes, which in turn might limit the opportunities available. The environmental perspective thus interacts with the two basic dimensions of accessibility: the land use and transport components.

Emission budgets have similarities with the temporal component of accessibility. A limited amount of time is available for activities. Likewise, a limited amount of emissions is accepted for completing activity chains. Thus, emissions could represent an additional accessibility constraint in the form of an authority constraint, which is imposed on individuals by external powers (Hägerstrand, 1970). In theory, emission budgets should be the same for each individual, but in reality, emission budgets will most likely be introduced in the form of emission pricing. Monetary constraints could be attributed to the individual component of accessibility (Büttner, 2017). If emission budgets can be reassigned from one person to another, accessibility levels would differ by person groups, since some people might be able to afford more emissions than others. Consequently, carbon-based accessibility could also be a social indicator, since people require access to opportunities at affordable costs. Providing for low carbon mobility options is thus both an environmental and a social challenge.

To conclude, the environmental perspective, which is present in carbon-based accessibility, is related to the four components of accessibility in different ways. However, it could best be understood as an additional component that views the travel costs contained in the transport component from an environmental perspective, thus imposing emission constraints on accessibility. Figure 46 highlights this position within the conceptualization of accessibility according to Geurs and Van Wee (2004).

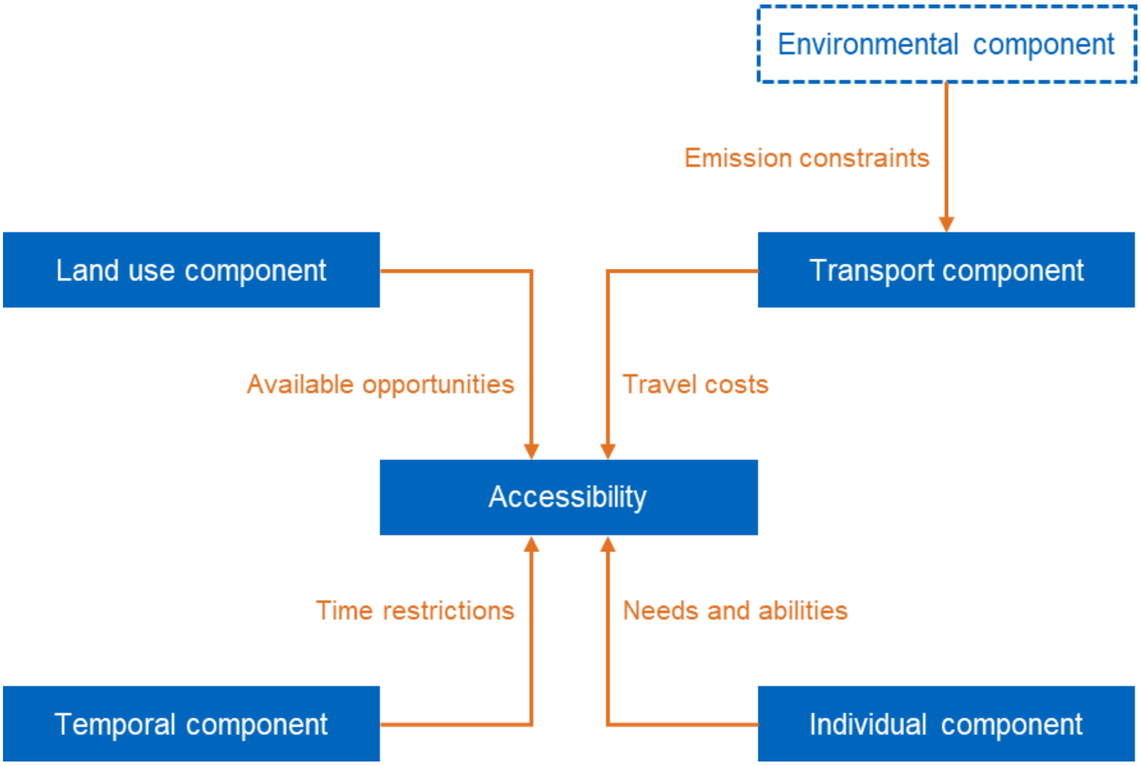


Figure 46. The environmental perspective in the conceptualization of accessibility. Source: Own illustration based on Geurs and Van Wee (2004).

The user perspective and the environmental perspective on accessibility are not necessarily contradicting. Instead, they could (and should) be considered as being supplementary. For example, while environmental concerns could be an additional layer determining the precise way of measuring the transport component, the individual component might still play a role in terms of the opportunities to consider. Time and emission constraints might superimpose to limit people's accessibility and require a compromise in terms of low emission costs and low travel time costs. The car is typically fast, but has high emissions. Non-motorized modes have low emissions, but are slower. By integrating land use and transport, accessibility planning in general and carbon-based accessibility planning in particular are suitable approaches to combine the needs of individuals and the needs of the commons.

8.3.2. Emission constraints: normative accessibility implementations

Carbon-based accessibility analysis provides a way to internalize external costs by linking CO_2 emissions to the accessibility of individual travelers. Based on the experiences gained during the applications within this research, a cumulative opportunities measure using emission budgets represents the most convenient approach for this type of normative implementation of accessibility. Cumulative opportunities enable striking visualizations of carbon catchments, but require a reasonable cutoff value. Emission budgets can be defined based on either a top-down or bottom-up approach. In the first case, total GHG emissions on an aggregated level are broken down to the level of a single trip. This aggregated level could refer to the total emissions of an entire country (Paper I) or one person (Paper II). In the second case, GHG emissions of a single trip are directly estimated based on average trip lengths and emission factors (Paper III). Both approaches can be used to define current emission budgets based on actual travel behavior and future emission budgets based on emission reduction targets (Paper II, Paper III). It should be noted that when using a bottom-up approach, the threshold value refers to a specific trip by a specific travel mode. Thus, it represents a reasonable emission threshold, but not necessarily the allowed emission budget per capita.

The following factors should be taken into consideration when determining an emission budget for carbon-based accessibility analysis:

- *The share of countries:* Climate change is a global issue. Both per-capita emissions and emission reduction targets vary around the globe, which clearly influences the budget implemented in a specific context. In theory, some countries could even increase their GHG emissions if other countries decrease their GHG emissions by a larger magnitude.

- *The share of (groups of) individuals:* Different people have different carbon footprints, depending on lifestyles and sociodemographic conditions (Brand et al., 2013). In principle, emission budgets should be valid for everyone, which reduces the importance of the individual component of accessibility. At the same time, it is logical that emission budgets could (or should) be redistributed among different groups of people (section 8.3.1). For example, workers might require an emission budget that is larger than the average budget, while children might produce less emissions than an average person.

- *The share of transport:* Emission inventories and emission reduction targets are typically defined on a national level and other sectors besides transportation contribute their shares (section 1.1). Consequently, the specific contribution of the transport sector should be taken into consideration. For example, the German emission reduction target for 2030 is -55 %, but the expected contribution of the transport sector is a relative reduction of -40 % (BMU, 2016).

- *The share of transport modes:* The transport sector includes both passenger and freight transport, both motorized and non-motorized, on land, water, and in the air. All of these categories have different shares of overall emissions and need to contribute to emission savings to a different extent. However, budget shifts between modes could be considered: People who are car dependent could increase their emission budget if other people who are able to rely on non-motorized modes do not fully exploit their budget.

- *The share of trip purposes:* Per-person emission budgets could easily be broken down to the trip level, assuming an average of three trips per day (Follmer and Gruschwitz, 2019). However, not all trips are the same: grocery shopping might be possible within the immediate vicinity, while the workplace location is typically located further away, thus requiring motorized travel. Also, CO_2 emissions should be considered separately for daily and long-distance trips (Reichert et al., 2016). Thus, different emission budgets could be assigned by trip purpose.

Clearly, the variations in these parameters can be large and they influence the emission budget used in a specific context. The budgets chosen in this work varied between 250 grams and 3,000 grams of CO_{2e}. Depending on the purpose of the analysis, average emissions can be used or more specific, individual budgets can be defined. The opportunities for emission budget scenarios are unlimited and the value can be changed in function of any given low carbon policy.

While the application of a distinct emission budget in the form of a cumulative opportunities measure seems more logical, gravity-based approaches to measuring carbon-based accessibility are still possible. The challenge lies in defining a suitable decay function, since the sensitivity to increases in emission costs is expected to be different from the typically used travel time elasticities. Based on the assumption that more emissions are worse, a linear decay without gradual change could be a good fit. The linear function can be calibrated according to the factors defined above, where the average emission budget would receive a weight of 0.5. However, developers should carefully consider whether a gravity-based indicator is useful for a given application, since it not only makes the analysis more complex for developers and practitioners (Paper IV), but also reduces the comparability of different implementations of accessibility, for example travel-time-based and carbon-based accessibility (Paper III).

Future research could explore other options of operationalizing carbon-based accessibility. For example, combined indicators that are in line with both political objectives and individual perceptions could help to serve both environmental and social goals (Cui and Levinson, 2018; Cui and Levinson, 2019). Furthermore, CO_2 emissions could be incorporated into completely different types of accessibility indicators, including person-based or utility-based measures.

8.3.3. Low carbon mobility options versus low carbon mobility behavior

Carbon-based accessibility enables planning for low carbon mobility options, which are certainly linked to travel behavior and transport-related emissions. However, the results could also be unexpected, since parameters that are important for the user, such as comfort and quality of the transport services, are not considered. Furthermore, carbon-based accessibility focuses on emissions on an individual level instead of considering the entire mobility system. This perspective tends to cause discrepancies between the system optimum and the individual optimum. Specific examples are listed in the following.

- The fact that carbon-based accessibility is analyzed on a per-passenger level results in unequal assessment of the effects of technological improvements or occupancy increases. Changes in the public transport system collectively affect the general public, whereas electrification or pooling in private cars could easily be implemented in an individual case, but are more difficult to take hold on an appreciable scale (see Paper I).
- At the same time, investments in the energy efficiency of a public transport line might be effective in terms of carbon-based accessibility, but not effective in

terms of encouraging a shift from private cars to public transport if the service quality from the user perspective (travel time, comfort, fares) remains insufficient.

- Public transport operates independently of the individual decision to travel. While the supply is clearly linked to the number of users, there is certain inertia in the system. In other words, the total emissions remain unchanged as long as the service frequency remains unchanged, independent of whether travelers use public transport or not. For car travel, this is different, since the impact is direct: Emissions are in fact generated due to an individual decision to travel, resulting in more cars on the road and an increase in total emissions. However, this could result in a bizarre situation, where a person changing from the car to low occupancy public transport might end up with an increase in their personal carbon footprint, even though total emissions have been reduced.

- High occupancy rates result in high levels of carbon-based accessibility due to less CO_2 emissions on a per-passenger level. At the same time, this could be an indicator of low service frequency compared to the existing travel demand, resulting in reduced comfort and low attractiveness, which might encourage people to choose a car. If low emission travel is enabled through high occupancy, carbon-based accessibility analysis suggests development at locations where demand is already high. This in turn exacerbates overcrowding, which reduces the attractiveness of public transport even further (Li and Hensher, 2011). Consequently, the capacity of the transport system must be considered in urban development decisions as well.

- At the same time, locations which perform worse in terms of carbon-based accessibility due to low occupancy rates in public transport might generate new demand if urban development takes place, which increases occupancy rates (in case of an appropriate quality of public transport supply). This might in fact be positive, since the existing system is used more efficiently, while total emissions remain the same.

- Increased frequencies in public transport are actually an improvement from a user perspective, but initially result in lower occupancy rates, since the rise in passenger numbers will be more gradual. In the long run, higher frequencies are likely to lead to an uptake of public transport ridership and a mode shift away from the car due to more flexibility, reliability, and an overall increased attractiveness. This effect could be reflected in a travel demand model or assumed in scenarios and again feed into carbon-based accessibility analysis. In any case, expected increases in passenger numbers might not be proportional to the increases in service frequency, resulting in reduced carbon-based accessibility with such service improvements. Emission savings due to less cars on the road are not included in the equation, but clearly contribute to an overall reduction in transport-related emissions.

8.3.4. Does carbon-based accessibility matter?

One could assume that, if provided with low carbon mobility options, people will resort to low carbon mobility behavior by reducing trip lengths or minimizing car travel in favor of other transport modes. However, as illustrated in section 8.3.3, low carbon mobility options cannot be equated with low carbon mobility behavior, since travelers' decisions are complex and influenced by multiple factors. The concepts of stable travel time budgets (Zahavi, 1974; Marchetti, 1994) and excess travel (Salomon and Mokhtarian, 1998) suggest that people do not aim for minimum travel costs, but maximum access to opportunities within a fixed travel cost budget. In their well-known study, Newman and Kenworthy (1989) found a negative correlation between residential urban density and energy consumption per capita. However, this has been challenged by other researchers, who claim that the relation is in fact mediated by fuel prices (Wegener, 1996; Monzón and Nuijten, 2006). Mobility behavior and transport energy consumption are largely dependent on internal travel cost budgets. Transport-related emissions are external costs and therefore do not have a comparable influence on mobility behavior. The long-term impacts of GHG emissions have to be paid for by society, not the individual traveler. While associated taxes might be included in fuel prices, they are barely perceptible. Conflicts regarding sustainability aims occur if the travel patterns produced by the desire to maximize opportunities within the acceptable limits of the individual result in negative externalities which are beyond the acceptable limits of the environment and society. The potential discrepancies between internal costs (e.g. travel time) and external costs (e.g. emissions) are illustrated in Paper III. People might not choose the most carbon efficient mode or might travel further than the defined emission budget.

Changes in travel patterns driven by socio-economic trends, new lifestyles, increased car ownership, and the existence of fast and affordable transport (Heinen and Mattioli, 2019; Stead, 1999; Kwon, 2005; Holz-Rau and Scheiner, 2019; Wegener, 1996; Reichert et al., 2016; Van Wee et al., 2006) could easily counteract efforts to provide for low carbon mobility options (Wegener, 1996; Greene and Wegener, 1997). Consequently, under the current emission costs of transport, improvements in carbon-based accessibility might not have the desired effects unless the internal costs – be it time, money or comfort

– of carbon intensive mobility are increased and/or the internal costs of low carbon mobility are decreased (Poudenx, 2008). As previously discussed, there are hopes for technological innovation to decarbonize transport to an extent where individual and societal travel cost budgets would be aligned (section 2.1.2). However, unconstrained travel could negatively impact urban patterns and such development could reinforce long distance travel and car dependence (for corresponding feedback loops see Wegener and Fürst, 1999; Litman, 2019). Without integrated land use and transport planning to actively counteract such development, the long-term result will be a diminishment of the mobility options with the lowest carbon footprint. On the contrary, carbon pricing could incentivize compact urban development.

These dynamics imply that the required action towards low carbon mobility needs to be two-fold: (1) provide low carbon mobility options and (2) shape travel demand to make best use of these options. Regarding the first aspect, it is important to acknowledge that carbon-based accessibility alone is not sufficient to realize low carbon mobility behavior, but is certainly a key prerequisite for emission reductions. Thus, technological innovation and integrated land use and transport planning should join forces to both create low carbon mobility options and counteract losses in low carbon mobility options due to sprawled development. The method of carbon-based accessibility planning, as introduced in this thesis, has the potential to contribute to these planning goals in a valuable way.

The second aspect is essential to make carbon-based accessibility planning effective. CO_2 emissions have a growing impact on individual travel decisions due to an increasing awareness of individual responsibilities regarding climate change mitigation (see for example the discussion on flight shame: Timperley, 2019). Still, complementary travel demand measures and a suitable policy framework, including restraints and promotions, are necessary to change mobility behavior (Vale, 2013; Greene and Wegener, 1997). Pricing strategies, regulated on national and supranational levels, are seen as an important lever to reduce transport-related emissions by encouraging behavioral change and accelerating the development of clean technologies (Holz-Rau and Scheiner, 2019; Santos, 2017). For example, the EU emissions trading system applies caps on GHG emissions from power plants, industrial plants, and the aviation sector, thus creating a market for emission allowances (EC, 2015).

Also individuals will eventually be more affected by emission pricing, resulting in spatial constraints in terms of opportunity choices and restrictions in terms of transport mode choice. If mobility becomes more expensive, decisions related to long-term and short-term mobility behavior will increasingly depend on basic needs and constraints rather than preferences and lifestyles (Wegener, 2011). The magnitude of this effect clearly depends on the price. Using again the example of Germany's Climate Action Program (compare section 2.1.2), the price to be paid by fuel and energy providers per ton of CO_2 is 25 Euros, starting in 2021, and will rise to 55 Euros per ton by 2025 (Die Bundesregierung, 2019). The originally intended starting price of 10 Euros per ton, which would have corresponded to additional costs of 3 instead of 8 Cents per liter of gasoline, was criticized by economists, environmental organizations, and politicians as being too low to have an impact (Stratmann and Greive, 2019). Germany aims to minimize the financial burden on individual citizens through reimbursements, for example by increasing the commuter allowance. However, it could be argued that the best approach to maximize environmental gains and at the same time minimize social harm with the introduction of emission budgeting and pricing is to provide for low carbon mobility options.

To summarize, all fields of action are mutually dependent on each other. Low carbon mobility options are not effective without the internalization of emission costs. Pricing strategies are not socially viable if people do not have any low carbon mobility options. Technological innovation cannot fully deploy its potential if sprawled urban development counteracts efficiency gains. Even if other fields of action can be seen as more important for the specific aim of climate change mitigation, the integration of land use and transport via accessibility planning (both carbon-based and traditional accessibility planning) should in any case be a top priority due to its co-benefits, including social health, equity, and livability (Holz-Rau and Scheiner, 2019).

8.3.5. Summary: Theoretical basis

The conceptualization of carbon-based accessibility employs an unusual viewpoint: travel costs are seen from an environmental perspective instead of a user perspective. Carbon-based accessibility differs from traditional approaches in this regard and has less clear links to travel behavior theory. However, it also enables normative implementations of accessibility based on maximum allowed emission budgets. While the method can be used to plan for low carbon mobility options, these are not equivalent to low carbon mobility behavior. CO_2 emissions are not (yet) a major determinant of people's travel decisions and acceptable travel costs from an individual perspective are larger than acceptable emissions from a collective perspective. This emphasizes the importance of accompanying measures, such as pricing strategies, which ensure that travel demand, determined by internal travel costs, matches the boundaries set by the associated external travel costs.

8.4. RQ4: Practical relevance

This section focuses not so much on solutions for low carbon mobility planning (the key levers are already known) or their concrete implications in a specific spatial context (the analysis results are not necessarily generalizable), but rather on the application potential and added value of carbon-based accessibility instruments for this purpose. The practical relevance of carbon-based accessibility planning is discussed based on the findings of the applications in the Munich region. Identification and assessment of intervention options in a different spatial context require a transfer of the method.

8.4.1. Application potential of carbon-based accessibility analysis

The experiential and planning practice applications point out potential decision-making purposes for which carbon-based accessibility analysis could be useful. The list of potential applications goes beyond the applications done within this research, since additional application purposes, which have not been tested, were identified during the research. It should be noted that the listed application purposes do not necessarily have to be addressed individually, but could also be addressed simultaneously and in an integrated way.

Identify and prioritize urban development options or intervention needs

Accessibility instruments are capable of analyzing the current situation and thus inspire the generation of strategies. Carbon-based accessibility instruments in particular can compare accessibility levels across different urban structures, based on different emission budgets and for different (motorized) transport modes to identify options or needs for intervention. The method can be used to compare public transport and private car in terms of their ability to provide for low carbon mobility options in a specific spatial context. Contrary to the general assumption, public transport is not by default more carbon-efficient than the car (Paper I, Paper III, Paper IV). Clearly, this result does not suggest that public transport should be abolished in low demand areas, but might initiate efforts to substitute non-ecological diesel buses by smaller, electrified, and/or on-demand alternatives. Furthermore, carbon-based accessibility analysis supports land use planning by highlighting differences according to spatial typologies (Paper II). Applying the analysis to multiple locations instead of single locations helps to identify areas where low carbon mobility options need to be ensured by appropriate land use and/or transport policies or to suggest development areas where low carbon mobility options are already available (Paper III, Paper IV).

A major strength of carbon-based accessibility analysis is the ability to show the spatial impacts of emission budgets and emission reduction targets. Visualizations of emission catchments deliver particularly striking impressions, since the catchment area shrinks with the introduction of emission reduction targets (Paper II). Carbon-based accessibility instruments thus make it possible to analyze the vulnerability of locations in terms of accessibility losses (Paper III). Depending on the specific land use and transport conditions, changes in accessibility can be disproportional to changes in emission budgets. For example, reducing the emission budget by 50 % could reduce accessibility by 80 % (Paper I) and limiting the emission budget to one quarter of the original value could cause accessibility to plummet to 1/30 of the original level (Paper II). This kind of analysis can support political decision-makers in identifying locations where strict enforcement of emission reduction targets would drastically reduce accessibility, which demands an increased focus on compact urban development oriented towards a low carbon transport system.

Assess the impacts of potential interventions

A second key area of application in the assessment of the accessibility impacts of various different scenarios due to interventions in the land use and/or transport system. For example, land use policies targeting increases in density and diversity could be assessed in terms of their impacts on carbon-based accessibility, also with respect to how well they are integrated with the existing public transport system.

Furthermore, the method can be used to assess the impact on accessibility of transport interventions aiming to reduce transport-related emissions, such as efficiency increases or increases in occupancy rates. Electrification of bus lines might be more worthwhile than initiatives targeting the electrification of private cars, given that sufficient occupancy rates can be achieved (Paper I). Also the benefits of electrified, on-demand services in rural areas (as suggested above), could be assessed with carbon-based accessibility analysis. Occupancy increases in both public and private transport have a positive impact on carbon-based accessibility, but require appropriate incentives and pricing strategies. As discussed in section 8.1, carbon-based accessibility analysis is incapable of modeling changes in travel behavior and associated changes in occupancy rates. Input parameters for calculating carbon-based accessibility can be based on travel demand models or assumptions, but could also be determined in line with the desired accessibility outcome. Once the required increase in occupancy rates is known, planners could search for appropriate measures, addressing price or comfort, to achieve this change.

Carbon-based accessibility analysis can also show the impacts of transport infrastructure investments and assess their contribution towards enhancing low carbon mobility options (Paper IV). Giving a larger weight to environmental objectives would clearly lead to decisions where more environment friendly investments are favored over less environment friendly investments. However, other sustainability goals should not be neglected, which is why carbon-based accessibility analysis should be applied in combination with other decision-making tools and methods (see section 8.4.3).

Support policies in the context of carbon pricing and budgeting

Carbon-based accessibility analysis makes it possible to link emission pricing and budgeting to a specific spatial and/or individual context (Paper III). Carbon pricing is expected to play an increasing role in the future, also affecting individual mobility decisions (section 8.3.4). Carbon-based accessibility instruments could highlight the number of accessible opportunities within a given emission budget or price on an individual level, thus addressing questions of transport equity and affordability. Also location choices of firms could be included in emission pricing, by raising taxes according to carbon-based accessibility levels.

Communication and awareness raising

Accessibility instruments are widely recognized for their ability to enhance communication between various stakeholders (section 2.2.2). Within this thesis, it was not possible to explore the communicative skills of carbon-based accessibility instruments in great detail. Nevertheless, based on the input of practitioners, it was possible to determine the application potential of these tools in this regard (Paper IV). Carbon-based accessibility analysis makes emission impacts tangible for non-expert decision-makers. The scenario building capabilities might help to convince politicians to support investments in low carbon mobility options (Paper IV).

Integrated land use and transport planning takes place on local and regional levels (section 2.1.2), while decisions on national and supranational levels have an impact on low carbon mobility planning as well (e.g. definition of emission reduction targets, introduction of emission prices or taxes, and aims regarding the electricity generation mix). Carbon-based accessibility analysis translates these impacts to local contexts, enabling local authorities to consider them in their planning decisions. Spatialization and visualization help to understand how all levels of decision-making are interconnected. For example, electric mobility seems to be a perfect solution on the local scale, but the benefits are limited if the electricity generation mix is not improved on the national scale (Paper I).

Not only the decisions of politicians and planners can be supported by carbon-based accessibility instruments – also individual decisions could be informed by such a tool. Simple, easily understandable maps can be effective in creating awareness among citizens (section 2.2.2), also regarding the emission impacts of short-term (e.g. mode choice) and long-term (e.g. location choice) mobility behavior. The tool can highlight the consequences of location choices or relocations, of not only households, but also of major traffic generators, such as firms, leisure activities, and other points of interest (Paper II). Knowledge about negative impacts can prevent poor decision-making. This is particularly important for location choices, because land use changes are long-term and poor location choices can barely be mitigated. Carbon-based accessibility instruments share this capability with residential location choice tools (section 8.1). Finally, a key advantage of the accessibility approach is the ability to support communication across disciplinary boundaries (section 2.2.2), in particular between land use and transport planners. This is central to the integration of land use and transport, which in turn is central for the provision of low carbon mobility options (section 2.1.2).

Table 16 presents an overview of potential use cases of carbon-based accessibility instruments.

Table 16. Overview of the application potential of carbon-based accessibility instruments.

Application purposes
Identification
Identify options or needs for interventions in the land use system
Identify options or needs for interventions in the transport system
Identify the spatial impacts of emission budgets and emission reduction targets
Assessment
Assess the impacts of interventions in the land use system on carbon-based accessibility
Assess the impacts of interventions in the transport system on carbon-based accessibility
Pricing
Connect carbon pricing strategies to individual impacts via carbon-based accessibility
Connect land taxes to potential emission impacts via carbon-based accessibility
Communication
Enhance interdisciplinary communication between planners from different domains
Enhance communication with political decision-makers to promote solutions
Enhance communication with private decision-makers (citizens and firms) to influence location choice and mobility behavior

8.4.2. The practitioners’ perspective

While section 8.1 has underlined the distinctive characteristics of carbon-based accessibility instruments compared to existing tools and methods, the potential usefulness needs to be verified by reflecting on carbon-based accessibility instruments from the practitioners’ perspective.

…on focusing on emission impacts

Prioritization of political objectives is clearly shifting and new goals are being formulated. Solutions contributing to emission reductions are gaining importance compared to travel time savings and economic concerns (section 2.1.1). However, the prominent role of climate change in the global discourse does not necessarily reflect on all decision-making levels. Practitioners in the Munich region confirmed the importance of reducing transport-related emissions, but specific processes or target values on local and regional levels are missing. Emission reductions turned out to be more relevant for transport planning than land use planning, due to an allegedly more direct relation to transport-related emissions: Transport planners from the county of Fürstenfeldbruck viewed emission reductions as a main objective, whereas the land use planner from the municipality of Haar confirmed that emissions are not a particular focus of assessment when generating land use strategies (Paper IV). In order to enhance climate change mitigation efforts, local governments should be made accountable for their actions in this regard by having to set, monitor, and report climate targets (Price, 2020).

As discussed in section 8.1, carbon-based accessibility analysis focuses on emissions in a significantly different manner than other decision-making tools, which quantify emissions as a result of travel behavior with differing sophistication levels. Carbon-based accessibility instruments highlight the extent of available low carbon mobility options by quantifying the number of accessible opportunities based on emission costs. Within this research, accessibility analysis was used to address a variety of planning issues. However, the planning practice applications revealed the need for emission quantification to argue for the effectiveness of measures in reducing transport-related emissions, to receive funding, and to attract support for projects (Paper IV). Emission quantification, not carbon-based accessibility, is the key performance measure for low carbon policy and planning.

…on integrating land use and transport

Both the limited realization of the potential contribution of land use policies and planning to reducing transport-related emissions and the need for emission outputs as the accepted assessment indicator instead of accessibility outputs allude to a perceived limited importance of integrating land use and transport. This observation brings up the question of how to overcome the general implementation barrier of accessibility (Hull et al., 2012; Te Brömmelstroet et al., 2014; Silva and Larsson, 2018). Land use and transport planning institutions are often isolated and neither land use nor transport policies are typically evaluated by accessibility approaches (Bertolini and Silva, 2019). Measuring accessibility might thus become obsolete from the practitioners' perspective, who are not familiar with accessibility outputs. The planning practice applications verified that the already known implementation gap of accessibility still exists. Nevertheless, there was general openness towards accessibility among practitioners, mainly because they appreciate visual outputs in map format. In fact, there is hope that accessibility-based planning approaches become more widely used in the near future (Handy, 2020). Practitioners are willing to test accessibility instruments and integrate them into their everyday planning practice, but new tools need to be made more accessible (Paper IV).

Since accessibility assessment is not a formal requirement, accessibility standards are generally unavailable. The lack of accessibility standards might in turn impede the implementation of accessibility in planning practice. This applies not only to carbon-based accessibility, but also accessibility in general. Independent of whether accessibility analysis is used for testing scenarios or for evaluating specific project, there is a demand for reference values. In particular, formal accessibility requirements, indicators, and thresholds need to be established. Simple accessibility measures and instruments can be of value while accessibility is not institutionalized, because they are easy to use and understand and already provide benefits in strategic planning. In the future, more complex indicators tailored for certain planning questions and objectives could be introduced, possibly even as part of project appraisal. The lack of binding processes and instruments to address certain planning issues can act as door opener for the introduction of new tools and methods. On local and regional scales, established methods to identify and prioritize low carbon land use and transport solutions barely exist. The momentum of climate change mitigation as a main objective could in fact be used to establish accessibility in planning, with the specific theme of low carbon mobility planning.

…on addressing decision-makers

The benefits of the communicative aspects of accessibility instruments were generally confirmed in the context of low carbon land use and transport planning (Paper IV). Due to the lack of accessibility requirements and standards, carbon-based accessibility might not play a large role for assessing the impacts of interventions (yet). However, it is certainly helpful to identify intervention options in strategic planning, provide a basis for discussion, and serve as argumentation support towards politicians. In order to successfully fulfill these tasks, the outputs should be transparent and understandable. Regarding a suitable visualization, maps should be intuitive and able to speak for themselves. It is especially important for the communication with decision makers that planners are able to explain the contents of maps and the basic working behind the outputs. Consequently, simple maps and impacts, such as carbon catchment areas, are most effective and understandable (Paper II, Paper IV). The fact that simple indicators are preferable to complex ones is in line with previous findings on the practical relevance of accessibility instruments in general (section 2.2.2). Strictly speaking, the mere visualization of catchment areas is not a full-fledged accessibility analysis. Nevertheless, such maps could represent an intermediate step to make practitioners understand the workings of the calculation of an accessibility index. The communicative skills of accessibility instruments are in fact useful: Firstly, there is a need for effective communication and secondly, maps are considered highly communicative (Paper IV). At the same time, other outputs besides maps could be needed for communication. Numerical outputs in the form of emission quantification are considered important and effective, especially when using relative numbers instead of absolute numbers (for example the percentage change in emissions rather than absolute savings in tons of CO_2).

Communicating with both political decision-makers, ensuring the spatial and regulatory framework, and the general public, adapting actual mobility behavior accordingly, is perceived as crucial. In fact, communication with citizens was identified as a potential use case of carbon-based accessibility by practitioners, but was not investigated in depth. In light of the still existent implementation barrier of accessibility in planning practice, the largest application potential of carbon-based accessibility at the moment might indeed lie in adding transparency and translating abstract discussions on emissions into specific local and individual contexts.

8.4.3. Complementing existing methods and approaches

Given the increasing complexity of adding more and more features and capabilities to one tool, it seems more valuable to effectively combine multiple simpler tools and methods rather than building more complex tools. The findings so far shed light on options or even needs of using carbon-based accessibility instruments in combination with other tools and methods. In combination, existing methods and carbon-based accessibility analysis might be embedded in a comprehensive, multi-criterial, and multi-phase decision-making process. Thus, carbon-based accessibility can be a useful instrument in addition to (not instead of) existing tools and methods. A number of relevant combinations are listed in the following.

- *Traditional accessibility instruments:* Carbon-based accessibility analysis proves useful in cases where motorized transport modes dominate the trip purpose under consideration, such as the journey to work. However, short trips by non-motorized modes are particularly beneficial for emission reductions (Neves and Brand, 2019; Tight et al., 2011). Consequently, traditional accessibility measures, using time or distance as travel costs, are highly relevant for low carbon mobility planning as well, as illustrated by the mobility hub example in Fürstenfeldbruck (Paper IV). Carbon-based accessibility analysis on a regional level could be combined with traditional accessibility measures for non-motorized modes on a local level in order to plan for low carbon mobility options on multiple spatial scales. Carbon footprints of different transport modes could be visualized and compared, for example to show how the accessibility levels by motorized modes with a strict emission budget might easily be achieved by bike.

- *Qualitative methods:* Quantitative and qualitative methods might mutually complement each other within mixed-method approaches. Quantitative methods, such as accessibility analysis, provide a factual basis to supplement qualitative methods. Using accessibility analysis on a local scale could bring added value, but a qualitative approach is still needed to exploit the detailed knowledge of practitioners (Paper IV).

- *Environmental assessment methods:* Simpler, more communicative methods such as the carbon-based accessibility instrument applied within this thesis are useful to analyze intervention options during strategic planning or to help different stakeholders find common ground. However, the scope of carbon-based accessibility instruments is limited to the spatial impacts of emission constraints determined by the given land use and transport conditions. Other tools and models are needed to assess the combined effects of a larger variety of strategies, addressing taxation, regulation, technological innovation, and behavioral change, in particular on national scales where specific spatial contexts are less important (Brand et al., 2012). Higher levels of disaggregation and sophistication are required to evaluate quantified emission impacts of concrete measures and projects on local and regional scales due to changes in travel behavior.

- *Comprehensive assessment methods:* Proper decision-making requires weighting of multiple criteria and interests. Carbon-based accessibility analysis highlights the spatial impacts of emission constraints, but the desirability of an intervention cannot be conclusively determined. The method should be embedded in multi-dimensional decision-making processes, considering different options and impacts (Van Wee, 2002; Litman, 2013). Obviously, environmental concerns are not the only determinant, neither in public nor private decision-making, since social and economic objectives need to be catered for as well. Despite a change in priorities, solutions in land use and transport planning should not only serve environmental goals. Even if targeted at reductions in transport-related emissions, mitigation strategies have more wide-ranging impacts, which require a full evaluation with respect to other factors besides environmental ones, which cannot be assessed by means of carbon-based accessibility analysis. Multiple tools need to be combined in a meaningful way as to not neglect the other dimensions of sustainability. In fact, these could also be accessibility-based, such as the full cost accessibility assessment proposed by Cui and Levinson (2018), integrating individual and common perspectives of accessibility.

8.4.4. Summary: Practical relevance

Carbon-based accessibility analysis can be useful for a variety of applications. These include the identification of intervention needs, the assessment of alternative land use and transport scenarios, and awareness raising. Regarding the assessment of the effectiveness of solutions, emission quantification is the key performance indicator, whereas accessibility is still facing the well-known implementation barrier. However, even if accessibility is not institutionalized in the near future, it is already useful for the generation of strategies and assessment of scenarios as well as for communication purposes throughout the planning process. The communicative capabilities of carbon-based accessibility instruments can promote the implementation of solutions and enhance the commitment of private stakeholders, such as citizens. Carbon-based accessibility could deliver valuable contributions in combination with existing methods and processes.

9. Conclusions

9.1. Reflections and recommendations

Within this research, a carbon-based accessibility instrument was developed and applied in order to explore its benefits and limitations for low carbon mobility planning. The research was developed along three criteria for low carbon mobility planning tools: focusing on emission impacts, integrating land use and transport, and addressing decision-makers. Based on the research findings, this section concludes on the extent to which carbon-based accessibility instruments comply with these criteria and the corresponding implications. The theoretical and practical advantages and disadvantages are summarized to provide a basis for further research and future applications of such tools.

Focusing on emission impacts

Carbon-based accessibility instruments expand on traditional accessibility instruments by adding a focus on emission impacts. This adaptation helps to address the particular planning and policy goal of reducing transport-related emissions. However, the need to model transport networks measuring CO_2 emissions accounts for added development effort compared to accessibility instruments that use time or distance as travel costs (section 8.2).

The output type is a main distinguishing feature compared to existing tools and methods for low carbon mobility planning (section 8.1). Carbon-based accessibility instruments use per-passenger CO_2 emissions as input to calculate accessibility levels as visual output in map format. All other identified tools calculate emissions or emission reductions as outputs, based on realized, modeled or planned travel behavior. CO_2 emissions are currently the accepted performance indicator to evaluate the effectiveness of strategies and measures in mitigating climate change (section 8.4), but carbon-based accessibility instruments are incapable of quantifying emissions on aggregate scales.

Clearly, the novel method for low carbon mobility planning proposed in this thesis entails both advantages and disadvantages compared to traditional accessibility instruments and other decision-making tools. A key strength and unique characteristic is the ability to spatialize and visualize emission impacts: Carbon-based accessibility instruments highlight the spatial impacts of CO_2 emissions or emission reduction targets, thus making them tangible in a specific local context.

Integrating land use and transport

Efforts to reduce transport-related emissions primarily target the transport system. Interventions are mainly related to technological innovation and pricing strategies. Land use policies and integrated land use and transport planning are essential to enable shorter trips and promote the use of low carbon travel modes, but do not represent the focus of action. Accordingly, decision-making tools in this context do not necessarily have a land use component. In contrast, carbon-based accessibility instruments contain both a transport component and a land use component and are sensitive to specific interventions in both systems (section 8.1). Analysis outputs are provided on the level of spatial units and help to highlight concrete options for intervention. This capability distinguishes carbon-based accessibility instruments from travel demand models, which react to land use changes, but provide outputs on the level of transport network links.

Due to inclusion of the land use component, carbon-based accessibility analysis helps to develop and assess integrated land use/transport policies to provide for low carbon mobility options. Clearly, the well-known implementation barrier and lack of institutionalization of accessibility in planning practice cannot be overcome solely by shifting the focus in accessibility analysis from internal to external travel costs. However, the increasing importance of climate objectives and the application potential of carbon-based accessibility for related planning problems could facilitate the implementation of such tools in planning practice (section 8.4).

The analytical capabilities of carbon-based accessibility instruments enable the generation of ideas, the identification of intervention options, and analysis of issues in an objective manner – capabilities, which are particularly relevant for strategic planning (section 8.4). Carbon-based accessibility instruments are also capable of assessing the impacts of interventions, but are (so far) less suitable for project appraisal. Established evaluation and funding frameworks require emission quantification rather than accessibility outputs. Furthermore, carbon-based accessibility instruments have a limited scope by focusing on the spatial impacts of emission constraints and reflecting structural changes in the land use and transport systems in addition to changes in occupancy rates and vehicle efficiency (section 8.1). Comprehensive appraisal processes require sensitivity to a larger number of parameters and nuances as well as consideration of a wider variety of objectives.

Shaping the land use and transport systems in an integrated way to create and/or maintain low carbon mobility options is a crucial prerequisite for low carbon mobility behavior (section 8.3). Clearly, this not only applies to regional mobility by motorized modes (carbon-based accessibility instruments), but also to local mobility by non-motorized modes (traditional accessibility instruments, section 8.4). The mere provision of low carbon mobility options is not sufficient, since the maximization of individual benefits is in conflict with the minimization of external costs (section 8.3). Additional measures besides integrated land use and transport planning are required to align both perspectives. These other measures, e.g. emission pricing, need to be assessed by other tools, which are capable of reflecting the impacts of behavioral change. Nevertheless, carbon-based accessibility instruments represent a reasonable compromise regarding the level of tool complexity: They are sensitive to specific interventions in both the land use and transport systems, which enhances their analytical capabilities compared to simple emission quantification tools, but cannot directly reflect the impacts of measures targeting behavioral change, which makes them easier to operationalize, use, and understand than other land use and transport modeling methods (section 8.1).

Addressing decision-makers

Carbon-based accessibility instruments counterbalance their disadvantages regarding analytical skills by outperforming other land use and transport modeling methods in terms of communicative skills (section 8.1). Communication is important throughout all phases of the planning process, from strategic planning to the actual implementation of solutions. In this context, carbon-based accessibility instruments help to translate abstract discussions into specific, local environments. This process is useful to ensure understanding and commitment among non-expert decision-makers.

During the planning practice applications, practitioners repeatedly emphasized the advantages of map-based outputs for communication and argumentation support (section 8.4). The potential added value of carbon-based accessibility instruments for political discussions and citizen engagement efforts was clearly recognized. These tools can accelerate the implementation process of solutions – not by quantitatively assessing a project, but rather by visualizing the benefits. If used as awareness raising tools, carbon-based accessibility instruments could influence the location choices and mobility behavior of citizens by making the emission impacts of decisions transparent. Thus, even though the method does not enable an assessment of mobility behavior, it might be used to influence long-term and short-term mobility choices. This capability can help to address other private decision-makers as well (e.g. firms and other traffic generating institutions), especially when carbon-based accessibility levels are linked to emission pricing and taxation (section 8.4). While carbon-based accessibility instruments clearly bring powerful communication skills to the realm of low carbon mobility planning and decision-making, the effectiveness of these capabilities needs to be verified in future research (section 9.2).

Carbon-based accessibility instruments have both strengths and weaknesses. To conclude, they are not a substitution, but a valuable addition to existing tools and methods aiming at reductions in transport-related emissions. While acknowledging that environmental objectives are only one dimension of sustainability, carbon-based accessibility instruments could strengthen climate concerns within existing decision-making processes.

9.2. Future research paths and outlook

This research provides answers to a number of questions relating to carbon-based accessibility instruments, but also identifies several paths and needs for future research. A potential agenda is outlined in this section.

Embedding carbon-based accessibility into decision-making processes

Other political objectives besides environmental ones and other solutions besides direct interventions in the land use and transport systems are relevant for real-world decision-making. Further research should go deeper into the possibilities of combining carbon-based accessibility analysis with other approaches, e.g. by considering generalized costs (Cui and Levinson, 2018). The focus should be on the question of how carbon-based accessibility analysis can – in combination with other methods – contribute to a sound planning process, which is able to deliver sustainable solutions within a wider context.

Digging deeper into practical relevance and implementation

An in-depth tool evaluation was not possible in the framework of this thesis, since practical relevance was only one aspect within a wider research focus. In future research, the functionalities of carbon-based accessibility instruments could be made available to private and public decision-makers, e.g. via an interactive online platform, to assess the usefulness and usability of the tool. The usefulness of carbon-based accessibility for raising awareness among the general public is an interesting aspect, which deserves particular attention. Interviews, focus groups, and other settings with potential tool users will help to deepen the gained insights.

Expanding on type, purpose, and mode of travel

Commercial vehicles and trucks significantly contribute to GHG emissions (section 1.1). Thus, consideration of freight transport in addition to passenger transport would be an interesting application of the method. Emission costs would not be measured per passenger-km, but per ton-km, which requires adaptation of the transport network to account for emissions of various types of freight vehicles, both road- and rail-based. Regarding the land use dimension, different points of origins and destinations would be of interest, such as ports, firms, and trading hubs. The spatial scope needs to be chosen depending on the analysis scale: freight transport can be local and regional, but also national and international. Urban freight movement could be one particular focus with the aim of assessing the benefits of small electric delivery vehicles. Furthermore, the method could be expanded to include trip purposes other than the journey to work, such as leisure trips, and travel modes beyond land travel, such as flying. Emissions can also be saved by combining different modes and using each travel mode where it performs best, which implies intermodal travel as an interesting research perspective. For example, mass transit in the core of metropolitan regions could be combined with smaller shared vehicles in the suburbs. This combination would most likely be an efficient option to maximize carbon-based accessibility.

Transferring the method

Climate change mitigation is a global challenge. Thus, carbon-based accessibility is expected to be relevant in other places as well. While the developed tool and the conducted analyses within this work refer to a local framework, the general method is transferable to any other context. Information on software and data requirements as well as points to consider can be found in section 8.2. The results of the accessibility analysis are likely different in other spatial contexts, due to differences in urban form, transport supply, fleet composition, occupancy rates and other determining factors. Malmström (2020) applied the method in a Swedish context, which highlighted how clean energy buses (biogas and electric) as well as an electricity generation mix largely based on renewables can contribute to significantly higher carbon-based accessibility levels. Further implementations in different geographical and institutional contexts would help to determine the compliance of the method with other planning issues and processes and enable a more thorough reflection on the practical relevance of carbon-based accessibility instruments.

Carbon-based accessibility instruments have the potential to support low carbon mobility planning and the importance of climate change might contribute to an uptake of such tools in practice. The intention of this thesis was to contribute to better planning outcomes, but also initiate a discussion on relevant decision-making tools and processes to combat climate change.

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Annex A: Documentation kick-off workshop

The workshop documentation was presented to all attendees in order to verify the accuracy of the content. The following text was translated from German to English by the author. Personal information and agenda items not pertaining to the focus of this thesis were omitted.

Date	May 5, 2017
Time	13:30 – 16:30
Location	MVV, Thierschstr. 2, Munich
Attendees	• County of Munich: two transport planners • County of Fürstenfeldbruck: two transport planners • County of Starnberg: transport planner • Municipality of Haar: building authority representative • LHM: planning authority representative • Municipality of Neubiberg: building authority representative • Regional planning association representative • County of Ebersberg: car sharing association representative and district administration representative • TUM: four representatives • MVV: five representatives
Agenda items	1: Introduction to the project 2: Report on project status 3: Presentation of tools 4: Collection of ideas 5: Discussion and summary

Agenda item 3: Presentation of tools

NaWo calculator for sustainable residential location choice

- MVV calculator, which provides citizens who are planning to relocate with the opportunity to compare different residential locations with regards to costs, time budget, and CO_2 emissions
- Special feature: calculation of CO_2 emissions by transport mode based on the MVV journey planner
- Within ASTUS: better communication and dissemination

Multimodal travel demand and travel time model

- Joint project of LHM, MVG, and MVV
- Comprehensive database for public and private transport
- Possibility for analysis and prognosis of transportation projects → estimation of the effects of measures

TUM Accessibility Atlas

- Continuous development and updates since 2009
- Applicable on different spatial scales (from the local level, e.g. railway station surroundings, to the level of the entire EMM)
- Important aspect: isochrones analysis → how far can one travel from an origin location within a given time, money or emission budget?

ASTUS – transnational methodology

- Adjusted basic formula to estimate the effects of measures on CO_2 emissions
- The individual parameters (occupancy rate, emission factor etc.) change depending on the assumptions/measure effects
- Interaction with the evaluation of measures for a more comprehensive analysis of the transport-related impacts of given measures

Other tools:

- CO_2 calculator of the UBA: comprehensive individual CO_2 balance + scenarios
- DB UmweltMobilCheck: comparison of travel times and CO_2 emissions for connections offered by DB
- MVV is looking for a way to display information about CO_2 emission savings within the MVV journey planner in an illustrative way (compare chocolate bars indicating calorie consumption within the bicycle journey planner → depiction in the form of air balloons could be an option)

Agenda item 4: Collection of ideas

All attendees are asked to write down their needs and wishes connected to ASTUS, in particular regarding the further development and application potential of tools. Three categories are available for this purpose (1 = citizen/passenger; 2 = administration/planning; 3 = policy):

Transport planner (county of Fürstenfeldbruck):

- 1 = modeling leisure travel → spontaneous trips due to 24-hour supply
- 2 = modeling interactions due to temporal extension of the supply → more passenger demand in regional bus services due to on-demand supply

Transport planner (county of Starnberg):

- 1 = What makes bus lines attractive? → What is a decisive factor to use public transport (frequency, journey time…?)
- 3 = What is the impact of designated bus lanes on journey time? → argumentation support for funding
- 3 = Funding orbital bus line → How to advance this project?

Transport planner (county of Fürstenfeldbruck):

- 1 = What makes transfers between different transport modes more attractive?
- 2 = How to address future residents of the county (NaWo)?
- 3 = Simplification of CBA → argumentation support
- 3 = CO_2 emission quantification with generally known comparative figures → simple representation of emission savings

Transport planner (county of Munich):

- 1 = better communication of the benefits of public transport towards citizens (e.g. NaWo calculator)
- 2 = Methodology for determining/planning the optimal tangential connection (demand assessment)
- 3 = Mediation/communication of the future aspect of CO_2 emission savings

Car sharing association representative (county of Ebersberg):

- 2 = Estimation of the CO_2 emission savings per car sharing user – validation or recalculation of the figure of 290 kg/year from previous studies (Switzerland)
- 2 = Actual reduction in vehicle mileage per car sharing user → how does travel behavior change
- Business as usual scenario needed

Building authority representative (municipality of Neubiberg):

- 1 = Development of demand-oriented (local) public transport models
- 2 = Model urban density/structure and changes in travel demand → determine the optimal density, where is densification recommended under consideration of the existing/prospective transport system?
- 3 = toolbox for climate-friendly planning → communication

Planning authority representative (LHM):

- 2= Modeling CO_2 emissions → densification versus new buildings at urban fringe locations

Building authority representative (municipality of Haar):

- 2 = CO_2 balance: densification within the existing built-up area → e.g. densification along federal road
- 3 = CO_2 balance: urban development within existing structures compared to peripheral locations

- 3 = CO_2 ranking of new, potential locations for urban development
- Furthermore, impacts of the improvement/expansion of taking bicycles onto public transport

Researcher (TUM):

- 1 = NaWo – option of a mobile app
- 2 = designing interactive tools → direct impacts and effects

Regional planning association representative:

- 2 = region-wide overview for residential locations or development sites for sustainable urban development within the existing system (accessibilities, infrastructure)
- 2 = bicycle highway network (simulation) → mode shifts (potentials) & impact on CO_2 emission savings

Agenda item 5: Discussion and summary

- Some of the needs and expectations could likely be covered by using the travel demand model (e.g. need for tangential lines, assessment of local accessibility versus express bus lines, possibly modeling leisure traffic)
- Others could be handled through market or transportation research (e.g. factors of attractiveness, what is missing from the perspective of customers, effects of car sharing on travel behavior, strengthening the combination bicycle & public transport)
- Another subject of research is improved and effective communication, which also reflects in some of the needs
- Also interesting would be a CO_2 calculator for urban planning → illustration of the effects of transit-oriented urban planning
- Many needs could also be implemented with the help of the Accessibility Atlas (e.g. highlighting options and spaces for urban development, the issue of optimal density) → similar applications were part of previous research in the county of Fürstenfeldbruck, using the Land Use and Public Transport Accessibility Index
- Also the potential of tangential connections or ring lines could be modeled in the Accessibility Atlas, just like improvements in the field of intermodal transport
- Regarding urban development, it is possible to model CO_2 catchments for planned urban areas

Annex B: Documentation strategy workshop

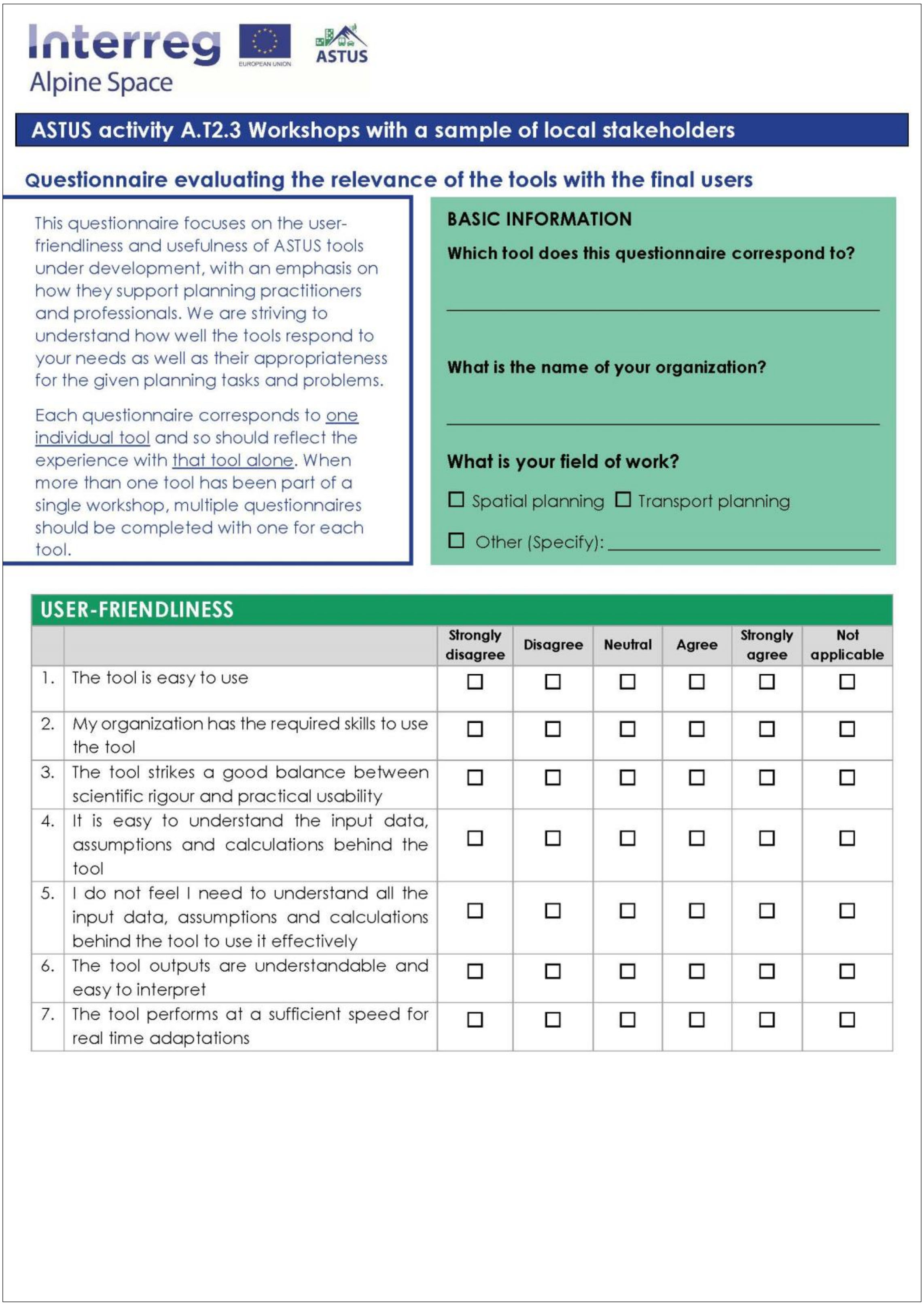
The workshop documentation was presented to all attendees in order to verify the accuracy of the content. The following text was translated from German to English by the author. Personal information and agenda items not pertaining to the focus of this thesis were omitted.

Date	November 22, 2018
Time	13:30 – 15:30
Location	LHM PlanTreff, Blumenstr. 31, Munich
Attendees	• County of Ebersberg: two car sharing association representatives and one district administration representative • County of Starnberg: transport planner • County of Fürstenfeldbruck: two transport planners • County of Munich: two transport planners • Regional planning association representative • LHM: planning authority representative • Municipality of Neubiberg: building authority representative • TUM: three representatives • MVV: two representatives
Agenda items	1: Report on project status 2a: Presentation of selected scenarios 2b: Tool evaluation 3: Development of strategies and action plans 4: Summary and outlook

Agenda item 2b: Tool evaluation

Following the presentation of the scenarios, the participants fill out an evaluation questionnaire for each tool.

The English version of the questionnaire is presented in Figure 47 *and* Figure 48*. For the performance of the tools with respect to each question see Kinigadner and Büttner (2019, pp. 75-87).*



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ASTUS activity A.T2.3 Workshops with a sample of local stakeholders

Questionnaire evaluating the relevance of the tools with the final users

This questionnaire focuses on the user-friendliness and usefulness of ASTUS tools under development, with an emphasis on how they support planning practitioners and professionals. We are striving to understand how well the tools respond to your needs as well as their appropriateness for the given planning tasks and problems.

Each questionnaire corresponds to one individual tool and so should reflect the experience with that tool alone. When more than one tool has been part of a single workshop, multiple questionnaires should be completed with one for each tool.

BASIC INFORMATION

Which tool does this questionnaire correspond to?

____

What is the name of your organization?

____

What is your field of work?

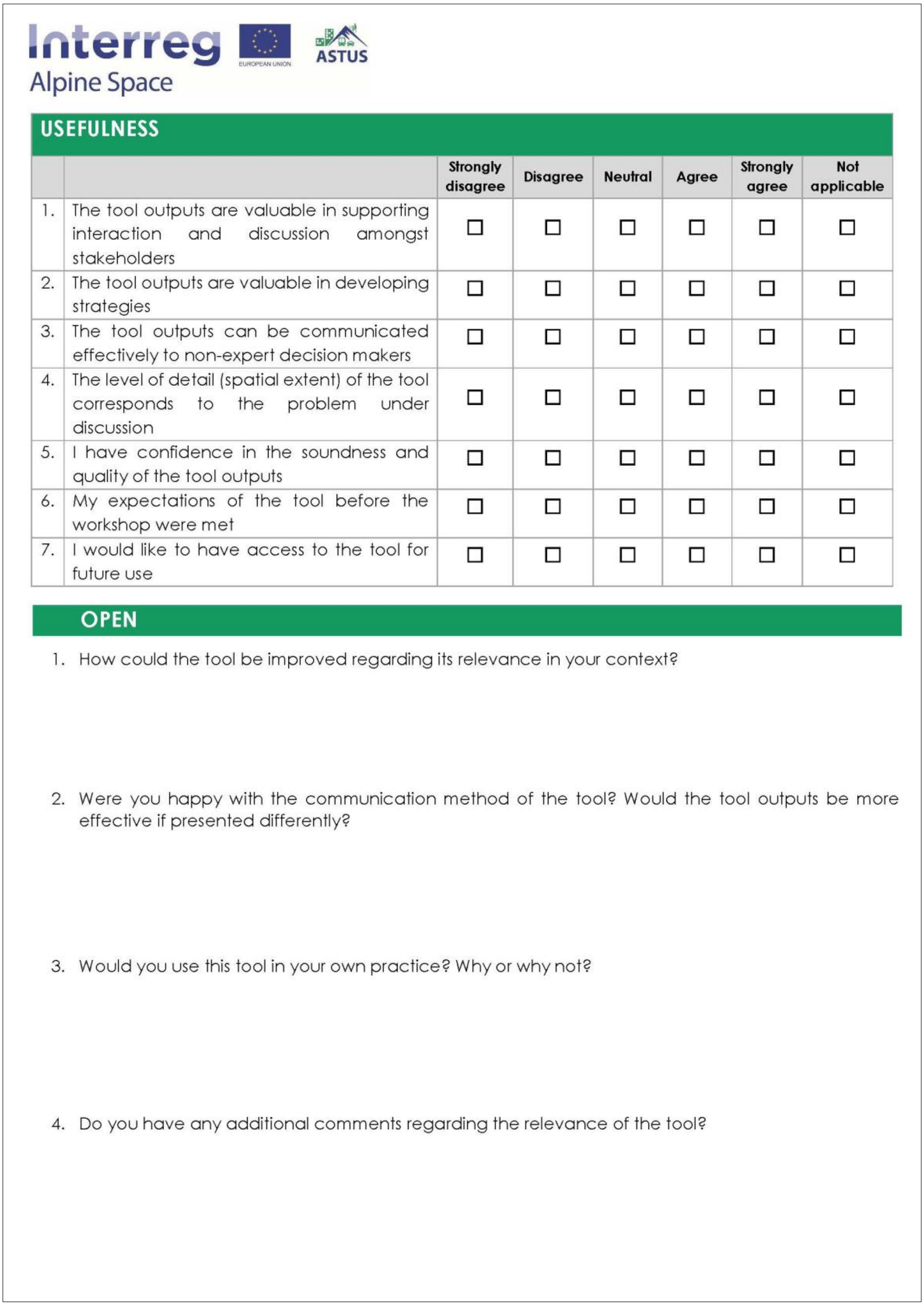
☐ Spatial planning ☐ Transport planning

☐ Other (Specify): ____________________

USER-FRIENDLINESS

		Strongly disagree	Disagree	Neutral	Agree	Strongly agree	Not applicable
1.	The tool is easy to use	☐	☐	☐	☐	☐	☐
2.	My organization has the required skills to use the tool	☐	☐	☐	☐	☐	☐
3.	The tool strikes a good balance between scientific rigour and practical usability	☐	☐	☐	☐	☐	☐
4.	It is easy to understand the input data, assumptions and calculations behind the tool	☐	☐	☐	☐	☐	☐
5.	I do not feel I need to understand all the input data, assumptions and calculations behind the tool to use it effectively	☐	☐	☐	☐	☐	☐
6.	The tool outputs are understandable and easy to interpret	☐	☐	☐	☐	☐	☐
7.	The tool performs at a sufficient speed for real time adaptations	☐	☐	☐	☐	☐	☐

Figure 47. First page of the user questionnaire.



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USEFULNESS

		Strongly disagree	Disagree	Neutral	Agree	Strongly agree	Not applicable
1.	The tool outputs are valuable in supporting interaction and discussion amongst stakeholders	☐	☐	☐	☐	☐	☐
2.	The tool outputs are valuable in developing strategies	☐	☐	☐	☐	☐	☐
3.	The tool outputs can be communicated effectively to non-expert decision makers	☐	☐	☐	☐	☐	☐
4.	The level of detail (spatial extent) of the tool corresponds to the problem under discussion	☐	☐	☐	☐	☐	☐
5.	I have confidence in the soundness and quality of the tool outputs	☐	☐	☐	☐	☐	☐
6.	My expectations of the tool before the workshop were met	☐	☐	☐	☐	☐	☐
7.	I would like to have access to the tool for future use	☐	☐	☐	☐	☐	☐

OPEN

1. How could the tool be improved regarding its relevance in your context?
2. Were you happy with the communication method of the tool? Would the tool outputs be more effective if presented differently?
3. Would you use this tool in your own practice? Why or why not?
4. Do you have any additional comments regarding the relevance of the tool?

Figure 48. Second page of the user questionnaire.

Annex C: Documentation closing workshop

The workshop documentation was presented to all attendees in order to verify the accuracy of the content. The following text was translated from German to English by the author. Personal information and agenda items not pertaining to the focus of this thesis were omitted.

Date	December 16, 2019
Time	14:00 – 16:30
Location	MVV, Thierschstr. 2, Munich
Attendees	• County of Fürstenfeldbruck: two transport planners • County of Ebersberg: car sharing association representative and district administration representative • Municipality of Neubiberg: building authority representative • Municipality of Haar: building authority representative • LHM: planning authority representative • County of Munich: transport planner • Regional planning association representative • MVV: two representatives • TUM: three representatives
Agenda items	1: Report on project status 2: Presentation of tools and analyses 3: Practical relevance of the results 4: Conclusions and outlook

Agenda item 2: Presentation of tools and analyses

TUM representatives present analyses and tools, which have been conducted or developed further since the previous meeting:

- Interactive accessibility instruments: support the identification of suitable locations for multimodal mobility hubs
- Emission quantification: CO_{2L} for mobility hubs
- Cost matrices: selected origin-destination relations
- CO_2 accessibility: visualizations in map format

Round 1: Positive aspects, negative aspects, and suggestions for improvements

In the first round, the participants are asked to document the positive and negative aspects of the four presented tools and analyses, and also propose specific improvements. Positive aspects are written on green sheets, negative aspects on red sheets, and improvements on yellow sheets.

Interactive accessibility instruments	
Positive:	• Applicable for updates of plans: concept for charging stations, rent-a-bike stations • Vivid depiction / visualization of matters: everything can be understood at a glance, easy to explain (e.g. to local councils) • Efficient location planning or densification based on points of interest is possible
Negative:	• Not clear how to access tools – additional information regarding GOAT can be found under: https://www.open-accessibility.org/
Improvements:	• Addition of car sharing (not only bike sharing) • Compare with car ownership to evaluate car sharing potential • Analysis of population and workplaces in the entire region → useful for planning cycling highways • Optimization of specific location of public transport stops • Interactions between mobility stations: compare supply and demand, take overlapping catchment areas into account, accessibility of other (neighboring) stations • Define absolute thresholds: What is the minimum for a mobility hub to be profitable? • Access to stations: Which distance is acceptable? • Place stations by mouse click and determine the CO_2 savings

CO_2 accessibility	
Positive:	• Good basis for argumentation due to comparison between public transport and private car

Cost matrices	
Positive:	- Previous experience has shown that the reactions, e.g. of district councils, are positive
Negative:	- Harder to read compared to maps, less clear accents
Improvements:	- A smaller matrix (per line, X900 among others) could improve readability

Emission quantification	
Positive:	- Although CO_2 emissions are hardly tangible and not very meaningful, emission quantification is important, e.g. when applying for funding
Negative:	- Calculations are not easily understandable
Improvements:	- Guideline to explain the workings and derivation of the data needed - Link to interactive accessibility instruments for an automated calculation of CO_2 savings

Round 2: Practical application

Based on Round 1, specific applications are being developed in Round 2 by three groups with three participants each. The groups describe how one or more of the presented tools and analyses could be used for everyday planning tasks, or in which way they need to be adjusted in order to be usable and useful for planning practice.

Group 1	
Tool/Analyses:	Interactive accessibility instruments
Use case:	Location planning for different purposes (e.g. retail locations, bus stops)
Added value:	Providing the foundations (e.g. points of interest)

Group 1	
Further development:	Add more mobility requirements: take not only workers into account, but also visitors, leisure travel and student travel

Group 2 – first use case	
Tool/Analyses:	Interactive accessibility instruments
Use case:	Highlight potentials for cycling highways
Added value:	Automation of analyses, good data basis and visualization
Further development:	Larger analysis units on the regional scale, change in framework conditions/in the data basis due to long-term effects of the infrastructure

Group 2 – second use case	
Tool/Analyses:	CO_2 accessibility
Use case:	CO_2 budget for projects, e.g. in terms of business trips and use of paper
Added value:	Create transparency

Group 2 – third use case	
Tool/Analyses:	CO_2 accessibility
Use case:	A CO_2 budget is being determined for the population of a given municipality. This way it is possible to analyze which opportunities are accessible by the users with the existing mobility services within the given budget (e.g. when identifying new development areas). Based on this, conclusions can be drawn regarding how a) the supply and b) the user behavior needs to change in order to comply with the budget.
Added value:	Create transparency, especially regarding abstract quantities like transport-related CO_2 emissions

Group 3	
Tool/Analyses:	Interactive accessibility instruments
Use case:	Public transport planning on county level, planning of new locations, evaluation and expansion of existing services
Added value:	The instruments can serve as a basis for discussion and decision support. Planning issues are presented in an objective way, illustrated and made comparable, which is particularly important regarding conflicts of aims between county and municipalities. Thus, there exists a good basis for resolutions. Illustrative outputs can be an add-on to traditional instruments and analyses, e.g. in the form of maps. The details are typically not as relevant for political decision-makers. It is also important to win the attention of the press and the citizens (passengers).
Further development:	Guideline for explaining the workings and data sources, ensure manageability of the instruments, update/expansion of the data basis.

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