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Incorporating CO_2 emissions into accessibility analysis: development of an instrument for low carbon land use and transport planning

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Abstract

In the context of climate change and ambitious emission reduction targets, low carbon transport has risen high on the political agenda. Despite some success in reducing specific emissions, total emissions continue to increase, highlighting the need for a comprehensive, well informed decision-making process in relation to climate change mitigation. Many methods for assessing transport-related emissions do not entail a spatial dimension and cannot be used to derive specific mitigation solutions. Others are very complicated to set up, use and understand. Accessibility instruments are promising with respect to the development of strategies for integrated land use and transport planning. However, a clear link to the specific objective of reducing transport-related emissions is currently missing. This paper describes the development process of an accessibility instrument for low carbon land use and transport planning. The TUM Accessibility Atlas, an existing instrument, is adapted for this purpose. CO_2 emissions are used as a travel cost in place of travel time or monetary costs. The instrument enables an assessment of locations with respect to the spatial constraints of emission budgets, thus identifying options for changes in the land use and transport system. An exemplary application in the Munich region enables better understanding of the particularities of a carbon-based accessibility analysis compared to traditional accessibility analysis. The application also provides a first preview of the instrument's capabilities related to its potential use in planning practice. Applying this instrument to real-world planning issues could be a valuable contribution to strategic decision-making on the local to regional level.

Keywords: Accessibility; CO_2; emissions; integrated land use and transport planning; PSS

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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 greenhouse gas 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 European Union (EU) were 22 % below 1990 levels in 2015, road transportation is the only source category where emissions have not been reduced (European Environment Agency, 2017). Road transportation is the second largest key source category after public electricity and heat production, accounting for 24 % of total CO_2 emissions in the EU (European Environment Agency, 2017). Despite such concerning results, decision-makers have been hesitant to restrict transport activities, mainly due to 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 (Rode and da Cruz, 2018) and not mobility by itself.

This finding contradicts with the nature of traditional transport planning focused on promoting mobility (Ferreira et al., 2012). Facilitating movement while not improving or even degrading accessibility will likely exacerbate undesired impacts from transport activities. Accessibility subsumes both mobility and proximity (Cervero, 2005; Bertolini, 2017), thus not only reflecting the characteristics of the transport system, but also the characteristics of the land use system. The concept provides a suitable framework for integrated land use and transport planning, which can support the achievement of economic, social, and economic sustainability goals (Bertolini et al., 2005). Travel impedance in accessibility analysis is usually measured in distance, time or money costs (Handy and Niemeier, 1997). However, in light of the challenges outlined above, the environmental costs of travel are gaining relevance.

This paper introduces an accessibility-based framework for assessing the potential environmental impact of locations as a consequence of urban form, transport supply or changes to these systems. More specifically, the first objective is to develop an accessibility instrument for planning practice that is able to support the formulation of low carbon strategies. The TUM Accessibility Atlas, an existing accessibility instrument for the Munich Metropolitan Region, is adjusted for this purpose (Wulfhorst et al., 2017). CO_2 emissions are used as travel cost indicator for private car and public transport in order to account for the environmental impact of travel. The second objective is to apply the instrument in an exemplary case study. The test application serves as a basis to reflect upon potential conceptualizations and the practical relevance of carbon-based accessibility modeling.

This paper is structured as follows: First, it reviews existing methods to assess the environmental impact, in particular CO_2 emissions, related to transport activities. The second main section describes the development process of the carbon-based accessibility instrument. Section 4 presents the test application, which is followed by the discussion and conclusions in the last section of the paper.

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

2.1. Existing tools, instruments and methods for assessing the environmental impact of transport activities

Good decision-making is challenging, if not impossible, without the availability of knowledge and information. Identifying effective actions and measures for reducing transport-related emissions requires decision support. Multiple tools, instruments, and methods exist for this purpose, ranging from simple online calculators for public use to complex models for expert use. An inventory of existing tools is presented in this section, with a particular focus on their relevance for low carbon land use and transport planning on the local to regional level. This section highlights the type of tool currently missing and outlines its ideal characteristics.

Most tools, instruments, and methods enable quantification or estimation of transport-related emissions on various scales of analysis. More sophisticated tools provide built-in functionalities for comparing emissions of different alternatives. A first category of tools 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 Handbook Emission Factors for Road Transport (HBEFA) (INFRAS, 2017) or modeled on a more disaggregate scale, as in the Comprehensive Modal Emission Model (CMEM) (Barth et al., 2000). While such tools are helpful in assessing the impacts of technological innovation, ITS or ecological driving, they do not capture changes in mobility behavior on a more comprehensive level.

Another subset of emission quantification tools focuses on transport mode choice comparisons. These 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 (Deutsche Bahn, 2016; Knörr and Hüttermann, 2016) or freight trips (EcoTransIT World). Emission calculation tools are also available on analysis scales beyond single trips, focusing on the mobility patterns of individuals, households, firms or municipalities (Carbon Footprint Ltd; Umweltbundesamt). Many of these tools are implemented as an online calculator. Information on trip length, mode choice, specific vehicle emissions, and occupancy rates is needed for quantifying emissions (Becker et al., 2009). Typically, the user has to input most of this information, as the tools provide only basic default values. The main purpose of such online calculators is to enhance individual awareness and decision-making.

Calculations on the level of vehicles or households can be summarized on a larger scale based on knowledge about vehicle fleets or sociodemographic structure within a given administrative unit. The outputs are especially relevant for monitoring emission reduction targets, for example on the national level. Some tools and methods are not limited to transport-related emissions, but support greenhouse gas inventories including multiple source categories (Intergovernmental Panel on Climate Change, 2006). ECOSPEED Region is a widely used web-based solution for energy and CO_2 balancing and benchmarking across different sectors, mainly on city or municipality level. Other inventories, such as the Transport Emission Model (Knörr et al., 2016) entail a special focus on transport-related emissions. Quantitative input data from databases and surveys is key to quantify current emission levels and outline future development trends. Even though such tools could provide recommendations for political action, they do not support decision-making concerning specific interventions in the land use and transport system.

A common weakness of all tools, instruments, and methods presented so far is the lack of a spatial dimension. As a result, they are limited to transport-related decision-making and do not enable land use-related decision-making. By contrast, a specific spatial context is given in the case of location comparison and affordability tools. These tools highlight the financial costs of different residential location alternatives and are also able to estimate the carbon footprint from mobility related to these choices (Housing and Transportation Affordability Index; Wohn- & Mobilitätskostenrechner). 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 assessing multiple locations on a municipal or regional scale. However, their suitability for the purpose of low carbon land use and transport planning is limited. Even though locations can be assessed in terms of emissions based on land use and transport characteristics, the flexibility of such tools is rather low. They do not enable scenario building, so that measures changing the land use and transport conditions cannot be reflected. In addition, the focus is on residential locations only.

Modeling methods are specifically designed to assess the impacts of various land use or transport policies. Conventional transport modelling is focused on traffic generation and distribution (te Brömmelstroet et al., 2016), as well as mode choice and route choice, thus providing essential input data for emission estimation. However, it is generally not suitable for evaluating land use and transport changes due to exclusion of the land use component (Geurs and van Wee, 2004). Land use and transport interaction models have been developed in order to overcome this shortcoming. An example for how such an instrument can be applied to assess the CO_2 impacts of a number of climate change mitigation measures can be found in Hensher (2008). 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. While scientifically sound, the complexity and data requirements of such models make them a difficult fit as a decision support instrument for policy making processes. A lack of transparency and understandability for decision-makers might hinder the use of such tools. The methods that seem to be most suitable for the municipal decision-making process related to low carbon land use and transport policies might never be used in planning practice due to their high level of complexity. One common feature of most assessment methods is a calculation of CO_2 emissions as an output. This calculation requires information about travel behavior – be it intended, revealed or modelled.

2.2. The potential of accessibility instruments for low carbon land use and transport planning

None of the reviewed tools, instruments, and methods seem to be suitable to support strategic municipal of regional-decision-making processes in the context of low carbon land use and transport planning. Some of them lack a spatial dimension and are only capable of quantifying emissions based on input transport data. Others are context-sensitive, but have a rather informative character and do not enable scenario building by assessing the impacts of changes in the land use and transport system. Still others are very complex, which makes their development effort and data requirements high and their understandability to non-expert decision-makers low. Thus, they are not suitable for communication and encouraging the discussion in early planning phases, but rather for detailed assessment in later planning phases.

A carbon-based accessibility instrument brings innovation to the spectrum of decision-making tools for low carbon transport. Section 2.1 highlights the need for a transparent, communicative, and context-sensitive decision-making tool for climate change mitigation in transport. Combining the silos of CO_2 and accessibility in a novel way might represent a suitable framework for low carbon land use and transport planning. The concept of accessibility is tied to travel behavior theory, but as a potential is independent of realized travel behavior (Hansen, 1959). Usually, accessibility acts as an input via land use and transport system variables to predict travel behavior and consequently estimate emissions (Zahabi et al., 2012; Barla et al., 2011). The approach presented in this paper views CO_2 emissions as a constraint in reaching activity destinations, rather than an output of travel activities. Using CO_2 as a travel cost instead of surveying or modelling travel behavior combines simplicity and efficiency (Määttä-Juntunen et al., 2011).

Finally, a strength of accessibility analysis is that outputs can be tailored for communicating with various stakeholders with different levels of expertise (te Brömmelstroet et al., 2016). Accessibility instruments, typically understood as planning support systems that enable accessibility analysis and planning (Papa et al., 2016), could be useful to support decision-making related to climate change mitigation. However, none of them are able to specifically address issues of climate change by using CO_2 as a travel cost. The development of such an instrument is described in the next section.

3. Development of an instrument for CO_2-based accessibility analysis

3.1. Involvement of local stakeholders

A stakeholder involvement process was initiated in order to verify the considerations related to the practical relevance of a carbon-based accessibility instrument. The awareness, early involvement, acceptability, and commitment of all respective stakeholders is key in order to cause a transition (Litman and Burwell, 2006; Hickman et al., 2011; Banister, 2011). Transport policy-making processes can be supported by suitable tools that help design appropriate strategies in a specific context; hereby, the argumentation for low carbon options can be strongly supported. To guarantee the usability and relevance of tools, stakeholder involvement should be initiated in the early phases of the project implementation (Hickman et al., 2011). The first step of a participation process should involve informing and sensitizing local stakeholders to the topic. This step is followed by active input gathering about the stakeholders needs, wishes, expectations and possible solutions regarding the issue at hand. To conclude the participation process, the stakeholders should be given a chance to evaluate the progress made. A successful implementation process includes the opinions of experts, stakeholders, and decision-makers, the application by professionals, the utilization of politicians to support their arguments, and the power to influence decision-making (Wulfhorst et al., 2017).

A workshop with local stakeholders was conducted in order to collect and discuss their planning issues and needs. The main aim was to determine whether a carbon-based accessibility instrument would be beneficial in municipal and regional decision-making processes related to low carbon transport. The interdisciplinary group of stakeholders includes the planning representatives of four counties surrounding the City of Munich and representatives from other relevant multi-regional institutions (e.g. public transport agency, regional planning authority). The workshop focused on relevant tools and instruments with regards to transport and spatial planning. In the first step of the participation process, stakeholders were sensitized to the importance and nature of tools and instruments in political and societal processes. For this reason, several existing tools and instruments were presented. In the second step the stakeholders' input for the further development of tools and instruments was gathered. To have a better structure, these inputs (visions and wishes) were subdivided into three categories depending on the target groups that should be reached (citizens, planning authorities and politicians). The following key requirements were identified by the local stakeholders:

- Tools should be able to quantify the impacts of various measures, such as the improvement of public transport supply. Thus, they need to be sensitive to interventions in the land use and transport system.
- Tool outputs can be useful as argumentation support. A main challenge in planning practice is to convince non-expert decision-makers to support measures suggested by expert land use and transport planners.
- Tools should be useful in communicating the benefits of measures not only to public officials, but also private stakeholders and individuals.

Concerning the visualization and argumentation in decision-making processes, accessibility instruments and maps can be of great value. Addressing the local trends resulting from the immense growth pressure, an instrument for sustainable planning of new settlements represents one shared vision of several stakeholders from different fields. The assessment of suitable locations for housing as well as jobs on a regional scale was mentioned in particular.

3.2. TUM Accessibility Atlas

The TUM Accessibility Atlas is a GIS-based planning support system for the Munich region developed at the Technical University of Munich (Büttner et al., 2014a; Büttner et al., 2012). The region is characterized by an attractive job market as well as a high quality of life (Büttner et al., 2014b; Kinigadner et al., 2015). More and more people are attracted to the greater Munich area, fueling further prosperity, but also causing increasing challenges for urban and transport planners. Fast population growth in combination with high car ownership rates result in congestion and pollution. For this reason, local politicians and planners have a major interest in shifting the travel demand towards other modes of transport.

The TUM Accessibility Atlas is designed as an accessibility instrument to assist local stakeholders in tackling these problems. The tool contains a multi-modal transport network as well as structural land use data in order to enable accessibility analysis on different spatial scales. Main aims are to visualize disparities between locations and modes, support integrated land use and transport development, and inform political decision-making (Büttner et al., 2018). The instrument's usefulness has successfully been tested in various planning practice applications (Wulfhorst et al., 2017). Since 2009, the TUM Accessibility Atlas has constantly been updated to address current needs and challenges.

Most accessibility instruments use travel time or distance to describe spatial impedance (Papa et al., 2016). The TUM Accessibility Atlas is capable of assessing the transport networks based on travel time, distance, and monetary costs. In order to close the gap outlined in section 2, CO_2 emissions are added as a fourth travel cost indicator. This enables accessibility analysis based on emissions rather than the traditionally used travel costs. An accessibility instrument equipped to specifically address the challenge of low carbon transport seems to be a suitable planning tool in light of the interests and needs of local stakeholders (see section 3.1).

3.3. Incorporating CO_2 as a travel cost in the private transport network

CO_2-based accessibility analysis requires information about the emissions generated when travelling across segments of a transport network. The topology is based on OpenStreetMap (OSM), which provides detailed information about the street network, including road types and speed limits. Emission factors are derived from the Handbook Emission Factors for Road Transport, HBEFA (INFRAS, 2017). HBEFA is a database providing information on fuel consumption and emission factors for a number of vehicle categories like passenger cars, trucks and buses. Results are given for different years, fleet compositions and traffic situations.

Even though HBEFA also provides CO_2 emissions, these values are not used for the network model. Instead, the model is based on fuel consumption. Fuel consumption acts as an intermediate variable, where emissions increase proportionally with increasing fuel consumption. Information about fuel consumption per network segment enables a more flexible and transparent approach. Emission factors per unit of fuel consumption might differ depending on the emission model used. The CO_2 values from HBEFA only consider tank-to-wheel emissions, ignoring emissions generated during upstream processes. A well-to-wheels approach is more comprehensive, especially when comparing electric and conventional vehicles, as done in section 4.4. As opposed to other pollutants, greenhouse gases do not have a local impact, emphasizing the importance of considering the entire energy chain. Furthermore, the application presented in this paper does not solely consider CO_2 emissions, but CO_2 equivalents. CO_2 equivalency is commonly used to quantify the global warming potential of human activates (Umweltbundesamt, 2018). Finally, a network model based on energy consumption can easily be adapted to model other emission types, for example NO_X.

HBEFA provides detailed consumption values per vehicle subcategory, but also aggregated values according to specific fleet compositions per country and year. The aggregation level for the network 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 have determined the level of service to be saturated in urban areas and free flow in rural areas, respectively. The network model can be updated to a more disaggregate data specification,

Fuel consumption values for both diesel and gasoline, urban and rural areas, as well as different road types and speeds need to be matched with the OSM road network. CORINE Land Cover is used to determine whether a street is located within an urban or rural area. The OSM road types are reclassified to match the HBEFA road categories. Based on this preliminary work, the specific fuel consumption values are assigned to the network segments. The length of each street link is calculated in ArcGIS and multiplied by the corresponding specific consumption. This multiplication yields the absolute amount of diesel or gasoline consumed by a passenger car on each OSM link.

Information about the energy consumption of electric vehicles is required in order to determine CO_2 emissions based on a defined electricity generation mix. HBEFA does not provide emission factors or energy consumption data for electric vehicles. While information about the average consumption of electric vehicles can be found rather easily, very detailed consumption values by road type or travel speed still require more research and testing (Braun et al., 2014). For this reason, the emission model for electric vehicles is simplified compared to the emission model for conventional passenger cars. The model for electric vehicles distinguishes between travelling on highways, travelling within urban areas and travelling outside of urban areas. The values used for fuel and energy consumption are presented in Table 1.

Table 1. Fuel and energy consumption of cars.

Vehicle type	Consumption	Source
Gasoline	grams/km by urban environment, road type and speed	INFRAS (2017)
Diesel	grams/km by urban environment, road type and speed	INFRAS (2017)
Electric:	0.208 kWh/km	Helms et al. (2016)

outside of urban areas		
Electric: within urban areas	0.199 kWh/km	Helms et al. (2016)
Electric: motorways	0.271 kWh/km	Helms et al. (2016)

In order to determine the emissions, the consumption is multiplied by the specific consumption emission factor for gasoline and diesel. The well-to-wheels emission factors used in the network model are presented in Table 2. In order to yield the average CO2 emissions, the emissions of diesel and gasoline are weighted by their share of the German fleet composition, as given in HBEFA. Two different scenarios of electric propulsion are implemented in the final car network: The electricity consumption for each network link is multiplied by an emission factor representing the average electricity generation mix and an emission factor representing eco-power, respectively.

Table 2. Emission factors of different fuel and energy types.

Emission factor	Value	Source
Well-to-wheels emission factor of gasoline	3.86 grams of CO2e/gram	Schmied and Mottschall (2014)
Well-to-wheels emission factor of diesel	3.9 grams of CO2e/gram 3240 grams of CO2e/liter	Schmied and Mottschall (2014)
Well-to-tank emission factor of electricity: German electricity generation mix	670 grams of CO2e/kWh	Deutsche Bahn (2016)
Well-to-tank emission factor of electricity: Eco power	20 grams of CO2e/kWh	Deutsche Bahn (2016)

Finally, a network dataset with emissions as cost attribute is set up in ArcGIS. The network dataset enables calculation of the emission costs of travelling, rather than time or money costs. Information about occupancy rates is required in order to convert emissions per vehicle to emissions per person. In Germany, the average occupancy is 1.5 persons per vehicle for all trips and 1.2 persons per vehicle for work trips (Umweltbundesamt, 2016). Occupancy is modeled as a flexible parameter in the network dataset and can be changed before each analysis.

3.4. Incorporating CO_2 as a travel cost in the public transport network

The coverage of the public transport network does not match the coverage of the private transport network. The transit network can only be accessed at stops, causing a need to model the connection between any point in space and the transit network. Access and egress are modeled by considering a catchment around transit stops. Typically, distances to and from stations are covered by foot. An OSM pedestrian network can be added in ArcGIS in order to analyze transit accessibility. Other intermodal concepts like park and ride are currently not included, but could be added in the future.

The topology of the public transport network is modeled based on two different approaches, depending on the analysis scale. A transport model available in the software PTV Visum is used on the regional scale. For generating a more detailed network on the local level, the emission network for public transport is modeled in a similar way as the network for private transport. The shapes of public transport lines are retrieved from OSM. Due to the characteristics of a transit network, several rules need to be respected in order to model it correctly. One link of the respective route type is required between each stop pair of a stop sequence. Passengers can only get on and off a line or change lines at stops. In order to ensure correct modeling of endpoint connectivity, stops need to be located directly on the lines and the links need to have end points at the stop locations. Connectivity between transfer stops is required as well. A lot of time effort is required to process the OSM network in order to ensure that all of these conditions are met. This is especially true for bus lines, which have more complex and variable routes than railbound transit.

Public transport poses additional challenges due to larger variations in vehicle types and occupancy rates. Units and quantities of energy consumption vary depending on the route type. Buses are usually diesel fueled, whereas all railbound transit in the Munich region runs on electricity. Information about fuel and energy consumption in public transport is provided in Table 3. The emission factors remain the same as for passenger cars (see Table 2).

Table 3. Fuel and energy consumption of public transport.

Transport mode	Consumption	Source
Specific:		
Regional bus	Liters of diesel/km by county and urban environment	Data provided by the Munich Transport and Tariff Association
Electric bus	kWh/km in light urban traffic by vehicle type	Study by Knote et al. (2015) conducted for the County of Munich
Default:		
Bus	0.005 Liters of diesel/seat-km	Deutsche Bahn (2016)
Tramway	0.023 kWh/seat-km	Deutsche Bahn (2016)
Subway	0.023 kWh/seat-km	Deutsche Bahn (2016)
Suburban train	0.022 kWh/seat-km	Deutsche Bahn (2016)
Regional train	0.024 kWh/seat-km	Deutsche Bahn (2016)

Occupancy rates of transit vehicles vary widely in space and time. Whereas the occupancy is typically constant for a trip in private transport, the number of passengers per vehicle might change after each stop in public transport. As a result, the emissions per passenger change as well. Additionally, occupancy rates may vary tremendously depending on time of the day or year. Very detailed information on these dynamics tends to be not available or is not published by the transport operators. Thus, trying to represent the true emissions per passenger-km on a specific trip is neither possible nor conducive. Average occupancy rates are easier to collect, but might deviate a lot from the actual occupancy. Spatial variations in occupancy are considered in the emission network model, whereas temporal variations are not considered. Total emissions generated within a spatial unit are equally distributed among all persons travelling within this district, independent of when they are travelling. Default occupancy rates are implemented in the model for the different route types, but can be substituted by specific values, if available, or adapted for scenario building purposes. The fact that total vehicle emissions increase with a heavier weight, making the relation between occupancy and emissions per passenger nonlinear, is not considered. Table 4 gives an overview of the occupancy rates and sources used in the network model. Different values were used, depending on whether specific local information was available or not.

Table 4. Occupancy rates of public transport.

Transport mode	Occupancy	Source
Specific:		
All modes	Daily number of passengers/link	Transport model of the State of Bavaria for the year 2015
Regional bus	Passenger-km/vehicle-km by county and day of the week	Data provided by the Munich Transport and Tariff Association for the year 2015
Default:		
Bus	0.21 passenger-km/seat-km	Deutsche Bahn (2016)
Tramway	0.21 passenger-km/seat-km	Deutsche Bahn (2016)
Subway	0.21 passenger-km/seat-km	Deutsche Bahn (2016)
Suburban train	0.31 passenger-km/seat-km	Deutsche Bahn (2016)
Regional train	0.26 passenger-km/seat-km	Deutsche Bahn (2016)

4. Exemplary application of carbon-based accessibility analysis

4.1. Introduction to the exemplary application

Carbon-based accessibility analysis can highlight spatial opportunities and risks connected to transport-related emissions. This capability could make it a suitable approach to support the political decision-making process related to low carbon land use and transport strategies. The accessibility instrument described in the previous sections is applied in an exemplary case study in order to assess its suitability for this purpose. The focus of this exemplary application is not as much on the results of the analysis, but rather on the usefulness and particularities of a carbon-based accessibility analysis.

The Business Park Gilching, located to the west of Munich, is selected for the test application of the carbon-based accessibility analysis. The campus is situated at the border of the two counties Fürstenfeldbruck and Starnberg and is frequently mentioned by local planners as one of the main transport generators in the region. Both counties are closely involved in the process of developing low carbon transport strategies. The focus of the application is on the business park's role as a workplace location. Employees need to travel to their workplace on a regular basis and the accessibility of a workplace location directly influences trip length and mode share. Zahabi et al. (2012) emphasize the important role of workplace locations by stating that a large share of greenhouse gas emissions is due to commutes.

The size, location and density of settlements, the distribution of urban functions, and the integration of urban areas with the transport network are the determining factors as well as the fields of action for low carbon scenarios (Banister, 2011). The TUM Accessibility Atlas is able to map spatial disparities by different land use and transport conditions as well as accessibility differences by transport mode. For integrated land use and transport planning, the question of how different measures and interventions affect accessibility is equally important. As in traditional accessibility analysis, the instrument will react to the construction of new infrastructure as well as land use changes. When using CO_2 instead of time as the underlying travel cost, different types of changes to the transport system can be analyzed. In the case of travel-time-based analysis, faster travel or increased mobility will result in accessibility impacts. However, the benefits of increased occupancy rates or more efficient vehicles will not reflect in the results of the accessibility analysis. The carbon-based accessibility concept enables to analyze land use changes, transport investments, technological innovation affecting emission costs, and strategies aimed at increasing occupancy.

Different scenarios help to understand the consequences of decisions or the effects of measures and serve as a basis for further discussion (Hickman et al., 2011). The exemplary application uses scenario analysis in order to show potential accessibility changes in case of the Business Park Gilching. In order to highlight the particularities of using CO_2 as a travel cost, the exemplary application will focus on the aspects of specific emissions and occupancy rates. The first scenario addresses an increase in occupancy rates of public transport. The second scenario compares accessibility by conventional and electric car. Before the results of the exemplary application are presented, the next section describes the accessibility indicator chosen for the test application.

4.2. Selection of an appropriate accessibility indicator

Incorporating CO_2 emissions into accessibility analysis brings along the question of sound conceptualization. Accessibility measures ought to be consistent with people's perceptions and values of the transport system (Handy and Niemeier, 1997; Bertolini et al., 2005). Travel-time-based accessibility indicators have closer ties with travel behavior theory, since individuals typically try to optimize travel times when making their travel choices (Vale, 2013). Emission costs are not directly perceptible by travelers, which lowers their importance in individual travel decisions. Carbon-based accessibility needs to be conceptualized in a way that is in line with political objectives, but also individual perceptions.

The abundance of accessibility measures available emphasizes the importance of selecting an indicator that is suitable for the planning issue under consideration (Geurs and van Wee, 2004). Several authors point out the dilemma between complexity and understandability of accessibility measures (te Brömmelstroet et al., 2016; Bertolini et al., 2005). The architecture of the TUM Accessibility Atlas is specifically designed for location-based accessibility indicators. Cumulative opportunities are the simplest type of location-based accessibility measures. This measure sums up the number of opportunities that can be reached within a given travel cost threshold. Unlike gravity-based measures, which weight opportunities in accordance to a specific impedance function, with cumulative opportunities the attractiveness of accessible opportunities is only given by their intrinsic characteristics. Cumulative opportunities measures are easy to use and understand, but still allow comparison of different land use and transport conditions (Bertolini et al., 2005). These characteristics make the measure especially suitable for supporting political decision-making. Despite some limitations, a plain indicator seems to be most appropriate for this purpose.

Since the analysis is focused on a business park, the opportunities are represented by the number of accessible workers. The question of employment accessibility is a relevant planning issue that has found particular attention in the past (Cheng and Bertolini, 2013). Data on the number of workers is available on municipality level from the Bavarian State Office for Statistics. In order to achieve a more accurate representation of the destination potential, this information was disaggregated into smaller spatial units based on the ATKIS dataset.

One of the main challenges of a cumulative opportunities measure is to select an appropriate cutoff value (Handy and Niemeier, 1997; Bertolini et al., 2005), in our case given by CO_2 emissions. Emissions are not easily perceivable by the traveler, but very much determined by policy goals. The question is not how long people are willing to travel, but what is the political target for the maximum CO_2 emissions of one trip. Policy makers may choose or adapt the accessibility measure depending on their planning goals. The budget chosen for the test applications in this paper is derived from information of the German Environment Agency (Umweltbundesamt, 2017). The total greenhouse gas emissions in Germany in 2016 are broken down to the share of one commuting trip. Emission reduction targets for 2030 require a reduction in current greenhouse gas emissions by 40 %. The assumption that contrary to the current trend (European Environment Agency, 2017) the transport sector should equally contribute to this target, yields an emission budget of 750 grams of CO_2 equivalents. This budget is selected as cutoff value in all presented accessibility analyses, but can easily be adapted to any low carbon policy goal or emission reduction scenario.

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 few 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. For public transport, emissions are accumulated along the fastest route between origin and destination stops. The service area for private cars was calculated solely based on emissions, meaning that the route choice is independent of travel time. We acknowledge that in reality, travelers might never choose the most carbon-efficient route if a destination can be reached faster via a less carbon-efficient route. Before further discussing shortcomings and possibilities for improvement (section 5), the two applications are presented in the following sub-sections.

4.3. Increased occupancy rate in public transport

Occupancy rate is one of the levers influencing transport-related emissions (Becker et al., 2009). Therefore, climate change mitigation strategies could be aimed at increasing occupancy rates. Occupancy is especially important in public transport: Highly loaded vehicles are climate efficient, whereas empty vehicles are just the opposite. In order to demonstrate how increased occupancy rates could affect the carbon-based accessibility measure, a scenario for occupancy changes in public transport is implemented in the TUM Accessibility Atlas. For public transport, the scenario presumes that the occupancy rate of regional buses increases by 50 %. The occupancy rates of other transit modes like suburban trains remain unchanged. Such a large increase is a rather optimistic, but not necessarily unrealistic considering the introduction and promotion of tangential bus rapid transit lines in the counties of

Fürstenfeldbruck an Starnberg, as well as the overall rising passenger numbers in the MVV region (Münchner Verkehrs- und Tarifverbund, 2015).

The carbon-based TUM Accessibility Atlas can be adapted to any desired occupancy scenario. The total energy consumption per vehicle-km is the basic variable in the public transport network (see section 3.4). Information about the number of passengers on the vehicle is required to break down the total emissions to individual passengers. This information can be based on actual data or can be freely chosen in order to analyze different scenarios. A distance of 600 meters was used to model egress walking from the destination stops. The following figures compare the standard occupancy scenario (Fig. 1) and the increased occupancy scenario (Fig. 2) for public transport accessibility of the business park.

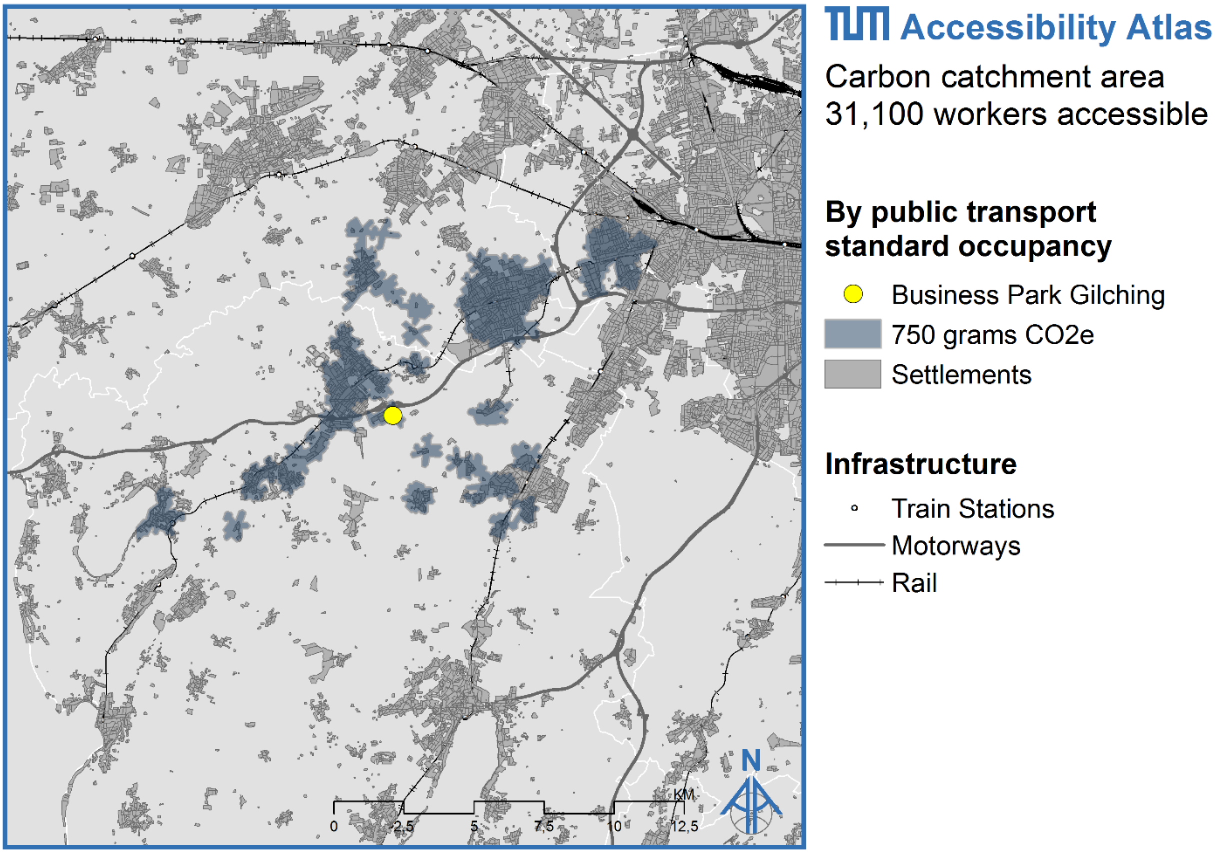

Fig. 1. Carbon catchment area by public transport at standard occupancy.

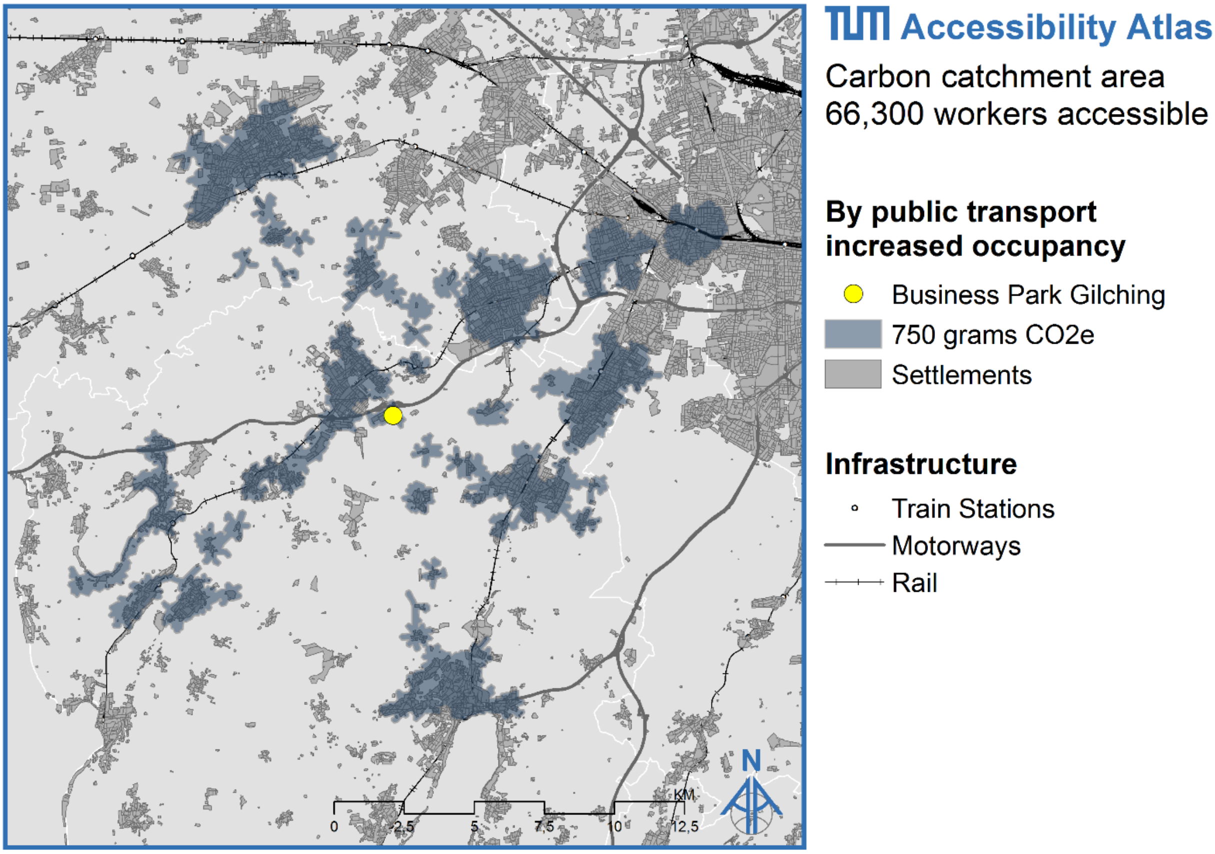

Fig. 2. Carbon catchment area by public transport at increased occupancy.

In the original situation, the carbon catchment is mainly extending along the northeast and southwest axes. This is due to the fact that the direction towards the city of Munich is served by suburban railway lines. Trains have a lower emission factor per passenger-km than buses. The north-south axis, on the contrary, is served by a tangential bus line. The total number of workers accessible is 31,100. If occupancy rates in buses increase, the catchment extends more homogeneously into all directions. The number of workers accessible increases to 66,300. Such an analysis might help to argue for the potential of attractive services, if accepted and intensively used by the passengers.

4.4. Comparing conventional car and battery electric vehicle

Stricter fuel economy standards and technological advances have caused increasing fuel efficiency in motorized vehicles. However, despite a decrease in specific consumption, the growth in travel demand exceeds the benefits of greater efficiency (Banister et al., 2011). The possibilities provided by technological innovation need to be embraced by a suitable economic and political framework in order to be able to actually reduce transport-related emissions (Schwanen et al., 2011). Also the question of whether electric vehicles are beneficial for the environment cannot clearly be answered (Burns, 2013).

The second exemplary application of a carbon-based accessibility analysis contributes to this discussion. The TUM Accessibility Atlas is applied in order to compare and visualize the carbon footprint of conventional and electric cars. In this context, it is especially important to use a well-to-wheels approach. Even though electric vehicles do not cause any local greenhouse gas emissions, they are not completely emission-free. The electricity generation mix plays a major role, as the coal combustion in a power plant might cause more emissions than the fuel combustion in a conventional car. Also, it should be noted that the manufacturing process of electric vehicles causes more greenhouse gas emissions than the production of conventional vehicles due to the battery (Helms et al., 2016). These impacts are not considered in the TUM Accessibility Atlas, but should be included in a complete life-cycle analysis. The test application compares the emissions caused by the operation of conventional cars and electric cars, respectively. Service areas for the threshold value of 750 grams of CO_2 equivalents are generated in ArcGIS with an occupancy of 1.2 persons per vehicle. The origin is centrally located in the business park Gilching. Figures 3 and 4 present the resulting accessibility maps for a conventional car and an electric car powered by the average German electricity generation mix.

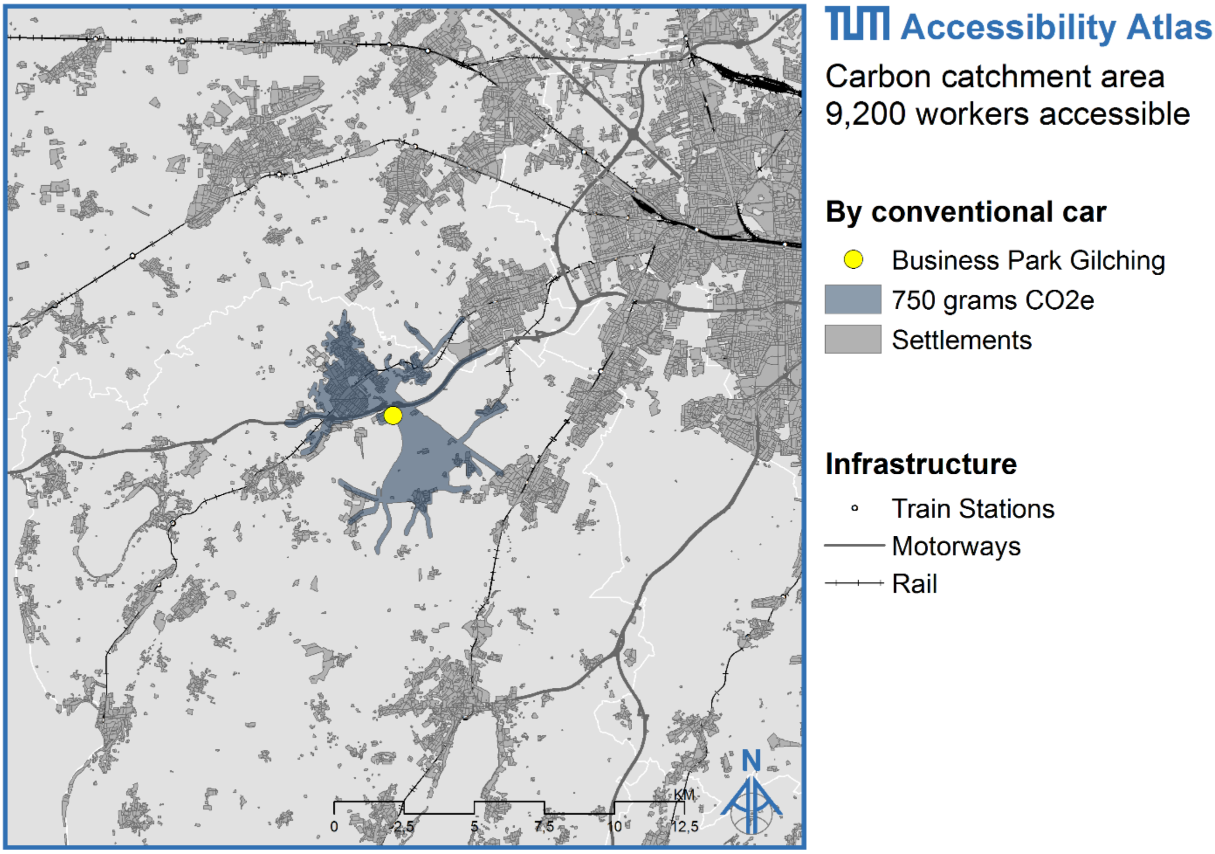

Fig. 3. Carbon catchment area by conventional car.

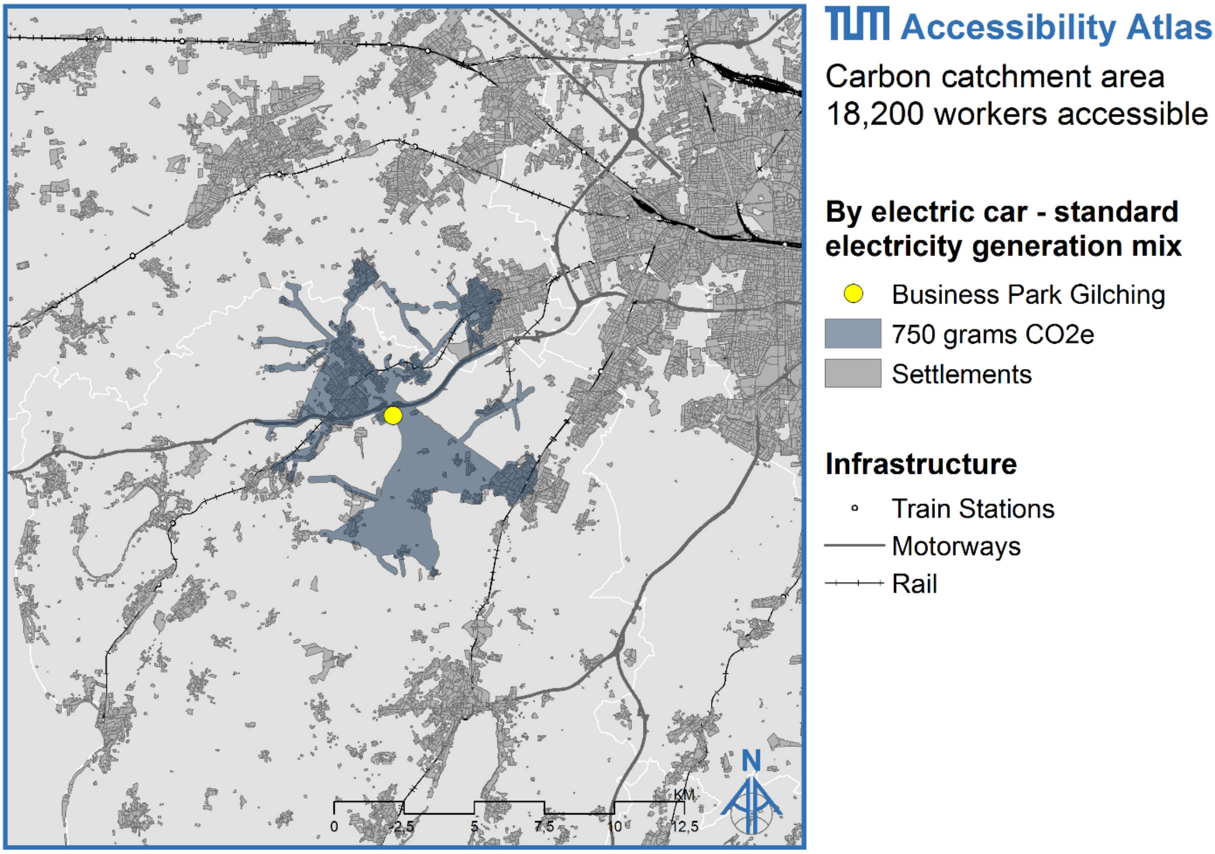

Fig. 4. Carbon catchment area by electric car with standard electricity generation mix.

The catchment area by electric car is slightly larger than the catchment area by conventional car. Accordingly, the accessibility is higher in the first case: 18,200 workers can be reached by electric car compared to 9,200 by conventional car. The comparatively large difference in accessible workers can be explained by the isolated location of the business park. Dense settlement areas are located just within the catchment of an electric vehicle, but are not accessible with a conventional car. This observation emphasizes the importance of considering the characteristics of not only the transport system, but also the land use system. Rather small increases in catchment size due to more efficient vehicles might increase accessibility by a larger factor in case of a favorable urban form. The same analysis is repeated with a change in 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 is a 20 % reduction, which results in an emission factor of 536 instead of 670 grams per kWh. The resulting map is shown in Fig. 5.

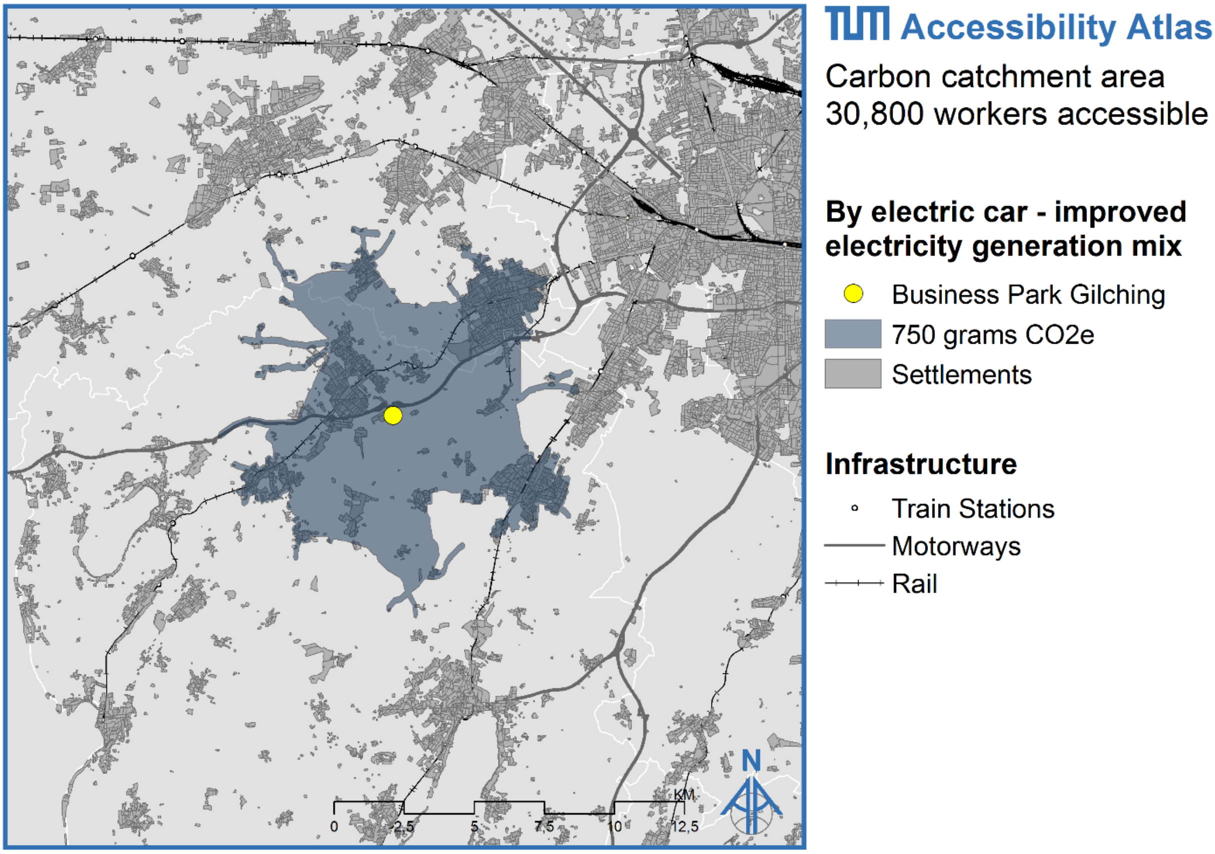

Fig. 5. Carbon catchment area by conventional car with improved electricity generation mix.

The number of workers accessible increases to 30,800. 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_2-equivalents. Improving the electricity generation mix significantly increases accessibility by electric car to a value comparable to public transport at standard occupancy. The scenario outlined in this analysis represents 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.

5. Discussion and conclusions

The approach presented in this paper relies on an accessibility framework in order to assess the environmental impact of different land use and transport conditions. This section discusses the usefulness and limitations of incorporating CO_2 as a travel cost in a location-based accessibility framework with respect to political decision-making processes.

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, the alteration of the electricity generation mix significantly increases the car carbon accessibility to values similar to the current public transport carbon accessibility. Nevertheless, an increase in the occupancy rate of public transport will still provide an accessibility to workers that is significantly higher than the previous results. 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. Given the current carbon-based accessibility, the electrification of buses will probably be a better solution that of cars, given their higher capacity and associated occupancy rate. It should be stressed that the outcome of the analysis is highly dependent on the underlying assumptions and input parameters. Energy consumption, emission factors, and occupancy rates feature large variations by location, vehicle type, and time of the day. Typically, this data is either not available or not measurable in great detail. Possibilities for further disaggregation and verification of the data should be exploited before using a carbon-based accessibility instrument for real-world applications related to climate change mitigation strategies.

According to Schwanen et al. (2011), climate change mitigation strategies can be classified into infrastructure provision and land use changes, technological improvements, behavioral changes, price changes, and adaptations in transport governance. Not all types of interventions aimed at reducing transport-related emissions can be examined with the instrument presented in this paper. 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. The outcome of the accessibility analysis depends on the environmental costs of travel and is sensitive to changes in occupancy rate or vehicle efficiency (see sections 4.3 and 4.4). In the context of climate change, it might be more valuable to reduce emissions rather than travel time or monetary costs. At the same time, this means that policies affecting travel costs (e.g. pricing strategies, which are typically discussed in climate change mitigation) cannot be assessed by 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. In light of the main objective of the carbon-based accessibility instrument – stimulating a communicative decision-making process in strategic low carbon land use and transport planning – this limitation can be deemed acceptable.

It might be argued that 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 modelling could enable a more precise assessment of the costs and benefits of various measures. Nevertheless, these methods are complex in setup and handling. The required data is seldom available to planners and practitioners. This challenge of finding the right balance between theoretically sound and sufficiently plain planning support systems has been repeatedly discussed in the literature (Bertolini et al., 2005). The accessibility instrument introduced in this paper might not necessarily be the best option to assess measures in the context of project appraisal, but is certainly helpful to identify potential measures and support the decision-making process. Even though the output is not quantifiable in terms of emission savings, a main strength in relation to political decision-making processes is the visualization in maps. The results highlight options or needs for interventions in the land use and transport system that are understandable to everyone involved and can serve as a basis for a common discussion.

Accessibility instruments and their analysis results are only valuable if they are implemented in planning practice. While the development of the instrument was based on the interests and needs of local stakeholders (section 3.1), the exemplary application was intended as a demonstration of usefulness rather than a solution-finding process for real-world planning issues. Therefore, the next steps in the process should further involve local stakeholders in order to be able to address their specific planning issues. The carbon-based accessibility analysis might assist the assessment of potential environmental impacts of alternative location choices. It could also be extended to a location assessment on a larger scale in order to identify development areas with the minimum climate impact. Such analysis might involve the use of a more complex indicator combining multi-modal accessibility. An estimation of the accessibility benefits of changes in transport system quality could be a valuable first step in a multi-dimensional decision-making process. Further development of the accessibility instrument and its application to current planning problems will show whether the tool will continue on its promising path of enhancing decision-making processes related to climate change mitigation in transport. A variety of real-world planning issues in both land use and transport planning will be addressed in order to determine the tool's practical relevance for the development of low carbon strategies. The challenge of climate change mitigation is a global one, making similar planning issues relevant all over the world. While the underlying spatial data limits the applicability of the TUM Accessibility Atlas to the Munich region, the concept of a carbon-based accessibility instrument could easily be transferred to any other spatial context.

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