Technische Universität München

Quantitative assessment of car dependence

An application in the public transport area of Munich, Germany

Study Project

at the **Chair of Urban Structure and Transport Planning** of the Technical University of Munich.

Supervisors M.Sc. David Durán Rodas

M.Sc. Elias Pajares

Assigning authority Prof. Dr.-Ing. Gebhard Wulfhorst

Chair of Urban Structure and Transport Planning

Submitted by Matthias Langer

03659886

Heßstraße 77

80797 München

matthias.langer@tum.de

Date of submission München, 30.12.2020

Table of contents

Table of figures

List of abbreviations

CDF……………………………………………….………………………Car dependence factor
LTM………………………………………………………………….……….Land transport model
MIT…………………………………………………………….…………Motorized individual traffic
MLR……………………………………..…...…………………Multiple linear regression
MVV……………………………………………….….. Munich Transport and Tariff Association
OSM…………………………….…………………………..…………………Open Street Map
POI …………………………………………………………...……………………Point of interest
PuT …………………………………………………………………………….…Public Transport

List of tables

Abstract

Car dependence is debated as a multifaceted problem. While the automobile has been seen solely as a benefit for everyone´s life for a long time, since the 1970s the scientific community also discusses drawbacks of car-oriented development. In addition to ecological issues, problems have been identified mainly regarding land use, equity, health, and economy. Car dependence cannot be aligned with a sustainable future. Whereas discussions about what car dependence exactly means are still on going, few methods exist to measure it. Based on a chosen definition for car dependence, a method was developed to assess car dependence quantitatively. It is structured in two parts, the calculation of an indicator for car dependence and its association with socio-spatial factors. A first application was conducted in the traffic area around the city of Munich, Germany. Car dependence was found to be most prevalent outside of towns and in areas with high car ownership. Other parameters, such as the local number of employees, average income tax payments or the sales price of land could be identified as factors associated with car dependence. For local stakeholders, the results are useful to explore car-oriented development in the area and for considering actions to prevent it. Future research can focus on the application in additional regions and further combination with qualitative research.

Zusammenfassung

Seit den 1970er Jahren wird das Phänomen „Car Dependence“ in den Verkehrswissenschaften vielfältig kritisiert. Während PKWs lange Zeit ausschließlich als gewinnbringend betrachtet wurden, werden seither auch die Kehrseiten diskutiert. Neben umweltrelevanten Problemen wurden weitere Kritikpunkte bezüglich Landnutzung, Gleichberechtigung, Gesundheit und Wirtschaft erkannt. Im Hinblick auf nachhaltige Entwicklung sollte “Car Dependence” verhindert werden. Auf Grundlage einer gewählten Definition des Problems, wurde eine Methode entwickelt, die der quantitativen Bewertung dient. In zwei Schritten wird zuerst ein neu definierter „Car Dependence“ Faktor berechnet und anschließend eine multiple lineare Regression durchgeführt. Dieser Ansatz wurde erstmals im Einzugsgebiet des Münchner Verkehrs- und Tarifverbunds (MVV) durchgeführt. Hier wurde „Car Dependence“ vor allem abseits von Städten und an Orten mit hohem Grad an PKW-Besitz festgestellt. Weitere Kennwerte, wie ArbeitnehmerInnenzahlen, Einkommensteuer oder Grundstückpreise in einer Gegend, konnten mit dem berechneten Faktor in Verbindung gebracht werden. Lokale Interessensträger können diese Ergebnisse nutzen um „Car Dependence“ zu ergründen und Maßnahmen dagegen zu ergreifen. Zukünftige Forschung kann sich auf die Anwendung in weiteren Regionen und die noch stärkere Kombination mit qualitativer Forschung konzentrieren.

1 Introduction

The matter of car dependence has been discussed in transportation for decades now. As early as the 1970s, urban planners as well as sociologists such as Goodman (1972), Lefebvre (1992) and Illich (1974) noted that the automobile and its vast industry were changing transportation patterns in unsustainable[1] ways. While they were thinking in large part about equity and equality issues, later on environmentalism was added as a critique (Lucas et al. 2001). Their criticism can be seen as a response to the automotive industry's discovery that increasing its influence can create dependence on the industry itself (Goodman 1972).

Currently, all kinds of ideas are being developed and, in some cases, also implemented to serve sustainable transport development, such as electric and hydrogen cars, micro mobility or car-sharing services. Nevertheless, the use of the car, which is the most common transport mode for Europeans, is steadily increasing (European Commission 2018). This is reflected in rising car ownership figures, a growing road network and increasing passenger kilometres. In some places, the car has become the only reliable means of transport (Goodwin 1995). This in turn is accompanied by problems of access and even justice for people who do not enter the automobile system for various reasons, including financial, physical, or personal motives (Lucas et al. 2001).

This study serves to discover existing car dependence. Thus, it can be seen as a commencing point for local stakeholders to find solutions to decrease the phenomenon. As Litman (2002) described in one of his articles, this study does not just aim to diminish the presence of cars, but to sustainably transform the current transport system.

> *“Reducing excessive automobile dependency is no more anti-automobile than healthy diets are anti-food. This investigation does not mean that automobiles are “bad,” or that governments should forbid driving. It simply suggests that communities could benefit from more balanced transportation systems and fewer market distortions that favor automobile travel.”* - Litman (2002)

[1] Without getting deeper into a discussion on sustainability, the term "sustainable" is understood here exclusively in reference to the Brundtland Report (World Commission on Environment and Development 1987) as a development that is ensuring the “the needs of the present without compromising the ability of future generations”.

1.1 Problem statement

The concentration of transportation on the automobile has led to a number of problems for the global society. Areas dedicated to parked or moving cars are increasing in many places (Umweltbundesamt 2020c). Automobile emissions contribute to a significant extent to climate change resulting from human activity and could not be reduced over the past 30 years (European Commission 2018). People who live near busy roads can expect sometimes severe effects on their health (Frumkin 2002). Nevertheless, automobile use is still popular. As an example, Schwedes (2019) recognized that in Germany automobility[2] is demanded by large parts of society and promoted by the government.

However, reducing the automobile´s influence on the traffic landscape could bring many advantages, such as transport equity and climate mitigation. This is where the concept of car dependence comes into play. Car dependence reveals a variety of problems caused by an increased focus on the automobile, while also disclosing the benefits of supporting alternative ways of future transport planning, such as public transit, walking or biking.

In order to name and understand the problem, car dependence has been described and defined in various ways. While the qualitative description of car dependence has been carried out comprehensively, there have been fewer attempts to illustrate the problem spatially. Additionally, those rarely led to changes in regional or national transport policies. This may be due to political decision-making of a country, but also to the impracticability of some of the methods. Many of them examine only dissociated aspects of car dependence, are not easily reproducible or too complicated to be implemented.

1.2 Need, objective and research questions

To solve the problem of car dependence on a large scale, a viable method to assess it quantitatively must be introduced first. This method must withstand the complexity of the problem, at the same time it should not be unnecessarily complicated or even incomprehensible. A technique is needed that considers as many components of the original problem as possible and is simultaneously reproducible and transferable so that it can be used in a variety of places.

This study project aims to fulfil the abovementioned need of an advanced way to evaluate car dependence. Hence, the overall objective is to develop a method to assess car dependence quantitatively in the most complete, understandable, and transferable way

[2] The term „automobility“ was established by Sheller and Urry (2000) to describe the role of the car in modern society.

possible. Therefore, the first research targets to assess car dependence quantitatively. Car dependence is not a phenomenon that appears out of nowhere. Spatial developments can mostly be comprehended by examining external factors. Therefore, secondly, it is relevant to see which spatial factors are associated with car dependence.

1.3 Project structure

To demonstrate the relevance of car dependence, the following chapter will examine the current state of the art. After a short description on how scholars began to treat this matter, consequences of car-oriented development are presented. Those are described regarding five categories: land use, emissions and environment, health, inequalities, and economy. Afterwards, the exact definition and different types of car dependence will be covered. Here a working definition of the concept is agreed upon. The last part of the following chapter focuses on previous attempts to assess car dependence.

After a summary of existing methods, an own technique is presented. The approach is structured in two steps, which are the implementation of an equation describing car dependence and a set of linear regressions aiming for deeper investigation of the matter.

In the fourth chapter, the aforementioned method is applied. The study area is the transport area of Munich. Here, the study area itself, the sources of data and applied software are described. Both steps of the approach are examined in detail here and its results are presented. In addition, a second attempt is carried out in which the formula for calculating the car dependence factor is slightly modified. This is intended to provide an even deeper understanding of the method.

In chapter five, the approach is discussed, and the calculated results are interpreted. The relevance of the results and the limits of the approach are presented. Finally, the conclusion summarizes the main research results. Matters for future research and suggestions for possible stakeholders will be considered.

Figure 1 depicts the structure of the study project, which includes six chapters.

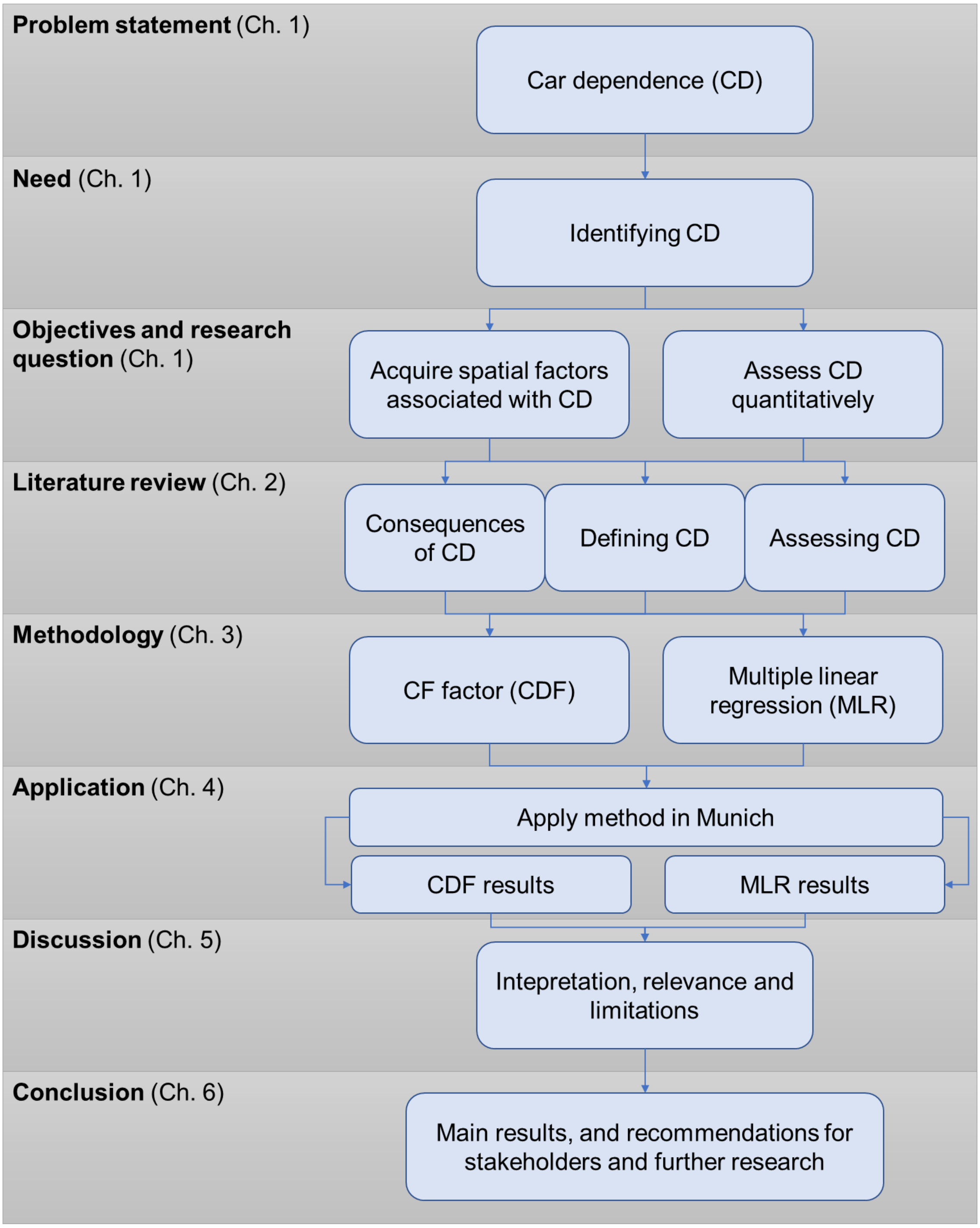


Figure 1: Project structure.

2 Car dependence

Since time immemorial, mobility has been one of the most important goods of the human species. Over the centuries, popular transport modes have changed. Due to the industrialisation in the 18th century, human- or animal-based transport modes were exchanged by trains, cars, and later by buses. Bumpy forest trails had to give way to kilometre-long rail networks, and it did not take long until roads and highways were built, which paved the way for comfortable car transportation (Mohajan 2019).

During the 20th century, the automobile became a particularly practical and successful mode of transport throughout the global North, associated with freedom. With Henry Ford´s introduction of the Model T in 1908, mass production of automobiles started in the United States. Ever since the 1920s, cars began shaping cities´ faces, replacing tram systems with freeways and parking spaces (Newman and Kenworthy 2015). A similar development took place in Europe, for example when national socialist Germany started to support the mass production of the Volkswagen in the 1930s and massive highway constructions (Grieger 2019).

After the Second World War, thanks to rapid techno-economic developments and the so-called economic miracle in the 1950s, which was also driven by the German automotive industry, almost everyone in the Western World was able to afford a car (ibid.). Townscapes and country sides have adapted to this development and many regions around the world were a bit at a time characterised by wide lanes and sweeping cities (Resnik 2010; Grieger 2019).

It was not long before the first concerns were raised against this development. After the implementation of the "Highway Trust Fund" in the United States in 1956 (Newman and Kenworthy 2015), Robert Goodman (1972) argued that this special tax would create transport inequalities in favour of the automotive industry. In fact, a quarterly newsletter of the asphalt industry described this as follows:

> *"Every new mile tacked onto the paved road and street system is accompanied by the consumption of about 50,000 additional gallons of motor fuel a year. […] In short, we have a self-perpetuating cycle, the key element of which is new paved roads. The 45,000 new miles added to the road and street network each year accommodate automotive travel, generate fuel consumption, produce road-building revenue" (Asphalt Institute Quarterly 1967 cited in Goodman 1972).*

The problem of spatial development, which is largely concentrated on automobile traffic, has been discussed intensely ever since. Lefebvre (1992) described the topic as a "vicious circle […] which for all its circularity is an invasive force serving dominant economic interests”. Illich (1974) spoke of a “radical monopoly” that creates a need which can only be satisfied by the industry itself. Soon the term car dependence[3] was used in many different ways. Exactly this phenomenon is described below. Firstly, different effects of car-oriented development on society and environment will be presented. Secondly, the definition of the term car dependence and its perceptions will be described in more detail. Finally, the focus will be on measuring and presenting the problem in a spatial planning context.

2.1 Consequences of car-oriented development

To consider the effects of a development oriented towards the automobile, it is crucial to examine the reasons for this change. The possibly most important factor therefore is accessibility, as the car is a fast and flexible mode of transport, which convinces with seamlessness and directivity (Lucas and Schwanen 2011). However, there are countless other reasons, ranging from personal attitude, available time and money, travel costs, availability of other means of transport, one's own physical condition and local infrastructure, to cultural norms and moral values (ibid.).

According to Canzler and Radtke (2019), for some years now, public transport and cycling have been publicly supported next to the automobile. However, in everyday traffic, active car promotion has been noticeable over decades. This trend can be observed in the current transport statistics of the European Union: Both freight and passenger transport play an extremely important role and are constantly increasing (European Commission 2018). While about 50 percent of freight transport is carried out on the road, the figure for passenger transport is about 70 percent (ibid.). It is obvious that car transport plays an important role in the European Union.

Urry (2004) described the consequences of this transport development:

> “*Automobility divides workplaces from homes, producing lengthy commutes into and across the city. It splits homes and business districts, undermining local retail outlets to which one might have walked or cycled, eroding town-centres, non-car pathways and public spaces. It separates homes and leisure sites often only available by motorized transport. Members of families are split up since they live in distant places involving complex travel to meet up even intermittently. People inhabit congestion, jams, temporal uncertainties and health-threatening city environments, as a consequence of being encapsulated in a domestic, cocooned, moving capsule.”*

[3] Also: car dependency, automobile dependence/dependency

This criticism already describes many of the consequences, which are presented and discussed in this sub-chapter. The externalities can thereby be divided into five categories: land use, emissions and environment, health, inequality, and economy. A short overview is shown in Figure 2. However, these do not always take place in the order shown by the arrows, but rather are interconnected in all directions.

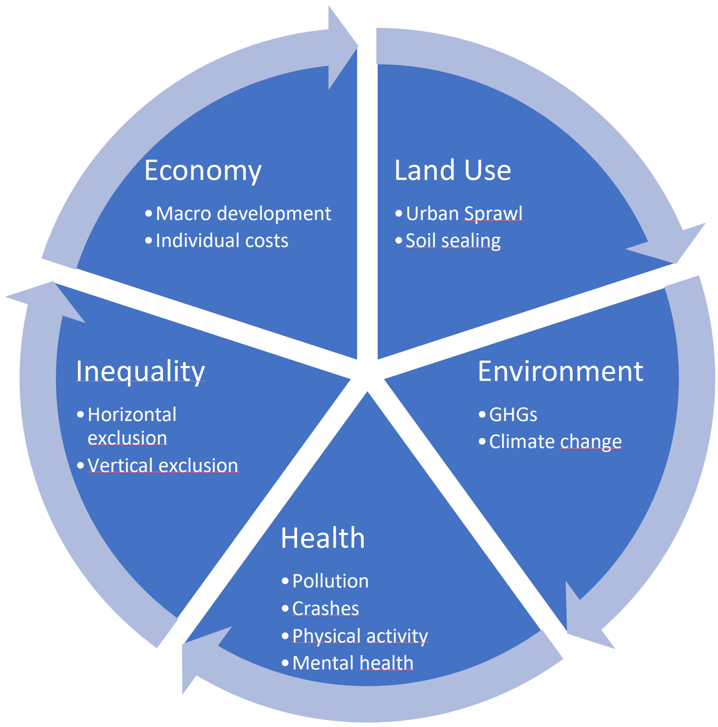


Figure 2: Consequences of car dependence.

2.1.1 Land use

Before the car was a predominant means of transport, land use and transport tended to be integrated in such a way that people were able to reach common places by foot and transit. The car enabled to separate this connection (Newman and Kenworthy 1999) and the increase of automobile ownership from 1920 on led to suburban growth (Frumkin 2002). Cities grew rapidly in all directions, but population growth could not keep up (Resnik 2010). Nevertheless, all major places could be reached within a short time (Newman and Kenworthy 1999) because the new means of transport were characterised by higher speeds.

Banister (2011) noticed that especially in the last 50 years both speeds and distances changed strongly and mentioned an increase in average commuting distance of just 10 km by 1960 to 50 km by 2000[4]. In that way, "large metropolitan areas with low

[4] The numbers were derived from a study in France by Grübler (2004).

population densities, interconnected by roads" were produced in which the inhabitants live predominantly in single-family homes and, due to the remoteness, are dependent on the car for daily activities (Resnik 2010). This could be caused mainly by the separation of neighbourhoods and areas of areas such as offices, industry, retail outlets, recreational facilities and public spaces such as parks (Frumkin 2002; Urry 2004; Wiersma et al. 2013).

Internationally, cities did not all evolve in the same way, but all of them share a combination of walking-, transit and car-oriented developments (Newman and Kenworthy 1999). Though, similarities could be found in the connection of urban density and transport energy use per capita as it is visible in Figure 3. Newman and Kenworthy (2015) also mentioned that denser cities with lower per capita energy consumption often support a broad public transport system, while the less densely populated cities, especially in the USA and Australia, rely heavily on their cars. Zhang (2006) in turn, criticized that car use does not depend on urban density alone, but on many other characteristics such as income, oil prices and urban transport patterns.

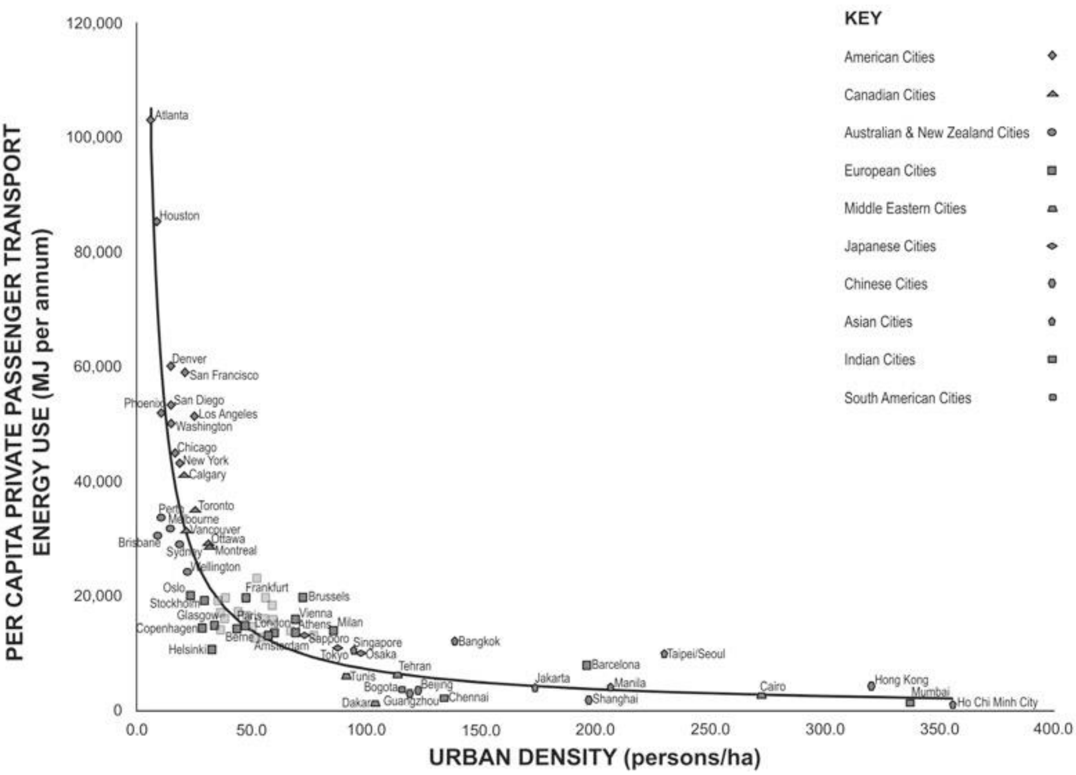


Figure 3: Per capita private passenger transport energy use per urban density. Source: Newman and Kenworthy (2015, p. 25).

The patterns visible in Figure 3 are commonly known as urban sprawl. The European Environment Agency defines urban sprawl as the opposite of compact cities and more in detail as a "physical pattern of low-density expansion of large urban areas, under market conditions, mainly into the surrounding agricultural areas", characterized by patchy development and “little planning control of land subdivision” (EEA 2006). They further examined the state of urban sprawl in the European Union and found that European cities are also affected. Central European countries such as the Netherlands, Belgium and Germany in particular were found to be highly sprawled, while countries such as Sweden and Greece have very low sprawl levels (EEA 2016). Once this form of land use is established, it is difficult to reverse and requires a slow process of change (Wiersma et al. 2013).

A side effect of this development is a high degree of land sealing for roads and car parks (Litman and Laube 2002). In the European Union, urban areas have grown by 78 percent since 1950, while the population has increased by only 33 percent (EEA 2006). The total sealed area is about 100,000 km^2, which is only about 2.3 percent of the EU territory, but calculated on the population, it amounts to 200 m^2 per person (European Commission 2012). These now disappearing areas were formerly used for agricultural or even natural uses on the countryside as well as for green spaces in cities.

Frumkin (2002) identified these problems and concludes that when “jobs, stores, good schools, and other resources migrate outward from the core city, poverty is concentrated in the neighbourhoods that are left behind”. Together with increased traffic emissions, this can lead to both health and equity problems, which are discussed below.

2.1.2 Emissions and environment

In view of climate change, the probably best-known effects of car-oriented traffic development are the environmental impacts of greenhouse gases, ozone, nitrogen oxides, the raw material oil and other direct traffic emissions, such as particulate matter or noise. Greenhouse gases actively contribute to man-made climate change and are therefore extremely harmful. The transport sector is the only one that has not shown an overall decreasing trend in greenhouse gas production since 1990 (European Commission 2018). In 2016, about a quarter of all greenhouse gases came from the transport sector (ibid.). Again, road transport accounts for 72 percent (ibid.). This can be broken down into 61 percent cars, 26 percent heavy duty trucks and buses, 12 percent light duty trucks and 1 percent for motorbikes (ibid.). Overall, it can be said that transport by car alone is responsible for eleven percent of all greenhouse gas emissions in Europe.

Ozone (O_3) is a trace gas which is formed from nitrogen oxides and volatile organic compounds by photochemical processes during strong solar radiation (Umweltbundesamt 2020a). It is called a secondary pollutant and can cause negative effects for humans and the environment. The precursor substances of ozone mainly originate from anthropogenic effects, more than a third of them from road traffic.

Compared to 1990, the amount of precursor substances decreased significantly (EEA 2007).

Nitrogen oxide (NO_X) is a collective term for various gaseous compounds consisting of nitrogen and oxygen. Motor vehicle exhaust primarily emits NO_X in the form of nitrogen monoxide (NO) and nitrogen dioxide (NO_2) (Dora and Phillips 2000). NO_X are responsible for ozone formation and also contribute to particulate matter pollution (Umweltbundesamt 2020b). Large amounts can pose problems for humans and the environment, for example by increasing the effect of allergens for asthmatics or acidifying soils (ibid.).

In the European Union, the transport sector is responsible for 33 percent of final energy consumption, of which 82 percent is accounted for by road transport (European Commission 2018). This fact is relevant as most of this energy comes from oil – a resource of limited availability of the raw material and often exported by democratically questionable regimes (Ross 2001). Mattioli et al. (2020) see car oriented developments as an important part of so-called "carbon lock-ins". Those are socio-economic, technological, and institutional barriers to achieving a low-carbon future.

In addition to environmental emissions, noise pollution must be mentioned here. These are described by the EEA (2017) as a “major environmental health problem” and “high risk to human health”, with road transport as the main source in the European Union. The consequences on health are described in the next section.

Another issue affecting the environment is water quantity and quality. Frumkin (2002) referred to a change in water quality and quantity due to high levels of sealing by traffic areas, while at the same time reducing natural soil cover. The European Commission (2012) shared this view. They point out that soil sealing leads to changes in the natural status of catchments such as impacts on biodiversity, food safety, air quality and ultimately the overall quality of life.

Lastly, reduced evapotranspiration, increased heat absorption from dark asphalt surfaces, and heat generated by traffic, among other things, can lead to the problem of the urban heat island effect (European Commission 2012). This manifests itself in the form of extreme heat waves, in which chronically ill and elderly people in particular have to struggle hard.

2.1.3 Health

For the analysis of health-related road traffic impacts, a schematic classification according to Frumkin (2002) is implemented. A distinction is made between direct effects of reliance on automobiles, effects of land use decisions and social aspects of sprawl.

Direct effects of reliance on automobiles

- *Air pollution:* Various articles refer to the excessive burden of transport emissions on human health. Increased ozone values can result in higher incidences and severities of respiratory symptoms, worse lung function, more emergency room visits and hospitalisations, increased medication use, risks of mortality and respiratory morbidity (Krzyzanowski 2005; Frumkin 2002). People with respiratory diseases are especially vulnerable. A high proportion of particulate matter can lead to similar problems, but also to increased mortality (Frumkin 2002).
  In general, traffic emissions can cause the following clinical pictures: increased risk of death (especially from cardiopulmonary causes), increased risk of non-allergic respiratory symptoms and diseases, allergic diseases and symptoms (e.g. asthma), cardiovascular morbidity, cancer, limitations in births and male fertility, significant increase in risk of heart attack, and increased incidence of lung cancer in people exposed to traffic-related air pollution for prolonged periods (Krzyzanowski 2005; Heinrich et al. 2005; Dora and Phillips 2000). Accordingly, a reduction of these emissions would lead to a reduction of asthma cases, a gain in life expectancy and, declines in bronchial hyperreactivity (Krzyzanowski 2005; Heinrich et al. 2005). Kuna-Dibbert and Krzyzanowski (2005) highlighted that the number of deaths from traffic-related air pollution is close to that caused by direct traffic accidents. Frumkin (2002) also mentioned that the scale of the problem of air pollution can often not be fully taken into account because it can be greater than expected due to winds.
- *Noise pollution:* Harmful consequences include premature death, cardiovascular diseases, cognitive and hearing impairments, difficulties with performance, increased aggression, heart diseases and (sleep) disturbance (EEA 2017; Dora and Phillips 2000). Therefore, “the WHO has categorised noise from road traffic alone as the second most harmful environmental stressor in Europe, behind only air pollution” (EEA 2017).
- *Motor vehicle crashes*: European accident statistics show how drastic road accidents can end. The numbers have been decreasing in the last decades thanks to improved safety technology, stricter traffic rules or stricter controls and penalties in terms of speed and alcohol. However, they still show that accidents are a problem in everyday life. In 2016, more than one million traffic accidents happened in the

European Union, which is a decrease of almost one third since 1990 (European Commission 2018). In this period, the number of fatalities declined by almost two thirds, but this still equates to 25 thousand deaths (ibid.). It might be interesting to know that in the same period the number of passenger cars per 1000 inhabitants increased by almost 50 percent (ibid.). According to Jackisch et al. (2015) this makes the European Region the worlds´ safest region in terms of road traffic mortality, but road crashes are still the leading cause of death for young people. Frumkin (2002) analysed data from the National Highway Traffic Safety Administration (NHTSA) and found incidences that high densities and proper public transportation systems have positive impact on the fatality rates. Peterson et al. (1999) remarkably stated that traffic accidents are predictable and avoidable and should therefore not be called "accidents".

- *Pedestrian injuries and fatalities*: Lucas and Jones (2009), Jackisch et al. (2015) and Frumkin (2002) noted that pedestrians and cyclists account for a high number of road accident victims. In the EU, this figure was almost 40 percent in 2016 (European Commission 2018). This affects above all the very young and the very old sections of the population (Lucas and Jones 2009). It is an indication that supposedly weaker groups of people are often disadvantaged in automobile-oriented road traffic. Frumkin (2002) added that footpaths can bring health benefits with them. However, if they are not safe and attractive, pedestrians would think twice before exposing themselves to potential danger.

Effects of land use decisions

- *Physical activity:* This effect is based on the assumption that the transport behaviour of the population is oriented towards given land use decisions and developments. In this case, decisions in favour of the automobile contribute to fewer people taking active forms of transport, such as walking or cycling. The modal splits, Pucher (1997) investigated for European and North American countries, may have changed in recent years, but they suggest that the role of active modes of transport varies in several countries. There is a big difference between (northern) European countries and the USA and Canada. For example, the Netherlands shows a mix of 30 percent cyclists, 18 percent pedestrians and 45 percent car drivers. In the USA, by contrast, 84 percent of motorists were met by only nine percent pedestrians and just one percent cyclists.

  Lucas and Jones (2009) and Frumkin (2002) attributed negative psychological and physical effects on health to this trend of traffic behaviour with little physical activity. Obesity, cardiovascular disease, strokes restricted mobility and altered child development were reported. Obesity itself comes along with multiple health risks, like diabetes, heart diseases, cancer, disability and increased morbidity (Branca 2007; Frumkin 2002).

- *Water quantity and quality*: With changes in biodiversity, food safety, air quality, Frumkin (2002) saw major health issues for affected populations.
- *Heat island effect*: Possible consequences, especially for chronically ill and elderly people are heat cramps or even heat strokes (Frumkin 2002). With respect to increasing urban sprawl in some regions, this effect is certainly more noticeable there.

<u>Social aspects of sprawl</u>

- *Mental health*: Here, Frumkin (2002) mentioned the following effects: Loss of closeness to nature, source of stress, stress-related health problems, physical complaints (e.g. back pain from commuting), cardiovascular diseases and road rage. Further, Dora and Phillips (2000) dealt with negative neurotoxic effects of lead emissions from petrol on the human brain function, post-traumatic stress disorders after traffic accidents, aggressions and nervousness.
- *Social capital*: Without elaborating further on the sociological concept of social capital, Frumkin (2002) reported lower civic engagement due to long commuting times. Furthermore, he presents an economic stratification of the population of individual districts. He also addresses the problem of "empty nesters". It describes events surrounding the loneliness of older people whose children have moved out from home and possibly even left the neighbourhood or the city. Dora and Phillips (2000) described changes in the social life of children caused by the lack of safe transport and leisure infrastructure.

2.1.4 Inequality

As a direct sign of transport related inequality, Lefebvre (1992) mentioned that “Owners of private cars have a space at their disposition that costs them very little personally, although society collectively pays a very high price for its maintenance”. Dupuy (1999) said that through the establishment of an automobile system a regular life without a car is increasingly difficult. Kenyon et al. (2002f.) described mobility-related exclusion as:

“The process by which people are prevented from participating in the economic, political and social life of the community because of reduced accessibility to opportunities, services and social networks, due in whole or in part to insufficient mobility in a society and environment built around the assumption of high mobility.”

The issue of equity currently plays a major role in the mobility sciences. Especially with regard to the use and distribution of cars, many different classifications and explanations can be found. Geurs et al. (2016) distinguished between process and outcome equity. Mattioli (2013) compared intra- and intergenerational equity. Intragenerational equity simply means that there is equity among people of the same generation. For example, inequities in the transport sector could be resolved by making it easier for the entire population to access cars, which in turn would lead to intergenerational inequity due to future environmental impacts.

Litman (2002) divided the problem into horizontal and vertical equity. Horizontal describes that people with equal skills and resources also have equal opportunities. Vertical equity is the provision of opportunities for people to participate in mobile life, irrespective of financial, health or other factors. This concept of equality and equity is also applied in recent publications, for example by Duran-Rodas et al. (2020), who added efficiency as a third distribution rule.

Regarding horizontal transport justice, people who have the possibility to buy a car but do not do so for personal reasons, still have to pay for the transport infrastructure and bear the negative externalities, while they need to rely on a comparatively poor public transport service. For “Vertical Equity with Respect to Income”, Litman (ibid.) mentioned that policies benefiting the poor would be necessary to reach equity.

Jeekel (2014) identified a spatial mismatch between living and working places for poorer and less educated households. He also noted that “many poorer households have cars, but their mobility comes at a price; a great part of their household income goes to car mobility” (ibid.). Mattioli and Colleoni (2016) named four main equality problems as being car deprivation, car-related economic stress, oil vulnerability and car-related time poverty. Coming up with the idea of relieving the burden on poorer households, for example by a parking subsidy, Litman (2002) replied that “a transport subsidy that can be used for any mode is more progressive because it benefits non-drivers too”, as a hint to “vertical equity with respect to need or ability”. Here he saw an extreme discrimination of all people who cannot or do not want to participate in car traffic.

Fol et al. (2007) emphasized that many employers sometimes see a driving license as a necessity for potential employees, which makes non-car users unemployable. Hawley et al. (2020) saw drivers´ licensing as an access barrier to social life for young people. They also referred to the concept of “forced car ownership” which describes people or households owning a car for accessibility reasons despite financial difficulties.

A large amount of literature focused on finding out which societal groups suffer most from automobile-oriented traffic development. Lucas and Jones (2009) found that non-motorized households are predominantly located in the lower income groups of the British population. Similarly, people in the lowest income group travel less than half the maximum annual travel distance. Fast (2020) found that in metropolitan areas in the United States low income groups often live in remote areas and therefore their children have longer journeys to school. She came to the result that black primary school pupils and pupils whose mothers have less than a high school diploma have the longest journeys to school.

Conducting a survey of 57 non-motorized households, Villeneuve and Kaufmann (2020) found that "more than three out of four respondents in the modest income group had experienced feelings of mobility-related social exclusion, whereas more than three out of five respondents from the affluent income group had not". Ermagun and Tilahun (2020) tested the accessibility of six different destinations in Chicago for people of different ages, backgrounds, educational and income levels. The results showed that there were disadvantages for African-Americans, Hispanics, low-income workers, less educated and older people, because they have poor access to the transport system. They also found that especially workplaces, hospitals and grocery shops are often difficult to reach. Due to the positive benefits that buying a car brings, few want to do without this luxury, which is reflected in the growing stock of registered vehicles in the EU (European Commission 2018). The resulting lower use of other traffic options leads to their reduction in quality and quantity (Litman and Laube 2002). For example, buses are offered only at lower frequency (Lucas and Jones 2009). The entry into the world of the automobile, which is indispensable for some people, thus leads to even greater problems for those who cannot participate (Lyons 2003). This is supported by the survey of Villeneuve and Kaufmann (2020) to whom respondents confirmed disadvantages in territorial accessibility, time-related aspects, and preferential treatment for car drivers in the labour market and at the political level.

2.1.5 Economy

Litman and Laube (2002) researched macroeconomic consequences of car oriented development. This in other words means the effects on general economic development, productivity, competitiveness, and employment. They found that many public policies assume that increased use of the automobile brings macroeconomic benefits. However, for these benefits to accrue to the whole economy and not just the motorists, car use must increase the productivity of the entire local industry. They concluded that automobile dependency can reduce economic development. In general, the phenomenon comes along with many external and internal costs that are not only borne by the car users themselves but also by society as a whole. The theoretical evidence showed that increased car usage brings less incremental benefits. They also emphasized that the automotive industry has not been particularly productive in recent years.

Litman (2002) explored the costs of automobile dependency to society and also the benefits of a more balanced transport system. Starting with the observation that numerous market distortions contribute to a preferential role of the car in the transport sector, he examined the costs of car dependence for consumers, society, and the economy. Eventually he concluded that car dependence brings benefits to motorists in some cases, but hardly any significant external marginal benefits. Instead, there are several economic, social, and environmental costs, such as land use and community impacts, that are primarily borne by society as a whole and often particularly affect disadvantaged groups.

2.2 Defining car dependence

According to Dupuy (1999), all of the previous mentioned negative externalities come from a "virtuous (magic!) circle of positive effects spurring the growth of the automobile system". He further referred to accumulating stages, which will finally lead to car dependence. This section deals with the definition and perception of the concept of car dependence. It explains how the term is understood and applied for this study project.

2.2.1 Working definition of car dependence

Since the terms Car or Automobile Dependence came up, different definitions have been used. Lucas and Jones (2009) noted that the term is often used to describe a variety of different issues related to car use and dependence. The main features entail a high share of automobile use and ownership, a car oriented land use pattern and limited travel alternatives (Litman and Laube 2002; Newman and Kenworthy 1999; Wiersma et al. 2013; Victoria Transport Policy Institute 2019). Zhang (2006) described car dependence as the likelihood that driving is the only element in a traveller's possible choice of transport modes, after forming the choice set of transport modes and the mode choice decision. Mattioli et al. (2020) depicted it as the process by which car use has become "a key satisfier of human needs, largely displacing less carbon-intensive alternatives". Mattioli (2013) also defined it as a "dynamic, unrelenting and self-reinforcing macro-social process with systemic properties, (…) that strongly resists any deliberate attempt to induce change, despite increasing awareness of its negative externalities." He adds that it "tends to progressively widen the gap between the benefits of the automobile system for car users and the situation of non-car users". Goodwin (1995) also acknowledged that it is more a process than a state operating on the individual and social level. Litman and Laube (2002) saw negative economic, social and environmental impacts as a part of this process. Both Litman and Laube (2002) and the Victoria Transport Policy Institute (2019) saw a balanced, multi-modal transport system as the opposite of the described phenomena.

According to some of the mentioned resources, for this study project, car dependence is understood as a transport development, which is focussed on the car as the main mode of transport. It is noticeable in terms of an accessibility gradient between cars and other transport modes as well as in a lower accessibility of opportunities without a car. The consequences are car-oriented travel decisions and thus negative externalities.

2.2.2 Types of car dependence

There are different approaches to describe car dependence. Lucas (2009) described three perspectives: car users and their degree of connection to the car, type of activities and the need for a car for these activities and finally the typology and accessibility with or without a car in different regions. In alignment with Lucas, Mattioli et al. (2016) referred to these as micro, meso and macro levels of car dependence.

A further classification into subjective and objective dependence was described by Behren et al. (2018). The subjective grading occurs through a "combination of the 'affinity' (..) and 'perceived need' of car use (…)", whilst the objectiveness can be seen in every individual´s travel behaviour and the question if "everyday life without a car is difficult or easily feasible" (ibid.).

Taking into account the aforementioned classifications, this project tests a method that analyses objective car dependence on a macro level. However, by considering different localities, the meso level is also included. Ideally, the results can help to bring about changes in transport and land use that influence people's subjective choice of transport mode and thus also the micro level.

2.3 Assessing car dependence

The definition and nature of the concept of car dependence vary widely, so do the assessment methods. At first, subjective assessment methods are considered here. Dupuy (1999) measured positive sectorial effects of the automobile sector for car drivers in terms of accessibility to services using data from France concerning automobile use and ownership. Zhang (2006) used a comprehensive traffic survey to calculate the likelihood that driving is the only element in one's travel choices as the degree of car dependence. Zhao (2011) developed a subjective measure of car dependence based on personal perceptions of a surveyed user group. In this way, subjective car dependence, actual travel behaviour and the intention to change it could be compared. It was found that actual car use explained about 50 percent of the variation in subjective car dependence. The focus of Mattioli et al. (2016) was on meso-level car dependence. They tried to find out why and in which activities cars are irreplaceable. For a list of 55 activities, the mobility intensity, and the probability that the activity is associated with car use were calculated. The data basis was the British Time Use Study. It emerged that especially accompanying children, shopping and transporting goods can be classified as car-dependent. Behren et al. (2018) questioned groups of people in Berlin, San Francisco and Shanghai on the components travel behaviour, psychological factors and awareness of technology, and afterwards calculated their objective and subjective car dependence. Zhang et al. (2020) analysed a household travel survey of 1280 respondents in Beijing to explore influences of accessibility and transit access on household car ownership using a machine learning approach.

These concepts led to interesting results, but the focus of this study project is on objective car dependence, which are now presented. However, parts of the mentioned methods will be integrated into the methodology for assessing car dependence in this study project. This will be discussed in detail in the following sections.

MacKenzie (2009) developed a scorecard which was used to calculate car dependence by analysing 34 transport related factors. These were divided into four categories: sustainable accessibility of opportunities, pedestrian and cycling infrastructure, reliability of the public transport network and pricing structure of public transport. Using the average scores of the regions studied in England, car dependence grades were compiled. Motte-Baumvol et al. (2010) investigated the travel behaviour in the Paris metropolitan region by using mobility data from a transport survey and dividing the population into car owners and non-car owners on the one hand and into four levels of car dependence on the other. Wiersma et al. (2013) analysed access to daily amenities and jobs in the Netherlands. Using predefined thresholds and the national mobility balance, they worked out where citizens never need a car, occasionally need one or need a car every day. The latter were then considered car dependent. Four spatial characteristics were identified as indications of car dependence: Population density, settlement size, transport infrastructure and mono- or polycentricity. Siedentop et al. (2013) developed an indicator approach for the Stuttgart test region, which analyses objective indications of the need for a private car due to the lack of mobility alternatives. Wang (2013) mapped the walking and public transit accessibility for the city of Xiamen, China in order to get an overall image of the objective car dependence. As a part of the research around the TUM Accessibility Atlas, Büttner et al. (2018) compared regional accessibility for automobile and public transport to jobs and population in the Munich Metropolitan Region. They found large discrepancies and recommended developing strategies to reduce car dependence and instead promote a competitive public transport system. Finally, Niklas et al. (2020) saw urbanity as a determinant of travel behaviour and therefore analysed it on a national scale at postcode level.

Referring back to the chosen car dependence definition, the approaches just mentioned tend to analyse either high car usage and ownership or public transport accessibility. The approach of this study work is to be distinguished from these approaches by considering both aspects. In addition, the role of routes covered on foot or by bicycle are also taken into account.

3 Methodology

Based on the concepts, definitions and methods mentioned above for measuring car dependence, a new approach is presented. It is intended to meet the following requirements: First of all, the properties for auto-oriented development should be considered. All components of the method must be comprehensible. To be able to represent the process clearly, it should be possible to visualize the results as detailed as possible. This leads to the last important feature, namely that the process can be reviewed without having to elaborate on the whole topic. Overall, the availability of the data required for the process must be ensured, especially in the study area. In order to apply the approach to other locations, it is useful to choose data regularly and easily available.

After initial considerations, a formula for calculating the degree of car dependence was developed. Car dependence has already been described as a traffic development that focuses on the car as the main mode of transport, with increasing disadvantages for public transport users, pedestrians, and cyclists. This definition already includes all components for the creation of an equation representing car dependence: the extent of car use and the accessibility for people without access to car traffic. The equation developed in this study project will be presented in more detail.

Subsequently, a method is needed to collect more insights on factors that indicate car dependent development. Multiple linear regression is a simple method to “directly accommodate multiple predictors” (James et al. 2013) to predict responses to events. In this case, it is useful to investigate whether certain factors of development can lead to car dependence. This method and its application are described in detail in subchapter 3.2.

3.1 Car dependence factor (CDF)

Mathematically, the formula’s structure is simple. Anyhow, it contains all the necessary elements of the definition of car dependence.

$$\mathrm{CDF} = \frac{\mathrm{CO}}{\mathrm{A}} \tag{1}$$

$$\mathrm{A} = \frac{1}{\mathrm{n}} \sum\nolimits_{i=1}^{n} x_i \tag{2}$$

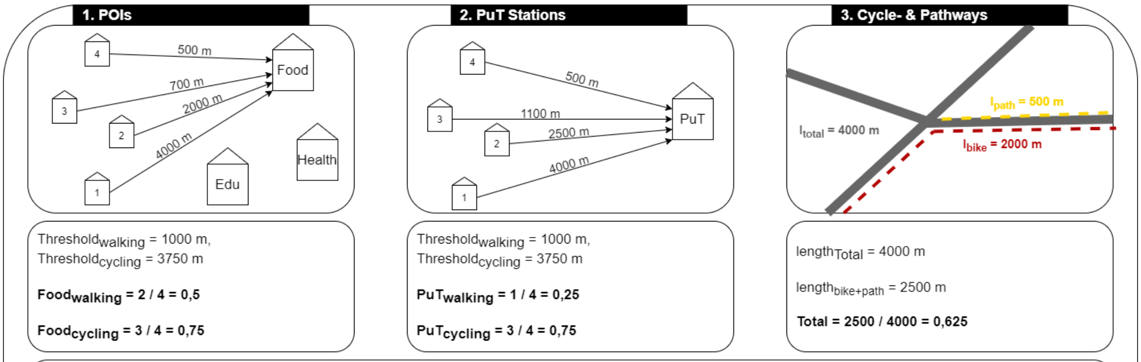
Car ownership

In equation (1), CO stands for car ownership, which is an indication for car usage, as it is generally the case in European countries (European Commission 2018). Car ownership refers to the degree of motorization, which is the average number of cars per one thousand inhabitants. In contrast to detailed listings of the use of different means of transport in different regions, car ownership is often documented by official institutions and publicly accessible (e.g., in the "Indikatorenatlas"[5] of the city of Munich). One of the main data sources of this study project is the land transport model (LTM) for Bavaria of the PTV Group, which also contains figures of car ownership. The model is described in Pillat (2017) and collects a set of traffic data for Bavaria, which is divided into individual traffic zones.

Factor A

The denominator A can be described as an indicator of limited travel alternatives, meaning qualitatively poorer transport possibilities due to a reduced supply of public transport, cycle, and footpaths. It is further referred to as accessibility of opportunities. In equation (1), A is the average of three components of this indicator. Figure 4 shows a graphical representation of the factor, which consists of three individual parts.

At first, accessibility to facilities aimed at satisfying basic needs is considered. Without going deeper into the widely discussed concept of basic or existential needs, the three categories food, health, and education were chosen. The second factor is the accessibility to stations of public transport (PuT) stations, which serves as a substitute for the automobile. These two parts are determined by verifying from how many building



$$A = \frac{0.5 + 0.75 + 0.25 + 0.75 + 0.625}{5} = 0.575 = 57.5\ \%$$

Figure 4: Exemplary graphic representation of A. Here, only food was considered as POI.

[5] Available online at: https://www.mstatistik-muenchen.de/indikatorenatlas/atlas.html

blocks the locations mentioned are accessible on foot or by bicycle. This proportion of buildings is then presented as a percentage.

For this step, various data is required: to begin with, all building blocks of the investigated area are required. These can be obtained from Openstreetmap (OSM)[6]. Furthermore, the selected points of interest (POI) are necessary. Those can be obtained from OSM as well. For the three categories the following locations are considered: Health includes the tags "doctor" and "hospital", food includes "supermarket" and "greengrocer", and education includes "kindergarten" and "schools". The public transport stations are taken directly from the Munich transport and tariff association MVV, whose network area is being investigated.

In order to obtain the percentage of POIs that can be reached on foot or by bicycle, the distances between all buildings and the nearest PuT station, health, education, and food supply are calculated. It is then examined whether these distances exceed a certain threshold value, which is chosen as the maximum distance for pedestrians and cyclists. For both pedestrians and cyclists a maximum travel time of 15 minutes is assumed. Whereas Siedentop et al. (2013) set the maximum walking time to PuT stations at 12 minutes, Sarker et al. (2020) found out that walking times up to 25 minutes are also accepted to a small degree. With the average speeds of three to five kilometres per hour for pedestrians and 15 kilometres per hour for cyclists described in Open Accessibility (2020), the limits for comfortable walking for pedestrians are set at one kilometre and for cyclists at 3.75 kilometres[7]. The percentage of buildings below this threshold is ultimately included in the accessibility of opportunities.

The third and last part of A is a proportional presentation of the availability of transport routes not explicitly intended for motor traffic. For this purpose, the road network in the study area is downloaded, once again by OSM. Within the individual traffic zones of the national traffic model (Pillat 2017), the total length of the road network and the length of the roads are then calculated, which are marked with the feature classes living street, pedestrian, bridleway, cycleway, footway, path and steps. The resulting proportion of the total network is then used as a last factor for A.

The three components mentioned above are combined to form the denominator, in which their average value is calculated. Finally, in the CDF, car ownership CO is divided by the access to opportunities A for each traffic zone. In this way, the equation primarily

[6] Via the platform “Geofabrik” (https://download.geofabrik.de/) OSM data structured by region and topic can be downloaded.

[7] Those travel distances go along with Daniels and Mulley (2013) and the European Commission (2020). Daniels and Mulley find that the average walking distance from home to public transport is less than one kilometre. The European Commission mentions an average trip length for cyclists of three kilometres in European countries.

indicates the degree of car ownership, divided by a potential lack of access to basic facilities with means of transport other than the private car. In the application one can think about a mathematical transformation of numerator or denominator, which can be useful for a more detailed investigation. For example, by replacing the actual denominator of the formula by the square root of the same denominator, particularly extreme values are relativized. Thus, a more precise examination of the otherwise rather average values is possible.

3.2 Association

To explore spatial factors associated with car dependence, a multiple linear regression (MLR) is conducted. Simple linear regression is an “approach for predicting a quantitative response Y on the basis of a single predictor variable X” which approximates a linear relationship between those two variables (James et al. 2013). MLR is an extension of this method by the number of predictors. The method is used here to explore the study area in more detail and to collect indications for the calculated CDF in the transport zones.

For the calculation of the MLR, integrated development environments like RStudio are practical. By saving the CDF together with potential predictors for every zone in a data frame, all necessary steps can be implemented. First, the correlations among the factors need to be identified. Since not all values will be normally distributed and outliers are to be expected (Hauke and Kossowski 2011), the Spearman correlation test (Spearman 1904) is applied. Following a conservative approach, factors are chosen whose correlation to the CDF is greater than 0.3. Furthermore, a threshold index of 0.7 is set to eliminate redundant variables (Duran-Rodas et al. 2019).

After selecting the factors, the MLR between CDF and these factors can be calculated. Factors with a p-value of less than 0.05 can be assumed to be reliable (Berkson 1942). In addition, the highest possible coefficient of determination R^2 is aimed for.

During the literature review, factors could be identified which are often related to transport development and car dependence. They can be categorized into the four groups POIs, population, transport, and land use. While some of the components regularly appear in socio-economic investigations, like income, gender or age, others are more uncommon, like the review of social milieus in Duran-Rodas et al. (2020).

Altogether, the approach consists of two parts: the calculation of the car dependence factor for every transport zone, and the multiple linear regression, which in the best case gives indications for these developments. The entire procedure is shown systematically in Figure 5. The complete application process and the results are described in detail in the next chapter.

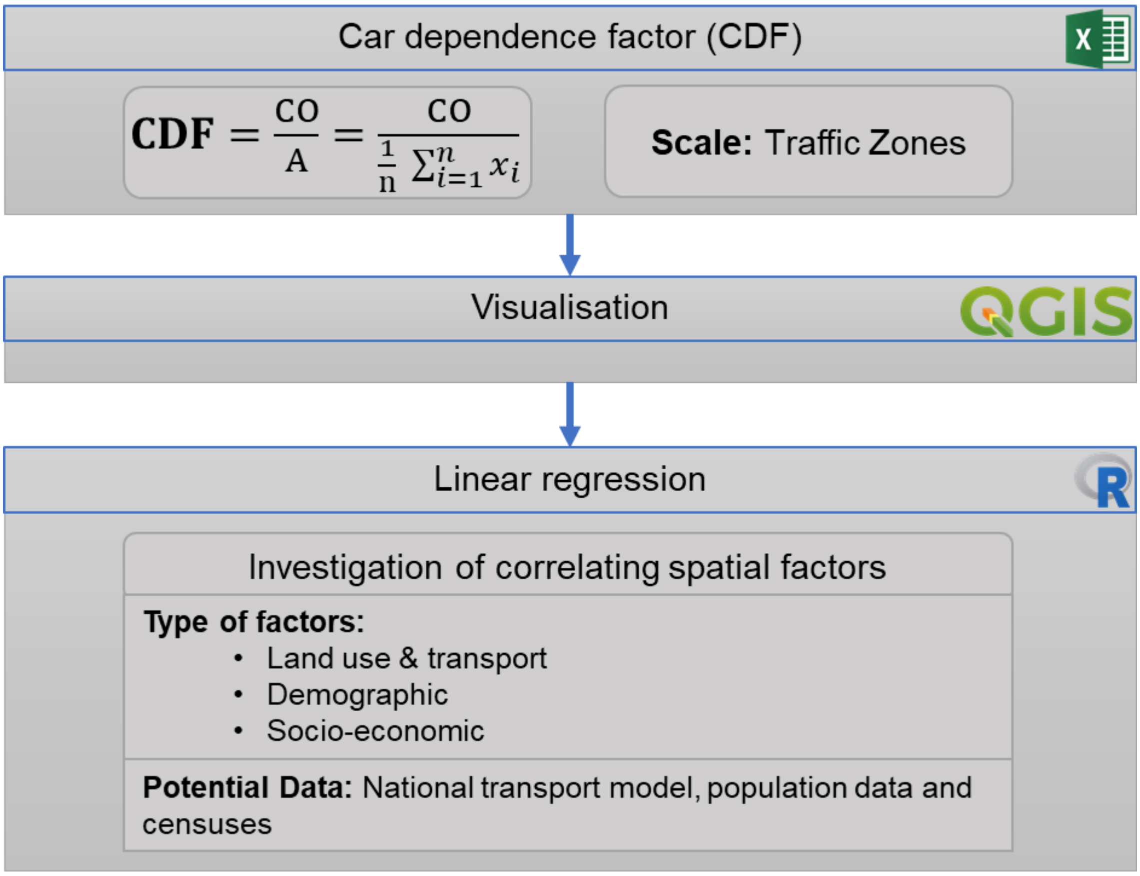


Figure 5: Approach to assess car dependence quantitatively.

4 Application

4.1 Study area

For this study project, the introduced method was applied for the service area of the Munich Transport and Tariff Association MVV. The study area consists of nine counties, which together cover 5711 km² with almost 3 million inhabitants in 176 municipalities (MVV 2020). Figure 6 depicts the study area and its location.

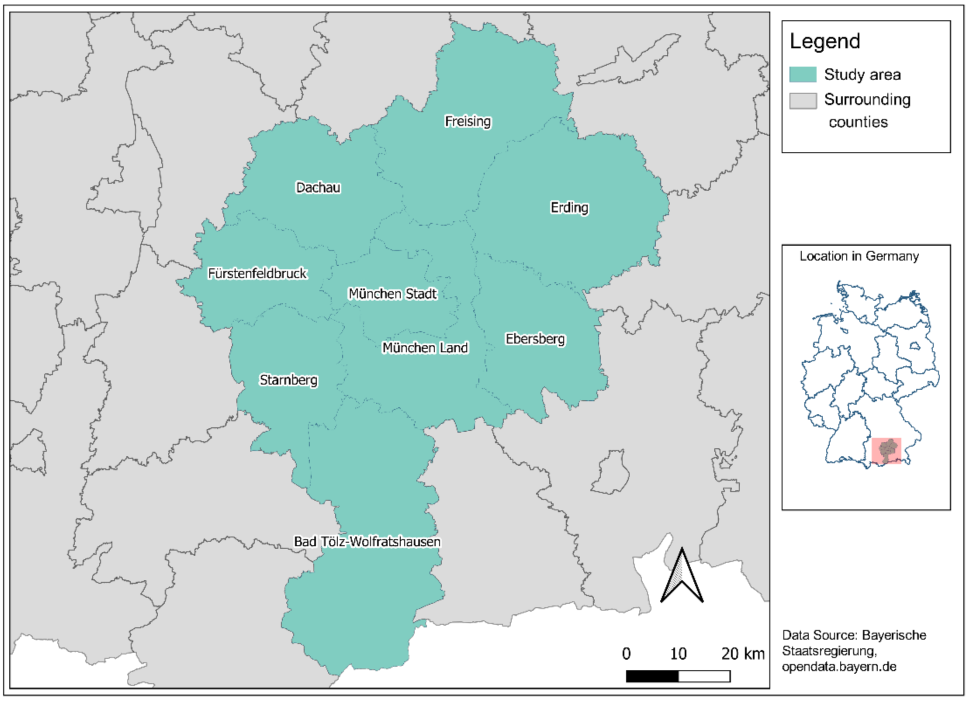


Figure 6: Location of the study area.

The area around the metropolis of Munich has various traffic attractors. One of them is the airport, which is the second largest airport in Germany with an annual passenger volume of 44.6 million (Landeshauptstadt München 2020b). Industry and higher education also play a key role. With BMW AG and MAN SE, two well-known players in the automotive industry are located here. The area can generally be described as extremely economic, with six of the 30 largest and highest-turnover listed companies in Germany located in the Munich area (Landeshauptstadt München 2020a). With three state universities and more than ten other institutions of higher education, the Bavarian capital is an important educational location in southern Germany (StMWK 2020).

In terms of traffic, almost 1.7 million passenger cars are registered in the area (MVV 2020). The public transport operator MVV offers 388 lines, which are served by subway, suburban trains, streetcars, and buses (ibid.). The main modes of transport are motorized individual transport (MIT)[8], which accounts for 46 percent of all distances travelled, and public transport, which accounts for 18 percent (Follmer and Belz 2018). Furthermore, 21 percent of the distances are covered on foot and 15 percent by bicycle (ibid.).

4.2 Data and software

The main data basis for the study of the Munich region was the Bavarian land transport model (LTM) of the PTV Group. It is a macroscopic model that is used to support operational and strategic planning in the area of road traffic as well as for traffic-related issues of public transport (Pillat 2017). In the model, data from 2014 was used to calculate zones for domestic traffic using the steps of traffic generation, distribution, modal split, and traffic assignment. Smaller communities often represent a single traffic cell, but larger ones are subdivided into individual zones (ibid.). Figure 7 shows the spatial division of the traffic area in and around Munich into 661 traffic zones.

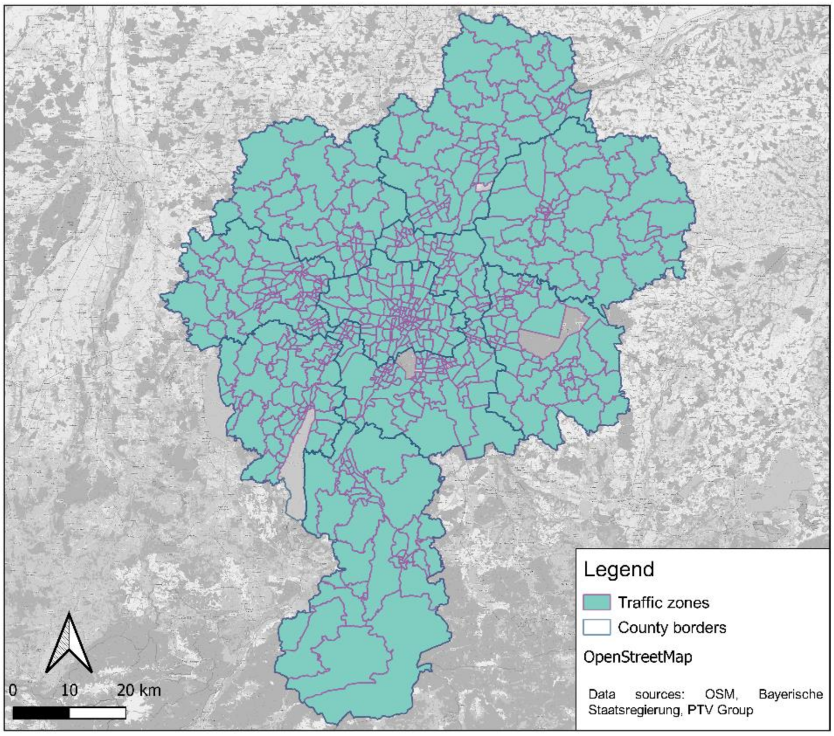


Figure 7: Traffic zones of the study area.

In addition to the zoning itself, the LTM contains various parameters on MIT and PuT as well as basic structural data such as inhabitants, jobs, POIs, and attraction potentials of the individual zones. Here, for the assessment of car dependence, the values of car

[8] In the present study, MIT includes car use, but also (small) motorcycles and commercial vehicles. The study also distinguishes between drivers (34 percent) and passengers (12 percent), which is not done here for simplicity reasons.

ownership, as well as key values for the linear regression were obtained from the model. Thus, Figure 8 shows the distribution of car ownership in the study area.

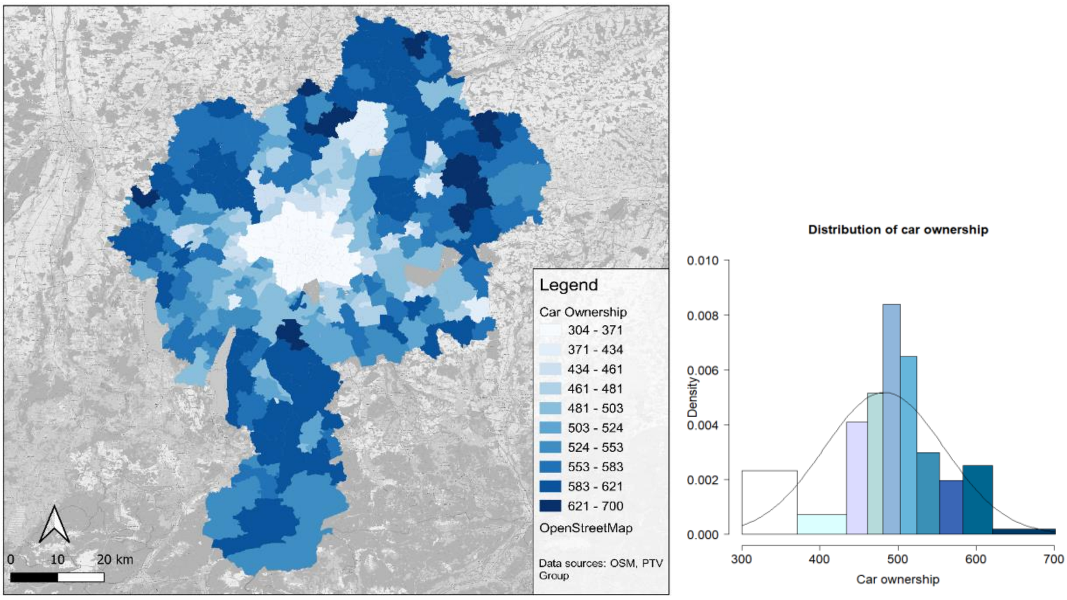


Figure 8: Car ownership [cars / 1000 inhabitants] in the study area.

The data, which was further necessary for the calculation of the car dependence factor could be obtained from different sources. The geodata of PuT stations were found directly at the transport provider „Münchner Verkehrs- und Tarifverbund GmbH (MVV) “[9]. The geodata for buildings in the study area, as well as both the selected POIs and the traffic network were obtained from OSM with the help of the provider "Geofabrik". As an additional source for regression factors, the statistics portal as well as the "accident atlas" of the German federal and state statistical offices was included.

The data processing was realized with QGIS, MS Excel and RStudio. QGIS is a geographical information system (QGIS 2020), which was used primarily for visualisation. Additionally, QGIS was used measuring areas and distances, as well as counting POIs. After a preparation of the different data, the car dependence factor was calculated using Microsoft Excel. Finally, the linear regressions were performed with RStudio, an integrated development environment and graphical user interface for the statistical programming language R (Rstudio 2020). The detailed implementation of the method and its results are described below.

[9] Available online at: https://www.mvv-muenchen.de/fahrplanauskunft/fuer-entwickler/opendata/index.html.

4.3 Applying the approach

In order to test the new method for the first time, it was applied to the study area. First, the CDF was calculated for all traffic zones and then the linear regression was performed.

4.3.1 CDF

Data pre-processing

The first step of the process was data pre-processing. The zones from the LTM have been loaded as a layer into QGIS. The LTM layer was reduced to the actual size of the study area, a geometry check was performed and unneeded properties[10] were removed. Furthermore, the area of each zone was calculated and stored in the layer. The 661 zones were thus described only by the following properties: Identification number, name, car density and area. These steps have been made to simplify the following process.

Distance calculation

Next, the geodata of all buildings, PuT stations and the POIs were added as separate layers. In the study area, there are approximately 700 thousand buildings, 5100 PuT stations, and almost 3200 POIs, divided into 1100 educational, 1100 health, and 1000 shopping facilities. After creating centroids for the buildings, which are represented as polygons by OSM, the shortest distances between all buildings and the closest PuT stations and POIs was calculated using the distance matrix function of QGIS. These distances were saved in a separate layer and exported as a CSV file.

This file could then be used to continue working in Excel. Figure 9 shows a section of the spreadsheet. Column A stores the identification numbers of all buildings. Column B shows the identification number of the closest PuT station and column C the distance to the station. In column D, the distance between the building and the PuT station

	A	B	C	D	E	F	
1	InputID	PuT_TargetID	PuT_Distance [m]	PuT_Real [m]	PuT_walk	PuT_bike	H_
2	5423	1010	196.33	255.23	1	1	
3	11929	291	154.20	200.46	1	1	
4	13171	1016	310.39	403.51	1	1	
5	14736	67	88.71	115.33	1	1	
6	14897	1	134.39	174.71	1	1	
7	15909	1464	117.80	153.15	1	1	
8	20383	6190	248.21	322.67	1	1	
9	20841	60	172.09	223.72	1	1	

Figure 9: Extract from the Excel file for calculating the distances between buildings and PuT stations.

[10] As mentioned above, the LTM contains various data related to the traffic zones. For this study project only, data related to the traffic network and the districts were needed. Data on routes, connections, counting points, matrices and stops could be removed.

calculated by QGIS is multiplied by a factor of 1.3, which is to get closer to the real path distance (Reneland 2001). Columns E and F were then used to verify that the resulting distances were less than the selected walking distance of 1000 meters long and the selected bicycling distance of 3750 meters, respectively. The result was output in binary form, where 1 stands for true and 0 for false. These steps were performed four times each for all buildings to evaluate their distance to PuT stations and the three categories of POIs.

Access to opportunities

The next step was to import the CSV file back into QGIS and intersect the traffic zones with the buildings and their distances. The total number of buildings within a traffic zone was counted, followed by the number of buildings within walking and cycling distance to the four different locations. This information was again stored in the layer of the LTM. Additionally, the OSM transport network file was loaded into QGIS. Here, the total length of the road network within a traffic zone, as well as the length of all roads that are not built for automobiles, was calculated. These values were also stored in the LTM layer.

CDF calculation

With the available data, the calculation of the CDFs were again performed in MS Excel. In a single spreadsheet, the factors that make up the denominator A in the CDF equation were calculated first. For the four factors linked to localities, the proportions of buildings in walking and cycling distance within each zone were calculated. The fifth factor was calculated proportionately from the length of routes that are not for cars and the total street length. The density distribution of the accessibility of opportunities A can be seen in Figure 10. As a final step, the CDF could now be calculated as described in equation (1) and (2). The outcomes were again loaded into QGIS and visualized. Figure 11 shows the result of the calculation.

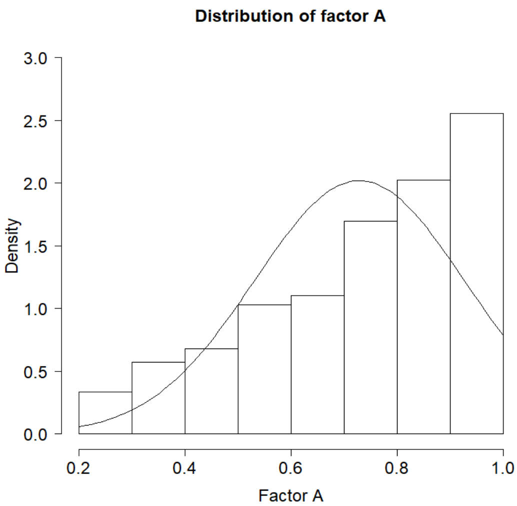


Figure 10: Distribution of denominator A.

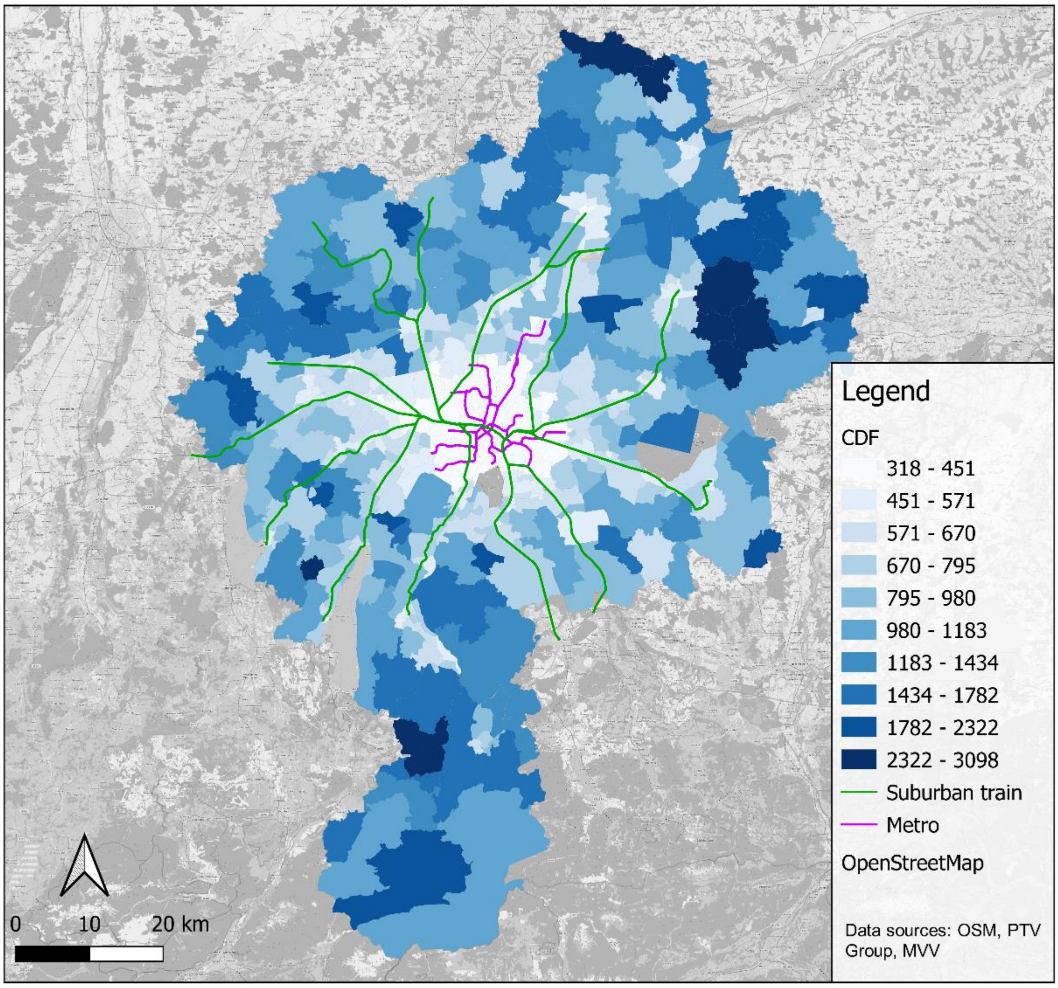


Figure 11: Car dependence in the study area.

4.3.2 Linear regression

Factors that can contribute to a change in traffic development could be taken from the literature research. Most notably, factors related to land use and transportation, demographics, and socioeconomic drivers were mentioned. The availability of these data was examined. In addition, the LTM and the Federal Statistical Office were searched for further possible indicators. The values that were considered for the multiple linear regression were stored in a CSV file zone by zone together with the calculated CDF. With the help of RStudio, the descriptive statistics could then be collected for the time being. In Table 1 all factors are summarized that were considered for the study area and publicly available.

Table 1: Descriptive statistics.

		Min.	St. Dev.	1st Qu.	Mean	3rd Qu.	Max.
	CDF	317.8	431.3	519.3	767.2	858.8	3098.4
1	**Crashes**	0	19.3	4	14.8	17	128
2	**Crashes with cyclist/pedestrian**	0	11.0	1	6.71	7	75
3	**Percentage of accidents involving cyclists/pedestrians [%]**	0	0.3	0.167	0.4249	0.647	1
4	**Population density**	0.01	39.4	2.41	27.39	37.71	312.34
5	**Job density**	0	56.6	1.14	21.97	17.94	690.76
6	**Proportion of old and young population**	0	0.0	0.31	0.3381	0.37	0.47
7	**Land purchase value [€/ha]**	263.6	753.5	660.6	1263.5	1703	2638.2
8	**Income tax (p. pers.)[11] [€]**	0	3.4	5.074	6.949	7.86	27.871
9	**Number of employees (p. pers.)**	0	0.4	0.276	0.5062	0.665	2.515
10	**Inbound commuters (p. pers.)**	0	0.4	0.125	0.331	0.405	2.41
11	**Residents (p. pers.)**	0	0.1	0.432	0.4648	0.508	0.657
12	**Outgoing commuters (p. pers.)**	0	0.2	0.28	0.3155	0.418	0.596
13	**Saldo (p. pers.)**	0	0.3	0.042	0.2066	0.271	1.958
14	**Total commuters (p. pers.)**	0	0.4	0.51	0.6472	0.84	2.86
15	**Proportion of women [%]**	0	0.0	0.507	0.5086	0.52	0.54
16	**Stations (p. zone)**	0	7.3	3	7.772	10	60
17	**Stations (p. ha)**	0	0.1	0.008	0.04276	0.056	1.828
18	**Distance to next town [m]**	40.9	3057.3	1328	3514.8	4876.3	20664.1

Description of the factors

- Factors 1 to 3 have been obtained from the “accident atlas” of the German federal and state statistical offices (Statistische Ämter des Bundes und der Länder 2020b), where all accidents with human injuries are registered nationwide. While **crashes** depicts the total number of crashes within a zone, **crashes with cyclist/pedestrian** shows the amount with involvements of pedestrians or cyclists. Factor 3 is then the percentage of both.
- Factors 4 to 6 have been part of the LTM. **Population** and **job density** are the number of inhabitants, respectively jobs divided by the area of every zone. The factor **proportion of old and young population** describes the proportion of

[11] "p. pers." stands for "per person". Factors with this abbreviation have been broken down to the population of the traffic zones.

people in the total population who are under 14 years of age or over 64 years of age. This factor was chosen with regard to the dangerousness of road traffic for weaker groups of people (see Chapter 2.1).

- Factors 7 to 15 are taken from the Federal and State Statistics Portal (Statistische Ämter des Bundes und der Länder 2020a). Since the values were collected at the municipal level, factors 8 to 14 had to be broken down to the respective population (p. pers.). In this statistic, employees are described as those who are subject to social insurance contributions. The **saldo** factor calculates the difference between outbound and inbound commuters. The factor **total commuters**, on the other hand, calculates their sum. Both factors were considered to identify possible differences. The factor **proportion of women** was included to identify possible gender differences. The proportion of men could just as well have been chosen as a counterpart with a similar result.
- Factors 16 to 18 were added from within the QGIS project. Both factors concerning stations relate to the MVV stations in every zone. The second one is referenced by the zones surface area. The factor **distance to next town** was obtained by calculating the distance from every traffic zones´ centre to the closest of all 43 towns or cities[12] within the study area.

Correlations and regression

Figure 12 shows the correlation matrix with Spearman's method, which was performed to find the correlations between CDF and the other factors. The main factors considered have an absolute correlation value greater than 0.3. These are crashes with cyclists/pedestrians (-0.52), percentage of accidents involving cyclists/pedestrians (- 0.46), population density (-0.80), job density (-0.81), land purchase value (-0.59), the number of employees in proportion to the population (-0.50), outgoing commuters (0.48), the commuter saldo (0.51), the share of women (-0.34), the number of stations per hectare (-0.61) and the distance to the next town (0.51). Additionally, income tax (-0.26) is also considered a possible regression factor, as its correlation value is close to 0.3.

Efforts were made to avoid using similar factors, as well as factors that have a high correlation to each other. Through several experimental runs of the MLR, the seven factors listed in Table 2 were proven to be statistically significant. The table also shows the individual p-values and the coefficient of determination.

[12] For this classification all elements defined as a town/city in the study area have been downloaded from OSM. The only “city” in the study area is Munich but there are 42 towns.

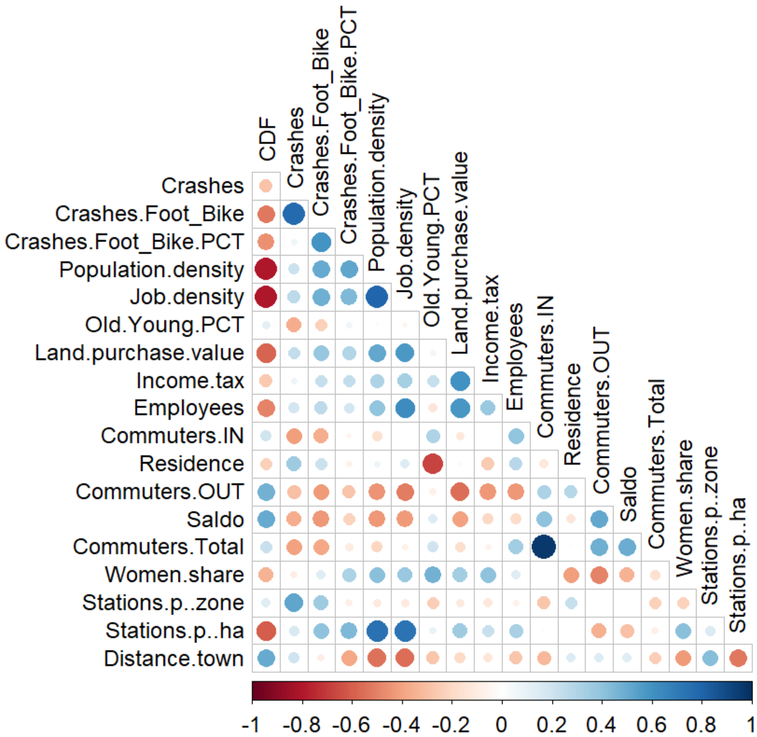


Figure 12: Correlation matrix of the studies variables.

Table 2: Feature selection and regression results.

	Std. Error	**Pr(>|t|)**	
Intercept	4.09E+01	< 2E-16	***
Percentage of accidents involving cyclists/pedestrians [%]	4.16E+01	3.67E-06	***
Land purchase value [€/ha]	2.25E-02	7.44E-10	***
Saldo (p. pers.)	7.50E+01	0.000000376	***
Income tax (p. pers.) [€]	3.69E+00	0.0332	*
Number of employees (p. pers.)	6.24E+01	0.000000775	***
Distance to next Town [m]	4.34E-03	< 2E-16	***
Residual standard error	294.6 on 654 degrees of freedom		
Multiple R^2		0.5377	
Adjusted R^2		0.5335	

Note: * p<0.05, *** p<0.001

4.4 Transformed approach

In order to describe the method for assessing car dependence, but also the study area, in more detail, a second trial was carried out. The CDF equation was simply changed so that the denominator A is square rooted. It was expected that this would normalize extreme values, allowing focusing on the car dependence expression in areas with average values. This permits for a two-step process in which the locations with extreme A values are assessed first, followed by the remaining locations.

$$\mathrm{CDF}_{new} = \frac{\text{Car ownership}}{\sqrt{\mathrm{A}}} \tag{3}$$

The steps for calculating the new CDF were the same as in the first trial. For the new factor, only the calculation formula in the spreadsheet was changed as shown in equation (3). The spatially represented results can be seen in Figure 13.

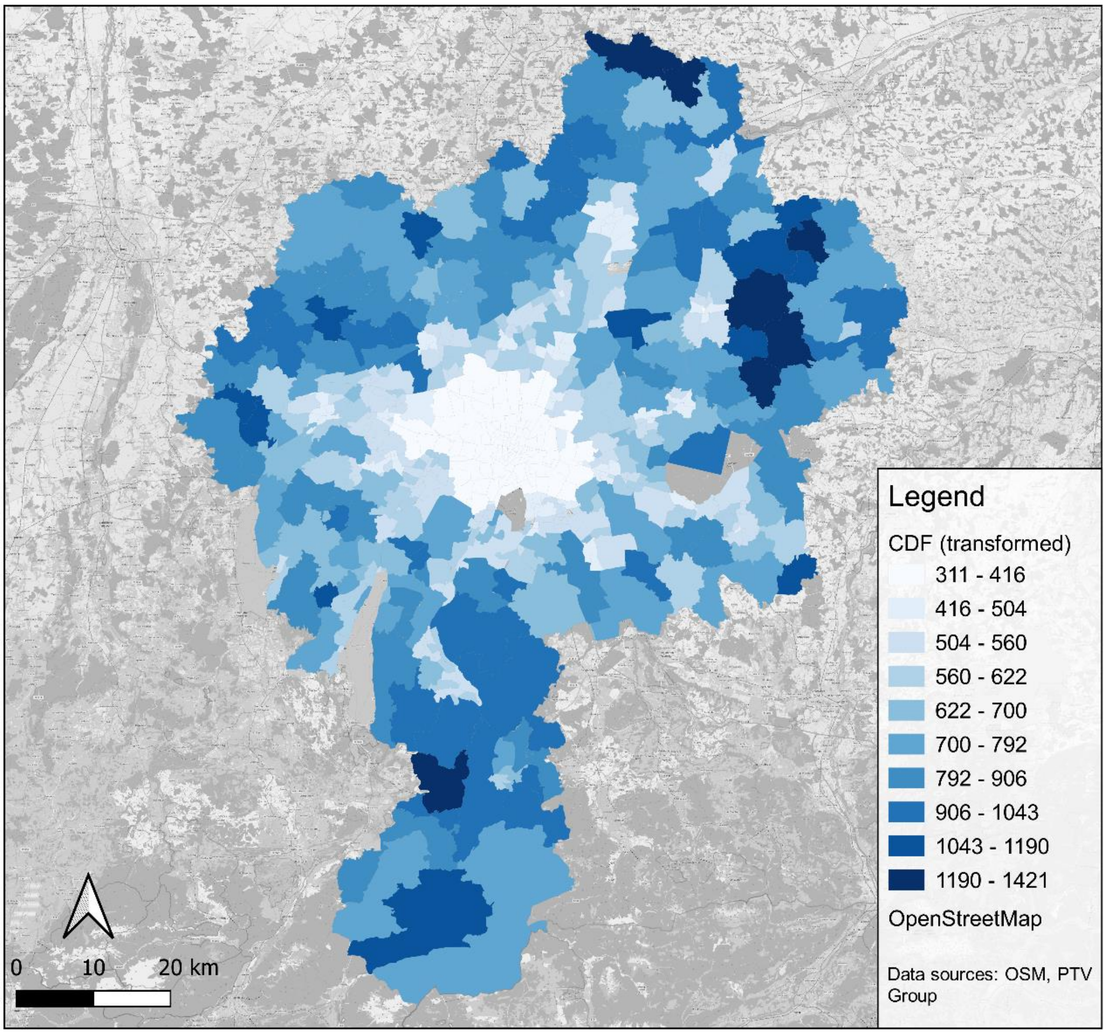


Figure 13: Representation of CDF_{new} in the study area.

The linear regression steps were also performed as before and with the same factors. Table 3 shows the descriptive statistics for the new CDF, all other values remained the same. In Figure 14 the distribution of CDF values of both trials are shown as a histogram. Figure 15 shows the recalculated Spearman Correlations matrix and Table 4 shows the results of the MLR.

Table 3: Descriptive Statistics CDF_{new}.

	Min.	St. Dev.	1st Qu.	Mean	3rd Qu.	Max.
CDF_{new}	310.6	190.5	488.8	597.2	671	1421

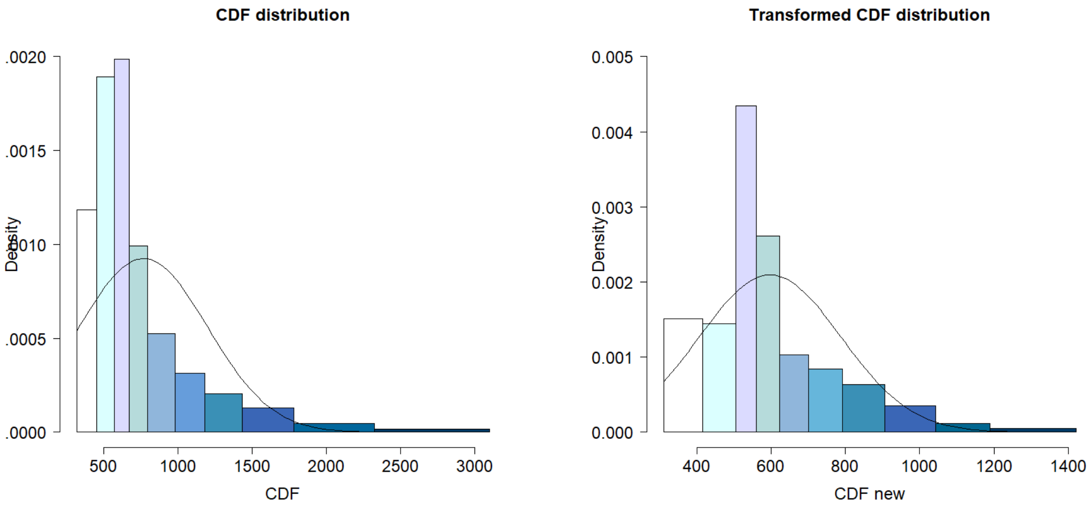


Figure 14: Distribution of CDF for both trials.

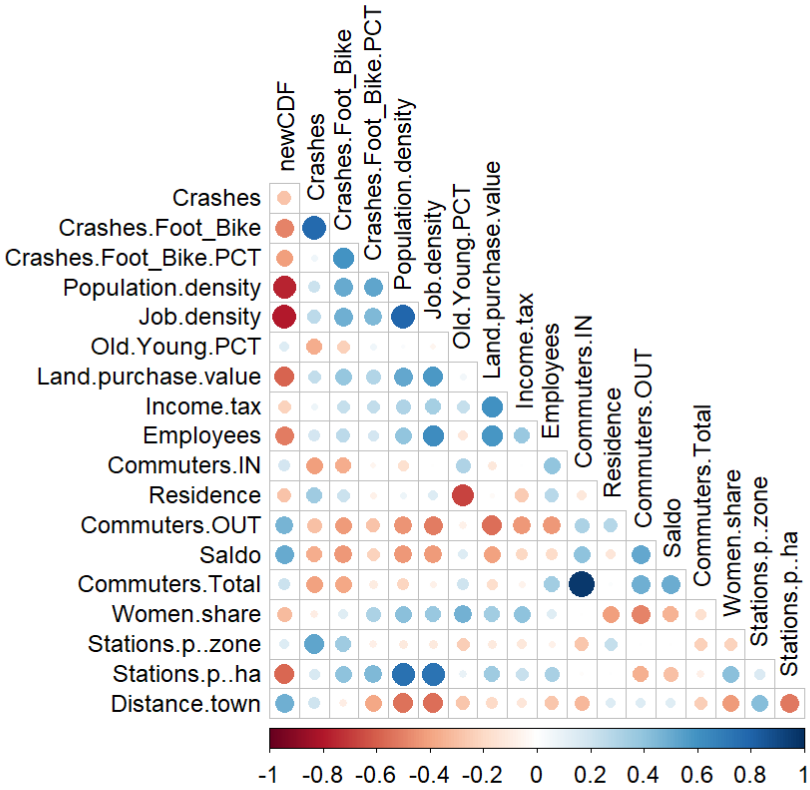


Figure 15: Correlation matrix for the transformed approach.

Table 4: Transformed feature selection and regression results.

	Std. Error	Pr(>|t|)	
Intercept	1.58E+01	< 2.00E-16	***
Percentage of accidents involving cyclists/pedestrians [%]	1.60E+01	6.22E-07	***
Land purchase value [€/ha]	8.68E-03	< 2.00E-16	***
Saldo (p. pers.)	2.89E+01	3.14E-11	***
Income tax (p. pers.) [€]	1.42E+00	9.55E-08	***
Number of employees (p. pers.)	2.41E+01	7.76E-11	***
Distance to next Town [m]	1.67E-03	< 2.00E-16	***
Residual standard error	113.6 on 654 degrees of freedom		
Multiple R^2		0.6476	
Adjusted R^2		0.6443	

Note: * p<0.05, *** p<0.001

5 Discussion

In this section, the results of the method for evaluating car dependence in the Munich traffic area, and the significance of the results are discussed. To conclude, the model is reviewed for limitations and possible improvements.

5.1 Interpretation of the results

In the two-staged approach of assessing car dependence quantitatively, the CDF was calculated first. A high CDF represents a high degree of car dependence and vice versa. Accordingly, regions with a high degree of motorization tend to be more car dependent. The lack the access to opportunities can then increase the CDF even further due to poor values. The MLR conducted afterwards led to information on spatial factors, which can be related to the given value of car dependence.

At first, the results of the first trial with the simple CDF equation are considered. Looking at the spatial distribution of the CDF, apparently region types play a role. In urban areas, the CDF seems to be lower than in rural areas. This is reflected in the study area by lower values in the centre, which increase towards the outside. Those areas with a minimal degree of CDF are the state capital Munich and parts of the cities of Garching, Erding and Freising in the north of Munich[13].

Maximum values are reached in zones, which are far from the centre of the study area. Except for the zone "Pöcking Aschering" in the southwest, all areas are located outside the catchment area of the suburban train. In general, proximity to the suburban train network seems to be a good indicator of rather low car dependence, as shown in Figure 11. A direct link is evident between CDF results and car ownership values. Areas with a higher number of cars have higher car dependence. However, areas with high car ownership rates, which are located close to the city or near the suburban trains, have relatively low CDF values. The coefficient of determination R^2 shows that the factors explain 53 percent of the variation in the CDF.

The results of the second run, with modified CDF equation show a similar spatial distribution. Cities, such as Munich, have a low CDF and more rural regions a higher one. Moreover, lower values are evident in areas close to suburban railroads, as well as in zones with generally lower car ownership rates. As expected, square-rooting the denominator led to a relativization of extreme values. This is less evident in the spatial

[13] These three cities are part of the Munich metropolitan region but are themselves quite prosperous. Garching and Freising are university locations TUM 2020 and both Erding and Freising benefit from Munich Airport Landeshauptstadt München 2020b, which is located in between both.

visualizations than in the comparison of the two histograms in Figure 14. Above all, it is noticeable that the frequency of extremely low car dependence values decreases.

The recalculated MLR results have changed in that the statistical significance of all factors has increased, as well as the coefficient of determination has improved. The factors can explain 64 percent of the variation in CDF values. Square-rooting the denominator resulted in higher statistical definiteness and significance.

Originating from the single factors of the conducted MLR, the following tendencies can be observed: Areas are more likely to be car dependent if they have a low number of employees, only few income tax revenues, low land purchase values, low shares of accidents affecting pedestrians or cyclists, a larger distance to the next bigger town and a high difference of out- and ingoing commuters. The exact bearing of these results will be discussed in the next subsection.

5.2 Relevance

The spatial visualisation of the study area authorizes that rural areas have higher car dependence values due to high car ownership and poor opportunities without car access. Some of the urban zones also have high values of car ownership, but due to public transport offers, proximity of POIs and a higher availability of walking- and cycling ways, have lower CDF values. That is the case in Erding for example. These results go along with Resnik (2010), Urry (2004) and Wiersma et al. (2013) and their explanations on car dependence, spatial separation, and urban sprawl. There is a uniform pattern of rural regions being more car dependent than urban regions due to greater travel distances.

The CDF alone can serve as an orientation for regional transport and urban planning. Furthermore, the regression provides references to spatial factors that have been addressed in the literature on spatial development and car dependence. The negative effects of distance to larger towns on the CDF, which were just determined in the spatial visualisation, could be confirmed by the linear regression factor "Distance to next town". Out of the three characteristic values for employees, income tax and the difference between inbound and outbound commuters, a common scenario can be identified. Places where few jobs are offered and generally less income tax is paid show higher car dependence. This effect has also been described by Fast (2020).

The regression factor of land sales values shows that structurally weaker regions tend to be more car dependent. Conversely, this would mean that land is more expensive if people in the area are less dependent on the automobile. This is interesting as Dargay (2001) has found a correlation between increasing wealth and car ownership. Wealthy people can hence afford an expensive property that is likely to be unaffected by car dependence. However, it is precisely these people who then contribute to car dependence by buying more cars.

The last regression factor can be interpreted in different ways. It displays that low shares of accidents affecting pedestrians or cyclists result in high car dependence. The other way around this would mean decreasing car dependence could end in higher numbers of cycling and pedestrian casualties. This outcome contradicts Lucas and Jones (2009), who mentioned that car dependence is especially affecting pedestrians and cyclists in terms of accidents. However, before continuing with the interpretation, it is worth examining the absolute proportion of active road users in regions with a high CDF. It is possible that in very car dependent areas the number of pedestrians and cyclists is very low, so that the accident possibilities are reduced. Furthermore, it will be useful to review the severity of accidents in car dependent regions.

The approach for assessing car dependence quantitatively, which was developed in this study project, can be understood as a contribution to transportation sciences. The method is useful to measure car dependence, if understood as the strong usage of cars with simultaneously few opportunities for other transport users. Additionally, linkages to existing literature on the topic are made via the linear regression. Those give insights into some factors, which can possibly influence areas concerning car dependent development.

From the results just described, some directions can be identified. For rural regions with high car dependence, better transport options must be created. In areas where the accessibility of opportunities is actually good, but car ownership is nevertheless high, more incentives must be created to drive less or even buy fewer cars. Here, the car users and their degree of connection to the car must be addressed.

Since car dependence is to a large extent also a topic of equity, this must also be addressed. In the study area, there is an equity gap between regions that are car dependent and those that are not. Car dependent areas are mainly found in the countryside and measured by jobs, income tax and commuting, tend to be structurally weaker. Furthermore, in areas that are not car dependent, land prices tend to be high. Thus, not everyone can afford to live in a car independent region. People with lower income must move to more remote places, where they need a car more often for daily activities, which would again lead to financial troubles. Reducing car dependence is therefore desirable in terms of equity.

5.3 Limitations

The method has its limits both in the application and in the interpretation. With car ownership as the numerator of the CDF, a specific value has been chosen that can give information on car usage but does not necessarily have to. One example would be an imaginary area, which is completely carless. Regardless of the value of the denominator A of the equation, meaning the access to opportunities without a car, the result would be a CDF of zero. This would lead to arguing whether cars might be helpful to improve the supply situation. In line with this, it would be important to classify why a zone reaches a high car dependence value whether due to high car ownership, fewer non-car options, both, or even none of both attributes. This becomes especially relevant if the car dependence study is to be followed by actions to improve the situation. For local stakeholders, it needs to be clarified whether car ownership or difficulties with transport for non-car users is an issue.

Regarding the factor of accessibility of opportunities, it can be noted that the availability of public transit was taken into account, but the hours of operation and the frequency of transport modes were not considered. Thus, in regions that have a PuT station, but the transport mode is very infrequent, the CDF values may be relatively low despite poor accessibility. Furthermore, only the three categories of health, education and food were considered as POIs.

Another potential problem could be the availability of data for the model. An attempt was made to select data and factors that are officially confirmed and publicly available, but this is not guaranteed everywhere. Furthermore, different data sources were combined in the application, which can always lead to inconsistencies. In any case, careful data maintenance is helpful and necessary.

Finally, it is worth mentioning that the Spearman correlation and the MLR should not be “overinterpreted” (Hauke and Kossowski 2011). Even if their results seem promising, they cannot be taken as evidence, but as indications.

6 Conclusion

This study project began with research of previous concepts of car dependence. The core part of the report was the description of a developed approach to assess car dependence. The defined method was then tested for the first time by applying it to the area of the public transport network of the city of Munich in Germany.

The major outcomes were that car dependence is mainly found in rural areas, which are far away from larger towns and the Munich S-Bahn network and have a high car ownership. Other factors associated to increasing car dependence were low numbers of resident workers, low-income tax revenues, a high difference between outbound and inbound commuters, low land prices, and a low proportion of cyclists and pedestrians involved in traffic accidents. The identified factors could explain the variation of car dependence for 53 percent in the first trial and for 64 percent in the modified approach.

Facing the effects of car dependence on environment and society, strategies to provide alternatives for car usage should be developed proactively and early. With the described approach for assessing car dependence quantitatively, related patterns can be identified and discussed directly with decision-makers and urban planners. Car dependence is a problem that has been created due to technical innovation, as well as economic, political, and cultural adaption. It may need the same forces to reorganize the socio-technical system of transport (Hopkins 2017).

The results of the method tested here for the first time can be used by local decision makers in various ways. The CDF can be used to discuss whether the car is perceived as the only viable mode of transport in an area. Existing public transportation structures can be expanded or the use of them can be encouraged. The factors considered in the MLR can also be looked at locally, such as the labour market or income tax revenues. While it is not expected that these values will change quickly, it can give an impression of how large the role of car dependence might be in the future. The overall process can serve to diminish car dependence: regions with already low CDF values will know how to proceed to avoid car dependence, while regions with higher values know that action should be taken. Especially with regard to higher car dependence in more rural regions and in places with little public transport, modern solutions such as on-demand mobility or carpooling should be considered. Furthermore, the integration of land use and transport with strategies such as densification, transit-oriented development and smart growth should be consulted. Zhang (2006) identifies two effects of these strategies in reducing car dependency: improving access and ultimately the actual modal choice of the population.

Recommendations for further research should be oriented to the amplification of the presented approach by dealing with the mitigation from the limitations already described. As components of the CDF equation, additional research can be conducted on car ownership and regarding the accessibility for opportunities without driving. Since car ownership is not the same as car usage, their connection should be further examined. Here, the procedure for regions without cars should also be considered. As part of denominator A, the availability of PuT stations was considered. The operating hours and frequency of the transport modes were left out but could be taken into account by inserting an additional factor, which still has to be figured out. Furthermore, additional research should be conducted on the topic of basic needs and the importance of individual localities as a contribution. Wang (2013), for example, implemented a weighting for the different types of amenities. Other methods of linking spatial factors with car dependence can also be considered. Like that, Zhang et al. (2020) describe an approach of nonlinear associations between accessibility and car ownership.

Ultimately, it will be helpful to automate the approach as much as possible to further explore and improve it. This will facilitate the implementation in further areas of investigation, which is necessary in any case to find out its overall added value.

Publication bibliography

Asphalt Institute Quarterly (1967). College Park, Maryland.

Banister, David (2011): The trilogy of distance, speed and time. In *Journal of Transport Geography* 19 (4), pp. 950–959. DOI: 10.1016/j.jtrangeo.2010.12.004.

Behren, Sascha von; Minster, Clotilde; Esch, Johanna; Hunecke, Marcel; Vortisch, Peter; Chlond, Bastian (2018): Assessing car dependence: Development of a comprehensive survey approach based on the concept of a travel skeleton. In *Transportation Research Procedia* 32, pp. 607–616. DOI: 10.1016/j.trpro.2018.10.015.

Berkson, Joseph (1942): Tests of Significance Considered as Evidence. In *Journal of the American Statistical Association* 37 (219), pp. 325–335. DOI: 10.1080/01621459.1942.10501760.

Branca, Francesco (Ed.) (2007): The challenge of obesity in the WHO European region and the strategies for response. Weltgesundheitsorganisation. Copenhagen: World Health Organization Regional Office for Europe. Available online at http://www.euro.who.int/document/E90711.pdf.

Büttner, Benjamin; Kinigadner, Julia; Ji, Chenyi; Wright, Benjamin; Wulfhorst, Gebhard (2018): The TUM Accessibility Atlas: Visualizing Spatial and Socioeconomic Disparities in Accessibility to Support Regional Land-Use and Transport Planning. In *Netw Spat Econ* 18 (2), pp. 385–414. DOI: 10.1007/s11067-017-9378-6.

Canzler, Weert; Radtke, Jörg (2019): Der Weg ist das Ziel: Verkehrswende als Kulturwende. Oder: Zur schwierigen Entwöhnung vom Auto. In *APuZ - Zeitschrift der Bundeszentrale für politische Bildung* 43/2019, pp. 33–38. Available online at https://www.bpb.de/apuz/298748/verkehrswende-als-kulturwende.

Daniels, Rhonda; Mulley, Corinne (2013): Explaining walking distance to public transport: The dominance of public transport supply. In *JTLU* 6 (2), p. 5. DOI: 10.5198/jtlu.v6i2.308.

Dargay, Joyce M. (2001): The effect of income on car ownership: evidence of asymmetry. In *Transportation Research Part A: Policy and Practice* 35 (9), pp. 807–821. DOI: 10.1016/S0965-8564(00)00018-5.

Dora, Carlos; Phillips, Margaret (Eds.) (2000): Transport, environment and health. World Health Organization. Copenhagen: WHO Regional Office for Europe (WHO regional publications European series, 89).

Dupuy, Gabriel (1999): From the “magic circle” to “automobile dependence”: measurements and political implications. In *Transport Policy* 6 (1), pp. 1–17. DOI: 10.1016/S0967-070X(98)00028-6.

Duran-Rodas, David; Chaniotakis, Emmanouil; Antoniou, Constantinos (2019): Automated open-source data collection and processing: an example of OpenStreetMap and bike-sharing. In *Transportation Research Procedia* 41, pp. 688–693. DOI: 10.1016/j.trpro.2019.09.117.

Duran-Rodas, David; Villeneuve, Dominic; Pereira, Francisco C.; Wulfhorst, Gebhard (2020): How fair is the allocation of bike-sharing infrastructure? Framework for a qualitative and quantitative spatial fairness assessment. In *Transportation Research Part A: Policy and Practice* 140, pp. 299–319. DOI: 10.1016/j.tra.2020.08.007.

EEA (2006): Urban sprawl in Europe. The ignored challenge: European Environment Agency (EEA report, 2006,10). Available online at http://publications.europa.eu/en/publication-detail/-/publication/5c1efd18-a7b9-41eb-8087-9bb2787267b6.

EEA (2007): Air pollution in Europe 1990 - 2004. Luxembourg: Office for Official Publ. of the European Communities (EEA report, 2). Available online at http://publications.europa.eu/en/publication-detail/-/publication/fef3121e-1b41-4ba2-b991-bc6e62f00330.

EEA (2016): Urban sprawl in Europe. Joint EEA-FOEN report. Luxembourg: Publications Office of the European Union (EEA report, No 11/2016).

EEA (2017): Managing exposure to noise in Europe. EEA Briefing 01/2017. European Environment Agency,

Ermagun, Alireza; Tilahun, Nebiyou (2020): Equity of transit accessibility across Chicago. In *Transportation Research Part D: Transport and Environment* 86, p. 102461. DOI: 10.1016/j.trd.2020.102461.

European Commission (2012): Guidelines on best practice to limit, mitigate or compensate soil sealing. Luxembourg: Publications Office.

European Commission (2018): EU transport in figures. Statistical pocketbook. Luxembourg: Publications Office of the European Union.

European Commission (2020): Walking and cycling as transport modes. Mobility and transport. Available online at https://ec.europa.eu/transport/road_safety/specialist/knowledge/pedestrians/pedestrians_and_cyclists_unprotected_road_users/walking_and_cycling_as_transport_modes_en, updated on 12/7/2020, checked on 12/7/2020.

Fast, Idit (2020): Unequal traveling: How school district and family characteristics shape the duration of students’ commute to school. In *Travel Behaviour and Society* 20, pp. 165–173. DOI: 10.1016/j.tbs.2020.03.008.

Fol, Sylvie; Dupuy, Gabriel; Coutard, Oliver (2007): Transport Policy and the Car Divide in the UK, the US and France: Beyond the Environmental Debate. In *International Journal of Urban and Regional Research* 31 (4), pp. 802–818. DOI: 10.1111/j.1468-2427.2007.00755.x.

Follmer, Robert; Belz, Janina (2018): Mobilität in Deutschland - MiD. Kurzreport Stadt München, Münchner Umland und MVV-Verbundraum. Studie von infas, DLR, IVT und infas 360 im Auftrag des Bundesministers für Verkehr und digitale Infrastruktur. Bonn, Berlin. Available online at www.mobilitaet-in-deutschland.de.

Frumkin, Howard (2002): Urban sprawl and public health. In *Public health reports (Washington, D.C. : 1974)* 117 (3), pp. 201–217. DOI: 10.1093/phr/117.3.201.

Geurs, Karst T.; Dentinho, Tomaz Ponce; Patuelli, Roberto (2016): Accessibility, equity and efficiency. In Karst T. Geurs, Roberto Patuelli, Tomaz Ponce Dentinho (Eds.): Accessibility, equity and efficiency. Challenges for transport and public services. Cheltenham: Edward Elgar Publishing (NECTAR series on transportation and communications networks research), pp. 3–8.

Goodman, Robert (1972): After the planners. Middlesex: Penguin Books.

Goodwin, Phil (1995): Car Dependence. In *Transport Policy* 2 (3), pp. 151–152. DOI: 10.1016/0967-070X(95)96744-6.

Grieger, Manfred (2019): Kleine Geschichte des Automobils in Deutschland. In *APuZ - Zeitschrift der Bundeszentrale für politische Bildung* 43/2019, pp. 12–18. Available online at https://www.bpb.de/apuz/298742/kleine-geschichte-des-automobils-in-deutschland?p=all.

Grübler, Arnulf (2004): Technology and global change. Cambridge: Cambridge University Press.

Hauke, Jan; Kossowski, Tomasz (2011): Comparison of Values of Pearson's and Spearman's Correlation Coefficients on the Same Sets of Data. In *Quaestiones Geographicae* 30 (2), pp. 87–93. DOI: 10.2478/v10117-011-0021-1.

Hawley, Greer; Macmillan, Alexandra; Field, Adrian; Hodgson, Rosee; Witten, Karen; Kearns, Robin A.; McKerchar, Christina (2020): The normative influence of adults on youth access: Challenges and opportunities in the context of shifts away from car-dependence. In *Journal of Transport & Health* 16, p. 100841. DOI: 10.1016/j.jth.2020.100841.

Heinrich, Joachim; Schwarze, Per E.; Stilianakis, Nikolaos; Momas, Isabelle; Medina, Sylvia; Totlandsdal, Annike I. et al. (2005): Studies on health effects of transport-related air pollution. In Michal Krzyzanowski, Birgit Kuna-Dibbert: Health effects of transport-related air pollution. Geneva: World Health Organization, pp. 125–183.

Hopkins, Debbie (2017): Destabilising automobility? The emergent mobilities of generation Y. In *Ambio* 46 (3), pp. 371–383. DOI: 10.1007/s13280-016-0841-2.

Illich, Ivan (1974): Energy and equity. New York: Harper & Row.

Jackisch, Josephine; Sethi, Dinesh; Mitis, Francesco; Szymański, Tomasz; Arra, Ian (2015): European facts and global status report on road safety 2015. Copenhagen: World Health Organization, Regional Office for Europe.

James, Gareth; Witten, Daniela; Hastie, Trevor; Tibshirani, Robert (2013): An Introduction to Statistical Learning. With Applications in R. New York, NY: Springer (Springer Texts in Statistics, 103). Available online at http://gbv.eblib.com/patron/FullRecord.aspx?p=1317587.

Jeekel, Hans (2014): Social exclusion, vulnerable groups and driving forces: Towards a social research based policy on car mobility. In *Case Studies on Transport Policy* 2 (2), pp. 96–106. DOI: 10.1016/j.cstp.2014.06.005.

Kenyon, Susan; Lyons, Glenn; Rafferty, Jackie (2002): Transport and social exclusion: investigating the possibility of promoting inclusion through virtual mobility. In *Journal of Transport Geography* 10 (3), pp. 207–219. DOI: 10.1016/S0966-6923(02)00012-1.

Krzyzanowski, Michal (Ed.) (2005): Health effects of transport-related air pollution: summary for polily makers. World Health Organization. Copenhagen: WHO Regional Office for Europe.

Kuna-Dibbert, Birgit; Krzyzanowski, Michal (2005): Health risk assessment of transport-related air pollution. In Michal Krzyzanowski, Birgit Kuna-Dibbert: Health effects of transport-related air pollution. Geneva: World Health Organization, pp. 185–190.

Landeshauptstadt München (2020a): Börsennotierte Unternehmen. Available online at https://www.muenchen.de/rathaus/wirtschaft/wirtschaftsstandort/wirtschaftsstruktur/dax-unternehmen-muenchen.html, updated on 12/15/2020, checked on 12/15/2020.

Landeshauptstadt München (2020b): Flughafen München. Available online at https://www.muenchen.de/verkehr/orte/217573.html, updated on 12/15/2020, checked on 12/15/2020.

Lefebvre, Henri (1992): The production of space. Original: La Production de l'espace published in 1974. Reprint. Oxford: Blackwell.

Litman, Todd (2002): The Costs of Automobile Dependency. and the Benefits of Balanced Transportation. Victoria Transport Policy Institute.

Litman, Todd; Laube, Felix B. (2002): Automobile Dependency and Economic Development. Victoria Transport Policy Institute; Institute for Science and Technology Policy, Murdoch University.

Lucas, Karen (2009): Actual and Perceived Car Dependence. In *Transportation Research Record* 2118 (1), pp. 8–15. DOI: 10.3141/2118-02.

Lucas, Karen; Grosvenor, Tim; Simpson, Roona (2001): Transport, the environment and social exclusion. Layerthorpe: York Pub.

Lucas, Karen; Jones, Peter (2009): The Car in British Society. Edited by RAC Foundation. London.

Lucas, Karen; Schwanen, Tim (2011): Understanding Auto Motives. In Karen Lucas, Evelyn Blumenberg, Rachel Weinberger (Eds.): Auto motives. Understanding car use. 1st ed. Bingley [England]: Emerald Group Pub, pp. 3–38.

Lyons, Glenn (2003): The introduction of social exclusion into the field of travel behaviour. In *Transport Policy* 10 (4), pp. 339–342. DOI: 10.1016/j.tranpol.2003.09.001.

MacKenzie, Duncan (2009): The Car Dependency Scorecard. A look at car dependency and what is being done around the country to reduce it. Campaign for Better Transport. London.

Mattioli, Giulio (2013): Car Dependence, Sustainability and the Transport Policy Stalemate: The Potential Trade-offs between Intra- and Inter-generational Equity. In *The International Journal of Sustainability Policy and Practice* 8 (1), pp. 45–57. DOI: 10.18848/2325-1166/CGP/v08i01/55416.

Mattioli, Giulio; Anable, Jillian; Vrotsou, Katerina (2016): Car dependent practices: Findings from a sequence pattern mining study of UK time use data. In *Transportation Research Part A: Policy and Practice* 89, pp. 56–72. DOI: 10.1016/j.tra.2016.04.010.

Mattioli, Giulio; Colleoni, Matteo (2016): Transport Disadvantage, Car Dependence and Urban Form. In Paola Pucci, Matteo Colleoni (Eds.): Understanding Mobilities for Designing Contemporary Cities. Cham: Springer International Publishing (Research for Development), pp. 171–190.

Mattioli, Giulio; Roberts, Cameron; Steinberger, Julia K.; Brown, Andrew (2020): The political economy of car dependence: A systems of provision approach. In *Energy Research & Social Science* 66, p. 101486. DOI: 10.1016/j.erss.2020.101486.

Mohajan, Haradhan (2019): The First Industrial Revolution: Creation of a New Global Human Era. In *Journal of Social Sciences and Humanities* 5 (4), pp. 377–387. Available online at https://mpra.ub.uni-muenchen.de/96644/.

Motte-Baumvol, Benjamin; Massot, Marie-Hélène; Byrd, Andrew M. (2010): Escaping Car Dependence in the Outer Suburbs of Paris. In *Urban Studies* 47 (3), pp. 604–619. DOI: 10.1177/0042098009349773.

MVV (2020): Der MVV in Zahlen und Fakten 2019. Münchner Verkehrs- und Tarifverbund GmbH. München.

Newman, Peter; Kenworthy, Jeffrey (2015): The End of Automobile Dependence. How Cities Are Moving Beyond Car-Based Planning. Washington, D.C.: IslandPress.

Newman, Peter; Kenworthy, Jeffrey R. (1999): Sustainability and cities. Overcoming automobile dependence. Washington, DC: Island Press. Available online at http://www.loc.gov/catdir/enhancements/fy0666/98042239-d.html.

Niklas, Ulrich; Behren, Sascha von; Soylu, Tamer; Kopp, Johanna; Chlond, Bastian; Vortisch, Peter (2020): Spatial Factor—Using a Random Forest Classification Model to

Measure an Internationally Comparable Urbanity Index. In *Urban Science* 4 (36). DOI: 10.3390/urbansci4030036.

Open Accessibility (2020): Routing Profiles. Available online at https://www.open-accessibility.org/docs/routing_profiles/, updated on 11/5/2020, checked on 11/5/2020.

Peterson, Timothy D.; Jolly, B. Tilman; Runge, Jeffery W.; Hunt, Richard C. (1999): Motor Vehicle Safety: Current Concepts and Challenges for Emergency Physicians. In *Annals of Emergency Medicine* 34 (3), pp. 384–393. Available online at https://doi.org/10.1016/S0196-0644(99)70135-6.

Pillat, Juliane (2017): Modellhandbuch Landesverkehrsmodell Bayern 2014/2030. With assistance of Jens Grösel, Steven Pfisterer, Alexandra Roos, Volker Waßmuth, Juliane Pillat, Regine Pohlner et al. PTV Group. Karlsruhe.

Pucher, John (1997): Bicycling Boom in Germany: A Revival Engineered by Public Policy. In *Transportation Quarterly* 51 (4), pp. 31–46.

QGIS (2020): QGIS - Das führende Open-Source-Desktop-GIS. Available online at https://www.qgis.org/de/site/about/index.html, updated on 12/22/2020, checked on 12/28/2020.

Reneland, M. (2001): The GIS research project: accessibility in Swedish towns 1980 and 1995. In *Transactions on the Built Environment* 52, pp. 145–153.

Resnik, David B. (2010): Urban sprawl, smart growth, and deliberative democracy. In *American Journal of Public Health* 100 (10), pp. 1852–1856. DOI: 10.2105/AJPH.2009.182501.

Ross, Michael L. (2001): Does Oil Hinder Democracy? In *World Pol.* 53 (3), pp. 325–361. DOI: 10.1353/wp.2001.0011.

Rstudio (2020): RStudio. Available online at https://rstudio.com/products/rstudio/, updated on 12/30/2020, checked on 12/30/2020.

Sarker, Rumana Islam; Mailer, Markus; Sikder, Sujit Kumar (2020): Walking to a public transport station. In *SASBE* 9 (1), pp. 38–53. DOI: 10.1108/SASBE-07-2017-0031.

Schwedes, Oliver (2019): AM STEUER? Instrumente und Anwendungsfelder der Verkehrspolitik. In *APuZ - Zeitschrift der Bundeszentrale für politische Bildung* 43/2019, pp. 19–26. Available online at https://www.bpb.de/apuz/298744/instrumente-und-anwendungsfelder-der-verkehrspolitik.

Sheller, Mimi; Urry, John (2000): The City and the Car. In *International Journal of Urban and Regional Research* 24 (4), pp. 737–757. DOI: 10.1111/1468-2427.00276.

Siedentop, Stefan; Roos, Sebastian; Fina, Stefan (2013): Ist die „Autoabhängigkeit“ von Bewohnern städtischer und ländlicher Siedlungsgebiete messbar? In *Raumforschung und Raumordnung* 71 (4), pp. 329–341. DOI: 10.1007/s13147-013-0240-0.

Spearman, C. (1904): The Proof and Measurement of Association between Two Things. In *The American Journal of Psychology* 15 (1), p. 72. DOI: 10.2307/1412159.

Statistische Ämter des Bundes und der Länder (2020a): Gemeinsames Statistikportal. Statistisches Landesamt Baden-Württemberg. Stuttgart. Available online at https://www.statistikportal.de/de/datenbanken#regionaldatenbank-deutschland, updated on 12/28/2020, checked on 12/28/2020.

Statistische Ämter des Bundes und der Länder (2020b): Unfallatlas. Statistisches Bundesamt. Wiesbaden. Available online at https://unfallatlas.statistikportal.de/, updated on 12/16/2020, checked on 12/28/2020.

StMWK (2020): Studieren in Bayern: Standorte in Bayern. Bayerisches Staatsministerium für Wissenschaft und Kunst. Available online at https://www.studieren-in-bayern.de/hochschulen/standorte-in-bayern/, updated on 12/15/2020, checked on 12/15/2020.

TUM (2020): Die Standorte der Technischen Universität München. Available online at https://www.tum.de/die-tum/die-universitaet/standorte/, updated on 12/28/2020, checked on 12/28/2020.

Umweltbundesamt (2020a): Ozon. Available online at https://www.umweltbundesamt.de/themen/luft/luftschadstoffe/ozon, updated on 2/11/2020, checked on 10/6/2020.

Umweltbundesamt (2020b): Stickstoffoxide. Available online at https://www.umweltbundesamt.de/themen/luft/luftschadstoffe-im-ueberblick/stickstoffoxide, updated on 9/17/2020, checked on 12/28/2020.

Umweltbundesamt (2020c): Siedlungs- und Verkehrsfläche. Available online at https://www.umweltbundesamt.de/daten/flaeche-boden-land-oekosysteme/flaeche/siedlungs-verkehrsflaeche#anhaltender-flachenverbrauch-fur-siedlungs-und-verkehrszwecke-, updated on 11/20/2020, checked on 12/10/2020.

Urry, John (2004): The ‘System’ of Automobility. In *Theory, Culture & Society* 21 (4-5), pp. 25–39. DOI: 10.1177/0263276404046059.

Victoria Transport Policy Institute (2019): Online TDM Encyclopedia - Automobile Dependency. Available online at https://www.vtpi.org/tdm/tdm100.htm, updated on 9/6/2019, checked on 10/8/2020.

Villeneuve, Dominic; Kaufmann, Vincent (2020): Exploring the Causes of Social Exclusion Related to Mobility for Non-Motorized Households. In *Transportation Research Record* 2674 (8), pp. 911–920. DOI: 10.1177/0361198120926167.

Wang, Hui (2013): Mapping Walking Accessibility, Bus Availability, and Car Dependence: A Case Study of Xiamen, China. In Mitsuhiko Kawakami, Zhen-jiang Shen, Jen-te Pai, Xiao-lu Gao, Ming Zhang (Eds.): Spatial Planning and Sustainable Development, vol. 8. Dordrecht: Springer Netherlands, pp. 249–267.

Wiersma, Jake; Bertolin, Luca; Straatemeier, Thomas (2013): How does the spatial context shape conditions for car dependency? An analysis of the differences between and within regions in the Netherlands. In *JTLU*. DOI: 10.5198/jtlu.2015.583.

World Commission on Environment and Development (1987): Our Common Future. Oxford University Press. Oxford.

Zhang, Ming (2006): Travel Choice with No Alternative. In *Journal of Planning Education and Research* 25 (3), pp. 311–326. DOI: 10.1177/0739456X05280544.

Zhang, Wenjia; Zhao, Yajing; Cao, Xinyu; Lu, Daming; Chai, Yanwei (2020): Nonlinear effect of accessibility on car ownership in Beijing: Pedestrian-scale neighborhood planning. In *Transportation Research Part D: Transport and Environment* 86, p. 102445. DOI: 10.1016/j.trd.2020.102445.

Zhao, Jinhua (2011): Subjective Measure of Car Dependence. In *Transportation Research Record* 2231 (1), pp. 44–52. DOI: 10.3141/2231-06.

Declaration

I hereby declare that I have written this study project independently, using only the sources and resources listed. This work has not been submitted for evaluation elsewhere.

____

Munich, December 30, 2020