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Master's Thesis

The Effects of the Design and Land-Use Diversity of the Built Environment on Cycling in Munich

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Declaration

I hereby confirm that this thesis is presented for the degree of Master of Science in Transportation Systems at the Technical University of Munich (Technische Universität München). This thesis has been composed entirely by myself and is based solely on the results of my own work, unless stated otherwise. No other person's work has been used without due acknowledgement. This thesis has not been submitted for any other degree or professional qualification.

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Thomas M. Scriba

ABSTRACT

This thesis investigates the influences the built environment in Munich has on the rates of cycling exhibited by the various 25 city districts. As cities strive to reduce congestions and commute times, many of them, including Munich, have looked to the bicycle as a solution. Previous research shows that increased shared of cycling are associated with better living conditions and lower rates of air pollution.

The City of Munich has done much to support cycling in recent decades. Cycling infrastructure has been built up, routes throughout the city marked with new signage, pavement marking improved to increase motorists' awareness, and organizations supporting cycling have run publicity and informational campaigns and events to raise the public profile of cycling.

This thesis utilizes a mixed-method approach combining a quantitative analysis of geographic built environment and demographic/social data with a qualitative study comprised of field surveys in 6 of the 25 districts. Stepwise multiple linear regression is used to determine the various influences the different dimensions of the built environment could have on the modal share of cycling by using geographic and demographic data describing each of the 25 districts along with the modal split information for each district. The field surveys throughout the city were recording and tracked as they followed preplanned routes to capture the various cycling experiences across the city. The findings of both the quantitative and qualitative study are brought together in a synthesis of both methods to combine the findings for a more comprehensive perspective of why certain areas of the city might have higher rates of cycling than others.

While no causal connections between any of the aspects of the built environment and the modal share of cycling could be made due to the design of the study, associations between the accessibility to common destinations, the density of built-up development, and certain aspects of the road network could be drawn. The qualitative study supplemented the findings of the quantitative study by showing the importance of park and green areas throughout the city as well as the quality and design of the cycling infrastructure along roads and sidewalks in Munich.

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1 INTRODUCTION

Broken down S-Bahn trains leave hundreds of passengers stranded in the cold (Schubert and Czeguhn 2018). Riders stand shoulder to shoulder on subway trains running at capacity (Völklein 2012; Krügel and Schubert 2017) and consistent traffic chokes the roads during peak hours frustrating hundreds of thousands of commuters and locals alike (Forster 2016; Wetzel 2017; Harloff, Unterhitzenberger, and Zajonz 2018). These are just some of the stories highlighting the weak links in the chain of Munich's transportation networks; points at which the system has been pushed too far by a city experiencing severe growing pains from both economic and population growth. Such issues are not only a frustrating waste of time for those caught up in delays and traffic, they're also threats to the environment and health of the city. In particular, increased vehicle kilometers traveled (VKT) is highly related to increased emissions of greenhouse gases, and exposure to heavy traffic is associated with higher rates of "cardiovascular and respiratory disease, cancer and adverse birth outcomes" as well as reduced life expectancy, accidents and injury, higher stress levels, and obesity and a general lack of physical activity (Dora et al. 2011).

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Figure 1.1: A packed U-Bahn platform for the U3 and U6 lines at Marienplatz. The U3 and U6 lines are some of the most heavily used subway lines in Munich. Source: Am Limit: Die Münchner U-Bahn erstickt am eigenen Erfolg, Tages Zeitung, Munich.

Facing increased awareness of these environmental health damages associated with motorized transport, there has been much ado about them in both the court of public opinion in Munich and within the walls of its famous city hall. In addition to the typical solutions to such problems like new public transport vehicles, infrastructure, and routes and tunnels to remove through-traffic from sensitive areas, for decades Munich has supported another mode of transport often left behind in the dust: the humble bicycle. (Zorn et al. 2010)

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Figure 1.2: Cyclists in Munich ride freely past cars stuck in traffic. The streets of Munich are often clogged with traffic during the peak hours in the morning and evening – but in many cases, cyclists ride freely past the traffic, avoiding delays and frustration. Source: Fahrradfahrer bekommen in München am meisten Stickstoffdioxid ab, Sueddeutsche Zeitung, Munich.

For decades, the City of Munich has been increasing its support of cycling as a means of shifting trips from the roads to the bike paths, promoting an active and healthy lifestyle, and reducing pollution. Various programs and measures have been implemented over the years, slowly building up the public profile of cycling and encouraging using it as a mode of transport. Munich has built up its cycling infrastructure, creating better connections both within and between different sections of the city. A special way-finding system developed for the network of designated cycling routes throughout the city was also implemented. Bike and ride facilities were vastly expanded, allowing people to safely and securely store their bikes as they continue on their way with public transport. Finally, public relations and marketing campaigns were initiated to foster an open cycling community in the city, working both with private residents and businesses. (Zorn et al. 2010)

All of these years of supporting cycling and improving the conditions for cycling around the city have definitely produced results, especially in recent times. Between the Mobilität in Deutschland study in 2002 and an evaluation of the city's efforts in 2011, the modal share of cycling rose drastically from 10% to 17.4% (von Sassen 2013). However, it cannot be said with certainty that the city's efforts are entirely, or at all, responsible for this shift in transport modes. A multitude of factors contribute to a complex decision like being able to or choosing to take a certain transport mode for any given trip. A person's economic and social position, their physical fitness, awareness of their options, access to a personal vehicle or public transport, their perceptions of the comfort of or desire to use the various modes of transport, and many more personal attributes can factor into the decision each person makes. But what of the physical attributes of where they live; can the aspects of the built environment really impact how people travel? This is by no means a new question, and it is one of increasing popularity in a world more and more conscious of the health and environment impacts of our travel patterns as described above.

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Figure 1.3: Munich's dense urban core around the Siegestor on Leopoldstraße. The Bavarian Alps in the background. Source: Zu niedrige Mieten in München? Gericht weist Klage ab, Abendzeitung, Munich.

Of all the ways of describing the built environment, the impacts the density of development on travel behavior have been acknowledged since as far back as the 1960's, in the nascent years of transportation planning (though it was most often limited to highways and streets). However, it wasn't until the urban renewal in the late 1980's and 1990's that planners and architects began to investigate the impacts which other characteristics of the built environment might have on people's travel behavior. More specifically, a seminal study by Robert Cervero and Kara Kockelman of the University of California (Berkeley) in 1997 included two more dimensions of the built environment which had been posited by planners and architects of the day as important to changing travel behavior: the diversity of land uses and the design of the infrastructure and neighborhoods within the city (Cervero and Kockelman 1997). From this point on, these so-called "three D's of the built environment", referring to the dimensions of density, diversity, and design, became a part of the common language in this field of research. Since then, the list of dimensions has grown over time, first to "five D's" to include destination accessibility and distance to transit, and then on to seven, and possibly even more "D's" (Ewing and Cervero 2010).

The growth in the ways of analyzing the built environment which begin with "D" in these studies has been matched, if not caused by, a massive growth in this field of research (Ewing and Cervero 2010). Hundreds of studies investigating the impacts of various characteristics of the built environment on various types of travel behavior have yielded results generally agreeing with the conclusions of the 1997 study since its publishing. Generally, these studies have agreed that increased density (often measured by population or job density), increased diversity of land uses (often defined as the level of mixture of various uses), more pedestrian/cycling-friendly design (characterized in many ways ranging from aesthetics to the arrangement of the street network), higher destination accessibility (often measured using the percent of a population within a certain distance or travel time of important locations or common destinations), and decreased distance to transit in neighborhoods reduce the use of personal vehicles and increases the rates of walking and cycling. In much of this research, the density of an urban environment often shows the strongest connection with the rates of walking and cycling among each of these dimensions, though the other dimensions have also associations with travel behavior patterns.

However, to put this body of research within the context of Munich, a 70% rise in the modal share of cycling over just nine years cannot be explained by a change in density; the city's population density increased only very slightly between 2002 and 2011. Therefore, it is possible that Munich's efforts to encourage cycling by improving the infrastructure, facilities, and public awareness and perception of cycling were all at least partially responsible for the drastic increase in its modal share. To the best of the author's knowledge, no such study of the influence the built environment has on cycling in Munich, similar to the 1997 study and others mentioned above, has ever been done. It is the aim of this thesis to do just that. Based on the findings of the research, this thesis will also make recommendations for the City of Munich's continuing support of cycling.

The main research question behind the research performed for this thesis is: "What elements of the built-environment influence cycling in Munich, how, and to what degree?". Additionally, several more specific questions under the main research question will be explored as well, namely:

1. Are there elements of the built environment's design or land-use diversity, independent of a district's density, which encourage cycling?
2. Does the presence of more green areas (parks, meadows, forests, etc.), specifically those with cycleways through them, encourage cycling?
3. What impacts, if any, do the street network and the cycle network have on the rate of cycling in the city?
4. Do the presence of offices, retail, restaurants and bars, other amenities, or the diversity of these land-uses influence the rate of cycling in a district?
5. Does access to public transport or a specific type of public transport (bus, tram, U-Bahn, or S-Bahn) affect the rate of cycling in a district?
6. What might the City of Munich do to continue to increase the modal share of cycling further?

Answers to these questions will be explored by examining Munich's 25 administrative districts and comparing various aspects of the built environment within them. In 2008, the most recent year with modal split data at the district level, the modal share of cycling ranged from 7% to 24% among these districts. The thesis utilizes a so-called "mixed method approach", which combines both a quantitative study and a qualitative study of the built environment and cycling in Munich. A brief overview of the approach, the reasoning behind choosing it, and the two methods themselves is presented in Section 2, next. Detailed descriptions of the methods along with the results of each of the studies are presented in Section 4 (for the quantitative study) and Section 5 (for the qualitative study).

It is the hypothesis of the author that the built environments of these districts do offer some explanation for the variation of the rate of cycling across the city. Specifically, the presence of green areas, cycleways, access to more destinations, and a more compact street network within a district are all believed to be positively associated with the modal share of cycling in Munich. Due to the design of this study and the data used, no causal connections between the built environment and the modal share of cycling can be made; however, associations between some of the variables studied and cycling in Munich can be confidently revealed by this study's design.

Aside from the sections covering the methodology of this thesis mentioned above, Section 3 will contain a literature review covering Munich and its transport networks focusing on cycling and its development in the city, as well as previous research on the built environment and its relationship to travel behavior. Section 6 presents a synthesis of the results obtained through the quantitative and qualitative studies, to bring together the findings of both these methods and combine and compare them to gain a broader perspective on how the built environment and cycling are related in Munich, and to attempt to answer the research questions posed above. Section 6 also contains a discussion of the limitations of this study and ways in which it could have been improved or could be improved if repeated in the future. Finally, at the end of Section 6, recommendations research into the topic of the built environment and its relationship to cycling and travel behavior are presented, finishing the report.

2 Conceptual Framework

To tackle the complex nature of studying the relationship between the built environment and travel behavior, in this case particularly cycling, a combination of quantitative and qualitative research methods was developed and implemented. This section covers the basic structure of the study and the reasoning behind the choice to employ multiple methods, as well as the choices of the methods themselves. Sections 4 and 5 of the report describe these methods in greater detail.

2.1 The Mixed-Method Approach

The usage of different methods, specifically both quantitative and qualitative methods, within a single study has been growing in popularity in recent years. This has been called the "mixed-methods approach" in previous literature, and its utilization comes with both advantages and disadvantages (Wisdom and Creswell 2013). The basic premise of the mixed-method approach is that by using a variety of methods, a more comprehensive view of the subject of the research can be achieved. The results of one method can complement those of another, filling in gaps of the researchers' understanding. At the very least, a second method can grant researchers another perspective on the research question at hand. However, the mixed-method approach is not without drawbacks.

Obviously, a study that uses multiple methods will often require more time to complete. A common way of alleviating the increased time requirement of mixed-method studies is to use less complex versions of the methods which are selected. That might mean, for example, a smaller set of variables analyzed through quantitative methods, a less intensive survey employed by a qualitative method, or both.

In the case of this study, a mixed-method approach was chosen for a few reasons. The first and foremost is the available data and its properties. Most of the data describing the city of Munich, namely the transport behavior of its residents, employment and economic statistics, and demographics, are only available aggregated by the city's 25 administrative districts (for more information on the city and its districts, see Section 3.1 below). Unfortunately, a finer resolution of data nor individual travel diary data from the most recent nationwide household travel survey, the 2008 Mobilität in Deutschland (MiD) study, were not available for use. The available data limited quantitative research methods to a cross-sectional aggregate study of the built environment's impacts on cycling travel behavior, from which no casual associations can be inferred. Additionally, associations which are discovered through the quantitative analysis will suffer from the ecological fallacy, relying too strongly on environmental factors to explain complex decisions like travel behavior (Zegras 2005; Ewing and Cervero 2010), and the modified Areal Unit Problem (MAUP), arbitrarily separating areas of the city into districts when in reality the city is much more of a continuous development under the city administration (Iacono, Krizek, and El-Geneidy 2010).

Even if more comprehensive data were available to this study, using solely quantitative methods to study the relationship between travel behavior and the built environment ignores a human factor in the equation: perception. Naturally, a person's individual perception of the built environment can differ greatly from the measured reality for any given element, be it aesthetic quality or even the presence of bike lanes (Black and Street 2014). Additionally, while the number of studies focusing on the built environment and cycling has been growing, it is still a relatively new branch of research, especially when compared to the library of studies exploring the built environment's relationship with automobile travel. This means that the set of built environment, natural environment, social and demographic, or other factors which impact cycling rates in the city may not be entirely understood yet. Including a qualitative method which focuses on subjective experiences in this study was intended to help understand a person's perception of cycling in various neighborhoods and districts of Munich, and to uncover any previously unknown factors not represented by the data in the quantitative study that might impact cycling rates across the city.

As previously mentioned, using the mixed-method approach can often be more time-consuming than single method studies, and since this project is a master's thesis, it was limited to a duration of six months. To ensure completion of the project within the limited timeframe, both methods used were somewhat simplified versions of what would normally be used in a single method study. Even though mixed-method studies are often performed in a predefined sequence to better explore the subject or explain some findings, this would have further extended the time required to complete the study. Therefore, the two methods were conducted in parallel, to expedite the process. The two methods used in this study are briefly described below and are presented in full detail in Section 4 (Quantitative Study) and Section 5 (Qualitative Study).

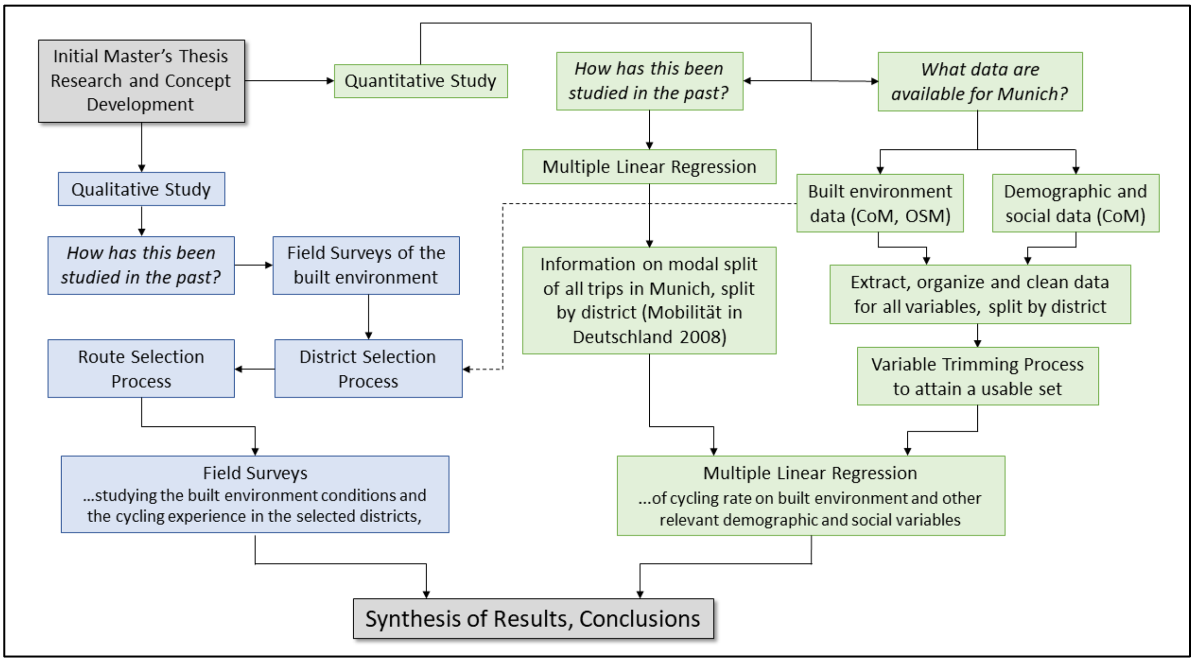

Figure 2.1: Flowchart of the conceptual framework and work breakdown structure of the study."CoM" refers to data from the City of Munich and "OSM" refers to data from OpenStreetMap. Source: own work.

2.1.1 Quantitative study

The quantitative study methodology was constructed following the example of several previous studies investigating the connection between the built environment and cycling – or more broadly non-motorized – travel behavior. Data describing the built environment (e.g. street networks, land use areas, building footprints, topography, cycling infrastructure, etc.) were gathered from a variety of sources and then organized using geographic information systems (GIS) software. Data on relevant demographic and societal characteristics (e.g. population density, age distribution, household size and type, unemployment rates, car ownership, etc.) of Munich and its 25 districts were also gathered, filtered, and organized into databases.

Using the GIS software, the built environment data were analyzed to generate values for the relevant variables to be investigated. The built environment variables of interest describe the variations in each district's density, land usage, urban design, transit accessibility, and distance to various important destinations within the city. While controlling for social, demographic, and other relevant factors, the associations between these built environment variables (the independent variables) and the modal share of cycling (the dependent variable) in each district were investigated using the statistical language R in R Studio. A multicollinearity analysis was first performed to find variables which coincided with another too closely, so that they could be noted or removed from further analysis. Next, a manual stepwise regression was used to filter out the remaining variables with insignificant or reversed influences on the rate of cycling in each district. The process and methodology of the quantitative study are described in detail in Section 4.

2.1.2 Qualitative study

As mentioned above, the qualitative study was intended to complement the data and analysis done in the quantitative study. It was designed to form a more complete picture of how the built environment in Munich might impact the rates of cycling across the city. Many qualitative studies of travel behavior and the built environment focus are designed around surveys of people who live or travel in a district, distributed either in person on the street or at home via mail or online. Unfortunately, several factors made surveys a poor choice for this study. Instead, a set of field surveys exploring the various types of built environments in the districts across Munich was utilized to gather firsthand experience cycling throughout the city.

Although it would have been interesting, cycling through each one of the 25 districts of the city would have been prohibitively time-consuming. Furthermore, there would have been no guarantee that riding through each individual district would have yielded meaningful or noticeable differences in the built environment. Thus, a set of districts intended to represent the diversity in the built environment in Munich was selected through a process which considered each district's size, population density, topography, location within the city, and level of access to city's public transport system.

Similarly, instead of cycling through the entirety of each district, each field survey followed a predetermined route traveling through a representative portion of the subject district. The routes were chosen by viewing maps of the districts and plotting out a course which passed through transit hubs, centers of activity, mainly residential areas, and any other points or areas of interest. The routes traveled along main streets, on cycleways in both developed and green areas, through quiet residential side streets, and on any other important cycling infrastructure in the district. The selection processes for the districts and routes of the field surveys, as well as the methods of the field surveys themselves, are described in full detail in Section 5.

2.1.3 Synthesis of Results

At the end of this paper in Section 6, the results of both the quantitative and qualitative studies are brought together to synthesize their results. By doing so, the information provided by one method can complement that of the other, forming a more complete picture of cycling in Munich and the relationship between it and the city's built environment. Questions raised during the process of the field surveys are investigated using the available quantitative results, and gaps in the quantitative data are explored using the results of the qualitative study. Also, in this section, the limitations of both methods and this study generally are discussed to highlight areas of uncertainty or improvement. Finally, at the end of the section, ideas for future research expanding and improving on this study are discussed.

3 Background and Literature Review

In this section, a review of the background and context of this study and the literature reviewed for it are presented. First, background information on Munich and some context pertinent to studying cycling in the city are given in Section 3.1. Section 3.2 contains a literature review of previous studies, articles, and projects relevant to this study which focused on relationship between non-motorized travel – more specifically cycling – and the built environment.

3.1 MUNICH, BAVARIA, AND GERMANY

Munich is the third largest country in Germany, and the capital of the country's largest and southernmost state of Bavaria. The city is located on the mostly flat plains about 60 kilometers north of the Bavarian Alps, 110 kilometers north-northwest of Salzburg, Austria, and 250 kilometers north-northeast of Zurich, Switzerland. The Isar, a relatively small river which feeds into the Danube further north, cuts through the center of the city flowing from south to north.

The area of the city proper (referred to as the City of Munich) is about 310 square kilometers. From west to east the longest straight-line distance within the city's borders is 26.9 kilometers, and from north to south the longest distance within the city area measures 20.7 kilometers (Thien-Seitz, Riedl, and Rappert 2009). Furthermore, Munich's area is divided up into 25 administrative city districts (Stadtbezirke), which vary in size from around two to 34 square kilometers, designated by historical development patterns and other natural and man-made boundaries and edges within the city's boundaries. As mentioned above, the city districts are the most specific level of detail for which travel information related to cycling (i.e. the modal split) is freely available from the Mobilität in Deutschland 2008 study results report for Munich (Belz, Follmer, and Gruschwitz 2010). Therefore, it is important to understand how these districts are structured and compare to one another, as they form the basis of this study. The 25 districts can be split into three rough groups:

- First, the core districts found in the center of the city, within and surrounding the ring road the "Altstadtring" (see Section 3.1.1 for more information). This includes the district at the city center, 01 Altstadt-Lehel, and five other central districts: 02 Ludwigsvorstadt-Isarvorstadt, 03 Maxvorstadt, 04 Schwabing-West, 08 Schwanthalerhöhe, and 05 Au-Haidhausen.
- Second, the city's inner districts which are either intersected or bordered by a second ring road – the "Mittlerer Ring" (see Section 3.1.1. for more information). This includes the districts of, 06 Sendling, 07 Sendling-Westpark, 09 Neuhausen-Nymphenburg, 10 Moosach, 11 Milbertshofen-Am Hart, 12 Schwabing-Freimann, 13 Bogenhausen, 14 Berg am Laim, 16 Ramersdorf-Perlach, 17 Obergiesing-Fasangarten, 18 Untergiesing-Harlaching, and 25 Laim.
- Third, and finally, is the group of outermost districts of the city. This group contains the districts: 15 Trudering-Riem, 19 Thalkirchen-Obersendling-Forstenried-Fürstenried-Solln (referred to as TOFFS in this report), 20 Hadern, 21 Pasing-Obermenzing, 22 Aubing-Lochhausen-Langwied, 23 Allach-Untermenzing, and 24 Feldmoching-Hasenbergl.

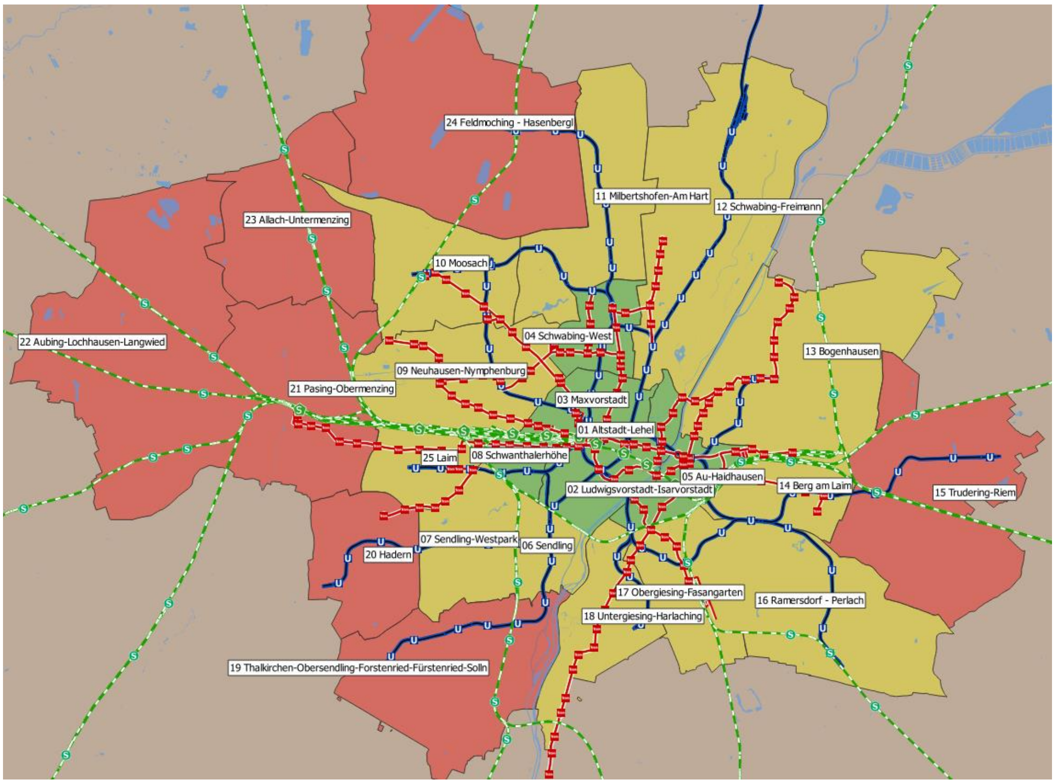

Figure 3.1: The districts of Munich, sorted into groups by their location within the city. Source: own work. GIS OMS sources listed in Section 4.1.

As can be seen in Figure 3.1 above, this classification system is not perfect, as a few of the districts don't follow the classifications exactly and could easily be placed in two groups. Most notably, 12 Schwabing-Freimann, 13 Bogenhausen, and 18 Untergiesing-Harlaching each border a core district and stretch out all the way to the city's border. Ideally, for the sake of this study, these districts would have been split up further as the built environment characteristics of these districts vary widely from one end to the other. For more information on the city districts, see Section 5.1 which describes the districts chosen for the qualitative study in detail.

The demographic and social characteristics of a population can also have important impacts for its travel behavior. Certain groups of people exhibit different travel behavior patterns, such as the propensity of employees for driving and that of students for public transport and cycling (Institut für angewandte Sozialwissenschaft 2010). Currently, Munich is home to over 1.5 million people, and the local region (including 8 surrounding counties) had a population of over 2.85 million in 2015 (Baudisch, Walter, and Breu 2015; MVG 2015). In 2008, the year of the latest major travel behavior study, Mobility in Germany (Mobilität in Deutschland), the city had a population of 1,367,314 and the region had over 2.6 million people (Thien-Seitz, Riedl, and Rappert 2009; Schulz and Walter 2010). With a land area just over 310.4 square kilometers in 2008, Munich's population density was around 4,405 inhabitants per square kilometer. The population was divided among 748,678 households, so that the average household size in that year was 1.83 persons; 16.6% of the households had children, and 53.9% were single-person households. (Thien-Seitz, Riedl, and Rappert 2009)

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Figure 3.2: The region of Munich. Blue areas are communities with denser development, gray areas are rural communities, light green represents forests and light blue represents lakes. Thick maroon lines represent motorways and thinner ones represent federal highways. Purple lines represent railways, and purpose dots stations. Source: (Baudisch et al. 2014)

Munich is home to several universities and as a result, has a large share of students living in the city. In 2016, over 133,000 students were enrolled at universities in the city, of which approximately 17% were from foreign countries (Studentenwerk München 2017). This is slightly lower than the city-wide rate of residents from other countries, 23.1% (Thien-Seitz, Riedl, and Rappert 2009). The unemployment rate in Munich is quite low, at only 4% on average across the whole city in 2008, and the rate of those receiving unemployment benefits (Arbeitslosengeld) was slightly higher at 5.4%. And finally, the age of the population was segmented so that 14.1% of residents were under 18 years old, 68.1% were between 18 and 65 years old, and 17.8% were over 65. (Landeshauptstadt München 2009)

A probable reason for the relatively low unemployment rate in Munich is the strong local economy. The city has long been the headquarters of several large manufacturers like BMW, MAN, and Siemens, as well as the large insurance companies Munich RE and Allianz. Additionally, after London and Paris, Munich has the third most office space in Europe. The city is also a leader in the tech sector, home to thousands of companies in fields like electronics, aviation, aerospace, and telecommunications. The wealth of the city is also shown by the purchasing power of its inhabitants – the per capita purchasing power of Munich was 30,901€ in 2016, which is over 37% higher than the national average of 22,531€ and significantly higher than other large cities in Germany (20,594€ in Berlin, 24,841€ in Hamburg, 23,294€ in Cologne, and 24,573€ in Frankfurt) as well. (Department of Labor and Economic Development 2017)

The above characteristics of the city – its economic, social, and demographic makeup – shape Munich just as the physical structure of its 25 districts does. More importantly for the purposes of this study, these characteristics affect the travel behavior of the city. Another major factor in the travel behavior of the residents of Munich is the available local transport infrastructure, the city's transport supply. An overview of the four major modes of transport in Munich (driving, public transport, cycling, and walking) as well as how they are used by the people of Munich is presented next in Section 3.1.1.

3.1.1 Transport in Munich

Getting around in Munich is done via the four main modes of transport: driving (both drivers and passengers of personal vehicles), public transport (bus, tram, subway/U-Bahn, and suburban trains/S-Bahn), cycling, and walking. In order to better understand the city's travel behavior with respect to cycling, it is also important to have an understanding of the other modes that are available and how they are used.

In this section, the travel behavior of the city with respect to the three most common modes (walking, driving, and public transport) will be presented, and the relevant aspects of the infrastructure networks associated with them briefly described. As the focus of this study, cycling behavior and cycling infrastructure in Munich will be covered in more detail in the following section, Section 3.1.2.

According to the Mobility in Germany 2008 study (Belz, Follmer, and Gruschwitz 2010), the most commonly chosen transport mode for all trips in Munich was individual motorized transport (IMT), with the combined modal share of drivers and passengers at 37%. IMT was followed by walking which had a modal share of 28%, public transport at 21%, and finally cycling at 14%. See Figure 3.3 below for the modal split in Munich overall, and broken down by trip purpose and demographic group.

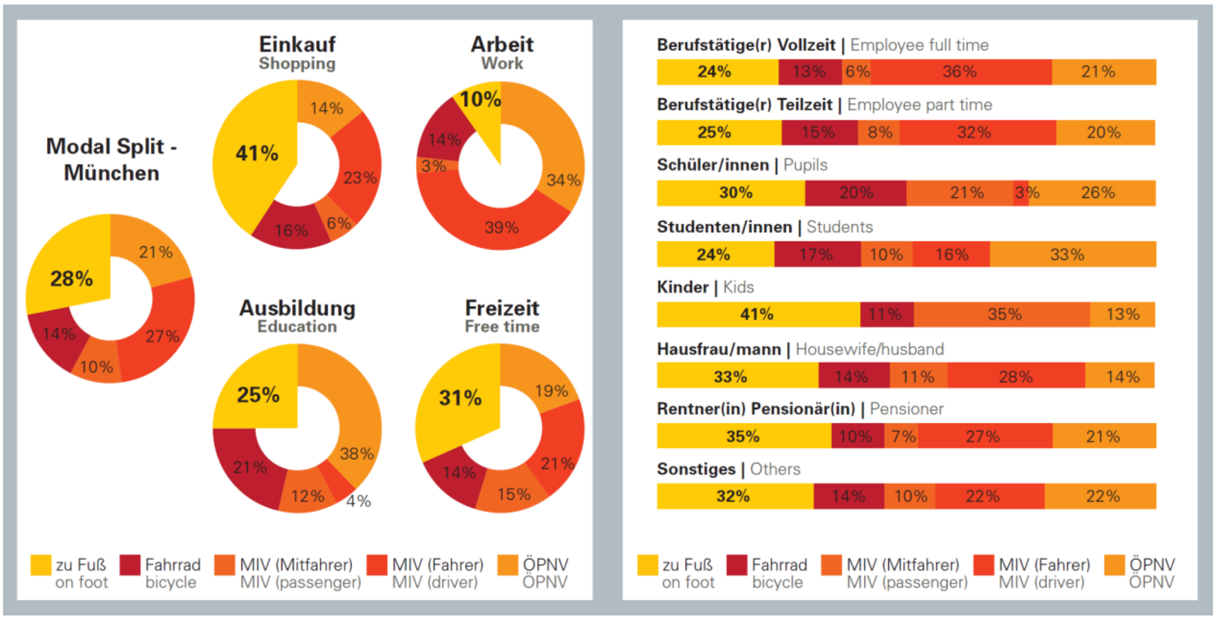

Figure 3.3: Modal split in Munich by trip purposes and demographic groups. Colors represent (counter-clockwise / from left to right): gold is walking, red is cycling, light orange is IMT passenger, orange is IMT driver, and orange-yellow is public transport. Source: (Referat für Stadtplanung und Bauordnung 2013)

As a relatively wealthy city, and one deeply connected with the auto industry, one might expect the number of vehicles per capita in Munich to be somewhat higher than average. However, within the City of Munich, the motorization rate (number of private vehicles, cars and motorcycles, as a percent of population) was just 37.6% in 2008. Including commercial and vehicles of other uses, the total motorization rate for the city was 47.0%. These values are similar to those in the other large cities in Germany with over a million residents, Berlin, Hamburg, and Cologne. (Landeshauptstadt München 2009)

Driving in Munich

The physical infrastructure which vehicles drive on and the characteristics of the network of highways, tunnels, roads, and streets, are both important factors which influence people's travel behavior (Guo, Bhat, and Copperman 2007; Crane and Crepeau 1998; Song and Knapp 2004). Knowing the basics of Munich's roadway network and how it is structured can help in understanding how the city gets around both in their cars and on their bikes. Most of the major roadways in the city, especially the larger ones, are accompanied by some form cycling infrastructure (discussed in further detail next in Section 3.1.2), but they also act as barriers which are difficult for pedestrians or cyclists to cross. The following is a quick overview of the major roadway networks in the city.

In Munich, there are three main ring roads which can be used as reference points for location within the city, as mentioned in Section 3.1 with respect to the classification of the city districts.

- The Altstadtring: the innermost ring road in Munich, which follows the general track of the old city walls, usually four or five lanes wide. It forms much of the border of the district 01 Altstadt-Lehel district and forms the outer boundary of "Altstadt", the old city quarter of Munich, which vehicles cannot drive through. The ring contains one tunnel, Altstadtringtunnel, which forms the northernmost section of the road and diverts non-local traffic from dense and sensitive development aboveground.
- The Mittlerer Ring: The "Middle Ring" of Munich is made up of the B2R federal highway (Bundesstraße) encircling the city, two to five kilometers outside the Altstadtring. Several

tunnels are a part of the ring road, helping to divert through traffic under areas of denser development. The Mittlerer Ring is connected to several other federal highways as well, namely the B2, B11, B13, and the B304. Additionally, the federal motorways (Autobahn) A8, A9, A94, A95, and A96 all stem from interchanges with the Mittlerer Ring.

- The Autobahn Ring: The outer ring of the city is comprised entirely of the federal motorway, A99. The A99 wraps around the city the western edge clockwise to the south eastern corner of Munich, with a notable hole in the southwest. It has interchanges with each of the motorways the Mittlerer Ring does, and an additional connection to the A92.

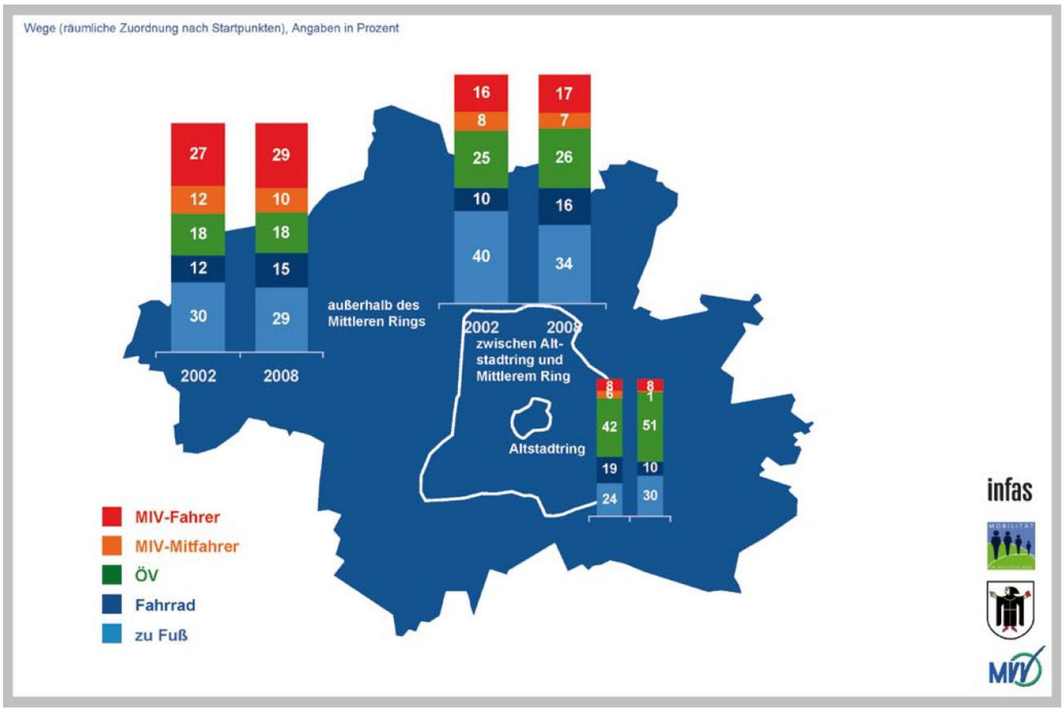

Figure 3.4: Modal split by location relative to major ring roads in Munich, in 2002 and 2008. Inside Altstadt Ring, inside Mittlerer Ring, and outside it. Modes represented from top to bottom of each bar: IMT driver IMT passenger, public transport, cycling, and walking. Source: (Belz, Follmer, and Gruschwitz 2010)

In addition to the ring roads, each of the federal highways mentioned above cross the city at various points, acting as arterials for outer Munich. Inside the Mittlerer Ring, several large city streets stemming from the Altstadtring collect the traffic from the web of smaller streets between them throughout the city's core districts. Bayerstraße, Arnulfstraße, Dachauerstraße, Schleißheimerstraße, Leopoldstraße, Prinzregentenstraße, Einsteinstraße, Rosenheimerstraße, Orleansstraße, and several others all connect the city together in this area.

In between all these major roads, the network of smaller city streets has some relevant characteristics which have been shown to impact travel behavior and could affect the cycling rate of the people living and working in the area. Many residential and other sensitive areas of the city's developed area are within so-called "Tempo 30 Zones". Tempo 30 Zones are areas, the entirety of which have a default speed limit is 30 km/h on all streets unless otherwise noted (for example, on arterial roadways), in order to protect the population, reduce both noise and air pollution, and to foster a more stable and free urban environment. Data on the conditions inside these zones have shown that they have been successful – there has been a reduction in average and peak speed levels, fewer accidents which result in physical injury, and lowered noise and air pollution levels. (Wulfhorst 2016)

As could be expected, the rates of driving vary between various types of users and also among differing trip purposes. In Munich in 2008, over 40% of work trips were done with a private vehicle, and as might be expected, over 40% of all trips taken by both full-time and part-time workers were by car. Even for children, the modal share of IMT trips (as passengers) was 35%. Only school children and students had significantly lower rates of IMT trips, with 24% and 26% respectively. This is also represented by the modal share of all education trips, which was also significantly lower than the modal shares for each of the other trip purposes, at just 16%.

Walking in Munich

As seen in Figure 3.3 above, after IMT (combining driver and passenger rates) walking is the second most common mode of transport in the City of Munich. Most notably from the image, is that 41% of all shopping trips in Munich were completed entirely on foot. This high rate of walking, especially for shopping trips, reflects the fact that for a large portion of the city's residents, common destinations like supermarkets, drug stores, and restaurants are within a tolerable walking distance. However, while nearly a quarter of trips made by employees are walking trips, only 10% of trips related to work were walking trips.

While the single most important feature of pedestrian infrastructure in the city is that it is ubiquitous, allowing residents and visitors to get where they need to go quickly and safely, this is not at all unique to Munich. However, Munich does have some noteworthy facilities for those on foot – the various pedestrian zones which dot the landscape and dominate the city's Altstadt area. Much of the city's Altstadt (the area contained by the Altstadtring mentioned above) is made up of a network of pedestrian only streets and areas as seen in Figure 3.5 below.

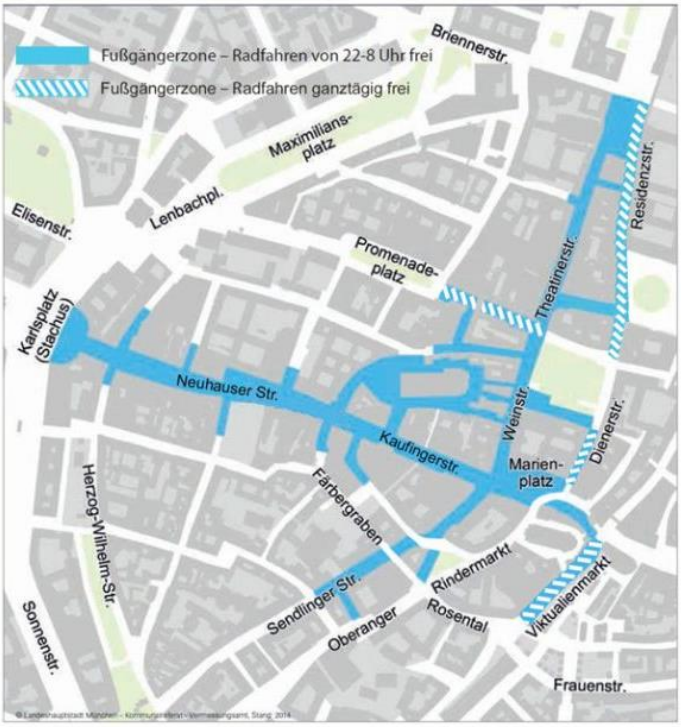

Figure 3.5: Map of the pedestrian-only streets in the city's Altstadt area.Solid blue areas are pedestrian only zones (which allow cyclists at night) and striped white/blue areas are open to cyclists at all times. Source: [Radeln in der Fußgängerzone, muenchen.de]

Outside of the Altstadt, there are many more pedestrian streets and zones in areas with high levels of development such as historical town centers, shopping streets, and areas around important train and subway stations. These pedestrian facilities are not only important to pedestrians, but cyclists as well. Within the streets marked with solid blue in Figure 3.5 above, cycling is only allowed at night – from 9 PM to 9 AM. However, with in the white/blue striped areas, cycling is allowed at all times. The zones which do not allow cycling act like barriers to cyclists, while those which allow it are car-free, but pedestrian-heavy, cycling routes.

Public Transport in Munich

Public transport in Munich – suburban trains (S-Bahn), subways (U-Bahn), trams, and buses – were the third most commonly used mode of transport for all trips in the city, with a modal share of 21% of all trips. By trip purpose however, public transport accounted for 38% of all education trips, the largest share, and 34% of all work-related trips, the second largest share after driving. The characteristics and structure of a public transport network are important factors in determining how attractive using it for certain trips would be, and therefore indirectly influence the relative attractiveness of cycling for those trips. In this section, a brief overview of the public transport modes in Munich is presented, so that their important role in travel within the city, and their impact and connection with cycling, can be better understood.

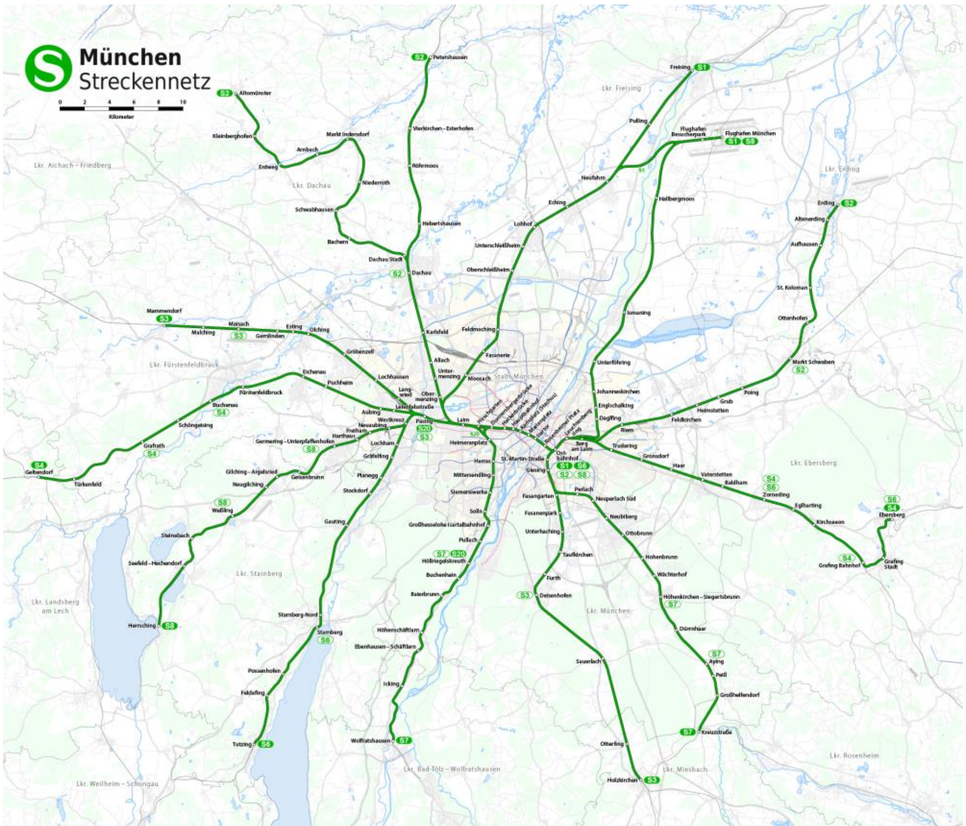

Figure 3.6: The S-Bahn rail network of Munich.The outer Autobahn ring can be seen surrounding the city proper. Source: [Maximilian Dörrbecker] (user "Chumwa") [CC BY-SA 2.0], via Wikimedia Commons. Background imagery from OpenStreetMap

The suburban rail or S-Bahn (see Figure 3.6 above) network in Munich stretches from the city's core out beyond the city's borders to exurbs and other nearby towns and cities. All but one (the S20) of the lines of Munich's S-Bahn network share a common stretch of track known as the Stammstrecke, traversing the city's core from Pasing in the west to Ostbahnhof in the east. From the Stammstrecke, the seven main S-Bahn routes extend in a radial network to the surrounding region with a total length of over 430 kilometers (of routes). The system serves around 800,000 people on a work day and connects areas of concentrated development in the city and the surrounding area to each other and to central Munich. (Deutsche Bahn 2017)

The S-Bahn network and cycling in Munich are closely linked. Many people ride their bikes to the station in order to catch an S-Bahn train for the next leg of their trip, leaving their bikes parked at the station until they return. This is called bike and ride (bike+ride), and most stations provide facilities for riders to store their bikes until they return, in some cases in locked protective shelters. There are over 55,000 bike+ride parking spaces for bikes at rail and subway stations in the MVV's service area (MVV 2017). Additionally, as the stations are often in areas of concentrated development or activity centers, the cycling infrastructure in and around the stations can be quite critical to cyclists in the area, not just those who are heading to and from the station itself.

The subway system, or the U-Bahn network (see Figure 3.7 below) in Munich, is naturally a more compact and limited system than the S-Bahn. The network consists of 95 kilometers of routes split into 6 main lines (U1 through U6) and 2 express lines (U7 and U8, which run along tracks of the main lines) serving 100 stations (MVG 2017). Unlike the S-Bahn, only one end of one line, the U6, extends beyond the city's borders. The structure of the network is radial like the S-Bahn, but unlike it, does not converge at a single station or a line of stations like the Stammstrecke in the city center. Instead, three separate stations, Odeonsplatz (with the U3, U6, U4, and U5, Hauptbahnhof (the central rail station, with the U1, U2, U4, and U5), and Sendlinger Tor (with the U1, U2, U3, and U6), form a triangle of main transfer stations around the city center and facilitating transfers between all of the lines.

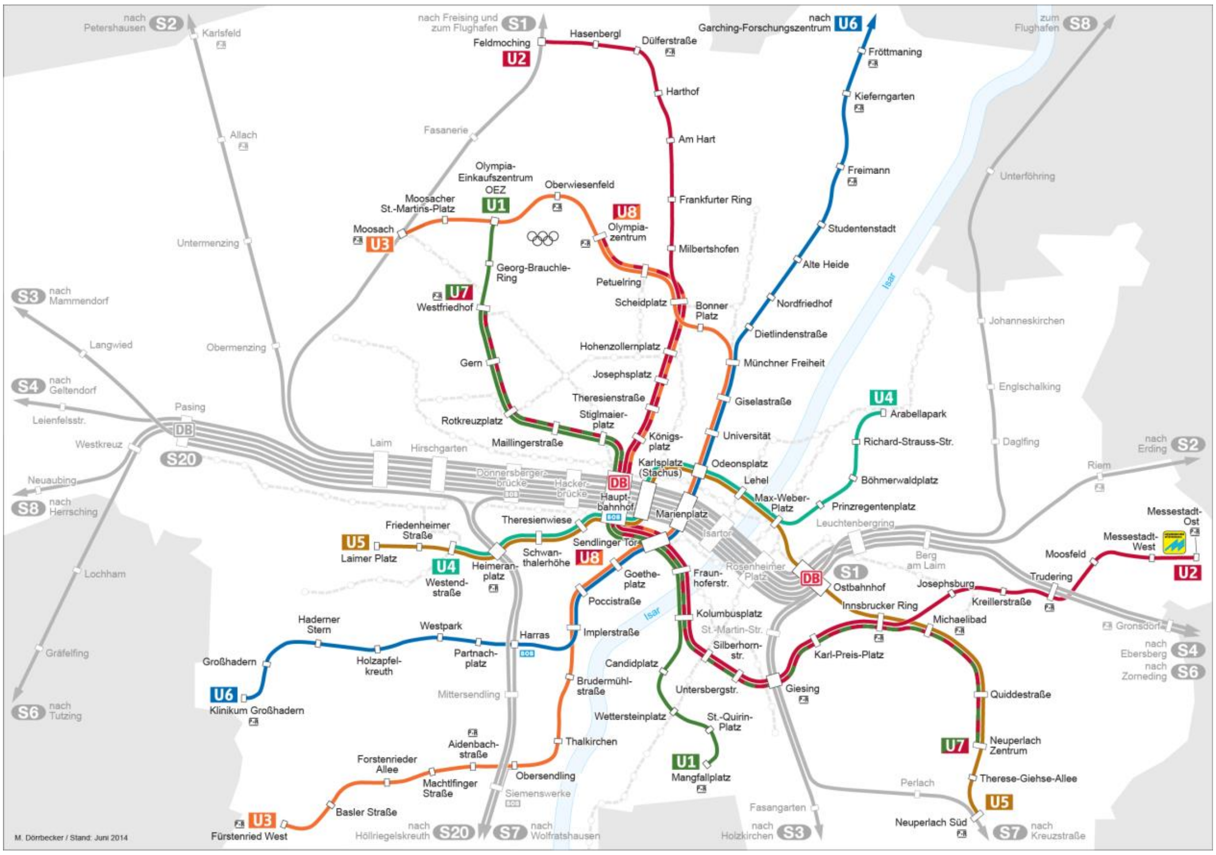

Figure 3.7: Munich's U-Bahn system as of 2014. The light grey outer area represents the land outside the city of Munich's borders. Source: [Maximilian Dörrbecker](#) (user "Chumwa") (Own work) [[CC BY-SA 2.5]](#), via Wikimedia Commons.

The U-Bahn system is Munich's most-used public transport mode, carrying 408 million passengers in 2016, over one million passengers per day on average (MVG 2017). Much like the S-Bahn system, many of these passengers use bike+ride facilities common at U-Bahn stations. Also similar to the S-Bahn stations, U-Bahn stations are almost always located in areas of concentrated development or activity centers. Therefore, the cycling infrastructure surrounding U-Bahn stations is very important to cyclists in the area, not only those going to or coming from the U-Bahn station itself.

Munich's tram network is even more compact compared to the city's U-Bahn network. Also, like the U-Bahn network, almost all of the tram lines – with one exception – are within city limits as seen in Figure 3.8 below. The tram network is densest at the city center, with a line cutting through the Altstadt and another surrounding its southern edge. The tram network is made up of 82 kilometers of routes and 172 stations, which transported an average of almost 330,000 passengers per day in 2016 (120 million passengers per year) (MVG 2017).

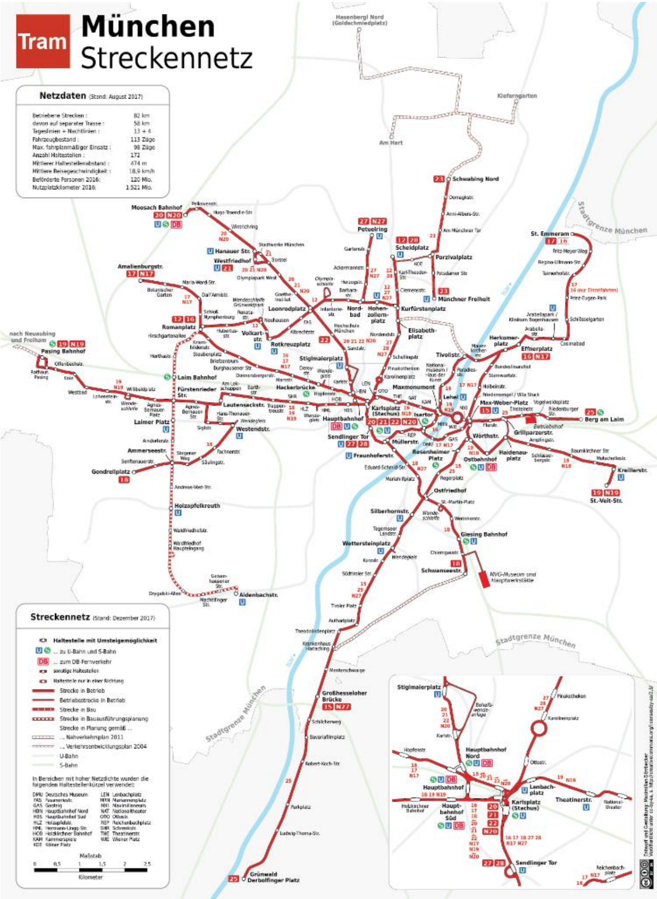

Figure 3.8: Munich's tram network. The outer gray regions represent areas outside the city borders - note that almost the entirety of the tram network is within city limits. Source: [Maximilian Dörrbecker](#) (user "Chumwa") (Own work) [[CC BY-SA 2.5]](#), via Wikimedia Commons.

Finally, Munich's network of bus lines is by far the most common and pervasive mode of public transport in the city. The bus network consists of 73 lines covering 495 kilometers of routes and 987 stations. The buses transported 200 million passengers in 2016, almost 550,000 per day on average.

Both the tram and bus networks in Munich are too ubiquitous for their stations to be crucial areas for cycling, however, the presence of tram tracks, tram and bus stops, and the vehicles themselves can have an impact on cyclists around them. Bus and tram stops adjacent to cycling infrastructure can cause conflict between cyclists and the vehicles themselves and passengers as they enter or exit them. Also, tram tracks in the road make it difficult for cyclists to maneuver freely as they can only be crossed confidently at certain angles.

3.1.2 Cycling in Munich

After IMT, walking, and public transport, cycling is the least common of the four major modes of transport in Munich with 14% of the share of trips city-wide in 2008 (Belz, Follmer, and Gruschwitz 2010). However, that number had already risen to 17.4% by 2011, an increase of almost 30% in just three years (von Sassen 2013). That growth was not random, the city has been supporting cycling and pushing the development of infrastructure and facilities which encourage cycling. Since 1986, Munich has created a separate Transport Development Plan (Verkehrsentwicklungsplan) for cycling to guide the future planning, development, and construction of cycling infrastructure and facilities. In the following decades, the city focused on creating a network of continuous interconnected cycling routes linking different parts of the city together. Connecting people to common important destinations like activity centers, schools, workplaces, and railway stations was prioritized. Measures such as routing cycling traffic into existing Tempo 30 Zones, converting lanes of primary and secondary roadways into bike lanes, especially during already planned maintenance and reconstruction, and clearly marking these routes with signs were taken to improve the cycling conditions in the city. (Bördlein 2000)

This support continued in the 2000's as the city continued to build out and improve its cycling infrastructure and adopted a new Transport Development Plan and a separate Bicycle Traffic Development Plan in 2006 which aimed to reduce vehicle traffic by shifting it to trips by foot, bike, and public transport. The 2006 Bicycle Traffic Development Plan planned for extensions to the 16 existing radial signposted cycle routes and two ring routes encircling the city and connecting each of the radial routes together. (Hogeback, Koppen, and Referat für Stadtplanung und Bauordnung 2006)

Later in 2006, the city redesigned its signage system (seen in Figure 3.9 on the right) for the signposted cycle routes to be clearer and more attractive to cyclists, and to remind those who don't cycle as often that it is a widely accepted option in Munich. The new system split the city into 4 major areas according to their location (northwestern districts, southwestern, etc.) and included the inner and outer cycling ring routes, as well as other major "green strips" in the north and south of the city, and along the Isar and Wurm rivers. The general layout of these routes and location of the green strips and other important segments can be seen in Figure 3.10 below. Other sections of the signposted cycle routes "mostly lead off the main roads through restricted traffic areas with a speed limit of 30 km/h and illuminated public parks" (Kinseher 2007) at this point, and the network of cycle infrastructure in Munich had a total length of over 1,200 kilometers (Kinseher 2007).

Figure 3.9: An example of the new signposting system implemented in 2006. Source: [Radl-Wegweisung](). radlhauptstadt.muenchen.de website.

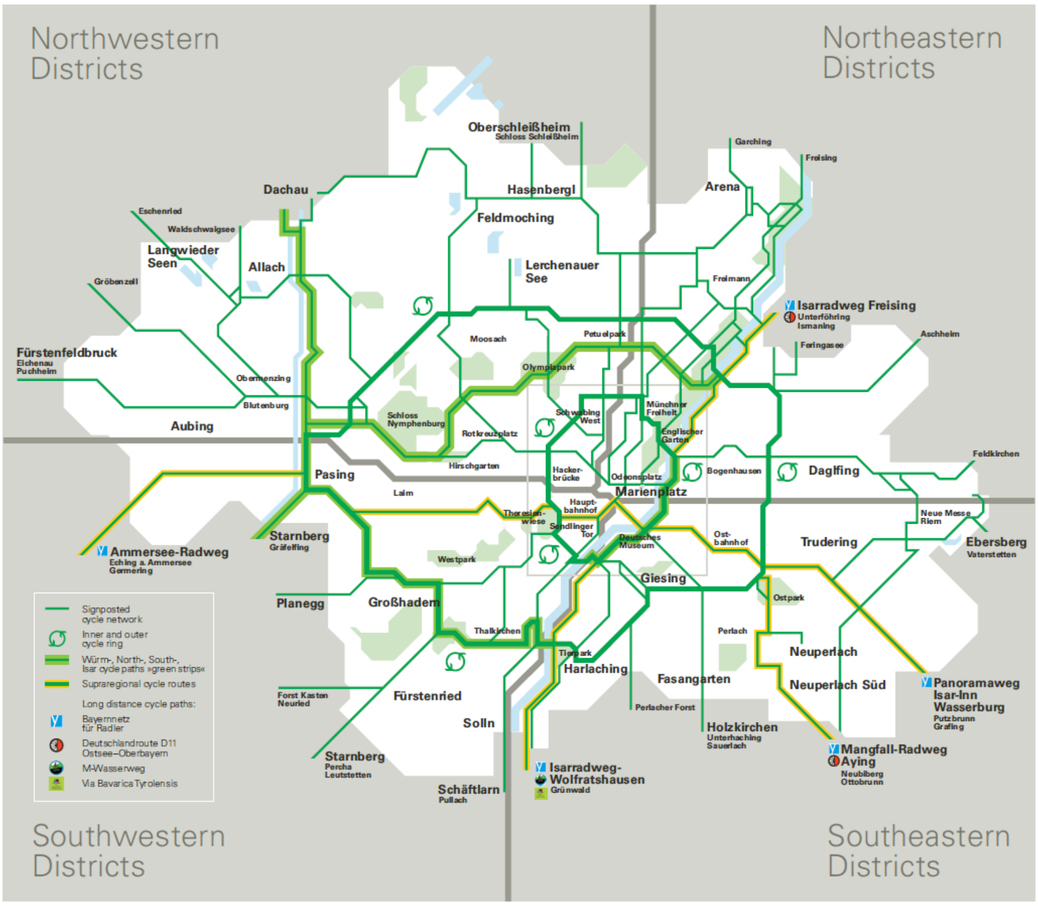

Figure 3.10: The network of signposted cycle routes in Munich as of late 2006. Source: (Kinseher 2007)

In terms of the infrastructure for cycling in Munich, many types have been built up over the years, there are:

- Cycle lanes, painted strips in the roadway for cyclists,
- Cycle paths, segments of the sidewalk paved with a different material or marked with pavement markings as separate from the sidewalk area for pedestrians, these are often further separated from the street by a green shoulder and/or parked cars.
- Dedicated cycle paths (also called cycle tracks), paths which are meant only for cyclists. Cycle paths through public parks or country fields and along country roads made up about 260 kilometers, or about 22% of Munich's cycling infrastructure network in 2010. (Zorn et al. 2010)

Cycle paths and cycle lanes along streets were about 42%, or around 500 kilometers, of the city's cycling infrastructure network in 2010 (Zorn et al. 2010). In recent years, the City of Munich has opened up many streets to cyclists, these are:

- Bicycle Streets, streets which are open to cyclists and in fact only meant for cyclists and local traffic. There were 42 such bicycle streets in 2013. (von Sassen 2013)
- Contraflow One-way Streets, one-way streets for cars which cyclists are allowed to go the reverse direction on. In 2013, there were approximately 300 of these across the city, or 42% of the city's one-way streets. (von Sassen 2013)

Cycling infrastructure along bicycle streets or contraflow one-way streets in Tempo30 Zones made up 450 kilometers, or around 38% of the city's cycling infrastructure network in 2010. (Zorn et al. 2010)

In addition to building up the network of cycling infrastructure, the city has greatly increased the number of public bike parking points throughout the city. In 2000, there were 17,920 public bike parking points in the City of Munich (Bördlein 2000), by 2013, this number had grown to over 28,000 (von Sassen 2013).

To support the use of all this additional cycling infrastructure and new facilities, the city began promoting cycling to raise awareness of its efforts and encourage the use of cycling among the residents. The Radlhauptstadt program which organizes advertisements, information brochures, large cycling-oriented events, and general marketing for cycling in the city was started and continues operation to this day. (von Sassen 2013)

With all this work in the past, the city still experiences a large amount of variation in the modal share of cycling throughout its 25 districts. As seem in Figure 3.11 below, the modal share of cycling ranges from 7% to 24% across the city.

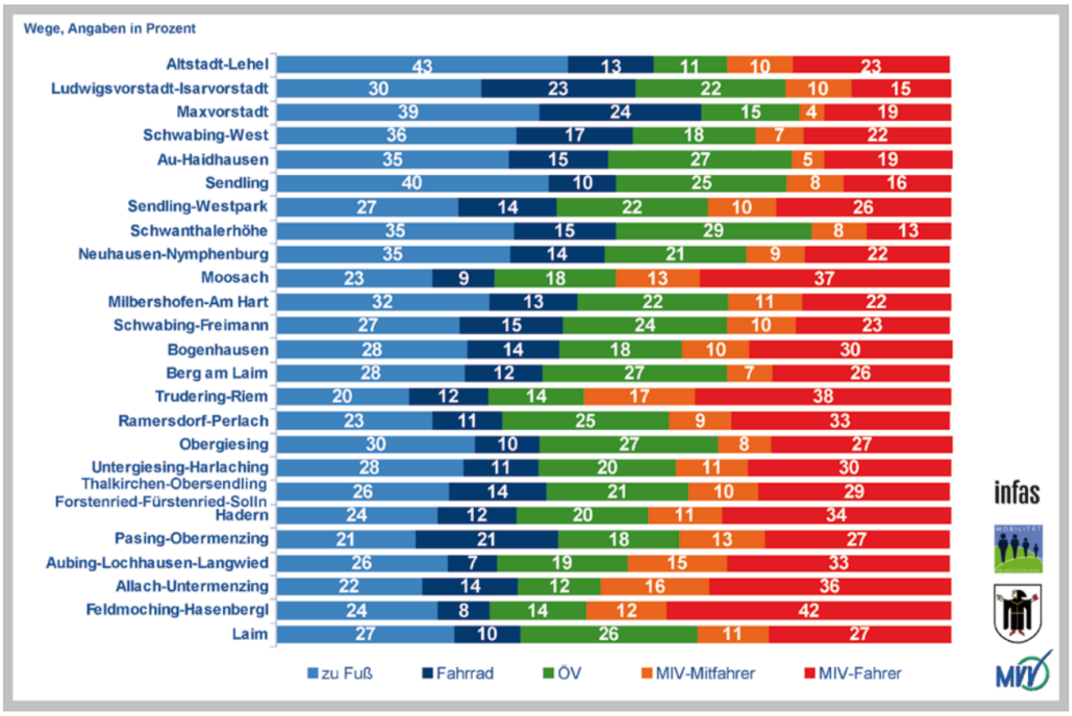

Figure 3.11: Modal split in Munich among the city districts. Modes represented from left to right - walking, cycling, public transport, car passenger, car driver). Source: (Belz, Follmer, and Gruschwitz 2010)

Still, there is much room to improve cycling in the city. As seen in Figure 3.12 below, in 2008, only 17% of households did not own a personal bike, and the average number of bikes per household was 2.

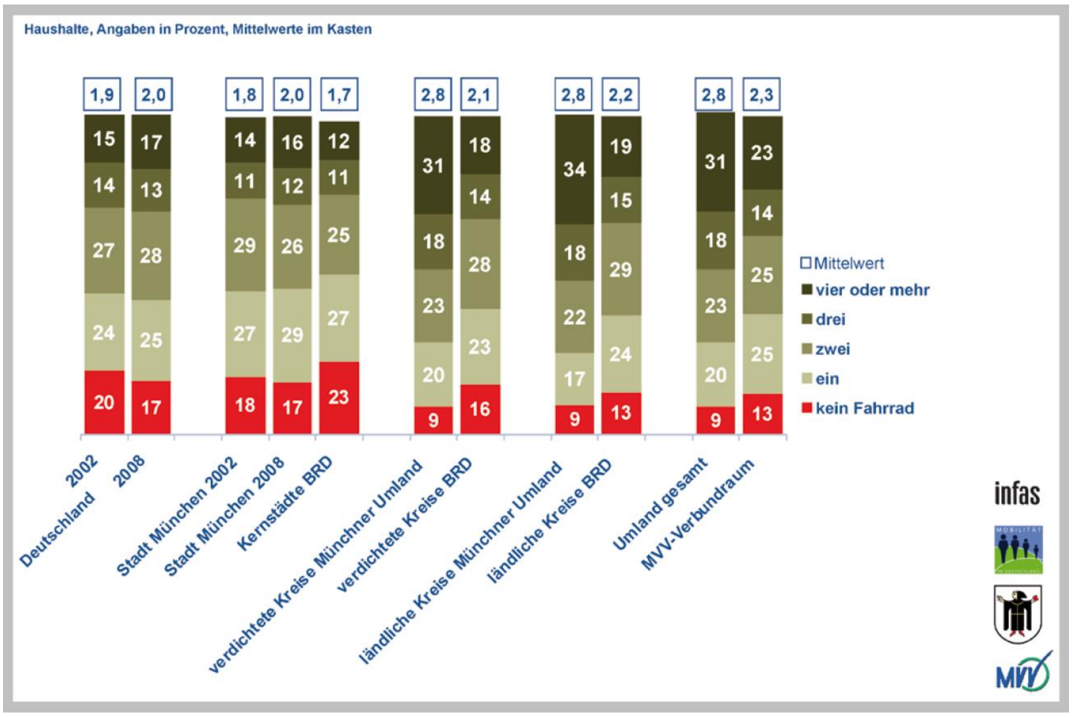

Figure 3.12: Number of Bicycles owned in households in Munich and across Germany. Results representing Munich are labeled "Stadt München (year)" and are presented in 6 groups, from top to bottom: the average (above the graph), 4, 3, 2, 1, and none at the bottom. Source: (Belz, Follmer, and Gruschwitz 2010)

In Figure 3.13 below, even though the vast majority of households owned a bike, still 31% of people in the city of Munich said they had not used a bike in recent months.

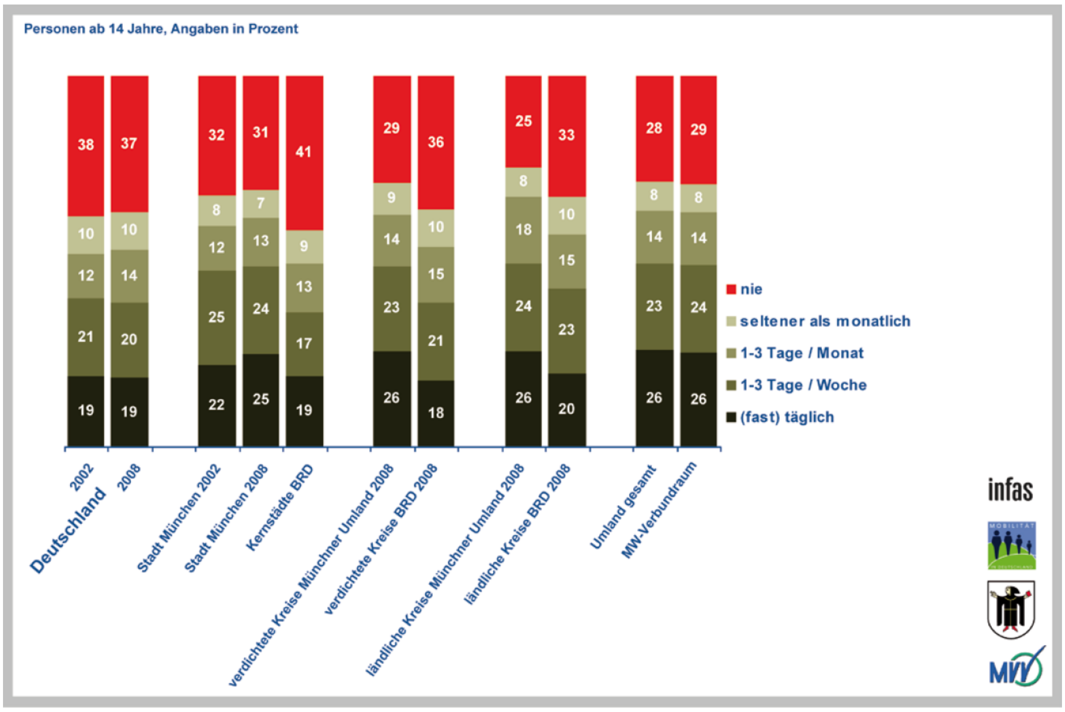

Figure 3.13: Bicycle usage frequency in Munich and across Germany. Results represent people 14 and older, and are segmented accordingly: "never", "less than monthly", "1-3 days a month", "1-3 days a week", and "almost every day" from top to bottom. Source: (Belz, Follmer, and Gruschwitz 2010)

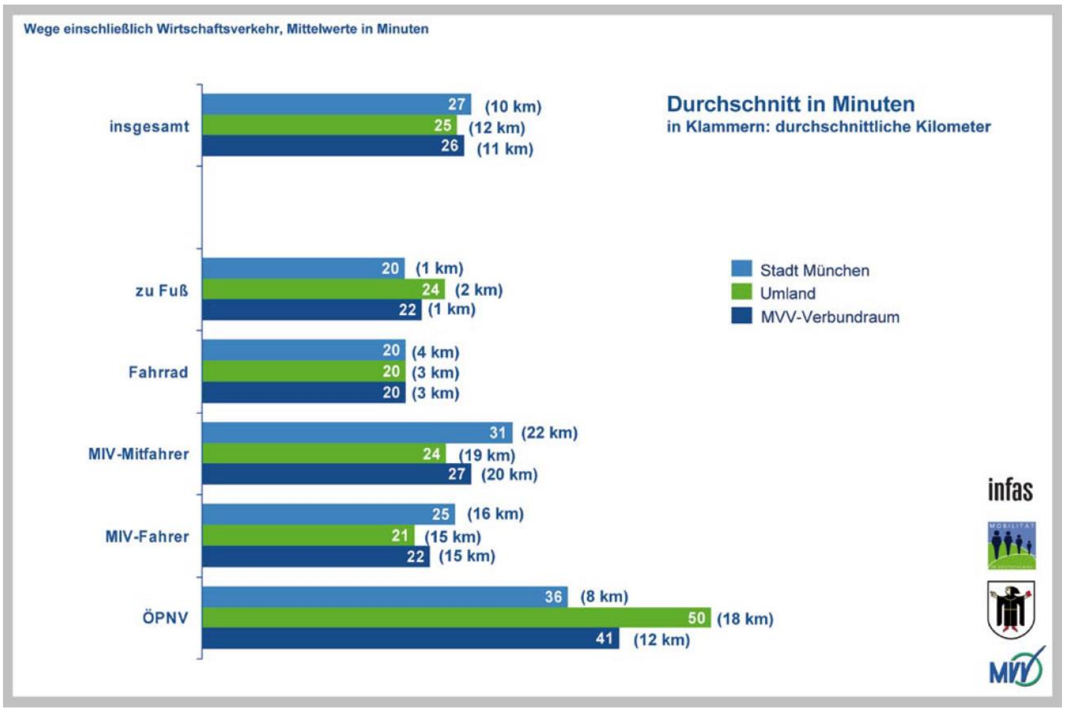

Figure 3.14: Average duration and length of trips by different transport modes in Munich. These values include commercial/business travel. Grouped by: total (at the top), walking, cycling, car passenger, car driver, and public transport (at the bottom.). Light blue bars represent the City of Munich, green the surrounding area, and dark blue the area which the local public transport company serves. Source: (Belz, Follmer, and Gruschwitz 2010)

What's more is that the average trip with a bike in Munich was 3.5 kilometers in 2008 as seen in Figure 3.14 above (Belz, Follmer, and Gruschwitz 2010). That fact combined with the fact that in in 2013, over 60% of all trips were less than five kilometers (von Sassen 2013), demonstrate that there is much room for further increased shares of cycling within Munich.

3.2 THE BUILT ENVIRONMENT AND CYCLING

The 1997 study by Cervero and Kockelmann highlighted the importance of the built environment for reducing the number of motorized trips and for increasing the share of non-motorized trips, and many studies since have added on to the results of their studies with supporting evidence showing that the various dimensions of the built environment can have an impact on the modal split of an area.

Starting with that 1997 study, in which the authors proposed the 3 "D"s of the built environment, density, diversity, and design, and posed that they influence travel demand by increasing non-motorized transport modes' share, reducing vehicular trips, and reduce travel distances and increase vehicle occupancy for produced vehicle trips. The 3Ds are broken down into several quantifiable variables and later combined into broader categories using factor analysis. For the statistical analysis of the article, regressions were run while including other relevant demographic and social variables like car ownership and mean salary. (Cervero and Kockelman 1997)

The study found that while there exists a "modest to moderate" associative relationship between the 3Ds and travel demand. They concluded that density was the strongest influencer of non-work trips. Land use diversity was found to have the largest effect on work trips mostly due to the presence of retail, and urban design had a moderate impact on the mode of non-work trips. (Cervero and Kockelman 1997)

Later, in 2003, Terri Pikora and colleagues attempted a different approach (T Pikora et al. 2003). This study investigated the built environmental factors influencing four different kinds of moderate physical activity in neighborhoods: walking for recreation and transport, and cycling for recreation and transport. The group reviewed literature and conducted interviews to create a framework of features, elements, and individual items (attributes) relevant to each type of physical activity. The study then determined the relative impact that each of these attributes in the frameworks might have on each type of physical activity through a Delphi panel. (T Pikora et al. 2003)

The four features within each framework of aspects impacting each activity were: 1) functional, the physical attributes; 2) safety, and the factors influencing personal and traffic safety; 3) aesthetic, the pleasing and interesting aspects; and 4) destination, the relative availability of facilities to travel to. These frameworks were later used in field studies to develop an audit tool used to assess local neighborhoods for the influence of their physical environments on walking and cycling activity (Terri Pikora 2000; T. J. Pikora et al. 2002).

In 2004, a case study of Portland, Oregon investigated the measurements of urban form the city and attempted to measure how the city had changed its urban development patterns over time (Song and Knapp 2004). The measurements of urban form used in this study included geographic aspects like street design layout, density of development, land use mix, accessibility, and pedestrian access.

The research defined 186 “block groups” (their unit of measurement) in the study area, and initially compared a typical post-war era neighborhood of Portland and one which followed a more modern set of principles. Having shown a significant difference between these two neighborhoods using their measures of urban form, the study then computed these geographic measurements for each of the 184 remaining neighborhoods in order to discover trends of development through the years. The study concludes that there was a significant shift in development patterns around 1990 towards more compact, dense, and better connected neighborhoods; however, they remained homogenous in land use. (Song and Knapp 2004)

Kevin Krizek and Pamela Johnson investigated two specific variables which are often studied in non-motorized travel demand research: the influence of cycling facilities (like separated bike paths and cycle lanes) and on biking rates and the impact neighborhood retail and other important services have on walking. The study paired geographic data of the area of research with disaggregate travel diary data. The study was conducted in the Twin Cities area in Minnesota, and used the travel diary data to categorize cyclists and walkers into groups by their distances to cycling facilities and neighborhood retail, respectively. (Krizek and Johnson 2006)

The study controlled for various demographic variables, and, using binary linear regression models, investigated the effect of these cycling facilities on biking and of nearby retail on walking. They studied all individuals as a whole and then split the data by the control groups to further understand any patterns in the data. They found that chances of cycling did not significantly change with respect to distance to these facilities overall, though those who lived within 400 meters of on-street cycling facilities had much higher rates of cycling than those more than 1600 meters from such facilities. For walking, nearby retail and services only had a significant impact if they were within 200 meters of the residential location. (Krizek and Johnson 2006)

In 2010, Iacono and colleagues investigated how non-motorized accessibility had been measured, and the various challenges associated with the way it was being assessed, and also looked into possible ways to address these issues and applied their solutions to a study area in Minneapolis, Minnesota. The study takes the traditional understanding of accessibility for motorized vehicles and applies it to non-motorized modes of cycling and walking. The issues it finds facing calculating such values are the lack of reliable data on travel behavior and land use, ill-defined or non-standard zone structure for non-motorized modes, and the use of completely random impedance functions for walking and cycling. (Iacono, Krizek, and El-Geneidy 2010)

To attempt to reduce the impact of these issues, the study then tested their hypotheses using an empirically estimated impedance function (evaluated using both time and distance) to calculate integral accessibility measures, and analyze accessibility by walking and cycling to shopping, work, schools, restaurants, and recreation. The study concludes by stating that further research is certainly needed, especially to further narrow the view and more deeply understand non-motorized travel behavior, however the researchers believe this method of calculating accessibility provides a useful tool to policymakers and consultants to develop plans and policies which increase accessibility for non-motorized modes through urban form and development regulations. (Iacono, Krizek, and El-Geneidy 2010)

Finally, a study in 2014 further investigated the influences certain attributes of the built environment could have on non-motorized travel. The attributes of the built environment investigated were accessibility, land use entropy, and density. The study also included various personal (job, gender, employment, income) and household (vehicle ownership, parking availability) characteristics into their investigation as well. The research focuses on different trip purposes and differentiates between inter- and intrazonal trips using travel survey and employed small-geographic scale neighborhood data from a study area in the Seattle region.

The research supports other previous research that certain built environment variables and demographic characteristics are statistically associated with non-motorized travel, but is careful to say that it is hard to understand these relationships. The authors could not conclude whether variations in non-motorized travel were caused by the environment, demographics, or if they were generated by self-selection of residents in certain types of areas. The article is able to conclude, however, that internal street connectivity, bus stop density, and non-motorized accessibility were positively associated with lower vehicle ownership rates, increased non-motorized modal share, and generally, more non-motorized trips, while demographic variables stayed constant. At the end, it notes the various downfalls of the study, such as the exclusion of topography, adjacent traffic, and the availability of quality cycling and pedestrian facilities.

4 Quantitative Study Methodology and Results

After researching the various methods used to quantitatively evaluate the built environment and analyze its impacts on travel behavior, as well as investigating the various datasets which are available, an approach to the quantitative study was designed. It was decided that a method utilizing stepwise multiple linear regression on a set of variables representing various dimensions of the districts (and other relevant demographic and social variables as not to ignore them) would be the best way to investigate if, how, and to what degree Munich's built environment influences the rate of cycling across the city.

In this section, first, the datasets used in the quantitative study will be introduced and described. Second, the variables used in the analysis, as well as the reasons for choosing them and their expected relationship with the modal share of cycling, will be presented in Sections 4.1.1 and 4.1.2. Next in Section 4.2, the methods used to extract and organize the geographic information data in GIS and the process of preparing the set of variables for analysis are detailed. Finally, in Section 4.3, the results of the quantitative analysis are presented and discussed.

4.1 Datasets and Variables

The datasets used as inputs to the quantitative study came from both official city, state, and federal government sources like open government data portals and unofficial online data sources like OpenStreetMap. While a few of the common variables used in built environment and travel behavior studies mentioned in Section 3 are straightforward and freely available in a usable format, many of them are slightly more complicated to attain or calculate. For example, much of the social and demographic variables came directly from the City of Munich, through one or another official publication available online and easily found through a couple of searches (Landeshauptstadt München 2009; Thien-Seitz, Riedl, and Rappert 2009). However, geographic information on the street network, public transport lines and stations, and land uses throughout the city are only freely available online through tools like OpenStreetMap.

While having such large and detailed databases available for free online through OpenStreetMap is immensely helpful and made this thesis possible, the data themselves often needed to be cleaned, organized, and extracted using GIS software. This was a very time-intensive part of the study; each of the built environment variables which were derived from OpenStreetMap data took time to thoughtfully carry out this process. In some cases, extracting the data for a variable was as simple as summing the number of points in each district, a relatively simple operation. However, other variables required measuring the distance between each of the thousands of addresses within a district and the nearest point of interest of any given type (nearest park, supermarket, transit stop, etc.). Limitations of this process and some recommendations for how to improve upon it in the future are discussed in Section 6.1.

In this section, each source of data used in the quantitative study will be presented and described, including a short assessment of the quality of the data with respect to how it would be used. Then, each of the 95 variables investigated in the quantitative study (both built environment and social and demographic variables) are discussed in detail. Reasons for why each variable was chosen, which source the data came from, how it was extracted or calculated from the source data (and the level of confidence in that, if appropriate), and the expected relationship between the variable and the modal share of cycling are given in Section 4.1.1 and Section 4.1.2.

OpenStreetMap Data

OpenStreetMap (OSM) is one of the world's largest freely available geographic information databases. According to their "About" page: "OpenStreetMap is built by a community of mappers that contribute and maintain data about roads, trails, cafés, railway stations, and much more, all over the world." (OpenStreetMap contributors 2018). Originally founded in 2004 in the UK, OpenStreetMap has since grown to over four million users worldwide. The data in the OSM database is available in a variety of formats and exports can be made directly from the website.

While the data itself is gathered on OpenStreetMap (OSM) and available on their website, many other services extract data from OSM, then process, edit, and package it for others to use as well. The OSM sources of this type used in this thesis are GeoFabrik, Mapzen, the Humanitarian OpenStreetMap Team (HOT), and the BBBike application data (discussed later under "Other Data Sources"). Each source has its own benefits and disadvantages, and much of the data overlapped. However, some of the sources provided better information in one area of interest than others had available. For example, the HOT data included highly detailed information on points of interest (all kinds of shops and amenities, often including names, addresses, and hours of operation) while the GeoFabrik data provided more information about the street network in Munich. These three sources are briefly described further below.

GeoFabrik is a German-based community and company which uses OpenStreetMap data (among other sources) to provide publicly available packages of OSM data as well as other GIS-related services such as consulting, training, and software development. The packages of OSM data the publish online for free are offered in many different file formats and are segmented into various sizes ranging from entire countries to administrative regions. For the quantitative study, GeoFabrik data was chosen as the best available source of the street network in Munich, which was then further organized and extracted to generate values for several street-related built environment variables.

Mapzen was an online platform which provided open-source search, rendering, navigation and other tools. Unfortunately, the service used by this thesis, their Metro Exports, shut down in January 2018, though records of their data are available online still as of mid-March 2018. Originally, Mapzen was used as a data source for many of the built environment variables. But due to their services shutting down and the availability of more suitable data via the Humanitarian OSM Team, Mapzen data was only used for the public transport-related variables. It was found that Mapzen had the most current information and was therefore chosen as the more accurate source available.

The Humanitarian OpenStreetMap Team (HOT) is an international organization and community which provides current maps tailored for use by relief organizations for free online, as well as other mapping-related services aimed at helping those most in need. The HOT data proved to be an invaluable source of data for this thesis, as the level of detail of points of interest (shops, restaurants, bakeries, offices, amenities, etc.) the data came with was far higher than available from other OSM data sources. For example, the data includes an attribute named “shop” for each of the points in the set. The “shop” attribute contains a description of the type of shop associated with each point, if there is one (e.g. supermarket, electronics store, clothing store, etc.), as well as information such as the address, name, and even opening hours. This information was invaluable for the calculation of many land use diversity and destination accessibility variables.

All OpenStreetMap data used in the quantitative study were the most recent set of data available. While the veracity of the data was examined with respect to current conditions on the street – and was found to be acceptable in most cases (see the specific variables for more information) – it is assumed that these data represent, at least in some way, the situation as it was in 2008. Very little reliable data on the built environment in 2008 is freely available, so the conditions represented in the GIS data used in the study are taken as a proxy for the conditions as they were at the time of the Mobilität in Deutschland 2008 study. Assessments of the quality of and confidence in the data are given in Section 4.1.1 and Section 4.1.2 on a variable-by-variable basis. More on this and the impact on the findings of the study are presented in Section 6.1.

Cycling Infrastructure Data from the City of Munich

To supplement the geographic built environment data from the sources described above, the author also obtained specific cycling infrastructure data from the City of Munich’s Department of Health and the Environment. After finding the city’s cycling map online and seeing the data available there (http://maps.muenchen.de/rgu/radlstadtplan), the author inquired at the city for the source data. After that, a representative from the city began the process of granting access to the data to the author. The geographic data provided by the city included shapefiles of lines which had a variety of attributes representing various characteristics of the cycling infrastructure associated with them. For example, there were attributes for the location of the cycle way – either in a green area (forest or non-forest) or in the streetscape.

Just as with the OSM data, this data on the cycling infrastructure in Munich is current (as of 2017), and not a direct representation of what the conditions of cycling infrastructure in 2008 were. Again, the data provided by the City of Munich was taken as a proxy for the conditions of cycling infrastructure in 2008.

Munich's Indicator Atlas (Indikatorenatlas)

One of the sources of several demographic and social variables is an online service and publication called "Indikatorenatlas". Indikatorenatlas is published by the City of Munich's Community Ministry Geodata Service (Kommunalreferat GeodatenService) and available online in both map service and downloadable spreadsheet form. The service tracks data of several types for each of the city districts, including many of the variables which were directly used in this study. Motorization rate, the unemployment rate, the age split of the population, and other relevant demographic and social variables were taken directly from this data source and used in the analysis. As this data is directly provided by the city, it is a trusted source.

Munich's Statistics Pocket Book (Statistisches Taschenbuch)

Another source provided directly by the city is the Statistics Pocket Book (Statistisches Taschenbuch), distributed by the City of Munich's Department of Statistics (Statistisches Amt). This annually published book provides a variety of information about the city as a whole and each of the 25 districts on a variety of topics. Geographic and land use data are supplied in each issue, like the area of certain types of land uses, as well as a host of demographic and social information, like the breakdown of age groups by their percentage of the population or the distribution of the size of households across the population. As a source is published directly by the city and the variables taken from it didn't require extra work to extract, it is considered very reliable.

Other Data Sources

Unlike the other OSM sources mentioned above, the data obtained from the BBBike application was generally not of a very high quality, except in one respect. The information regarding the location of bicycle parking and rental facilities in this dataset seemed to be quite reliable. While certainly not every bike parking location was included in the set, from the several central bike parking locations known to the author that were checked, all existed in the data set.

Additionally, the Professor for Modeling Spatial Mobility provided a spreadsheet of data containing estimates of the distribution of total jobs and the various types of jobs within each of the city's 25 districts. This data was used to calculated the job density variable discussed below. While this number was based on estimates, the data values made sense to the author and matched with expectations based on the values of other relevant variables.

The Mobility in Germany Study (Mobilität in Deutschland)

Finally, the last source of data used in the quantitative study is the source of the modal share data, the Mobility in Germany 2008 study. A document published by the City of Munich's Ministry for City Planning and Construction (Referat für Stadtplanung und Bauordnung) provided a wealth of information on transportation in the city as described in Section 3.1. This document also included a chart which contained the modal split for each of the city's 25 districts. The modal share of cycling of the trips (the percentage of cycling within the modal split) became the dependent variable of the quantitative study. As the Mobility in Germany is the country's largest travel behavior survey, and the only one with the modal splits in Munich broken down by city district, it was taken as the best source available.

4.1.1 Built Environment Variables

Through the review of literature presented in Section 3.2, it was determined that the most relevant dimensions of the built environment to include in this study were density, diversity of land use, urban design, destination accessibility, and distance to transit. The built environment variables investigated in the quantitative study are presented in this section, grouped by their classification into one of these five dimensions.

For the full list of variables, including the intermediate values used to calculate some of them, see the Master Data Table in Appendix B, or for simply the full list of variables in one place, see the Descriptive Statistics of Variables Table in Appendix A.

Density Variables

The variables listed below in Table 4.1 are the variables used in the quantitative study which were classified as related to density. The units of measurement of the variables, descriptive statistics of each variable, and the source of the data are included as well. The variables are described further after the table.

Table 4.1: The variables used to measure the density of each district.

Density Variables	Unit	Min. Value	Max. Value	Mean	Median	Std. Dev.	Source
Population Density	inh. / km² (dev. land)	3,189.738	16,437.827	8,490.226	8,088.998	3,893.735	Statistisches Taschenbuch 2009
Job Density	jobs / km² (dev. land)	553.706	17,668.357	4,018.294	2,645.385	3,752.820	Professor für Räumliche Modellierung (jobs model)
Employed Persons Density	employees / km² (dev. land)	1,065.806	6,140.826	3,200.524	2,870.044	1,633.361	Jahreszahlen, Arbeitsmarkt 2008 (München Statistisches Amt)
Proportion of Developed Land of Total Land Area	%	34.964%	94.619%	73.259%	73.723%	15.780%	Statistisches Taschenbuch 2009
Altstadt	nominal (0 or 1)	0	1	NA	NA	NA	"Dummy variable", 1 for Altstadt-Lehel and 0 for other districts

Both Population Density and Job Density have been used in previous studies as measures of the density of the built environment (Cervero and Kockelman 1997; S. L. Handy et al. 2002; Mertens et al. 2017), both thought to be correlated with high rates of non-motorized travel. Population Density of each district is directly taken from the Statistisches Taschenbuch 2009 (Thien-Seitz, Riedl, and Rappert 2009). The Job Density variable was calculated using estimates of the total number of jobs in each district as modeled by the Professor of Spatial Modeling (Moreno Chou and Moeckel 2017) and dividing by the number of square kilometers of developed land in the district (further described below). The Employed Persons Density variable was used as another way of measuring the density of the population and was thought to also be positively associated with higher rates of non-motorized travel.

The variable "Proportion of Developed Land of Total Land Area" was calculated from data for each district available in the Statistisches Taschenbuch which details the area covered by various basic types of land use. The "developed land" in a district was a combination of these areas, namely: the areas belonging to buildings, service uses, transportation, and other uses. It was thought that a higher ratio of developed land to total land would be associated with a higher modal share of cycling.

The areas which were combined to make the attribute "developed land", and the others presented in the Statistics Pocket Book, are used in other variables in the quantitative study as well, so they are described in detail below for reference. Each bullet point below corresponds to a subset of area recorded in the Statistisches Taschenbuch. The descriptions for each subset are translated from the General Geographic Information 2008 (Statistisches Amt München 2009).

- Entire area of the district (Fläche insgesamt)
    - Buildings and attached areas (Gebäude- und (zugehörige) Freiflächen): described as areas with buildings and those which are used for buildings' purposes, like courtyards, front and back yards, storage areas, playgrounds, driveways and more.
        - Buildings with Living Area (Wohnen)
    - Service areas (Betriebsflächen): described as un-built areas which are mostly used for industrial, transport, waste management and other city services.
    - Recreational areas (Erhölungsflächen): described as un-built areas which are mostly used for sport, recreation, or as natural reserves for plants and animals including green areas like parks, zoos, and botanical gardens, sports areas and camping areas.
        - Sports areas (Sportanlagen)
        - Green areas (Grünanlagen und -flächen)
    - Transportation-use areas (Verkehrsflächen): described as areas of streets, railways, or designated for air transport use. This includes paths in meadows, forests, and other footpaths, as well as parking areas, highway rest stops, and market squares.
    - Agricultural areas (Landwirtschaftsflächen): described as areas used for agriculture, pastures, and horticulture including orchards and plant nurseries. It also includes moor and health land, scrub, and other agricultural service areas.
    - Forested or woods areas (Waldflächen): described as areas with natural or planted forest trees or shrubs, tree nurseries, lumber storage areas, and other wooded areas.
    - Water areas (Wasserflächen): described as areas which are covered by flowing or standing water for the majority of the year, both of natural or man-made sources, including embankments and small islands associated with the bodies of water.
    - Other use areas (Flächen anderer Nutzung): described as other areas and those which have no stated use, including military training grounds, historical areas, and cemeteries.

Finally, the "Altstadt" variable was introduced as a dummy variable with a value of 1 only in the Altstadt-Lehel district and 0 in all other districts. This was used during the variable trimming process as described in Section 4.2.2 to account for this extreme outlier district with respect to many variables.

Diversity Variables

The variables listed below in Table 4.2 are the variables used in the quantitative study to define and measure the land use diversity of the districts. The units of measurement of the variables, descriptive statistics of each variable, and the source of the data are included as well. The variables are described further after the table.

Table 4.2: The variables used to define the land use diversity of each district.

Diversity Variables	Unit	Min. Value	Max. Value	Mean	Median	Std. Dev.	Source
Percent of Area of Infrastructure Facilities of Total Dev. Area	%	17.910%	40.638%	28.388%	27.174%	5.495%	Statistisches Taschenbuch 2009
Percent of Area of All Buildings of Total Dev. Area	%	58.705%	77.315%	68.544%	70.188%	6.041%	Statistisches Taschenbuch 2009
Percent of Area of Residential Buildings of Total Dev. Area	%	21.524%	60.479%	42.757%	43.853%	9.667%	Statistisches Taschenbuch 2009
Ratio of Health and Recreational Area to Total Dev. Area	ratio	0.0569	0.5167	0.2237	0.1947	0.1292	Statistisches Taschenbuch 2009
Ratio of Health & Recreational, Forest, and Water Areas to Total Dev. Area	ratio	0.0569	0.6750	0.2865	0.3001	0.1679	HOT Export Tool OSM Data
# of Offices and Administrative Buildings per Dev. Area	offices / km²	0.111	29.030	6.976	3.421	8.289	HOT Export Tool OSM Data
# of Educational Facilities per Dev. Area	education fac. / km²	0.997	12.441	4.052	2.737	3.221	HOT Export Tool OSM Data
# of All Stores and Shops per Dev. Area	all stores / km²	5.539	377.390	55.991	26.003	80.112	HOT Export Tool OSM Data
# of Shopping and Retail Stores per Dev. Area	shopping / km²	1.551	266.661	31.041	10.801	55.432	HOT Export Tool OSM Data
# of Bakeries and Cafes per Dev. Area	bakeries & cafes / km²	1.005	17.418	5.092	3.238	4.583	HOT Export Tool OSM Data
# of Restaurants, Cafes, & Bars per Dev. Area	eateries / km²	1.994	165.471	32.009	12.601	42.802	HOT Export Tool OSM Data
# of Cultural and Social Facilities per Dev. Area	rec. facilities / km²	0.185	14.930	2.484	1.079	3.570	HOT Export Tool OSM Data
# of All Food Stores per Dev. Area	food stores / km²	1.329	43.130	8.311	4.444	9.235	HOT Export Tool OSM Data
# of Supermarkets per Dev. Area	supermarkets / km²	0.2215	8.6515	3.2586	2.4035	2.4034	HOT Export Tool OSM Data
Stores and Shops Diversity (1km)	Avg. # of types of shops within 1km	8.620	106.230	39.215	31.100	25.775	HOT Export Tool OSM Data
Stores and Shops Diversity (3km)	Avg. # of types of shops within 3km	32.360	197.280	106.988	102.230	45.453	HOT Export Tool OSM Data
Amenity Diversity (1km)	Avg. # of types of amenities within 1km	7.720	47.810	23.438	21.080	10.031	HOT Export Tool OSM Data
Amenity Diversity (3km)	Avg. # of types of amenities within 3km	25.950	82.560	51.048	47.940	16.285	HOT Export Tool OSM Data

Jobs-Housing Balance	ratio	0.1296	5.8752	1.1408	0.5078	1.4126	TUM Professor für Räumliche Modellierung & Indikatorenatlas

The first five of the variables listed above use the same data from the Statistics Pocket Book of the areas of basic types of land uses to describe the land use diversity of the city's districts. The first, the percent of total developed area classified as "transportation-use" was used to analyze how much of the developed space in the district is taken up by these facilities. It was believed that this variable would be negatively associated with the modal share of cycling in the city. With transportation facilities (roads, railways, depots, etc.) covering more of the developed land in a district, the overall amount of developed land left for other uses (housing, retail, etc.) within range of cyclists would be lower, resulting in a lower cycling share. Also, a higher value for this variable could also imply the more railway infrastructure or motorways above ground in the district, creating barriers for cyclists and a more common attribute of the outer districts which had lower modal shares of cycling. On the other hand, the next four variables relating to the share of certain land uses in relation to the developed land in a district were all expected to be positively associated with the modal share of cycling. As the share of land uses classified as buildings and residential buildings increases, it was expected that the modal share of cycling would also increase. Higher rates of buildings per developed land use area could be a sign of denser, more central development where cycling is more common. The shares of certain types of land uses (residential, commercial, etc.) have been used as measurers of land use diversity in many previous studies, many of which demonstrated them to be significant, such as (Cervero and Kockelman 1997; S. L. Handy et al. 2002; Ewing and Cervero 2010; Zegras 2005) among others.

Per developed area rates of certain types of buildings, stores, and services are measured by the next set of variables on the list. These values were calculated by extracting the total number of these types of locations within each district from the points included in the HOT Export Tool's dataset. The information associated with each of these points included two important attributes, "shop" and "amenity". For those points in the data which represented shops and amenities, a value for these attributes was given which described the points. For example, points representing supermarkets had the value "supermarket" for the "shop" attribute, and those which represented drug stores were marked with the value "chemist". As it may not be immediately clear which types of shops or amenities would fall into which group, an overview of which types of each point fell into each group is available in Appendix M. The expected relationship between these variables and the modal share of cycling was a positive association. If a district has more shops, amenities, and other points of interest per area of developed, it likely has a more diverse offering of them. Per unit area rates of commercial, industrial, retail, and other locations have been used in previous studies to measure the diversity of land uses within a neighborhood, and shown to be a factor associated with non-motorized transport as in (Cervero and Kockelman 1997; Cervero 2002; Zegras 2005; Ewing and Cervero 2010) and others.

The next four variables are a more direct measure of the diversity of shops and amenities as a whole. Each was measured by counting the number of types of shops or amenities within one or three kilometers of each address point in the database. The distances used in these variables were chosen as easy and comfortable cycling distances, and both were used to investigate which would have a stronger association with the modal share of cycling. Each of the OSM databases included a layer which contained a point for each address in the defined area of the dataset (Munich, the region of Oberbayern, etc.). From these address points, a buffer of variable width was projected depending on the variable in question. The number of different values for the "shop" or "amenity" among the shop and amenity points within these buffers was counted and averaged over the complete set of addresses within each district. It was expected that there would be a positive relationship between both shop and amenity diversity and the modal share of cycling. With a larger variety of options available to cyclists within a comfortable cycling range (one or three kilometers), more trips can be completed via cycling. This technique of counting points within a radius of one or three kilometers (and other values for public transportation variables) around each address point in the dataset was used in several other variables named in the following subsections.

Finally, the jobs-housing balance variable is a measure of the ratio of jobs to households within a district. This value has often been used to describe the diversity of land uses in a district in several studies in the past (Cervero 1996, 2002; Comendador, López-Lambas, and Monzón 2014; Khan, Kockelman, and Xiong 2014), and shown varying results in association with the modal share of non-motorized modes. It was expected that higher jobs-housing balances would be associated with higher modal shares of cycling, as this would signify that the area in question contained a greater mix of uses. The data on the number of jobs for this variable came from an estimate of the distribution of jobs among the city districts performed by Dr. Ana Tsui Moreno Chou of the Research Group of Modeling Spatial Mobility at the university. These numbers were used with the number of private households recorded in the Statistics Pocket Book of 2011, the corresponding year. Because they were calculated using an estimate, the values of this variable should be taken into consideration, but not as fact.

Design Variables

The variables listed below in Table 4.3 are the variables used in the quantitative study to analyze the urban design of a district. The units of measurement of the variables, descriptive statistics of each variable, and the source of the data are included as well. The variables are described further after the table.

Table 4.3: The variables used to analyze a district's urban design.

Design Variables	Unit	Min. Value	Max. Value	Mean	Median	Std. Dev.	Source
Length of Cycling Infrastructure along Streets per Dev. Area	km cycle street / km²	1.773	8.614	5.738	5.694	1.809	CoM & Statistisches Taschenbuch
Length of Cycle Paths in Green Areas per Dev. Area	km green path / km²	0.000	3.207	1.267	1.084	0.882	CoM & Statistisches Taschenbuch
Length of Cycle Paths in Urban Green Areas per Dev. Area	km urban green path / km²	0.000	1.803	0.736	0.594	0.543	CoM & Statistisches Taschenbuch
Length of Signposted Cycle Ways per Dev. Area	km cycle route / km²	0.569	3.400	1.713	1.517	0.745	CoM & Statistisches Taschenbuch
Meters of Cycleway Underpasses per Dev. Area	m / km²	4.196	487.533	123.664	96.303	103.859	CoM & Statistisches Taschenbuch
Area of All Streets open to Cycling per Dev. Area	m² / km²	495.540	65,990.44	16,879.622	11,274.99	16,906.37	CoM & Statistisches Taschenbuch
Area of "Bicycle Streets" per Dev. Area	m² / km²	0.000	21,373.15	4,048.444	1,689.074	5,716.863	CoM & Statistisches Taschenbuch
Area of "Against One Way Streets" per Dev. Area	m² / km²	187.095	57,399.47	11,898.414	7,438.934	13,553.12	CoM & Statistisches Taschenbuch

Median Distance to a Park or Natural Area	meters	104.450	215.310	144.568	129.610	34.326	GeoFabrik & HOT Export Tool Data
# of Bike Parking Points per Dev. Area	parking racks / km²	0.509	43.744	8.657	4.273	10.282	BBBike OSM Data
# of Bike Rental Points per Dev. Area	sharing docks / km²	0.000	3.318	0.984	0.515	1.115	BBBike OSM Data
Intersection Density	intersection points / km²	326.772	897.441	542.555	521.775	153.269	GeoFabrik & HOT Export Tool Data
Average Block Length	meters	88.500	171.671	123.882	121.788	19.173	GeoFabrik Data
Average Street Speed Limit	km/h	35.000	44.000	40.920	41.000	2.499	GeoFabrik Data
Percent of Roadways with a Speed Limit of 30 km/h or lower	%	30.658%	73.425%	49.964%	50.427%	11.012%	GeoFabrik Data
Length of All Roadways per Land Area	km all roads / km²	4.989	15.465	10.663	10.568	2.921	GeoFabrik Data
Length of Autobahn per Dev. Area	km Autobahn / km²	0.000	3.576	0.595	0.227	0.884	GeoFabrik OSM Data
Length of Trunk & Primary Roadways per Dev. Area	km Primary / km²	0.000	3,541.946	1,178.555	852.707	986.715	GeoFabrik OSM Data
Length of Secondary Roads per Dev. Area	km Secondary / km²	0.989	5.848	2.604	2.038	1.363	GeoFabrik OSM Data
Length of Tertiary Roads per Dev. Area	km Tertiary / km²	0.000	1.933	0.794	0.792	0.432	GeoFabrik OSM Data
Length of Side Streets per Dev. Area	km Side Streets/ km²	6.460	12.219	8.932	8.567	1.578	GeoFabrik OSM Data
Length of Pedestrian Paths per Dev. Area	km Pedestrian / km²	7.319	26.810	17.009	17.257	4.960	GeoFabrik OSM Data

The first subset of eight variables on this table relate to cycling infrastructure of various types which all stem from data received from the City of Munich's Department for Health and the Environment. Each of these eight variables drawn out of the city's data correspond to an attribute of the data, for example, the location of the cycle way (in a green area, a forest, or along the streets), lines representing the network of signposted cycle routes through the city, or polygons representing the areas of different types of streets open to cycling. The presence of cycling infrastructure has been connected to increased modal shares of cycling in the past (Krizek and Johnson 2006; Pucher, Dill, and Handy 2010), so each of these variables was expected to be positively associated with the rate of cycling across the city. Unfortunately, the data only represents the cycling infrastructure in the city in 2017, not 2008, the year of the modal share data. However, though the network has been expanded, these variables can act as proxies for the conditions of the cycling network in 2008 since much of it was already in place then as well. Still, the values of these variables should be taken with consideration, as they do not directly represent the state of cycling infrastructure in 2008.

The next variable, the Median Distance to a Park or Natural Area was used as a way of measuring how well distributed green areas are within each district. The definition of a "Park" or "Natural Area" differs from the "Green Areas" described above from the Statistical Pocket Book data (used in the land use diversity variables), as those values were only reported as sum for each district. For this variable, data from both the GeoFabrik and HOT Export Tool were used to locate parks, natural areas like forests and meadows, parks, and other recreational green areas within each district and calculate the median distance from each address point to the nearest one of these areas. The modal share of cycling was expected to be positively related to this variable, as the closer people live to pleasant cycling areas, the more likely they might be to cycle.

The next two variables, bike parking and bike rental facilities per developed area, come from yet another source of OSM data, extracts of data used by the bike routing application, BBBike. The data associated with this app had information about the location of these two types of cycling facilities not available in any other dataset. While the veracity of these data is not entirely known, they seem to match expected locations of bike racks and rental docks in reality. Several points in the data were compared to locations of bike parking and rental facilities known to the author, and each of them were present in the data. Still, not every bike rack in the city is in the set, but districts with more racks are likely to be better represented in the data, so it was considered at least worth including these variables to investigate their possible connection to the modal share of cycling. It was expected that the modal share of cycling would be positively associated with the number of bike parking and bike rental facilities in a district.

Continuing down the list of variables above, the next four (Intersection Density, Average Block Length, Average Street Speed Limit, and the Percent of Roadways with a Speed Limit of 30km/h or lower) all describe the structure or conditions of the street network inside each district. Each of these variables were extracted from GeoFabrik's OSM dataset, which was found to have the most detailed and reliable information about Munich's street network. Intersection density is simply the number of intersections between roads and streets per unit of area within a district.

In the process of extracting the Intersection Density values, it was noticed that multiple lanes of the same roadway, or multiple spurs and ramps between intersections also counted as individual intersection points. This is not ideal, as in reality, each of these points still belong to the same central intersection between two roadways. The problem was especially prevalent at motorways, with each lane, offramp, onramp, and cloverleaf ramp forming intersections with one another and the main lanes themselves. As a result, a single "intersection" between two motorways could be counted over 10 times as much as it should have been. Luckily, however, the problem was limited to motorways and large roadways, and was only as bad as described when two of these types of roads intersected one another.

Both Intersection Density and Average Block Length have often been used as measures of an area's street connectivity, an important feature of its urban design. Studies such as (Khan, Kockelman, and Xiong 2014; Ewing and Cervero 2010; Song and Knapp 2004) among others have used it in the past. As Intersection Density increases and Average Block Length decreases – both indicating higher street connectivity and a denser network – it was expected that the modal share of cycling would increase.

The next two variables in this subset consider the speed of vehicles on the streets of a district. Not all of the streets in the GeoFabrik dataset had values for the speed limit, but many did and most of the trunk, primary, secondary, and tertiary streets did, as well as the motorway segments. The Average Street Speed Limit variable was expected to be inversely correlated with the modal share of cycling, because higher values would imply a larger share of busy, fast, and high-volume roads which are not conducive to cycling. On the other hand, the Percent of Roadways with a Speed Limit of 30 km/h or lower variable was expected to have the opposite relationship, as a higher share of calm streets in the network could encourage cycling. In the calculation of both of these variables, streets with no value for the speed limit were not considered, so there could be some bias to districts with a higher share of streets with detailed information. However, it is not known which districts this would apply to, so the values for these variables should be taken with consideration.

Finally, the last subset of variables measuring the per-area lengths of each street classification were included as a way of describing the street network in each district. Districts with a higher density of motorways and trunk and primary roadways were considered to be less bike-friendly and therefore would be inversely associated with the modal share of cycling. Conversely, those districts with higher densities of secondary and tertiary roadways, side streets, and pedestrian paths were expected to exhibit higher modal shares of cycling, since these less busy streets are more conducive to cycling than the much larger trunk and primary roads.

Destination Accessibility Variables

The variables listed below in Table 4.4 are the variables used in the quantitative study to define the level of access to destinations of the districts. The units of measurement of the variables, descriptive statistics of each variable, and the source of the data are included as well. The variables are described further after the table.

Table 4.4: The variables used to define the destination accessibility of a district.

Destination Accessibility Variables	Unit	Min. Value	Max. Value	Mean	Median	Std. Dev.	Source
Median Distance to the Altstadt	meters	530.410	11,915.260	5,278.479	4,916.897	2,834.971	HOT Export Tool Data
Median Distance to the Isar	meters	599.424	8,056.417	3,421.574	2,547.401	2,372.027	HOT Export Tool Data
Median Distance to a "Stammstrecke" S-Bahn Station	meters	361.701	6,970.284	3,094.540	3,255.692	1,847.468	HOT Export Tool Data
Average Number of Offices and Administrative Bldgs. w/in 1km of Addresses	# of offices and admin bldgs.	0.185	72.100	18.815	9.820	21.450	HOT Export Tool Data
Average Number of Offices and Administrative Bldgs. w/in 3km of Addresses	# of offices and admin bldgs.	5.310	385.060	145.525	104.540	115.682	HOT Export Tool Data
Average Number of Educational Facilities w/in 1km of Addresses	# of edu. facilities	2.490	27.390	10.762	8.080	7.718	HOT Export Tool Data
Average Number of Educational Facilities w/in 3km of Addresses	# of edu. facilities	16.980	192.130	84.134	71.890	51.264	HOT Export Tool Data
Average Number of All Stores and Shops w/in 1km of Addresses	# of all shops	13.400	893.900	159.992	73.240	205.482	HOT Export Tool Data
Average Number of All Stores and Shops w/in 3km of Addresses	# of all shops	105.930	3,312.050	1,117.608	749.870	972.741	HOT Export Tool Data
Average Number of Retail and Shopping Facilities w/in 1km of Addresses	# of retail facilities	3.730	625.070	89.852	29.950	140.839	HOT Export Tool Data
Average Number of Retail and Shopping Facilities w/in 3km of Addresses	# of retail facilities	35.680	1,975.290	607.707	341.260	598.156	HOT Export Tool Data
Average Number of Bakeries and Cafes w/in 1km of Addresses	# of bakeries and cafes	2.600	46.060	14.394	10.030	12.212	HOT Export Tool Data
Average Number of Bakeries and Cafes w/in 3km of Addresses	# of bakeries and cafes	20.830	260.720	105.596	79.680	75.259	HOT Export Tool Data

Average Number of Eateries w/in 1km of Addresses	# of eateries	4.710	455.310	90.649	33.830	117.464	HOT Export Tool Data
Average Number of Eateries w/in 3km of Addresses	# of eateries	45.350	1,995.510	648.273	373.840	608.962	HOT Export Tool Data
Average Number of Cultural and Social Bldgs. w/in 1km of Addresses	# of cult. and soc. Bldgs.	0.560	43.130	7.121	2.440	10.347	HOT Export Tool Data
Average Number of Cultural and Social Bldgs. w/in 3km of Addresses	# of cult. and soc. Bldgs.	4.540	154.730	51.353	30.020	48.293	HOT Export Tool Data
Average Number of All Food Stores w/in 1km of Addresses	# of all food stores	3.160	104.390	24.012	14.320	24.378	HOT Export Tool Data
Average Number of All Food Stores w/in 3km of Addresses	# of all food stores	21.510	456.110	170.727	133.260	129.093	HOT Export Tool Data
Average Number of Supermarkets w/in 1km of Addresses	# of supermarkets	0.400	23.340	9.379	6.750	6.694	HOT Export Tool Data
Average Number of Supermarkets w/in 3km of Addresses	# of supermarkets	7.380	160.570	70.120	62.440	45.349	HOT Export Tool Data

The destination accessibility variables included in the quantitative study can be categorized into two groups, first the accessibility of a district with respect to core locations within the city, namely the city center (Altstadt), the line of S-Bahn stations which all or most suburban trains service (the Stammstrecke), and the Isar river. Second, is the accessibility within a district to important common destinations like supermarkets, retail shopping, offices, and eateries. Both of these accessibilities were calculated using the address points mentioned above in previous sections covering other variables.

The variables measuring the median distance to core locations in the city (the Altstadt, the Isar, and to a Stammstrecke S-Bahn station) describe a district's degree of centrality. Centrality is an important concept of urban form describing the relative importance of an area within the city and has been associated with the rates of non-motorized travel in several studies in the past (Song and Knapp 2004; Ewing and Cervero 2010; Taxer 2013; Preciado 2012). Following these and other studies, more central districts, those with shorter median distances to the core locations, were expected to have higher rates of cycling. To calculate these variables, the shortest distance between all of the address points in a district and the core location in question was measured. The median shortest distance to the Altstadt within a district became the value of the Median Distance to the Altstadt variable for that district, and likewise for the other two variables.

For the second group of accessibility variables, the process of using buffers of a certain distance around each address point was used, similar to the process of extracting values for the Shop Diversity and Amenity Diversity variables described above. However, in this case, the total number of points representing each common destination (supermarkets, retail shops, etc.) was counted within the buffers around each of the address points in a district. The mean of these counts for each district were then taken as the values for the variables. A higher level of accessibility to destinations, especially within a short distance (one or three kilometers from each address), has been associated with higher rates of cycling in the past (Ewing and Cervero 2010; Rodríguez and Joo 2004; S. Handy, Cao, and Mokhtarian 2005; Khan, Kockelman, and Xiong 2014; Krizek and Johnson 2006). Therefore, it was expected that districts with a higher average number of the common destinations within both tested buffer distances would be more likely to have higher modal shares of cycling.

As described above, the data for these common destination variables stemmed from the various types of values given for the “shop” and “amenity” attributes for points in the HOT Export Tool dataset. While the data provided are not perfect, the level of detail and comprehensiveness were vastly better than what was given by other freely available sources. Again, these variables used the same method of classifying the values of these attributes into groups of common destinations as the land use diversity variables, and the information is available in Appendix M.

Distance to Transit Variables

The variables listed below in Table 4.5 are the variables used in the quantitative study to measure the distance to transit within a district. The units of measurement of the variables, descriptive statistics of each variable, and the source of the data are included as well. The variables are described further after the table.

Table 4.5: The variables used to measure distance to transit within a district.

Distance to Transit Variables	Unit	Min. Value	Max. Value	Mean	Median	Std. Dev.	Source
Median Distance to Nearest Bus Stop	meters	146.154	252.978	195.718	189.902	29.060	Mapzen OSM Data
Median Distance to Nearest Tram Stop	meters	200.988	3,578.238	1,252.536	736.024	1,124.525	Mapzen OSM Data
Median Distance to Nearest U-Bahn Stop	meters	312.575	6,266.667	1,107.070	607.966	1,368.872	Mapzen OSM Data
Median Distance to Nearest S-Bahn Stop	meters	361.701	3,384.178	1,435.118	1,208.735	841.043	Mapzen OSM Data
Average Number of Bus Stops within 200m of Addresses	# of bus stops	0.790	2.070	1.264	1.260	0.330	Mapzen OSM Data
Average Number of Bus Stops within 400m of Addresses	# of bus stops	3.020	7.030	4.868	4.800	1.105	Mapzen OSM Data
Average Number of Bus Stops within 1km of Addresses	# of bus stops	15.680	37.500	28.007	28.470	5.840	Mapzen OSM Data
Average Number of Tram Stops within 200m of Addresses	# of tram stops	0.000	0.560	0.152	0.080	0.168	Mapzen OSM Data
Average Number of Tram Stops within 400m of Residence	# of tram stops	0.000	2.200	0.566	0.360	0.611	Mapzen OSM Data
Average Number of Tram Stops within 1km of Addresses	# of tram stops	0.000	13.320	3.502	2.560	3.731	Mapzen OSM Data
Average Number of U-Bahn Stations within 400m of Addresses	# of U-Bahn stations	0.000	0.950	0.346	0.320	0.269	Mapzen OSM Data
Average Number of U-Bahn Stations within 1km of Addresses	# of U-Bahn stations	0.000	5.700	1.920	1.760	1.482	Mapzen OSM Data
Average Number of U-Bahn Stations within 3km of Addresses	# of U-Bahn stations	0.000	30.490	14.248	12.960	9.396	Mapzen OSM Data
Average Number of S-Bahn Stations within 400m of Addresses	# of S-Bahn stations	0.000	0.610	0.095	0.070	0.123	Mapzen OSM Data
Average Number of S-Bahn Stations within 1km of Addresses	# of S-Bahn stations	0.000	2.360	0.598	0.410	0.623	Mapzen OSM Data

Average Number of S-Bahn Stations within 3km of Addresses	# of S-Bahn stations	0.660	8.740	4.333	3.950	2.236	Mapzen OSM Data
Bus Stop Density	Bus stops / km² (dev.)	5.946	15.861	10.712	10.091	2.726	Mapzen OSM Data
Tram Stop Density	Tram stops / km² (dev.)	0.000	5.391	1.313	0.807	1.500	Mapzen OSM Data
U-Bahn Stop Density	U-Bahn stops / km² (dev.)	0.000	2.903	0.684	0.570	0.624	Mapzen OSM Data
S-Bahn Stop Density	S-Bahn stops / km² (dev.)	0.000	1.442	0.302	0.153	0.403	Mapzen OSM Data

Each of the variables in the Distance to Transit set all attempt to measure the same concept of accessibility to public transport in different ways. Using varying methods of describing the concept of distance to transit was done to discover which method had the strongest association with the modal share of cycling. For these variables, the important data source was Mapzen's Metro Extract of Munich, which included separate data for points of access or nodes in the public transportation network. As discussed in Section 3.2, several studies have investigated the connection between an area's accessibility to public transportation and its modal split. While the majority of these studies focus on walking and public transportation use in connection with the access to transit, associations with the modal shares of cycling have also been made (Ewing and Cervero 2010; Crane and Crepeau 1998; Kerr et al. 2016; Pucher, Dill, and Handy 2010).

The first subset of variables measuring the median distance to the nearest point of each public transportation mode were measured using the same methods as the variables measuring median distance to a park or natural area, or to a common destination as described above. It was expected that as the median distance to a public transportation access point becomes larger, the modal share of cycling would decrease. The impact of dense urban structure with more access to public transport was expected to have a stronger impact on the share of cycling than the impact of more people choosing public transport over cycling.

For the next set of variables, buffers of varying size depending on the transport mode around each address point were generated to measure the level of access to each mode. Variables measuring access to the city's bus and tram networks were measured using 200-meter, 400-meter, and one-kilometer buffers, as these modes are more often used for shorter trips and people are less willing to walk longer distances to them (HESS et al. 1999; Forsyth and Oakes 2015; Zegras 2005; Pratt et al. 2012). Consequently, the buffers used to measure access to subways and suburban trains were larger (400-meter, one-kilometer, and three-kilometer), to compensate for resident's willingness to travel further or use bike and ride facilities to access them. As the average number of access point accessible within the buffers around each address point increased, it was expected that the modal share of cycling would also increase.

Finally, the last set of variables describing the distance to transit dimension use district-wide measures of the density of each type of public transport point. For example, the Bus Stop Density variable was calculated simply by dividing the total number of bus stops in the districts by the square kilometer area of developed land of the districts. The other public transportation density variables were calculated in a similar fashion. The densities of public transportation access points within a district were expected to be positively associated with the modal share of cycling across the city.

4.1.2 Demographic and Social Variables

Besides the built environment variables, some which described the demographic or social aspects of a district were also used, so that they were not ignored during the analysis. The variables listed below in Table 4.6 are the variables used in the quantitative study to describe the demographic and social makeup of the districts. The units of measurement of the variables, descriptive statistics of each variable, and the source of the data are included as well. The variables are described further after the table.

Table 4.6: The variables related to social and demographic aspects of the districts.

Distance to Transit Variables	Unit	Min. Value	Max. Value	Mean	Median	Std. Dev.	Source
Motorization Rate	%	27.9%	49.2%	37.460%	37.1%	5.605%	Indikatorenatlas
Percent of Population Under 18 Years of Age	%	8.4%	20.5%	13.988%	13.5%	2.796%	Indikatorenatlas
Percent of Population Between 18 and 65 Years of Age	%	60.7%	79.5%	68.464%	67.6%	5.087%	Indikatorenatlas
Percent of Population Over 65 Years of Age	%	11.3%	22.8%	17.548%	18.0%	3.180%	Indikatorenatlas
Percent of Households in the District with Children	%	9.16%	26.07%	16.792%	15.96%	4.256%	Indikatorenatlas
Percent of Households which are Single Person Households	%	38.58%	68.56%	53.694%	54.77%	8.626%	Indikatorenatlas
Unemployment Rate	%	2.4%	5.4%	3.944%	3.8%	0.917%	Indikatorenatlas
Percent of Population Aged 15 to 65 receiving Unemployment Benefits (ALG 2)	%	2.4%	8.7%	5.260%	5.1%	1.689%	Indikatorenatlas

Variables related to demographic and social aspects of the districts were all sourced from the Indikatorenatlas archive described in Section 4.1. Each of the variables were included as so-called “control” variables which also have an impact on the modal share of cycling, but do not describe the built environment. Each of these variables are described below:

- Motorization Rate: The Indikatorenatlas calculated this value by dividing the number of privately held vehicles by the total number of residents in a district. This was expected to be inversely associated with the modal share of cycling, since the more access residents have to vehicles, the more likely they are to use them (Khan, Kockelman, and Xiong 2014).
- Percent of Population Under 18 Years of Age: It was believed that this variable would be inversely associated with the modal share of cycling in a district. While schoolchildren exhibit higher rates of cycling in Munich, other modes still represent more than 50% of their modal split. Also, other demographic groups associated with schoolchildren (full-time employed parents and those who stay at home) have below-average rates of cycling, which are expected to have a larger effect than the schoolchildren’s’ increased modal share of cycling alone.
- Percent of Population Between 18 and 65 Years of Age: On the other hand, this age group was expected to be positively associated with the modal share of cycling, as the cycling rates for several demographic groups in this age group are above average. Students and those living in

single-person households (the majority of households) both have higher modal shares of cycling.

- Percent of Population Over 65 Years of Age: The prevalence of this age group in a district was expected to be inversely correlated with the modal share of cycling, as the older residents become, the less likely they are to cycle.
- Percent of Households in the District with Children: This variable was expected to be inversely related to the modal share of cycling for the same reasons as stated above describing the variable “Percent of Population Under 18 Years of Age”.
- Percent of Households which are Single Person Households: This variable was expected to be positively associated with the modal share of cycling for the same reasons as described above in the bullet point for “Percent of Population Between 18 and 65 Years of Age”.
- Unemployment Rate: The unemployment rate was used as a measure of the socio-economic conditions in the district. While most of Munich generally has very low unemployment as discussed in Section 3.1, there is still some variation among the districts. It was expected that as the unemployment rate increased, the modal share of cycling would also increase, as it is relatively inexpensive compared to driving and public transportation. However, this is purely speculation, so the variable would not be removed from the analysis if it was found to have the opposite relationship to the modal share of cycling.
- Percent of Population Aged 15 to 65 receiving Unemployment Benefits (ALG 2): This variable is very similar to the unemployment rate and was included as another measure of the socio-economic conditions in the districts, to be considered alongside the unemployment rate. It was expected to have a positive correlation with the modal share of cycling just as the unemployment rate was. Again, this variable’s relationship with modal share is purely speculative.

4.2 Quantitative Study Analysis Methods

After the values for each of the 95 quantitative variables had been extracted and organized into a spreadsheet, and before the actual multiple regression analysis, an intermediate process of preparing the data for multiple regression was carried out. With so many explanatory variables (95) and relatively few observations (one for each of the 25 city districts), a reliable multiple regression is not directly possible in R. Therefore, the set of explanatory variables must be first trimmed down to a set of independent variables fewer in number than the number of observations (each city district), which contains no redundant or collinear variables.

For the rest of this section, variables are referred to by their shorthand symbol which was used in R so as to save space in each of the tables. Please refer to Appendix A if it is not clear which variable a variable symbol is supposed to represent.

4.2.1 The Variable Trimming Process

As mentioned above, the variables selected to be included in the stepwise multiple regression should be the most relevant to the modal share of cycling and also not redundant or collinear with each other. This was accomplished through the following “variable trimming process”:

1. First, individual multiple linear regressions of the modal share of cycling on each of the 95 explanatory variables were performed. The estimates for the coefficients, p-values, and R^2 and adjusted-R^2 values of each regression model were extracted and printed for analysis. In each regression model, the dummy variable *altstadt* was also included to reduce the impact

of this district as an outlier. The basic regression equation for each of these preliminary models is below. For each explanatory variable i (n = 95),

$$Y = \beta_0 + \beta_1 X_i + \beta_2 X_{alt}$$

Where: Y represents the dependent variable (the modal share of cycling), β_0 represents the intercept of the equation, $\beta_1 X_i$ represents the product of the coefficient and the value of the i-th explanatory variables (such as *btwn1865, devoftotal, cyclegreen_dev, allshops_1km, tramstops_1km,* etc.) and $\beta_2 X_{alt}$ represents the product of the coefficient and the value of the a*ltstadt* variable. The full results of this step, in the form of the code and output from R including the regression summary values are available in Appendix C. The R script itself is available in Appendix I.

Variables which exhibited the opposite association with the modal share of cycling from what was expected or didn't make sense were removed from further analysis, with the exception of variables for which the expected association was purely speculative (like the unemployment rate).

2. Second, the variables and their associated adjusted-R^2 values were listed in a table and sorted from largest to smallest according to the adjusted-R^2 values in order to bring the most relevant among them to the top. The top 23 variables were selected and moved onto the next step.

   Instead of the top 25, the top 23 variables were taken in order to leave space in the actual multiple regression equation for the constant, β_0, and for the "altstadt" dummy variable. The full list of 95 variables sorted by their adjusted-R^2 values is in Appendix D.

3. Next, this list was inspected for redundant variables which represented the same aspect of the built environment, but which were simply measured in diverse ways. For example, one of the most relevant variables to come out of this process was *allshops_1km*, which measures the average number of all shopping locations within one kilometer of every available address in the districts. However, there are a few other explanatory variables in the set which also measure similar, if not functionally identical aspects of the built environment, such as *allshops_3km*, the same variable, but with a wider radius around each address (refer to Section 4.1.1 for a more detailed descriptions of the variables). Of these and other redundant variables which appeared in the initial list of the 24 most relevant variables, only the most relevant variable was kept on the list. The removed redundant variables were then replaced by a set of the next-most relevant variables from the original list of 95. This was completed until a set of 23 non-redundant variables remained.

Table 4.7: The results of the first iteration of Steps 2 and 3 of the variable trimming process. Orange shaded variables are those which were removed from this set due to redundancy with a more relevant variable.

No.	Variable Name	Adjusted R-Squared Value
1	culturalsocial_1km	0.5357256
2	retail_1km	0.505327
3	culturalsocial_dev	0.4801508
4	allshops_1km	0.4784947
5	eateries_1km	0.4725702
6	retailshopping_dev	0.4303359

7	allfoodstores_1km	0.4285842
8	alleateries_dev	0.4200362
9	contraflow_dev	0.4072805
10	allshops_dev	0.399738
	retail_3km	0.3759951
	culturalsocial_3km	0.3753347
	allshops_3km	0.3617004
11	supermarkets_dev	0.3574745
	eateries_3km	0.3561552
	allfoodstores_dev	0.3480339
12	allopenstreet_dev	0.3409297
	super_1km	0.3405257
13	bakeriescafes_1km	0.3395396
	allfoodstores_3km	0.3333796
14	btwn1865	0.33145
15	avg_amenitytypes1km	0.3286811
16	avg_shoptypes1km	0.3223645
	super_3km	0.3085688
17	bakeriescafes_dev	0.3069048
18	bikeparking_dev	0.3061126
	avg_amenitytypes3km	0.3058934
19	offadmin_1km	0.2880298
20	educational_3km	0.2822855
21	ALG_15to65	0.2767252
	bakeriescafes_3km	0.2762928
	avg_shoptypes3km	0.2660325
	educational_1km	0.2638969
22	offadmin_dev	0.2616178
23	hh.single	0.2604965
	offadmin_3km	0.2501962

Table 4.7 above shows the results of Steps 2 and 3 of the variable trimming process. As each row of the table was filled with the next most-significant variable from the master list of 95 variables, it was checked for redundancy with the variables already in the table, as described above. Redundant variables which were removed to create the set of 23 are shaded with orange. Refer to Appendix A for the full variable names which correspond to these shortened symbols which were created for analysis in R.

4. Finally, the variables in the tables created by Steps 2 and 3 were checked for multicollinearity with each other. This was done in by creating a correlation matrix in R using the *cor(x)* function, exporting it to a .CSV file, and exporting plots of the correlation matrix using the *corrplot* package. The resulting correlation matrices are in Appendix E, and the exported correlation plots are in Appendix F. The R script for the multicollinearity checks is available in Appendix J.

An example correlation plot produced by the *corrplot* package is below in Figure 4.1, the blue values represent positive correlation and the red values represent inverse correlation.

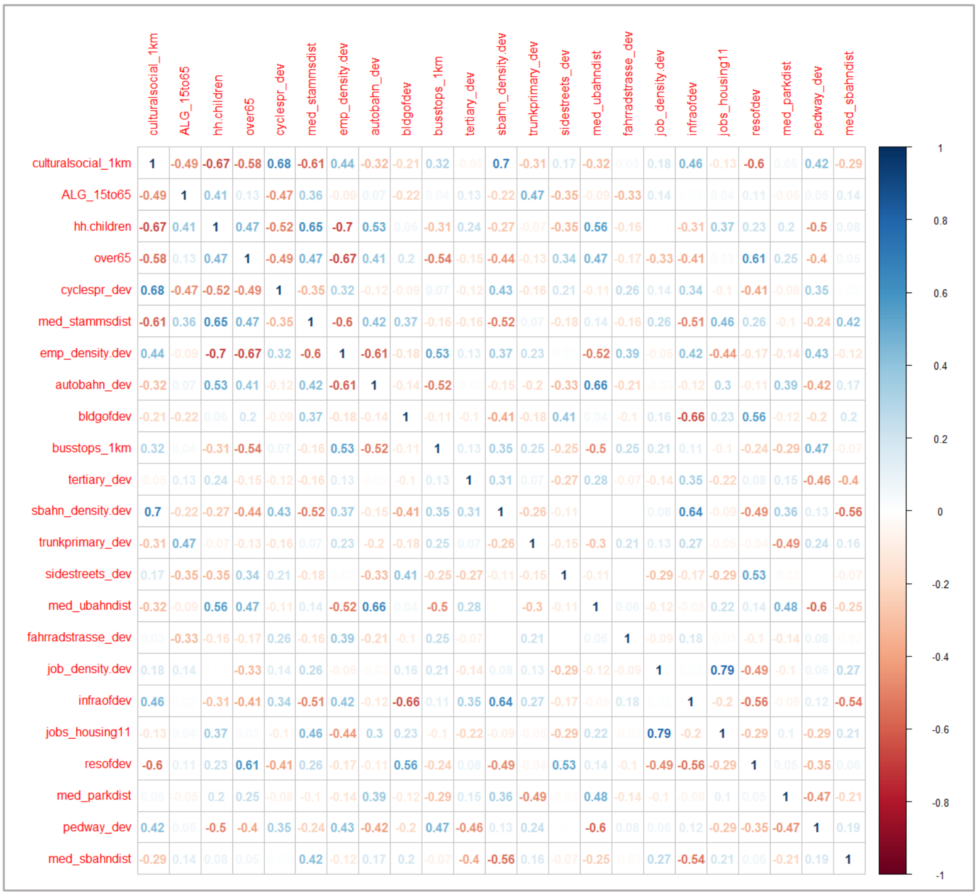

Figure 4.1: An example correlation plot exported from R. This plot came from the 4th set of variables to come out of the variable trimming process.

These matrices were then checked for the collinearity factors between each pair of variables, moving from the most relevant variables to the least (left to right or top to bottom in the matrix). If two variables had a high level of collinearity (a correlation factor greater than an absolute value of 0.7 as seen in the correlation plot above and in Appendix E), the variable which had a higher adjusted-R^2 value (the one represented in the the highest row or leftmost column of the two variables) was kept and the other variable removed from the list. Again, the removed variables were replaced with the next most-significant from the master list created in Step 2.

Steps 3 and 4 were repeated until the original list of 95 explanatory variables was trimmed down to a list of non-redundant and non-collinear independent variables. The final list contained 22 variables and is presented below in Table 4.8. The progression of the iterations of Steps 3 and 4 is presented in the spreadsheet in Appendix G.

Table 4.8: The final set of variables produced by the variable trimming process.

No.	Variable Name	Adjusted R-Squared Value
1	culturalsocial_1km	0.5357256
2	ALG_15to65	0.2767252

3	hh.children	0.2290034
4	over65	0.2104234
5	cyclespr_dev	0.1788011
6	med_stammsdist	0.1491571
7	emp_density.dev	0.08164369
8	autobahn_dev	0.05177482
9	bldgofdev	0.048742
10	busstops_1km	0.03538199
11	tertiary_dev	-0.01665228
12	sbahn_density.dev	-0.01868694
13	trunkprimary_dev	-0.03580497
14	sidestreets_dev	-0.05176047
15	med_ubahndist	-0.05226221
16	fahrradstrasse_dev	-0.07355686
17	job_density.dev	-0.07742016
18	infraofdev	-0.07794633
19	resofdev	-0.0820925
20	med_parkdist	-0.08723013
21	pedway_dev	-0.08897956
22	med_sbahndist	-0.08978222

4.2.2 Stepwise Multiple Regression Analysis

Once the trimming of the list of independent variables was complete, the process of the stepwise multiple regression analysis could begin. Though there are ways to perform stepwise multiple regressions automatically in R, it was decided to go through the process manually for more control over how variables were removed, and to make the process more transparent. After each regression run was completed, the least significant variable was identified from the resulting summary, by finding the variable of the regression which had the highest p-value. A new set of variables was created omitting this variable, and then the regression was run again on this new set.

The basic regression equation for step of the multiple regression is below. For each independent variable from the final set produced by the trimming process (n = 22):

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \cdots + \beta_n X_n$$

Where: Y represents the dependent variable (the modal share of cycling), β_0 represents the intercept of the equation, and each pair of $\beta_i X_i$, where i represents the number of the corresponding variable from the final set of variables in Table 4.8. For i=1, these correspond to the variable cutlturalsocial_1km, for i=2 they correspond to ALG_15to65, and so on. After running the regression process initially with the *Altstadt* dummy variable, just as the individual regressions were conducted during the variable trimming process, it was discovered that the inclusion of this variable vastly skewed the results. In order to obtain a more reasonable looking result, it was omitted from the multiple regression equations. Below is the summary output from R of the first run of multiple regression on the initial set of variables as determined from the variable trimming process:

```
> summary(fit1)

Call:
lm(formula = cyclingrate ~ ., data = multreg1)

Residuals:
        1         2         3         4         5         6         7         8 
-0.089882  0.264055 -0.101739  0.191536  0.228545 -0.386855  0.310871 -0.313562 
        9        10        11        12        13        14        15        16 
 0.210374  0.461239 -0.083294 -0.077980 -0.479312  0.021360  0.098372  0.005393 
       17        18        19        20        21        22        23        24 
 0.096420 -0.046274  0.040859 -0.033898 -0.103743  0.073560  0.051021 -0.133193 
       25 
-0.203874 

Coefficients:
                     Estimate Std. Error t value Pr(>|t|)  
(Intercept)         1.277e+02  2.093e+01   6.101   0.0258 *
culturalsocial_1km  2.581e-01  1.237e-01   2.086   0.1723  
ALG_15to65          7.718e-01  2.665e-01   2.896   0.1014  
hh.children        -1.180e+00  2.295e-01  -5.143   0.0358 *
over65             -8.259e-01  3.052e-01  -2.706   0.1137  
cyclespr_dev       -1.814e+00  1.013e+00  -1.791   0.2151  
med_stammsdist      8.865e-04  5.503e-04   1.611   0.2485  
emp_density.dev    -1.712e-04  5.546e-04  -0.309   0.7867  
autobahn_dev       -7.375e-01  1.040e+00  -0.709   0.5517  
bldgofdev          -2.573e+01  1.148e+01  -2.241   0.1543  
busstops_1km       -4.795e-01  1.255e-01  -3.821   0.0622 .
tertiary_dev        6.537e+00  1.600e+00   4.086   0.0550 .
sbahn_density.dev   1.215e+01  2.480e+00   4.899   0.0392 *
trunkprimary_dev    1.814e-03  6.416e-04   2.827   0.1056  
sidestreets_dev     6.222e-01  4.682e-01   1.329   0.3152  
med_ubahndist       1.956e-03  8.984e-04   2.177   0.1615  
fahrradstrasse_dev  2.549e-04  1.005e-04   2.536   0.1266  
job_density.dev    -2.024e-04  1.986e-04  -1.019   0.4153  
infraofdev         -1.620e+02  2.181e+01  -7.427   0.0176 *
resofdev           -1.462e+01  1.241e+01  -1.178   0.3598  
med_parkdist       -9.128e-02  1.814e-02  -5.033   0.0373 *
pedway_dev         -4.215e-01  1.675e-01  -2.517   0.1282  
med_sbahndist       2.294e-04  7.042e-04   0.326   0.7756  
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.7497 on 2 degrees of freedom
Multiple R-squared:  0.9974,	Adjusted R-squared:  0.9684 
F-statistic: 34.38 on 22 and 2 DF,  p-value: 0.02863
```

Figure 4.2: The summary of the first iteration of the stepwise multiple regression process.The set of variables in this regression is the same as the final set produced by the variable trimming process as described in Section 4.2.1. Source: own screen clipping from R.

This process of removing the least significant variable from the set and running the regression again without it was done until there were only significant variables left in the set (all variables had p-values less than 0.05). Nine iterations were required to reach this point. The summary output from R of the regression on the ninth and final set of variables is below:

```
> summary(fit9)

Call:
lm(formula = cyclingrate ~ ., data = multreg9)

Residuals:
     Min       1Q   Median       3Q      Max 
-1.35419 -0.23350 -0.03099  0.35952  0.94073 

Coefficients:
                     Estimate Std. Error t value Pr(>|t|)    
(Intercept)         9.256e+01  8.777e+00  10.546 9.74e-07 ***
culturalsocial_1km  2.814e-01  4.070e-02   6.915 4.12e-05 ***
ALG_15to65          4.428e-01  1.946e-01   2.276 0.046120 *  
hh.children        -7.379e-01  7.740e-02  -9.534 2.46e-06 ***
over65             -4.565e-01  7.470e-02  -6.111 0.000114 ***
bldgofdev          -1.594e+01  4.790e+00  -3.328 0.007649 ** 
busstops_1km       -2.868e-01  6.100e-02  -4.701 0.000840 ***
tertiary_dev        5.180e+00  5.892e-01   8.791 5.11e-06 ***
sbahn_density.dev   7.805e+00  1.401e+00   5.573 0.000236 ***
trunkprimary_dev    1.553e-03  3.139e-04   4.949 0.000580 ***
med_ubahndist       9.786e-04  2.114e-04   4.629 0.000938 ***
fahrradstrasse_dev  1.788e-04  4.215e-05   4.242 0.001711 ** 
infraofdev         -1.282e+02  1.173e+01 -10.928 7.01e-07 ***
med_parkdist       -7.332e-02  1.128e-02  -6.502 6.88e-05 ***
pedway_dev         -4.199e-01  6.996e-02  -6.002 0.000132 ***
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 0.7591 on 10 degrees of freedom
Multiple R-squared:  0.9865,	Adjusted R-squared:  0.9676 
F-statistic: 52.12 on 14 and 10 DF,  p-value: 1.949e-07
```

Figure 4.3: The summary of the final iteration of the stepwise multiple regression process.Each of the variables in this final set produced by the stepwise process is significant. Source: own screen clipping from R.

The code and corresponding output from R generated during the iterative stepwise multiple regression process are available in Appendix H. The full R script is available in Appendix K.

4.2.3 Further Quantitative Analysis

Although at this point this run of the stepwise multiple regression process was complete, further investigation was required to properly answer the questions posed by this thesis. Looking over the signs of the estimates in this resultant set produced by the stepwise multiple regression process, it seems that many of them have switched from their initial sign direction demonstrated by the individual regressions conducted with each variable separately. This indicates that further analysis is needed to properly determine which aspects of the built environment might impact the modal share of cycling, and in what ways.

Additionally, the results of the stepwise multiple regression process show an extraordinarily high R^2 value, which could have simply meant that this set of variables explained the variation in the modal share of cycling very well. However, it was also possible that the regression had either too many variables or not enough observations, resulting in an over-specified model. This was another reason for continuing the multiple regression process by running additional regression processes on different combinations of variables.

The first step taken to examine the quantitative data further was the removal of the most collinear variables left in this set. Though variables which exhibited a high level of collinearity (defined as those with collinearity factors of 0.7 or larger) were removed during the variable trimming process, several remaining variables exhibited moderate (collinearity factors between 0.50 and 0.70) or low levels of collinearity (factors between 0.30 and 0.50).

To improve the quality of the regression, the set of variables produced by the variable trimming process was taken and checked for moderate collinearity. If any pair of variables with a collinearity factor greater than 0.5, that with a lower R^2 value was removed, just as in Step 4 of the variable trimming process. The correlation matrix used to determine which variables to remove is also available in Appendix E. The resulting set of variables was then used as the initial set for another stepwise multiple regression process. Below is the resulting summary of the initial iteration of the new stepwise multiple regression process using this new set of variables:

```
> summary(fit_f1)

Call:
lm(formula = cyclingrate ~ ., data = MultReg_F1)

Residuals:
   Min     1Q Median     3Q    Max 
-3.957 -1.472 -0.099  1.077  5.993 

Coefficients:
                    Estimate Std. Error t value Pr(>|t|)  
(Intercept)       -8.963e+00  1.348e+01  -0.665   0.5188  
culturalsocial_1km  2.750e-01  1.796e-01   1.531   0.1517  
ALG_15to65        -5.721e-01  7.497e-01  -0.763   0.4601  
emp_density.dev    5.233e-04  5.967e-04   0.877   0.3977  
bldgofdev          3.609e+01  1.767e+01   2.043   0.0637 .
tertiary_dev       3.085e+00  2.525e+00   1.222   0.2451  
trunkprimary_dev   4.029e-04  1.075e-03   0.375   0.7143  
sidestreets_dev   -4.355e-01  6.577e-01  -0.662   0.5204  
fahrradstrasse_dev  2.777e-06  1.547e-04   0.018   0.9860  
job_density.dev   -1.592e-04  3.101e-04  -0.513   0.6171  
med_parkdist      -5.791e-03  2.588e-02  -0.224   0.8267  
pedway_dev        -1.547e-01  2.899e-01  -0.534   0.6033  
med_sbahndist      1.520e-03  9.655e-04   1.575   0.1413  
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 3.041 on 12 degrees of freedom
Multiple R-squared:  0.7396,	Adjusted R-squared:  0.4792 
F-statistic:  2.84 on 12 and 12 DF,  p-value: 0.04149
```

Figure 4.4: The summary of the first iteration of the second stepwise multiple regression process.This second regression process was completed for further analysis of the quantitative data. Source: own screen clipping from R.

Just as in the original stepwise multiple regression process, the least significant variable from the set (that with the lowest p-value) was removed, and the regression was run again with the resulting set of variables. This was again done until the only significant variables were left in the set. The process took 10 iterations until the only remaining variables were significant. For the console code and output of this process, see Appendix N. The R script of the process is available in Appendix O. The summary of the tenth and final iteration of this second stepwise multiple regression process is pictured below:

```
> summary(fit_f10)

Call:
lm(formula = cyclingrate ~ -1 + ., data = MultReg_F10)

Residuals:
    Min      1Q  Median      3Q     Max 
-5.4976 -1.7877  0.1493  1.3636  4.5941 

Coefficients:
                   Estimate Std. Error t value Pr(>|t|)    
culturalsocial_1km  0.16659    0.05924   2.812   0.0104 *  
ALG_15to65         -0.84964    0.34481  -2.464   0.0225 *  
bldgofdev          20.80216    3.05460   6.810 9.83e-07 ***
tertiary_dev        3.24859    1.33469   2.434   0.0239 *  
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

Residual standard error: 2.828 on 21 degrees of freedom
Multiple R-squared:  0.9664,	Adjusted R-squared:   0.96 
F-statistic: 150.9 on 4 and 21 DF,  p-value: 3.767e-15
```

Figure 4.5: The summary of the final iteration of the second stepwise multiple regression process.This second regression process was completed for further analysis of the quantitative data. Source: own screen clipping from R.

4.2.4 Variables of Interest Analysis

Finally, the last step of the multiple regression analysis was running extra regressions with variables of interest that had previously been excluded due to the variable trimming process. If a variable was found to be moderately collinear with any variable in the existing set shown above in Figure 4.5, or if it had been dropped during the second stepwise multiple regression process, it would not be added back into a regression as no new information would have been gained.

Variables of interest are those which were expected to have an impact on cycling or are directly inquired about in a research question of the thesis. Instead of testing each variable in the list again, a new set of variables was created. This set was created by creating a correlation matrix of all of the variables and removing all those which were at least moderately correlated with the variables of the set in Figure 4.5. The correlation matrix for all of the variables in the study is also in Appendix E.

Next, all the variables from the initial set of the second multiple regression process (as seen in Figure 4.4) were removed as well, since these were either already included or had been removed through the previous stepwise multiple regression process already. Variables which had originally been removed for having the opposite sign as expected were again removed, as well as some redundant variables (*busstops_1km* made including *busstops_400m*, *busstops_200m*, and *med_busdist* redundant in this case). In the end, this process produced a set of 10 variables. These variables were:

- *pop_density.dev*
- *roadways_area*
- *med_tramdist*
- *autobahn_dev*
- *devoftotal*
- *cyclestreet_dev*
- *busstops_1km*
- *motorizationrate*
- *med_ubahndist*
- *jobs_housing11*

Each of the 10 variables was then individually included in a multiple linear regression run with the set of variables in Figure 4.5. The code and output of each individual regression from this set is included in Appendix P. The R Script associated with this "variables of interest analysis" is available in Appendix Q.

When most of the variables were included into a multiple regression with the variables of the final set produced by the second stepwise multiple regression process, they simply became non-significant variables and simultaneously the least significant variable in the set, plus they worsened the R-squared values of the regression. However, two of the variables produced interesting results, *med_tramdist* and *motorizationrate*.

The variable representing the median distance to a tram station within a district (*med_*tramdist) was actually more significant than another variable already in the set when added to the regression. When the latter was removed, and another iteration of multiple linear regression run, *med_tramdist* remained significant and the resulting solution was actually had a slightly higher R-squared value compared to the original set from Figure 4.5. See Figure 4.6 below for the code and output of this interesting regression process including the median tram distance.

```
> fittest3 <- lm(cyclingrate~-1+culturalsocial_1km+ALG_15to65+bldgofdev+tertiary_dev+med_tramdist, data = all95_quantvar)
> summary(fittest3)

Call:
lm(formula = cyclingrate ~ -1 + culturalsocial_1km + ALG_15to65 +
    bldgofdev + tertiary_dev + med_tramdist, data = all95_quantvar)

Residuals:
    Min      1Q  Median      3Q     Max
-4.4795 -1.6088 -0.1172  1.5107  4.1291

Coefficients:
                    Estimate Std. Error t value Pr(>|t|)
culturalsocial_1km  0.1150804  0.0615016   1.871   0.0760 .
ALG_15to65         -0.8434690  0.3236327  -2.606   0.0169 *
bldgofdev          23.0276758  3.0835757   7.468 3.32e-07 ***
tertiary_dev        3.4635368  1.2574519   2.754   0.0122 *
med_tramdist       -0.0010842  0.0005532  -1.960   0.0641 .
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 2.654 on 20 degrees of freedom
Multiple R-squared:  0.9718,    Adjusted R-squared:  0.9647
F-statistic: 137.8 on 5 and 20 DF,  p-value: 8.681e-15

> fittest4 <- lm(cyclingrate~-1+ALG_15to65+bldgofdev+tertiary_dev+med_tramdist, data = all95_quantvar)
> summary(fittest4)

Call:
lm(formula = cyclingrate ~ -1 + ALG_15to65 + bldgofdev + tertiary_dev +
    med_tramdist, data = all95_quantvar)

Residuals:
    Min      1Q  Median      3Q     Max
-4.3114 -1.6318 -0.1233  1.7050  5.4157

Coefficients:
              Estimate Std. Error t value Pr(>|t|)
ALG_15to65    -1.0442976  0.3229895  -3.233  0.00398 **
bldgofdev     26.2031538  2.7235969   9.621   3.8e-09 ***
tertiary_dev   3.7408380  1.3209625   2.832  0.00999 **
med_tramdist  -0.0015266  0.0005291  -2.885  0.00886 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 2.808 on 21 degrees of freedom
Multiple R-squared:  0.9669,    Adjusted R-squared:  0.9605
F-statistic: 153.2 on 4 and 21 DF,  p-value: 3.242e-15
```

Figure 4.6: The results of including the "med_tramdist" variable into the multiple regression. Source: own screen clipping from R.

Another variable, *motorizationrate*, also produced interesting results when included in multiple regression with the 4-variable set from the final iteration of the second stepwise multiple regression process. When it was added, not only did it not become insignificant, it simply improved the quality of the regression overall, and none of the other variables became insignificant as well. The results of adding this variable into the regression this are in F below:

```
> fittest9 <- lm(cyclingrate~-1+culturalsocial_1km+ALG_15to65+bldgofdev+tertiary_dev+motorizationrate, data = all95_quantvar)
> summary(fittest9)

Call:
lm(formula = cyclingrate ~ -1 + culturalsocial_1km + ALG_15to65 +
    bldgofdev + tertiary_dev + motorizationrate, data = all95_quantvar)

Residuals:
    Min      1Q  Median      3Q     Max
-2.4818 -1.9331 -0.6333  0.9478  4.9084

Coefficients:
                   Estimate Std. Error t value Pr(>|t|)
culturalsocial_1km  0.11797    0.05097   2.315  0.03139 *
ALG_15to65         -0.97435    0.28655  -3.400  0.00284 **
bldgofdev          37.64642    5.68000   6.628 1.87e-06 ***
tertiary_dev        3.62662    1.10548   3.281  0.00374 **
motorizationrate   -0.29106    0.08799  -3.308  0.00351 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 2.33 on 20 degrees of freedom
Multiple R-squared:  0.9783,    Adjusted R-squared:  0.9728
F-statistic: 180.1 on 5 and 20 DF,  p-value: 6.459e-16
```

Figure 4.7: The summary of the multiple regression with the "motorizationrate" variable included. Source: own screen clipping from R.

These and the other results of the quantitative study methods are discussed further in Section 4.3 next.

4.3 Quantitative Study Results

Even at the very beginning of the variable trimming process, some interesting results began to appear. A few of the variables removed early on, due to having a correlation with the modal share of cycling opposite the expected direction, had been initially expected to be strongly supportive of cycling in theory. These variables, grouped by their similarity, were:

- the per developed area kilometers of cycleways in green areas, in urban green areas, and meters of cycleway underpasses (*cyclegreen_dev*, *cycleugreen_dev*, and *cycleunder_dev*);
- the ratios of all types of natural areas and all health and recreational areas to developed area in a district (*allgreentodev* and *healthrectodev*);
- and the share of streets with a speed of 30 km/h or lower and the average speed of the roads in a district (*share30kmh* and *avgspeed*)

It is worth noting that both variables measuring the socio-economic conditions of the districts, *unemployment* and *ALG_15to65*, were also found to have the opposite correlation with the share of cycling than expected but were not removed from the regression analysis as this association was based purely on speculation.

The removal of the first two groups of variables above so early in the variable trimming process was quite surprising, as it was expected that they would have strong positive associations with the modal share of cycling. Additionally, the data for these four variables came from some of the most reliable sources in the study, the City of Munich's geographic cycling infrastructure data (the first group) and the land use values from the Statistics Pocket Book (for the second group). Even with reliable data, these four variables were found to be inversely associated with the modal share of cycling in Step 1 of the variable trimming process. A couple of reasons for this might be:

- the modal share data was from 2008 and the cycling infrastructure data was from 2017,
- outer districts which generally had lower rates of cycling had large amount of forest cycle ways (a subset of green cycleways), which possibly overpowered the lengths of cycleways in urban green environments (parks, green strips, etc.) in more central districts with higher rates of cycling,
- the amount of urban green cycleways, those in green areas which were not classified as forests, was relatively small compared to those which were, and with a limited number of observations, a proper association wasn't possible,
- the land use variables compared the area of natural areas to the area of developed land in a district, which in retrospect, could be negatively associated with the modal share of cycling in Munich. Larger outer areas more likely to have lower cycling rates generally had more green and natural areas than the densely developed core districts. It was thought that creating the ratio of these areas with the area of developed land would equalize the effects of the size of the larger, relatively less developed, outer districts. However, another method of doing so might have given better results, such as using the rates of green and natural areas to population density or other aspects of the built environment.

The third group of variables, those relating to the speed along the roads in a district, isn't as surprising as the other two. As previously mentioned in Section 4.1.1, the data for the speed limits on the roads was taken from the GeoFabrik OSM dataset which did not have information for every street in the city. With an incomplete dataset like this, these variables could easily have been biased by streets with higher classifications (primaries, secondaries, etc.) which could be more likely to have speed limit information recorded and also are more likely to have higher speed limits.

From Step 2 of the variable trimming process, more interesting results were already appearing. Ranking the variables by their relevance to the modal share of cycling (from highest to lowest R^2 values) clearly showed that the most relevant dimensions of the built environment for cycling in Munich were land use diversity and destination accessibility. This was demonstrated by the high number of destination accessibility variables (*culturalsocial_1km*, *retail_1km*, *eateries_1km*, etc.) and land use diversity variables (*culturalsocial_dev*, *alleateries_dev*, *avg_amenitytypes1km*, etc.) at or near the top of this list. Additionally, these variables were all highly collinear with each other, and most of them were also collinear with the density dimension variables (*pop_density.dev*, *emp_density.dev*, etc.). This shows that not only are areas with one type of shop or amenity are much more likely to have the other type, but that the built environment's dimensions of density, destination accessibility, and land use diversity are closely interrelated to each other.

Of all the design dimension variables, the per developed land area rate of the area of one-way streets open to cyclists going against the flow of traffic (*contraflow_dev)* had the strongest association with the modal share of cycling in Munich. The rate of bike parking and rental facilities per developed land area (*bikeparking_dev* and *bikerental_dev*) were also relevant to the modal share of cycling in the city, however, both were highly collinear with destination accessibility variables higher on the list, and so they were never used in a multiple regression. Of the other types of cycleways, the variables representing signposted cycle routes and the cycleways in street environments (*cyclespr_dev* and *cyclestreet_dev*) were both moderately correlated with the modal share of cycling. The *cyclestreet_dev* variable was dropped due to multicollinearity issues in the fourth iteration of the variable trimming process, and though *cyclespr_dev* made it through the trimming process, it was dropped during the stepwise multiple regression process as it was not significant. Even though *cyclestreet_dev* was used again in the variables of interest analysis in Section 4.2.4 it proved to not be significant when added to the set of variables determined by the second stepwise multiple regression process (see Appendix P).

It is still unclear whether the final set of variables used in the initial stepwise multiple regression process (see Figure 4.3) created an over specified, also called over fit, or not. While the process described in Section 4.2.3 used a different set of variables limited by a lower allowance of collinearity, the adjusted-R^2 value for the final regression iteration of the second process was slightly lower than that produced by the larger set of variables in the final set of the initial process (a value of 0.960 in the second process vs. 0.9676 in the first). However, the set of four variables produced by this second process (as seen in Figure 4.5) were all also found in the final set produced by the initial process (see Figure 4.3). This means that each the variables remaining at the end of the initial process might contribute to the built environment's influence on the modal share of cycling. But, it is clearer that the four variables from this set which also remained at the end of the second stepwise multiple regression process described in Section 4.2.3 have a stronger association with the modal share of cycling.

Another interesting result of the second stepwise multiple regression process was the group of variables which made up the final set produced by the process themselves. Each of the variables represents a different dimension of the built environment, according to how they were split up in Section 4.1.1:

- *culturalsocial_1km* represents the destination accessibility dimension, as well as the density dimension, due to its high levels of correlation with other destination accessibility variables and density variables.
- *ALG_15to65* represents the demographic variables.
- *bldgofdev* represents the land use diversity variables.
- And *tertiary_dev* represents the urban design variables.

Additionally, the only two variables from the variables of interest analysis in Section 4.2.4 which produced a change in the multiple regression were the *med_tramdist* and *motorizationrate* variables as seen in Figure 4.6 and Figure 4.7. The *med_tramdist* variable represents the one missing dimension of the built environment from those listed above, distance to transit. However, it proved to be more significant than *culturalsocial_1km* and caused both variables have a p-value greater than 0.5, so a second regression was run without the *culturalsocial_1km* variable. As seen in Figure 4.6, the resulting set was actually slightly more reliable (had a higher adjusted-R^2 value) than the original set from Figure 4.5. On the other hand, adding the *motorizationrate* variable simply improved the quality of the regression without making any one of the variables in the set insignificant, as seen in Figure 4.7. This variable also represents the demographic and social set of variables used in the quantitative study but measures a different aspect of the city's demographics than the *ALG_15to65* variable already in the set.

The limitations of the quantitative study are further discussed in Section 6.1, and the conclusions made by combining the results of the quantitative study described above and the qualitative study described below in Section 5.3 are presented in Section 6.2.

5 QUALITATIVE STUDY METHODOLOGY AND RESULTS

To complement the quantitative methodology, the qualitative method was designed to take a deeper look at the differences in the cycling experience across the city of Munich. Several qualitative studies investigating the relationship between travel behavior and the built environment have utilized online or in-person street-level surveys to gather information on people's experience with a given mode or system (SOURCES). However, in the qualitative part of this study, surveys of cyclists' or residents' experiences were not used, for a variety of reasons.

First, it is likely that the they would have yielded a very low response rate, as asking cyclists on their way to stop and answer questions, even for a minute, seemed intrusive and inappropriate. Additionally, there would have been no guarantee that a cyclist surveyed in a given district would or could separate their cycling experiences in that particular district from their experience in the city as a whole. Also, the author's native language is not German, which would have potentially caused communication issues with residents, skewing the results or further limiting the response rate. Instead, a study utilizing firsthand experience cycling through the city was conducted.

The qualitative study was designed to examine the cycling experience across the city using field surveys of select districts across the city. These field surveys were designed to capture the cycling experience within a district by personally cycling a route that explored a representative set of areas and streets inside each chosen district. Also, the limited set of districts examined through these field surveys was selected to represent the variety present among the districts of Munich as a whole. The process for selecting the districts included in the qualitative study – which would be examined via field surveys – is described in Section 5.1. In Section 5.2, the methods for planning the field survey routes are detailed, as well as the methodology of performing the field surveys themselves, and the results are presented in Section 5.3.

5.1 The District Selection Process

Unlike the Quantitative Study described above, the Qualitative Study instead focuses on a limited set of six of Munich's 25 city districts. These six districts were specifically selected to produce a set to represent the overall city based on a group of characteristics relevant to the study. The intent of this selection process was to ensure that these six districts would be representative of the range of these characteristics within city of Munich. The characteristics the selection process was based on included demographic, geographic, and transport-related elements. A map of Munich displaying or graphically demonstrating these characteristics, by district, was created using GIS software (QGIS). A diverse set of six (6) districts was generated by viewing this information on one map and comparing the characteristics of each district relative to the others.

Demographic Characteristics

The demographic characteristic considered during the selection process was the population density of each district. Population density was considered as a proxy for the "density" of the districts, the general level of its development as described by (Cervero and Kockelman 1997). It was determined that Munich's districts can be categorized into 3 groups by their population densities (in 2008, the year of the Mobilität in Deutschland study): districts with less than 4,000 inhabitants per square kilometer (km^2); those with between 4,000 and 9,000 inhabitants/km^2; and those with over 9,000 inhabitants/km^2. At least one district from each of these groups was included in the qualitative study to ensure a diverse set.

Geographic Characteristics

Various geographic characteristics of the districts were also considered when selecting districts for the qualitative study. First and foremost is a district's location relative to the city center (mainly Altstadt-Lehel, but also including the core districts of Ludwigsvorstadt-Isarvorstadt, Schwanthalerhöhe, and Maxvorstadt) and its location relative to the Mittlerer Ring. In addition to a district's location within the city, it's overall size was also taken into account. Smaller, more uniform districts were preferred over larger ones with more heterogeneous diverse built environments.

For example, the district of Schwabing-Freimann is a long narrow shape starting near the city center adjacent to Altstadt-Lehel, that stretches all the way to the northern boundary of the city. Additionally, Schwabing-Freimann consists of many types of built environments with varying densities, access to public transport, and urban design. Because this district encompasses such a large geographic area and such a wide variety of built environments, it would be considerably more difficult to define a route or set of characteristics which represent it well. Therefore, Schwabing-Freimann and other similarly expansive and heterogenous districts were excluded from consideration during the district selection process for the qualitative study.

The physical topography of a district can also play an important role in the rate of cycling. Although Munich sits on an area of relatively flat plains north of the Alps, there is some variation in the hilliness between the districts, especially along the banks of the Isar which should not be ignored. At least one "hilly" district along the Isar was included in the district set, as to include this factor in the qualitative study.

Finally, the ratio of green or forested areas to the total developed land in each district was included in the district selection process as well. This was done to include the difference between districts with more green areas, which are often considered more pleasant or easier to cycle in (T Pikora et al. 2003; Dora et al. 2011), and those which have higher levels of developed land.

Transport-related Characteristics

Another crucial factor that could affect the rate of cycling in a district is its access to public transport (Ewing and Cervero 2010). As discussed in previous sections, the public transport network in Munich consists of buses, trams, a subway system (U-Bahn), and an aboveground metropolitan area rail network (S-Bahn). Because every district has access to bus services, this mode of public transport was not included in the district selection process. Tram, U-Bahn, and S-Bahn access were all considered, however, so it was important that the set of 6 districts in the qualitative study contained varying levels of access to each of these modes.

In addition to the access to public transport within a district, the prevalence of cycling infrastructure (cycling routes, paths, lanes, streets, etc.) within each district, was considered in the district selection process. Districts with varying densities of cycling infrastructure were selected as to represent the variety of levels of access to such facilities that residents of different districts have.

Using the GIS data from the City of Munich, a map of the cycling infrastructure in the city (in 2017) including the 17 signposted routes and all other cycling lanes, paths, streets, etc. was created. This map was set as an overlay on top of the city map with the other important district selection factors so that the level of cycling infrastructure in each district could be compared alongside the other important characteristics for district selection.

As this study attempts to uncover built environment effects on cycling in Munich, the actual rate of cycling in each district was included as part of the qualitative study's district selection process. In 2008, the modal share of cycling in the districts of Munich ranged from 7% in Aubing-Lochhausen-Langwied to 24% in Maxvorstadt (Belz, Follmer, and Gruschwitz 2010). The set of districts included in the qualitative study was selected to represent this diversity by including districts with relatively high, average, and low modal shares of cycling.

5.1.1 The Districts Included in the Qualitative Study

After going through the district selection process, the districts chosen to be included in the qualitative study were: 04 Schwabing-West, 06 Sendling, 14 Berg am Laim, 21 Pasing-Obermenzing, 19 Thalkirchen-Obersendling-Forstenried-Fürstenried-Solln (TOFFS), and 24 Feldmoching-Hasenbergl. A map of Munich with these districts highlighted and the city's rail-based public transport lines shown is below.

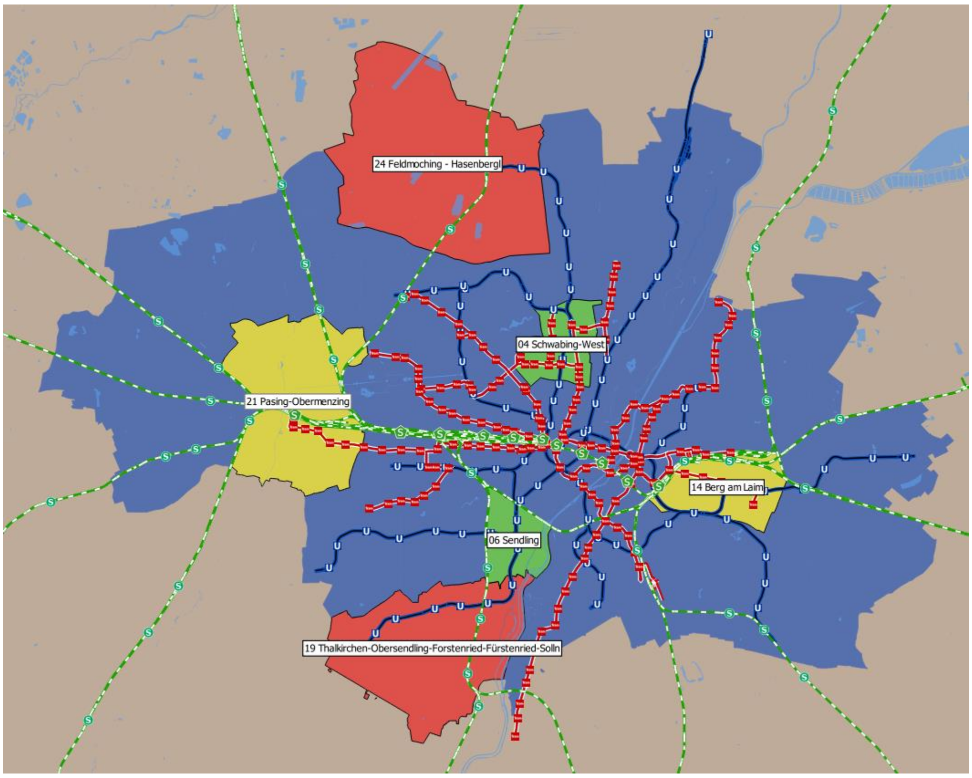

Figure 5.1: The area of Munich highlighting the districts included in the qualitative study. The districts shaded in red were considered outer districts, those shaded with yellow were considered middle districts, and shaded with green were considered core districts. S-Bahn lines are green-white alternating lines, tram lines are red with white outlines, and the subway lines are black with blue outlines. Source: own work, OSM sources listed in Section 4.1.

The map above was used in conjunction with a summary data table containing only the relevant information for the district selection process. Below is an image of that data table, containing each of the districts and the values for the variables considered during the process. After the table, each district included in the study is described in detail regarding its size, population density, transport infrastructure, location within the city, and other important characteristics for the district selection process.

District Name and Number		Basic Data					Mobility Info
	UNIT:	hectares	people	people/km² (dev.)	people/km²		% trips
DistrictNo	DistrictName	surfarea	pop2008	popdensity_dev	popdensity_total		cyclingrate
1	Altstadt-Lehel	314.57	19,505	8,089	6,201		13
2	Ludwigsvorstadt-Isarvorstadt	440.15	47,599	13,727	10,814		23
3	Maxvorstadt	429.64	48,884	12,361	11,374		24
4	Schwabing-West	436.30	62,541	16,438	14,334		17
5	Au-Haidhausen	421.96	55,853	15,309	13,237		15
6	Sendling	393.88	38,335	13,796	9,733		10
7	Sendling-Westpark	781.45	52,257	8,931	6,687		14
8	Schwanthalerhöhe	207.02	27,778	14,266	13,418		15
9	Neuhausen-Nymphenburg	1,291.59	87,043	9,731	6,740		14
10	Moosach	1,109.36	48,451	5,586	4,367		9
11	Milbertshofen-Am Hart	1,338.31	68,198	8,179	5,083		13
12	Schwabing-Freimann	2,566.98	64,350	4,294	2,507		15
13	Bogenhausen	2,371.17	77,112	5,860	3,252		14
14	Berg am Laim	631.46	40,038	7,305	6,341		12
15	Trudering-Riem	2,245.05	59,031	3,818	2,629		12
16	Ramersdorf-Perlach	1,989.50	104,089	7,288	5,232		11
17	Obergiesing-Fasangarten	572.04	48,282	9,176	8,440		10
18	Untergiesing-Harlaching	805.66	49,391	8,479	6,131		11
19	Thalkirchen-Obersendling-Forstenried-Fürstenried-Solln	1,775.43	82,771	6,322	4,662		14
20	Hadern	922.39	46,385	5,955	5,029		12
21	Pasing-Obermenzing	1,649.79	65,290	5,543	3,957		21
22	Aubing-Lochhausen-Langwie	3,405.76	38,327	3,210	1,125		7
23	Allach-Untermenzing	1,545.17	28,796	3,190	1,864		14
24	Feldmoching-Hasenbergl	2,869.74	55,667	5,137	1,924		8
25	Laim	528.58	51,329	10,267	9,711		10
100	**LHM München**	**31,042.95**	**1,367,314**	**6,915**	**4,401**		**14**
	DESCRIPTIVE STATISTICS	**surfarea**	**pop2008**	**popdensity_dev**	**popdensity_total**		**cyclingrate**
	Min	207.02	19,505	3,190	1,125		7
	Max	31042.95	1,367,314	16,438	14,334		24
	Mean	2387.92	105,177.54	8,429.63	6,507.42		13.53846154
	Median	1015.875	51,793	7,697	5,682		13.5
	Std. Dev.	5911.22	258117.654	3827.559	3790.691		4.130
		Sources	**Sources**	**Sources**	**Sources**		**Sources**
		Statistisches Taschenbuch 2009 (München insgesamt)	Indikatoren Atlas	Statistisches Taschenbuch 2009 (developed land area), Indikatoren Atlas (population)	Indikatoren Atlas		Ergebnisbericht MiD 2008 | München und Münchner Umland (2010)

Figure 5.2: A segment of the data table used in the district selection process. The districts shaded in orange were considered outer districts, those shaded with yellow were considered middle districts, and shaded with green were considered core districts.

District No. 04 Schwabing West

Schwabing-West is a small, high population density district neighboring the city's core district of Maxvorstadt to the north. In 2008, the modal share of cycling in the district was 17% of all trips. The U-Bahn and tram network are both quite accessible from most parts of the district, with both U2 line stations (Hohenzollerplatz, Scheidplatz) and U3 line stations (Bonnerplatz, Scheidplatz, Petuelring) within it. Also, the U3/U6 line (serving stations Gieselastraße and Münchner Freiheit) runs north-south just to the east of the district, following under Leopoldstraße. Although there isn't an S-Bahn station in the district, Munich's Hauptbahnhof is only about three kilometers to the south of the district's center.

Schwabing-West is almost surrounded by areas of similarly dense development, and it's bounded by one of Munich's major outdoor recreational areas, Olympiapark, on the northwest side. While it's not adjacent to the city's famous English Garden, the park is roughly three kilometers away from the furthest point inside Schwabing-West and is only a little over 500 meters away at its closest point. The district also contains a 33-hectare park called Luitpoldpark, a major feature on its north side. The park hosts many paved and dirt trails weaving through it.

Other than the trails in Luitpoldpark, other areas of the district have a fair amount of cycling infrastructure as well. Most of the major streets (Schleißheimerstraße, Ackermannstraße/Karl-Theodor-Straße, and parts of Belgradstraße) and many of the smaller streets have some sort of cycling infrastructure along them, and there is a significant number of Shared Zones and Contraflow One Way Streets.

District No. 06 Sendling

Sendling is a small, high population density district on the west bank of the Isar, directly south of the core district of Ludwigsvorstadt-Isarvorstadt – the district which holds Munich's Hauptbahnhof. In 2008, the modal share of cycling in Sendling was relatively low, at 10%. On the east side of the district along the Isar, a large forested area with several cycling and walking paths provides plenty of green area for the district. This is part of the Flaucher Park, a very popular summertime swimming and grilling destination for the whole city.

The Mittlerer Ring (Bundesstraße B2R) cuts through the center of the district from west to east, though the Brudermühlstraße tunnel moves most of its traffic underground in the center of Sendling. A large interchange between the B2R and the B11 dominates its western edge but is surrounded by a large green area, Sendlinger Park.

Outside of the paths along the Isar, cycling infrastructure in Sendling exists in a few areas: adjacent the Mittlerer Ring, and on two major north-south streets in the district (Implerstraße/Thalkirchner Straße and Schäftlarnerstraße). A route of the Signposted Cycle Route Network follows Thalkirchner Straße from north to south, among a few other short stretches within the district. U-Bahn and S-Bahn access is widespread in Sendling, with stations along two U-Bahn lines, the U3 (at Implerstraße, Brudermühlstraße, and Thalkirchen) and the U6 (at Implerstraße and Harras), and the stations on the S7 S-Bahn line (at Harras and Mittersendling).

Finally, due to its location along the Isar river, there is a significant difference in elevation between the east and west sides of the district. The northwest corner of the district, near where Lindwurmstraße and Plinganserstraße intersect, is significantly higher in elevation than other parts of the district as well.

District No. 14 Berg am Laim

Berg am Laim is a small to medium-sized, medium population density district in the east of Munich, just to the east of Au-Haidhausen, a district which borders the city's core. While it isn't very far from the city center, Berg am Laim sits directly east of Ostbahnhof (the eastern end of the S-Bahn Stammstrecke) and is bound on its western and northern sides railway tracks serving the station, somewhat separating it from more central parts of the city. The station and others along the tracks do provide much of the district with access to the S-Bahn system, specifically S2, S4, S6 and S8 S-Bahn lines at Leuchtenbergring and Berg am Laim Bahnhof along the northern edge of the district. In addition to this S-Bahn access, most of the district is served by the U-Bahn (lines U2 and U5), and a couple of tram routes also operate within it.

Other important transport infrastructure in the district includes the Mittlerer Ring which runs through the western side of the district from north to south, Berg am Laim Straße/Kreillerstraße (B304, a federal roadway) which cuts through its center from east to west, and another large roadway, Anzinger Straße/Bad-Schachener-Straße/Heinrich-Wieland-Straße, forming its southern border.

Berg am Laim has a fair amount of cycling infrastructure, with cycle lanes and paths running alongside all the previously mentioned major roadways, and several paths running north-south and diagonally between them. Finally, at the district's center is a large green area with athletic fields and parks, and Ostpark, a large 56-hectare park with an indoor/outdoor swimming pool (Michaelibad) inside it, is just across its southern border. In 2008, the cycling modal share in Berg am Laim was 12%.

District No. 21 Pasing-Obermenzing

Pasing-Obermenzing is a large, low population density district in the west of Munich. The district is bifurcated by railway tracks, and the station in the middle of the district, Pasing, is the western end of Munich's S-Bahn Stammstrecke. On its eastern side, it borders the Nymphenburg Palace (Schloss Nymphenburg) in the district of Neuhausen-Nymphenburg in the north, the district of Laim in the south. Neither Laim nor Neuhausen-Nymphenburg are core districts, but both are adjacent to central city districts.

Both the S-Bahn and tram networks are present in Pasing-Obermenzing. A single tram line reaches the district's center at the Pasing S-Bahn station on the Stammstrecke. Two other S-Bahn stations on the S2 line, Obermenzing and München-Untermenzing, lie along the district's border with Neuhausen-Nymphenburg in the northeast.

As for major roadways, the Autobahn A8 ends in the northwest corner of the district and merges with the local road network there. Also, the A96 runs east-west about three kilometers to the south of the district, and the Bundesstraße 2 (Landsberger Straße in eastern Pasing) runs along the southern edge of the Stammstrecke from east to west through the district. Cycling infrastructure exists along most of these major streets, specifically the B2, Landsberger Straße, and Weinbergerstraße/Planegger Straße in the south, and Meyerbeerstraße/Offenbachstraße, Alte Allee, and Verdistraße in the north. In 2008, the cycling modal share in the district was relatively high, at 21%.

There are a few green areas and parks of note in the district. The Wurm River runs from north to south through the entire western side of Pasing-Obermenzing. A signposted cycle route and a strip of green area follow the entire length of the river in the district, including the forested Pasinger Stadtpark in the south. The south of the district also houses the indoor/outdoor swimming pool Westbad, which is surrounded by a large green area with plenty of trees. On the north side of the district, the green area and paths which flank the Wurm River continue, just as in the south, and connect to a small park around the Blutenburg Castle. Finally, an open green area with several paths runs across much of the district just to the south of Verdistraße, and another follows Marsopstraße along the Pasing Nymphenburg Kanal.

District No. 19 Thalkirchen-Obersendling-Forstenried-Fürstenried-Solln

Thalkirchen-Obersendling-Forstenried-Fürstenried-Solln (TOFFS) is a large, low to medium-low population density district at the very southern tip of Munich. It is bordered by the Isar river to the east, and Munich's districts of Sendling, Sendling-Westpark, and Hadern to the north. Südpark, a roughly 60-hectare park with paths weaving through dense forests and open grasslands, also sits just across the district's northern border. Forstenrieder Park, a very large (over 37 square kilometers, larger than many of the city's districts) forested area outside Munich's city limits, borders much of the district to the southwest. Forstenrieder Park is home to many paved and dirt paths for cyclists to use.

The U3 U-Bahn line enters the district from Sendling in the northeast, and turns to continue westward, running through the northern side of TOFFS. The U3 stations within the district are Thalkirchen, Obersendling, Aidenbachstraße, Machtlfinger Straße, Forstenrieder Allee, Basler Straße, and Fürstenried West (the end of the line). Also coming down from Sendling is the S7 S-Bahn line, servicing the stations Siemenswerke and München-Solln in the east of the district.

Major roadways in the district include the A95 Autobahn cutting through the far west side of the district and along its northwest border, the Bundesstraße B11/Wolfratshauser Straße running north to south on its eastern side. Additionally, Drygalski-Allee and Murnauer Straße/Aidenbachstraße/Plattlinger Straße run through the center of the district from north-south, and Boschetsrieder Straße, Kistlerhofstraße/Züricher-Straße, Stäblistraße/Lochhamer Straße/Siemensallee, and Neurieder Straße/Herterichstraße traveling west-east.

Cycling infrastructure accompanies these major roadways, and smaller roads throughout the district. Cycling paths also exist on either side of the A95 Autobahn. Also, on the eastern edge of the district, there are several cycling paths along the banks of the Isar. Outside of these locations, cycling infrastructure is somewhat limited. In 2008, the modal share of cycling in the district was the same as the city-wide average, 14%.

District No. 24 Feldmoching-Hasenbergl

Feldmoching-Hasenbergl is a large, low population density district at the northern tip of Munich. It is bordered by Allach-Untermenzing to the west, Moosach to the south, and Milbertshofen-Am Hart to the south and east. The A99 Autobahn cuts through the district from west to east, creating a northern half that is almost entirely farmland, and a southern half which almost all the development in the district, and a large amount of farmland as well. In the southern half, most of the development is on eastern side, though there is some in the south and pockets in the west as well. Much of the southwest border of the district is formed by the large DeutscheBahn Cargo railyard. Railroad tracks from the yard continue to the east to form the rest of the southern border of the district.

Besides the A99, other roadways of note in the district are Karlsfelder Straße, Düflerstraße, and Am Blütenanger traversing east-west, and Feldmochinger Straße, Lerchenauer Straße, Lerchenstraße, and Schleißheimer Straße (the eastern border of the district) running north-south. The S-Bahn line S1 enters the district from the southwest and runs through the center of the district from south to north, stopping at two stations in the district, München-Fasanerie and München-Feldmoching. The east side of Feldmoching-Hasenbergl also has U-Bahn access via 3 stations on the U3 line, Düflerstraße, Hasenbergl, and Feldmoching (the end of the line). Other stations on this line in Milbertshofen-Am Hart are also nearby, about 500 meters east of Schleißheimer Straße, the eastern border. Also, the U3 line station of Oberwiesenfeld is only a couple hundred meters from the district's southern border, though being on the other side of the railroad tracks does make it more difficult to reach.

A fair amount of green and forested land in Feldmoching-Hasenbergl, especially around three lakes in the southern half of the district. Lerchenauer See, Fasaneriesee, and the largest, Feldmochinger See, each are accessible by cycling infrastructure along roadways and have cycling paths in the green areas surrounding them. Cycle paths or lanes are present on many of the major roadways mentioned above, though none of them have a continuous path throughout the district; many roads contain both dedicated cycle lanes and areas where cyclists share the road with vehicles. However, there are many sections of other roads – a considerable amount – in the district which are intended as shared spaces for cyclists and vehicles alike. In 2008, the modal share of cycling in the district was relatively low compared to others, at only 8%, the second-lowest value in the city.

There are three large forested areas near or within the district. Allacher Lohe, a 150-hectare forested nature preserve is just over the western border, and 280-hectares of protected forest and meadow in Panzerwiese und Hartelholz are just over the eastern border. Both nature preserves offer many trails for visitors to enjoy. Also, in the far north of Feldmoching-Hasenbergl, a nature preserve called "Schwarzhölzl" offers almost 80 hectares of forest, also with plenty of paths.

5.2 Field Survey Methodology

The field surveys performed for the qualitative study were designed to capture the experiences of cyclists in the district and to give the author some insight into how the built environment of each district might be perceived by cyclists.

5.2.1 Planning the Field Survey Routes

Just as the set of districts included in the qualitative study was chosen to represent Munich as a whole, the field survey route within each district was chosen to represent the district as a whole. Routes for the field surveys were planned as to thoroughly and efficiently represent the cycling conditions within each district. To generate each district's route, various types of areas and key points and infrastructure were defined to be included in each study. The types of such areas considered when the field surveys were being planned are listed below:

- Main thoroughfares through the district, i.e. those with denser commercial development and/or higher traffic flows.
- Important (high-traffic or large) bridges, intersections, or tunnels which may affect the cycling experience as they can often act as bottlenecks limiting pedestrian and bicycle traffic.
- Areas surrounding S-Bahn and U-Bahn stations, as well as major tram and bus stations (i.e. Scheidplatz and Hohenzollerplatz in Schwabing-West).
- Residential side streets in multiple areas of the district, to include the cycling experience at beginnings and ends of a resident's trips.
- Major cycleways and cycle paths, especially segments of the 14 signposted routes running throughout the city.
- Green areas and parks with cycleways or mixed traffic paths (i.e. Luitpoldpark in Schwabing-West and the forested areas along the Isar in Sendling)
- Paths through and around neighborhood amenities such as commercial activity centers, recreational facilities, cultural hot spots, among others.

Using the map produced for the district selection process in conjunction with Google Maps, these key points and areas were identified for each district and a route between them generated through the following process.

Using Google Maps' My Maps feature, first a starting point in the district was chosen based on its importance to the district as well as its location relative to how the observer would be arriving. If arriving by train, the starting point would simply be at that train station, as it is already a central and key area in the district. However, if arriving to the field survey district by bike, an easy to access point on the side of a district closest to where the observer was coming from was chosen to prevent having to cycle through the same area multiple times.

From that starting point, the next points were added in sequence to trace a path through the district which efficiently and thoroughly explored the various areas and key points described above. The routes for each field survey are displayed along with its results in Section 5.3. Geographic data containing the routes of each field survey are available upon request to the author.

5.2.2 Performing the Field Surveys

Performing the field surveys, it was important to maintain a standard protocol for each study, as to keep the impression and experience of each district as unbiased as possible. Therefore, each field survey was conducted using the same equipment, at the same time of day, and in similar weather conditions.

The field surveys were completed using the author's own personal bike, a standard city bike with 21 gears, and all began in the morning between 8:50 AM and 9:20 AM, except for Field Survey 6 (24 Feldmoching-Hasenbergl) which began at 10:32 AM as the district had to be reached by S-Bahn train. Initially, it was planned to start each study at 8:30 AM, but the logistics of starting each study in districts located across the city proved to be difficult. Most of this large discrepancy in time was mostly due to unexpected delays, traffic, and the fact that instead of by bike, Feldmoching-Hasenbergl was reached by S-Bahn before beginning the survey. Bikes are only allowed on public transport in Munich after 9 AM. The S-Bahn was chosen instead of cycling, in this case, because simply reaching this district required a 14-kilometer ride from the author's home, which was so significant that it might have made the observer tired enough to bias the results.

Additionally, as each field survey lasted from one and a half to four hours, the exact starting time of the survey proved to be less important. The original idea was to start at the same time to experience the peak hour traffic conditions for cyclists in each district. However, with the surveys covering so much ground and lasting a few hours, there would be no way to experience the peak hour conditions across the entire route in each district. This was taken into consideration while cycling through areas around stations and along major roadways, which could be much busier than they were during the surveys. It was noted if an area seemed to have inadequate infrastructure for peak hour traffic conditions, though it might have been fine for the conditions present during the time of the survey.

To record the experience along each route, a sports camera (an Apeman A80 4K Action Camera) was mounted on the handlebars. The camera was encased in a waterproof case in the event of rain or snow and was mounted in a way so that it would not move around or shift during operation. Video was recorded at 30 frames per second with a resolution of 2560x1440 pixels (QHD). When compared to the other resolutions and frame rates available in the initial tests with the camera mounted on the handlebars, this combination of resolution and frame rate performed better than all other options in terms of smoothness of the video and discernable detail. The camera also utilized a gyroscope function which helped reduce the impacts of bumps, drops, and other sudden movements along the route on the quality of the video. The battery level on the camera was checked before and during the separate segments of each field survey route (see the screenshots of the routes below), and extra batteries were brought along to replace the battery after two or three segments to ensure no data was lost.

On the other side of the handlebars, a smartphone was mounted which both recorded the GPS position of the surveyor (using the myTracks application in the background) and served as a navigation tool (using the GPX Viewer application) to display the field survey's route at all times. In the event of rain or snow, the phone could be placed inside a waterproof case mounted at the center of the handlebars. The phone performing the recording and navigation during each survey had a large enough battery to last for several hours of continuous recording and navigation operation, however, extra batteries for both it and the camera were stored in the waterproof case on the center of the handlebars.

The observer also brought food and water with so that most of the field survey could be completed without stopping for too long. Also, it was important to maintain the same mental conditions of the observer during the study as to not bias the results. Finally, the bike's wheels were properly pumped, and the bike was checked to be in full working condition before each survey, to further standardize the experience of each survey. Below, Figure 5.3 shows the setup of the bike used for each survey and Figure 5.4 shows the recording equipment setup on the handlebars.

Figure 5.3: The bike used for each survey setup for recording. Source: own photo.

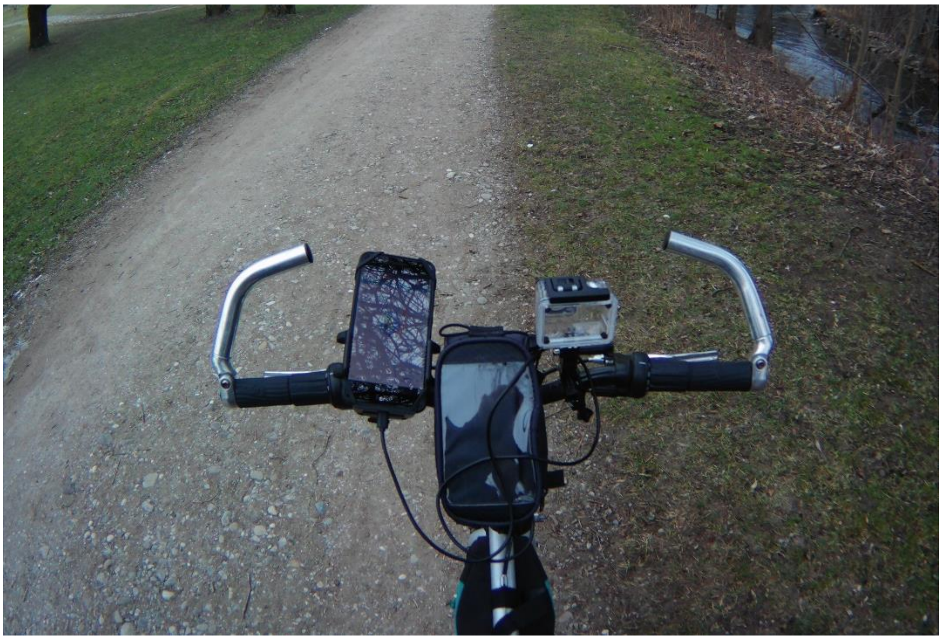

Figure 5.4: The recording equipment setup on the handlebars of the bike. On the left, the phone used for recording and navigation is mounted, in the middle is the case containing extra batteries for both devices, and on the right is the housing for the sports camera (which was being used to take this picture). Source: own photo.

5.2.3 Interesting Aspects of the Built Environment

During each field survey, various interesting aspects of the built environment were marked in the video recordings by quickly placing a hand in front of the camera so that the time and position in the video could be marked, and whatever observations made during the survey worth noting could be remembered during the review later. Several aspects of the built environment which could be relevant to the observer's cycling experience or perception of cycling are defined below.

The areas marked along the route are locations which could have either a positive or negative impact on the cycling experience or on how the district is perceived by cyclists. A list of aspects of the built environment and other interesting locations which were marked by the observer during the surveys is below:

- Highs and lows in the volume, speed, and noise level of the traffic.
- The quality of the cycling infrastructure (width, ride quality, alignment, slopes, continuity, maintenance level, etc.)
- Disturbances in the cycling infrastructure, impeding the cyclists progress (garbage bins, tree roots, vehicles, pedestrians, etc.)
- Greenery (trees, shade, shrubs, water features, etc.)
- Aesthetic (architecture, design, complexity, proportions, etc.)
- Intersection quality (ease of understanding, ample space, timing, comfort in traffic, lanes and signals for cyclists, etc.)

On the day of the survey or the day after, the video recordings of the route were reviewed and a detailed recap of the cycling experience of the survey was written. Areas of interest which were marked by the observer were paid close attention and notes describing the experience were written. These detailed notes and the rest of the recap of each field survey are available in Appendix L. Summaries of the overall experiences and important features within each district are available in Section 5.3 next.

5.3 Qualitative Study Results

In this section, the results of the six field surveys are presented and discussed individually. A screenshot of the route followed during each survey is included in each section, as well as general notes about the survey which could be important for understanding the context of each individual survey relative to the others. Also, each subsection below contains a summary of the observations during each survey describing important areas, roads, paths, and other aspects of the built environment which impacted the experience or perception of cycling in each district.

Full notes of each field survey broken down into each segment are available in Appendix L. Video recordings and GPS tracking data are available upon request for academic purposes only.

5.3.1 Field Survey 1: Schwabing-West

Date	February 9th 2018
Starting Time	08:48 AM
Ending Time	10:28 AM
Total Distance	20.9 km

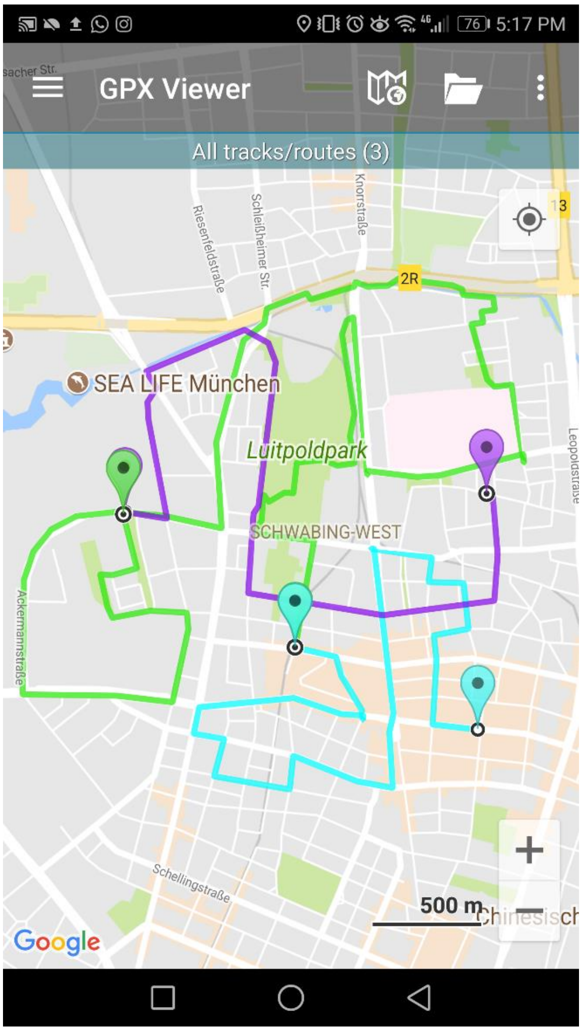

Figure 5.5: The route of Field Survey 1 (4 Schwabing-West). Segment 1 - cyan, Segment 2 - green, Segment 3 - purple. Source: a screenshot of the route loaded into the GPX Viewer app which was used to navigate during the survey.

General Notes

Weather: Partly Cloudy/Sunny. No precipitation, little wind. Temperatures were chilly, about -1° C.

The field survey area was reached by bike, which was about a 15-minute ride from where the observer lives. As the first field survey conducted for this project, some ideas for small improvements to make future field surveys easier to conduct, more comprehensive, and safer.

Summary of Observations

The field survey was a generally pleasant ride. Schwabing-West (outside of the newly developed areas in the west of the district) is filled with quiet residential streets, many of which seemed to be (quite clearly) marked as "Fahrradstraße", or Tempo30 Zones, or Shared Zones. Main streets were mostly well-equipped with sufficient cycle lanes or paths in the sidewalk.

Most every street felt safe. Quite often, drivers let cyclists cross a somewhat busy street, or generally drove in a way that signaled their awareness and respect for other road users. It is possible this is due to the high proportion of Tempo30 Zones, or the character of relaxed and calm streets throughout the district.

Central plazas, major transport hubs (Hohenzollerplatz and Scheidplatz especially) seemed to have sufficient bike storage for private bikes as well as for bikesharing (MVG Rad).

Luitpoldpark in the north of the district was quite well-used by people. Several groups of walkers, dog walkers, and other people enjoying the green space were out and about. As a cyclist though, it was of limited use with a normal bike. Most of the trails (not all!) were not cleared of snow, but very few were icy.

In the north along the 2R, some areas were hard to find the proper place to cycle (if there is one). Much of the area behind the residences along the stream and below the hill over the 2R tunnel was icy.

5.3.2 Field Survey 2: Sendling

Date	February 12th 2018
Starting Time	09:20 AM
Ending Time	10:52 AM
Total Distance	18.51 km

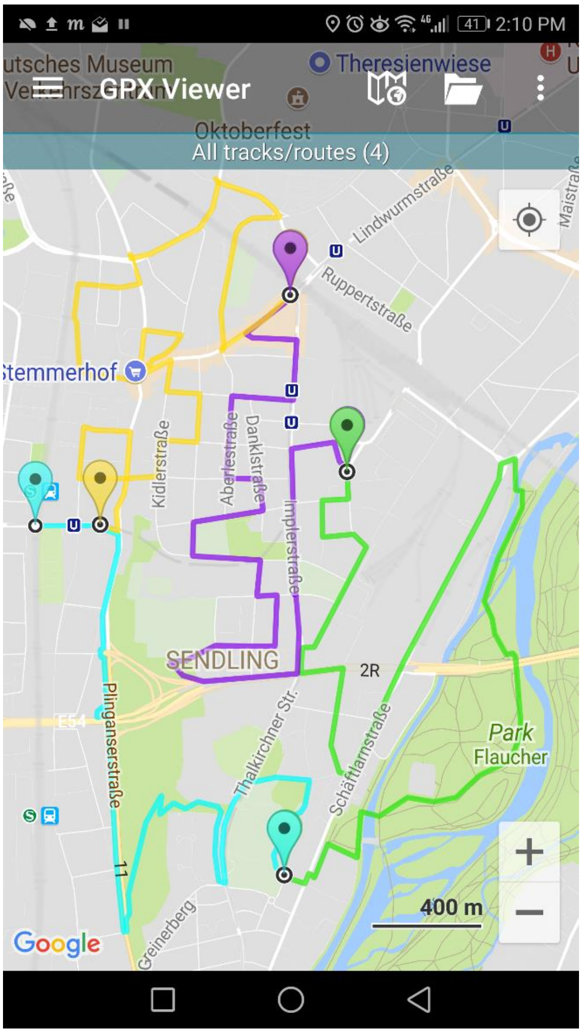

Figure 5.6: The route of Field Survey 2 (7 Sendling). Segment 1 - cyan, Segment 2 - green, Segment 3 - purple, Segment 4 - yellow. Source: a screenshot of the route loaded into the GPX Viewer app which was used to navigate during the survey.

General Notes

Weather: Partly Cloudy/Sunny. Flurries at the beginning which delayed the start, but otherwise no precipitation and very little wind. Temperatures were again chilly, at about 1° C.

The field survey area was reached by bike, which was about a 30-minute ride from home.

Summary of Observations

Sendling was a very easy district to cycle in, save for a few select areas. The areas which were good for cycling include:

- The area surrounding the interchange between the 2R (the Mittlerer Ring) and Plinganserstraße which had surprisingly wide paths and plenty of grass and trees to reduce the impacts of having such high-volume roads running through the area.
- The forested areas around the Flaucher Park on the east side of the district were quite green, and the paths were in good condition, well covered with gravel and sand for traction in the winter snow.
- Most residential areas were quiet and easy to cycle through, with many Shared Zones, Tempo30 Zones, Gegeneinbahnstraßen, Fahrradstraßen, and a relaxed feel.
- The plaza around the Harras public transport station was quite large and included wide bike paths. As in many busy areas, conflicts with pedestrians were common, but the wide lanes and large pedestrian area gave everyone room to maneuver around each other.

There were some areas which felt difficult to cycle in, and some aspects of the district which made it more difficult or less comfortable:

- Schäftlarnstraße had a nice cycle path, but riding next to the massive industrial logistics facility, and all its machines running producing noise and pollution would not be pleasant every day. Plus, the entrance is not even large enough to fit one semitruck, meaning cyclists and pedestrians on the west side of the road often need to navigate around the back end of a large truck. On busy days, riding past and through a line of diesel semitrucks does not sound very comfortable or healthy.

- A seemingly larger portion of residential streets were paved with cobblestones and stones.
- While the main roadways Implerstraße, Thalkirchner Straße, and Lindwurmstraße, all have cycle lanes or paths along the road, Plinganserstraße only has cycle paths along it south of its intersection with the Mittlerer Ring (2R).

Sendling also has a large difference in elevation between its western edge (especially along Plinganserstraße) and its eastern side (at its lowest in the Flaucher Park of course, but the developed area along the river are low as well). The difference is around 150m in elevation between the high northern end of Plinganserstraße where it intersects with Lindwurmstraße, and the area in the Flaucher Park.

5.3.3 Field Survey 3: Berg am Laim

Date	February 13th 2018
Starting Time	9:00 am
Ending Time	11:16 am
Total Distance	29.75 km

General Notes

Weather: Sunny and cold. Temperatures ranged from -1C to +1C.

This field survey was significantly longer than the 2 previous, for a couple of reasons. The district itself is larger, and there are several distinct areas within it, so visiting each and cycling along all the major roadways, of which there are several, made for a more complex and longer field survey route.

Summary of Observations

In most areas of Berg am Laim, there are no inhibitors of cycling. Residential streets are wide enough, bike lanes and paths flank the major roadways, and a large green park with paths crisscrossing it sits in the middle of the district makes it easy to avoid traffic and get from A to B with a bike in this part of the Berg am Laim. Also, a large park, Ostpark, sits on its southern border, as does the indoor/outdoor pool Michaelibad. However, most of the area east of the Mittlerer ring is purely residential, with a couple of exceptions south of Berg am Laim station and along the B304.

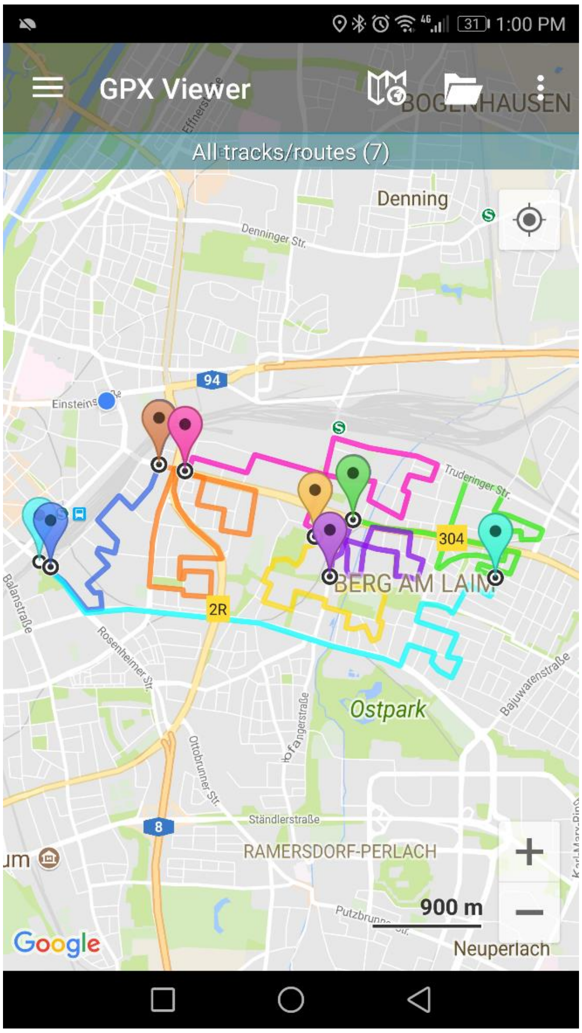

Figure 5.7: The route of Field Survey 3 (14 Berg am Laim). Segment 1 - cyan, Segment 2 - green, Segment 3 - purple, Segment 4 - yellow, Segment 5 - magenta, Segment 6 - orange, Segment 7 - blue. Source: a screenshot of the route loaded into the GPX Viewer app which was used to navigate during the survey.

Cycling facilities are limited along Truderinger Staße and Baumkirchner Straße which have direct access to the S-Bahn station Berg am Laim. In the industrial area directly east of Ostbahnhof is under real redevelopment which is limiting direct access through much of the area.

The road which forms the southern border has decent cycling facilities along it but cycling for any long distance on it would be quite boring and uncomfortable. The vehicles are moving very fast, the path isn't too far from the road (a line of parked cars), and the road is very straight without very much to look at in most places, which all make cycling along it less than ideal. Another less than ideal cycling experience in this district is the path along the eastern side of the Mittlerer Ring (2R) in Segment 6 of the field survey. This cycle path is not protected from the very busy and high-traffic (esp. with trucks) roadway at all, and the trucks coming from nearby construction have covered the road in dust, which is then thrown into the air when other trucks pass. Depending on the circumstances, this situation may last for a very long time during the development going on in the district. Regardless of the dust issue, the cycle path being directly on the edge of the pavement, not separated from the traffic by anything makes this roadway feel very unsafe and uncomfortable.

5.3.4 Field Survey 4: Pasing-Obermenzing

Date	February 15th 2018
Starting Time	9:01 AM
Ending Time	12:55 PM
Total Distance	41.85 km

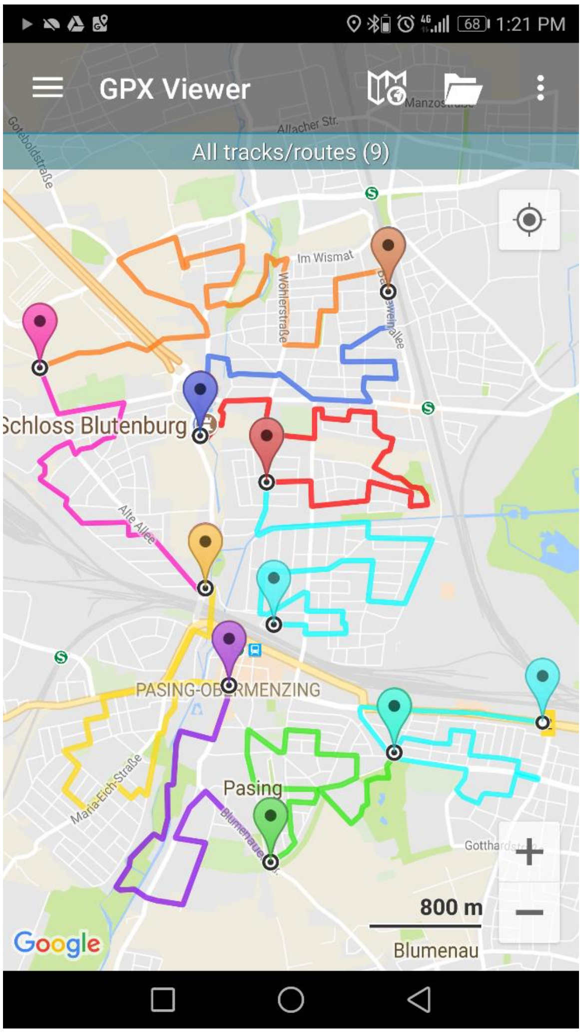

Figure 5.8: The route for Field Survey 4 (21 Pasing-Obermenzing).Segment 1 - cyan (in the southeast), Segment 2 - green, Segment 3 - purple, Segment 4 - yellow, Segment 5 - magenta, Segment 6 - orange, Segment 7 - blue, Segment 8 - red, Segment 9 - cyan (north of the railway tracks). Source: a screenshot of the route loaded into the GPX Viewer app which was used to navigate during the survey.

General Notes

Weather: Mostly cloudy with moments of sun. Very cold, and somewhat windy early on. Temperatures ranged from -7C to -1C.

This was the longest of the field surveys so far again. The district is quite large and also varied in its styles of development. It was still chosen because of its abnormally high rate of cycling for a low-density district. The district was cycled too, which took longer than expected but did not significantly tire out the observer.

Summary of Observations

Most roads and streets, outside of the Bundesstraße B2, Landsbergerstraße, Verdisstraße, and Pippinger Straße, were very low traffic, or low traffic enough to cycle along. Even those in the center of Pasing-Obermenzing felt safe and easy to ride along or cross.

The residential areas all across the district were similarly low density, however pockets of denser development like at the center of Pasing (especially surrounding the S-Bahn station and stretching to the south) and along some stretches of Planegger Straße (on the Pasinger Stadtpark).

The large stretch of forested area, grasslands, and general green park space that surrounds the Wurm River from the Pasinger Stadtpark in the south all the way up to the edge of the district in the north connects the whole district together with a continuous, almost unimpeded, and very pleasant cycling route… almost like a bike highway would.

The green area with paths running through it which crosses the district from east to west in the northern half of the district (just south of Verdistraße) also acts as a sort of collector and connector, allowing for bike trips in this area which require moving in this direction to be completed in a much safer and more pleasant way.

Cycling between the farms in the northern half of the district was about just as pleasant as cycling through woods and forested areas. Plus, the wide paved access roads were very easy to cycle on.

Surprisingly, the A8 didn't disturb cycling in the area too much thanks to the Brieter Weg road which had an underpass. The intersections just after the autobahn ends were also not very busy, but I assume at rush hour they could be much more hectic.

5.3.5 Field Survey 5: Thalkirchen-Obersendling-Forstenried-Fürstenried-Solln (TOFFS)

Date	22.02.2018 & 02.03.2018
Starting Times	9:10 AM & 11:16 AM (02.03)
Ending Times	10:04 AM & 2:48 PM (02.03)
Total Distance	42.66 kilometers

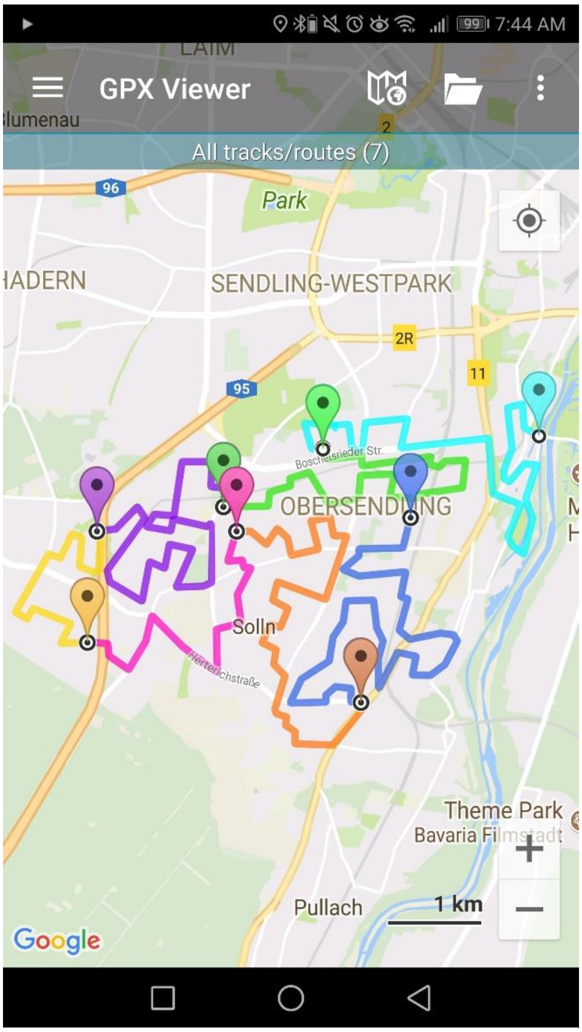

Figure 5.9: The route of Field Survey 5 (19 TOFFS).Segment 1 - cyan, Segment 2 - green, Segment 3 - purple, Segment 4 - yellow, Segment 5 - magenta, Segment 6 - orange, Segment 7 - blue. Source: a screenshot of the route loaded into the GPX Viewer app which was used to navigate during the survey.

General Notes

Weather: (22.02.2018) Cold and gray, with a little sun appearing later in the morning. High of -4C. (02.03.2018) Very cold but sunny for most of the survey. High of -4C.

On the 22nd of February, the author had an accident riding west on Boschetsrieder Straße near the end of the first segment. After getting up and finishing the segment, the author went home and to the doctor to see if there were any major injuries. The author felt good enough and the weather had cleared up enough on the 2nd of March so that the field survey could be resumed.

On the second day of the field survey, March 2nd, Munich had previously had days of very cold temperatures and some snow, as a result, many of the residential side streets were frozen over with ice, and had to be traversed very carefully, especially as to avoid another accident. This significantly slowed the progress of the field survey but will not be taken into consideration as to the general cycling experience and conditions of the built environment as it is an anomaly.

Summary of Observations

Generally, this district is made up of 5 separate communities which have melded together in recent decades. The developmental history of these areas is still present. The district is most dense in the northeast near Obersendling. Solln and the area near the S-Bahn station in the southeast are very similar, both made up of somewhat dense older housing with many areas of large houses. Forstenried and Fürstenried are lower density areas with pockets of high-density due to large apartment buildings built up especially along the motorway.

There are several industrial and commercial parks in the district which were usually a little harder to get around on a bike than residential areas. Paths within these areas didn't connect, in poor conditions, and generally seemed an afterthought, especially compared to the newer residential areas which seemed to make an effort to make cycling easier for the residents.

The areas surrounding the motorway with large apartment buildings usually also had large green strips running between the buildings with paths for cycling and walking. These paths were well connected to the network of streets with proper cycling infrastructure (Forstenrieder Allee, Drygalski-Allee, Zuricher Straße, Aidenbachstraße, Lochhamer Straße, and Herterichstraße among a few others) allowing cyclists to reach many destinations without dangerous conditions.

Though having cycling and walking paths in the wooded area flanking the motorway as it cuts through this district is certainly a good idea, many of the paths were unusable due to snow and ice. It is not known if these paths are normally cleared of snow at all during the winter, though some of the areas did have signs indicating that they definitely were not going to be cleared.

5.3.6 Field Survey 6: Feldmoching-Hasenbergl

Date	March 9th 2018
Starting Time	10:32 AM
Ending Time	2:14 PM
Total Distance	46.84 kilometers

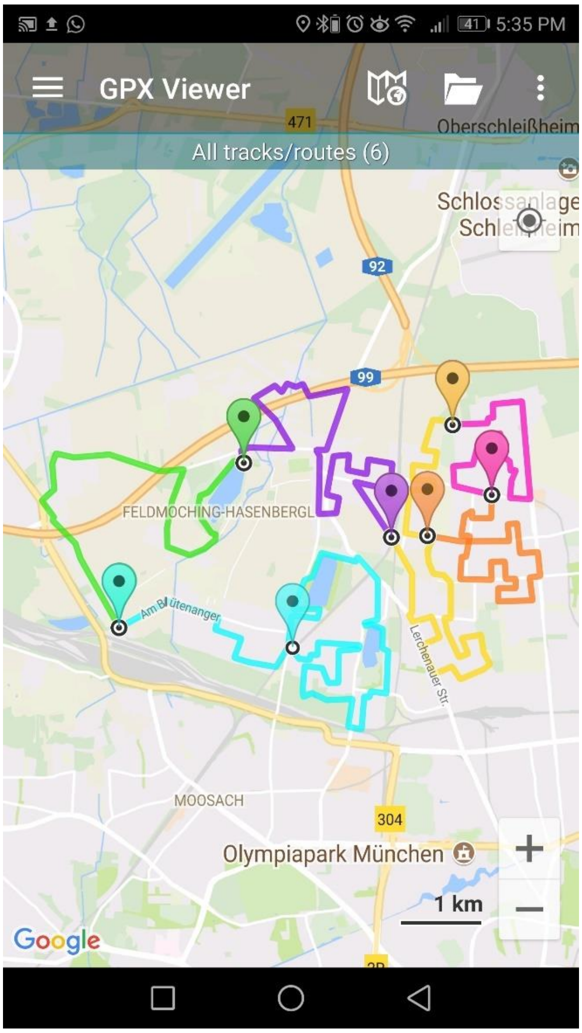

Figure 5.10: The route of Field Survey 6 (24 Feldmoching-Hasenbergl). Segment 1 - cyan, Segment 2 - green, Segment 3 - purple, Segment 4 - yellow, Segment 5 - magenta, Segment 6 - orange. Source: a screenshot of the route loaded into the GPX Viewer app which was used to navigate during the survey.

General Notes

Weather: Cool to warm, and sunny. Low of 6C and a high of 12C. This was by far the most pleasant day to cycle of all the days of field surveys.

The Feldmoching-Hasenbergl area was reached by S-Bahn, which only allows bikes on board after 9 AM. This delayed the start to later than desired.

Summary of Observations

The development around motorways was surprisingly varied. Some areas were industrial or farming land, and some were purely residential of high or low density. Much like TOFFS, many of the high density residential developments along the motorway included green strips with paths between the buildings and underpasses under the motorway, which were common enough to make cycling from these locations more convenient.

Paths are marked through the forested area along the railway tracks which form the southern border of the district. While there were some makeshift paths in this area, they were not paved with anything, and more trails made in the grass through the woods. This was a very nice area to cycle in that felt separate from the city, but it could be better connected to the cycling network of the district. Entering the area required getting off the bike and carrying it over a small muddy ridge on the side of the road through a narrow opening in the trees. If it were better connected, it could provide a large area open to non-motorized travel, enabling users to get from one side of the district to the other without interacting with vehicles too often.

There are signposted cycle routes throughout the district, but in some areas the routes follow roads with very substandard cycling conditions. There are some busier roads which are a part of the signposted cycle route network which have no cycle lanes, nor paths on the sidewalk which is too narrow and restricted further by cars parking up on the curb. Major or important roads without dedicated cycling infrastructure and with generally poor cycling conditions (e.g. busy roads with parking along the side and narrow sidewalks) appeared in other parts of the district as well, not just along signposted cycle routes. It was especially noticeable in the more developed areas of town, where these busy roads became constricted by buildings on either side, and sacrificed cycling for more road lanes, parking, or cramped sidewalks. Some streets in these areas had good cycling conditions but they seemed rarer than those with poor cycling conditions.

In areas of less dense development it seemed that more roads had been recently rebuilt with proper infrastructure for cyclists and pedestrians in mind, though not all. In fact, roads which had cycle lanes or paths in areas where they traveled through farm fields or woods lost this infrastructure once they entered areas of residential or other built-up development.

Still, this district had plenty of cycling paths through forested areas, fields, and around lakes which were very pleasant to cycle along. Additionally, very low traffic residential and service streets in the outer edges of the district were common and often well-marked as open for cyclists.

5.3.7 Synthesis of Field Survey Results

Throughout these field surveys, several patterns in the built environment of districts overall and specific areas within districts were noticed by the observer. Some of these patterns were found in multiple districts of varying types (i.e. in both central and outer districts) and some were found to only in districts of similar types (i.e. only in central districts).

- More centralized long (or large) green areas with shared paths or dedicated cycle paths (like the green strips in Pasing, the central park area in Berg am Laim, or even the wooded areas flanking the Isar) make it much easier, more comfortable, and pleasant to cover longer distances and reach more destinations without interacting with vehicles, or at least only a limited number of points.
- Major roadways, especially federal highways (Bundesstraßen), throughout Munich seem to have less sufficient cycling infrastructure. They often felt less safe and secure to ride along, not only due to the speed and volume of the traffic, but also because there was often less protection from it, or older or poorly maintained infrastructure. For example, there were many stretches along major roadways with narrower cycling lanes or narrow sidewalks shared with pedestrians which squeeze cyclists between people and cars. This was a problem throughout the city, though it was not as much of a problem in the core districts.
- The comfort and security of cycling through a residential area seems to change with the density of the development, the width of the street and setback of the buildings, the presence of cycling infrastructure, and the presence of cars parked along the street or in dedicated parking spaces. Residential streets with dedicated areas for parked cars, wider streets, and dedicated cycling infrastructure are much nicer to cycle through.
- Residential areas made up of tall separated apartment buildings in a single development complex often had long strips of green areas with trees running between them, making for a nice way of connecting the buildings to each other and to the cycling network around them.
- Often having small green areas or parks breaking up the landscape of apartments and houses in residential areas makes the area feel much more diverse and welcoming, not to mention interesting to cycle through. However, in some residential zones these little green areas were often broken up by streets without proper curb cuts or a no-parking zone which made crossing the street uncomfortable.
- Purely residential development areas (with medium to low density) were seemingly more likely to have uncleared paths and sidewalks and streets, making winter riding more difficult for those living in these areas when snow or ice is on the ground. Purely residential areas are much more common in less central districts, as they were only found in the middle and outer districts.
- There are several different forms of purely residential development in the city, and their forms can have an impact on the cycling experience within them. They range from areas with row

houses and gardens situated on quiet narrow streets to areas with groups of separated high-rise apartment buildings on bigger roads (though usually not directly on major roads). Outside of the city's core, each of these types of development can be found, but in the urban core, there were far fewer purely residential areas.

- Office parks and commercial areas are often filled with paths that don't connect or are shown online but blocked by fences. This makes it hard to get from place to place without going out of your way. Additionally, the paths in these office and industrial parks are usually only meant for pedestrians or are at least not very wide. All this can create large blocks of land not easily traversable by cyclists going to these areas or trying to go through them. These were mostly found in outer districts.
- Newer suburban areas in the middle and outer districts and recently renovated central areas seemed to provide much more cycling facilities and they often and had better connections to the main cycling network than older neighborhoods across the city.
- Major roadways in the outer districts were much more likely than those in middle or core districts to not have any cycling infrastructure along them and therefore felt quite unsafe and insecure to cycle on. However, some of these major roadways in the outer districts – outside higher density areas like town centers – seemed more likely to have been recently rebuilt with new well-designed cycling infrastructure. Those within higher density areas rarely had proper cycling infrastructure or even good conditions for cycling.
- Motorways don't seem to be as large of barriers for cycling as expected. While motorways certainly do separate communities, as far as cyclists are concerned, they didn't seem to be as big of a problem as expected. There were plenty of underpasses and overpasses in the districts with motorways running through them – enough to make cycling from one side to the other not too inconvenient. Additionally, in many areas the motorways were flanked by wooded areas with walking and cycling paths. As they follow the corridor of the motorways, the paths in these areas provide a mostly uninterrupted route and pleasant cycling experience.
- Signposted Routes often were very helpful in guiding cyclists around and informing them of their general direction and distance to various important locations, as well as making them confident that they belong on the paths as well. However, it was sometimes confusing which path was actually part of the route, and in some areas, infrastructure making up the route was not very bike friendly (like in Feldmoching-Hasenbergl and other outer districts).

A 2014 report by Philip Black and Emma Street explored the impacts cyclists' perceptions of the built environment around them might have on their behavior. They concluded this report with a set of urban design audit criteria, which "provide an initial template [for] analyzing and evaluating the sites regarding the provision of a quality cycling environment". This set of criteria was adapted to fit the purposes of this study, so that the results of the field surveys could be interpreted through a comprehensive framework and discussed using a commonly understood language. The next section addresses each of these criteria and uses them to describe the experiences cycling across the city. Aspects or conditions of the built environment across the city relevant to each of these criteria will be presented and discussed below. The table of the urban design audit criteria from Black and Street's paper is replicated below in Table 5.1. (Black and Street 2014)

Table 5.1: Urban design audit criteria, adapted from (Black and Street 2014).*It is used as a framework for describing the built environments experienced during the qualitative study's field surveys.*

Urban Design Audit Criteria	Descriptors
Imageability	Capturing attention / sense of place / distinct / memorable / vernacular architecture

Legibility	Spatial understanding and ease of navigation / sense of orientation
Enclosure	Streets / definition through buildings, walls, trees / heights, widths, and proportions
Human Scale	Size / articulation of physical elements in relation to humans / building and street detail
Transparency	Degree to which people see and perceive what lies beyond / human activity
Complexity	Visual richness of a place – architectural / landscape / streets / signage / human activity
Coherence	Visual order – consistency in scale, character and arrangement
Tidiness	Condition and cleanliness of a place / well-maintained

Imageability

Imageability varied greatly depending on the district and type of area within the districts and was impacted by a variety of aspects of the built environment. Examples of good imageability due being distinct, memorable, or aesthetically pleasing: the long stretch of forested green area along the Wurm and the forested area around Westbad in Pasing-Obermenzing, the town centers in Pasing-Obermenzing and Sendling, Schwabing-West's Hohenzollerplatz, Hohenzollerstraße, and Herzogstraße, the lakes in Feldmoching-Hasenbergl, the open central park area of Berg am Laim, the paths along the Isar in Sendling, Plinganserstraße in Sendling, Benediktbeuerer Straße, the Asam Schlössl, and the forested areas and paths along the motorway in TOFFS.

Unique buildings, intersections, or even green areas with some special feature like a stream or river were the main sources of distinct areas throughout the city. Even after riding through only six of the 25 districts, many of the main streets and residential developments begin to blur together. In reviewing the footage of the field surveys, it is clear that there certainly are typical types of development in Munich which all look somewhat similar. This is, however, not limited to the suburban developments outside the city's core. Some streets in Sendling and Schwabing-West had no distinct characteristics to them. Streets with retail and apartments were rarely ever boring, while purely residential areas all tend to blend together with others of the same type.

Areas with U-Bahn and S-Bahn stations, as well as streets with tram lines were all very memorable and distinct. Signs signifying the signposted cycle routes improved imageability, as well as specifically marked cycle lanes and paths (with pavement markings or signs), the added benefit of these is that they also greatly improved the next criterion, legibility.

Legibility

Legibility for a cyclist in the city of Munich comes down to two simple questions, "Which way do I go?" and "Do I belong on here?". In both cases, the signposted cycle routes throughout the city help greatly, and other signage indicating that cycling is allowed help to ensure cyclists that they aren't riding where they aren't supposed to be. Pavement marking in the form of dashed or solid white lines denoting a cycling lane, red-filled in cycle lanes in intersections, or the white and blue "Fahrradstraße" symbol stamp are probably the easiest types to pick out in the busy cityscape while looking out for traffic and other obstacles.

Unfortunately, while the signposted cycle routes are a great guide, it is not always clear which path or way is meant to correspond to each direction listed on the sign – especially at points with several destinations on the sign or many paths intersecting in once place. It was sometimes impossible to tell which path to go down to keep following the route based on the small arrow symbols pointing in the general direction of their corresponding destinations. At times like these, stopping and reviewing both the directions on the sign and the available directions of paths was the only way to determine which path would follow which route.

Intersections were another area in which legibility was an important factor. Through intersections with continuous bike paths and properly marked lanes, crossing was never an issue. However, many intersections, especially in the outer areas of Munich, had crossing points for bikes on the sidewalk, although cyclists were meant to have been cycling on the street. At such intersections, it isn't clear if the cyclist should get off the road, cross using the crosswalk, and then reenter the road on the other side of the intersection. Navigating through left turns at intersections was also troublesome. If crossing is meant to be done only at these crosswalks beginning on the sidewalk, a left turn would require waiting for at least two cycles of the signal to cross both streets. Standing in the middle of a busy intersection waiting for cars to pass to turn left is already not pleasant, but it is worse if the cyclist is unaware if they belong on the street or not.

Enclosure

The central areas of Munich generally had a more positive feeling of enclosure to them as opposed to the outer areas. Much of this is due to the constant wall of mostly mixed-use buildings on either side of most streets in the core districts. However, major roadways throughout the city in all types of districts often felt wide open and undefined. Parks and paths like the lakes in Feldmoching-Hasenbergl, the area following the Wurm river in Pasing-Obermenzing, and the paths along the Isar in Sendling all felt well-defined and safe due to the surrounding trees.

Major roadways can feel safer to cycle along if the cycle path is offset from the road by a wide enough green shoulder (two meters or more) and a line of trees or other greenery. This made the cycling and pedestrian area feel separate from the big roadway. Additionally, the green areas with paths for pedestrians and cyclists between large apartment buildings in the outer regions of Munich would feel very open and out of proportion if it weren't for the trees that often filled them.

Human Scale

Much like enclosure, the core districts of Munich feel more aligned with the human scale than the outer areas, due to the speed of the traffic and the width of the streets. However, there is a type of cycling infrastructure common in all areas of the city felt misaligned with the human scale. In areas where a small cycle lane was narrowly squeezed between traffic and parked cars, or when a cycle path was bound on one side by parked cars with very little buffer space and on the other side by a narrow sidewalk, cycling was an anxious and tough task. Cycling along these types of cycling infrastructure felt very constrained. If a pedestrian suddenly walked into the cycle path, or a car drove into the cycling lane, and the driver or passenger of any one of the cars opened their door, there would often be no place for the cyclist to go.

This problem is made worse by the fact these many of these constrained cycle lanes and paths were in busy dense areas, which meant that the opportunity for conflicts was higher, as was the opportunity for conflicts with no possible way out except for hitting someone or something.

Transparency

The main issue of transparency noticed during the field surveys was the inability to see around obstacles when approaching an intersection. On main streets and major roadways, it was sometimes difficult to see around the corner due to some large vehicle parked right on the corner of the road the observer was on. This was observed all over Munich but seems to have been more of a problem in dense city areas which had more spaces for vehicles to park on the corners.

In many purely residential areas with single-family homes, in both middle and outer districts of the city, the issue of cars being parked on the corner also existed, but another issue did as well. Fences, walls, or landscaping placed right up along the corner of the sidewalk also made it difficult to see if any traffic was approaching from around the corner.

Complexity

The complexity of the built environment impacts the cycling experience in many ways. First would be the visual complexity of the surroundings – the buildings, the trees, and whatever else fills the background. As mentioned in the section on enclosure, large, especially straight, roadways often felt boring and tiring to ride along, while city streets with constant buildings, parks, and lots of human activity other than driving were always engaging to cycle along. In residential areas, the more diverse the houses or apartment buildings were the more engaging it was to cycle through. In many of the outer areas of Munich though, developments built with the same style or type of housing were monotonous and somewhat uninviting to cycle through.

However, too much complexity can have a negative impact on the cycling experience as well, as explained in the section on legibility. Some intersections in the core districts of Munich are quite complex and even with existing pavement markings difficult to understand. In other places along signposted cycle routes, having too many destinations on one sign can lead to confusion over which path leads to which destination.

Other complexity factors which had a positive impact on the cycling experience were the curves of streets and human activity. Curved streets and roads were more engaging to cycle along, as there was always something new appearing around the bend. Areas with more human activity, both busy streets and parks, were more pleasant areas to cycle in than those with no one around. For this reason alone, the denser more central districts were generally more pleasant to cycle in than the sparse outer districts.

Coherence

For the most part, the development in the City of Munich is rather coherent. Especially in the central districts in the qualitative study, most of the development matches the development around it. The only places in the field surveys that felt disconnected or separate in an incoherent way were the areas in Feldmoching-Hasenbergl or TOFFS around the motorways, where large areas of single-family houses were often directly next to complexes of large high-rise apartment buildings. Another incoherent location is the area on the western side of Berg am Laim, between Ostbahnhof's railyard, Rosenheimer Straße, and the Mittlerer Ring. Two other major roadways, Aschheimer Straße and Anzinger Straße also cut through this area, further breaking it up into odd shapes with areas of industrial or commercial development across the street from big apartment buildings or other residential development. Even in these areas of inconsistent development patterns, coherence didn't impact the overall cycling experience in the districts too much.

Tidiness

The tidiness of the built environment seems quite important to the City of Munich, and it certainly had an impact on the cycling experience in the city. Throughout most of the city, cycling lanes and paths are well-maintained and clean like the streets and parks are as well. As might be expected, however, in some areas of the outer districts the maintenance level of roads and cycling infrastructure is not up to the standard of other areas in the city. Paths inside parks were also less tidy in the outer areas of Munich as well – with many having ruts, potholes, muddy sections, and other issues that were not present in the parks of the central or even middle districts. Also, poorly maintained and narrow sidewalks were more common in the outer districts as well, often along somewhat busier streets in areas where cyclists are meant to share the sidewalk with pedestrians.

During the winter, another problem of tidiness surfaces after snow falls on the ground – the gravel used to increase traction for cars on the road can build up in the cycle lanes and even on cycle paths in the sidewalk, actually decreasing the traction for cyclists. This is exactly what caused the accident during the fifth field survey in TOFFS. There were other contributing factors to the accident as well, as described in the full review notes of the Field Survey 5 in Appendix L. If this gravel one the roads isn't cleared often enough, cycling on the streets in the winter becomes more difficult than it should.

The results described above are combined with the results of the quantitative study as discussed above in Section 4.3 in Section 6.2 below.

6 Discussion and Conclusions

With the quantitative study and the qualitative study complete, the methods of both are analyzed in Section 6.1 to reveal the limitations of this study and some recommendations for improvement. Next, the results of both are combined to form a more comprehensive picture of the relationship between the built environment and cycling in Munich, and to answer the research questions posed in the introduction to this report. Finally, some recommendations for future research to build upon this thesis and further investigate cycling in Munich are presented.

6.1 Limitations of the Study and Recommendations for Improvement

As discussed in Section 2, the usage of the mixed-methods approach itself poses one major limitation on the study, namely the extra time required to design, research, perform, and report on two mostly separate studies instead of one. While this approach offers the benefit of looking at the topic from two complementary angles – and indeed that is why this method was chosen – this main disadvantage impacts the study in many ways throughout the process as a result. With less time to dedicate to each of the methods, both of them will be less complex and thorough than if they each had been the sole method of the thesis. Also, because of the time constraints on the thesis, these methods were completed in parallel, instead of sequentially. Performing the methods in a different sequence would have allowed the qualitative study to be used as an exploratory method to determine which variables might be most important to gather data for and include in the quantitative analysis.

The restricted time available for the quantitative method meant there was less time available to spend forming new combinations of the data to make new variables which might have better explained the variations in cycling's modal share throughout the city. For example, as it was noticed that the destination accessibility variables were all highly collinear with each other, they could have been combined into an agglomerated accessibility variable, which might have been a better way of describing the main way the access to destinations of a district impacts the modal share of cycling. Other groups of variables could have been combined or modified to better reflect reality as well. Also, other new variables could have been added and tested given more time:

- The level of access to the various public transportation modes was measured simply by access to the stations, treating all stations as equal. However, stations with more modes available, more lines, or more frequent service offer a much different level of accessibility than a singularly bus, tram, S-Bahn, or U-Bahn station alone.

- Since it was noticed that the cycleways in green areas were found to have the opposite impact on the modal share of cycling as was expected, new ways of measuring the prevalence of cycling infrastructure could have been devised and calculated to find a variable that represents reality more completely. For example, variables describing access to cycleways of various types by measuring the median distance to a cycling infrastructure or by measuring population within a buffer distance around the infrastructure could have been used.
- The land use diversity data could have been much more detailed given more time. Instead of mainly looking only at the generalized data available in the city's Statistics Pocket Book publication and the per developed area rates of common destinations, cleaning and sorting the land use and building footprint data available from the OSM sources could have provided a much more detailed representation of the land use diversity of the districts.
- A factor analysis could have been done to determine the relative impacts of the variables within each set for the dimensions of the built environment. This would have cleaned up much of the multicollinearity issues and removed the need for a variable trimming process altogether.
- More information on the cycling infrastructure throughout the city could have been gathered, such as bike and ride facilities at public transport nodes, distinct data on the individual signposted cycle routes (the data only contained one large polyline with all signposted cycle routes in one feature). More reliable data on the location of public bike parking facilities would have provided a better inside to the areas which visibly support cycling more.
- Any number of combinations or modifications of variables could have been done to improve the quantitative study's findings, but time restricted this process and so the methods described in Section 4.2 were all that could be fit into the time frame.

Even if the data had been configured differently, however, it would still have a couple major flaws. First, using geographic data from 2017 combined with some data on density and land use diversity from 2008 to analyze the modal share of cycling in 2008 is not ideal. Data all from the same year would naturally have been better, but archives of OSM data back to 2008 are not available for Munich, and the little geographic data that was available freely online was not as detailed or complete as the current data which was used in the quantitative study. If data had also been available for 2008, in addition to the results of the 2016 Mobility in Germany study (still being completed at the time of this report), a study comparing the changes in Munich built environment with its changes in cycling rates would have been possible. Such a study would have been able draw more sound conclusions than this one.

Another problem with the methods and data used in the quantitative study is that they are susceptible to ecological fallacy problem and the modified areal unit problem, or MAUP. The ecological fallacy occurs when a narrow set of "ecological" (in this case built environment) factors are used to define a complex human decision process that contains hundreds of other factors. The presence or lack of a single cycle lane doesn't often change a resident's decision to cycle or not. They might not feel comfortable cycling, or they might be used to driving or taking the bus, or, they might work odd hours and cycling at night is not practical. While the built environment can certainly steer people towards different modes of transport, it is ultimately a personal decision with myriad other factors involved.

In the case of this study, an ecological fallacy is also present in that the concept of residential self-selection is not addressed. Residential self-selection refers to the concept that people do not simply change their mobility behavior once they move to a new area, they might have in fact chosen that area because it aligns with their needs and desires for mobility. (Scheiner 2014; Cao, Mokhtarian, and Handy 2009)

The modified areal unit problem, or MAUP, arises from the fact that the borders drawn to distinguish the districts in this study are, for the most part, imaginary. There are physical manifestations of these borders in some cases, such as major roads or the Isar river, however even these do not resolve the MAUP issue. The city is a continuous spread of gradually changing and diverse built environments and populations. Breaking it up into arbitrary zones and peoples is only so useful in analyzing the importance of the average characteristics of each area in question, and is not useful for predicting the changes which will happen if these characteristics are changed in one section of the district. (Iacono, Krizek, and El-Geneidy 2010)

Because this thesis used aggregate data in a cross-sectional study which was susceptible to the ecological fallacy and modified areal unit problems, and due to the limited number of observations available (the 25 districts in Munich with modal share data), no direct causational connections between aspects of the built environment can be drawn. However, the associations between the various variables in the quantitative study, combined with the findings of the field surveys can provide some insight into which aspects of the built environment seem to support cycling and those that don't. In general, all conclusions in this study should be taken as possible associations between the built environment and cycling, and not as fact because of the nature of the study and the data used within it.

In addition to the quantitative study, the qualitative study also had limitations due to the time restraint and due to its design. If more time had been allowed, more areas of Munich could have been studied, which could have helped to answer questions raised from the data about these districts. For example, Pasing-Obermenzing was chosen to be included in the qualitative study for multiple reasons explained in Section 5.1. One of the main reasons was that it was such an outlier in the data. In 2008, it had an extraordinarily high modal share of cycling compared to all of the districts around it and others like it. There were other districts in Munich which could have been included like Pasing-Obermenzing was to study the cycling experience within them and how it might have impacted the cycling rate.

Another limitation of the qualitative study is that it uses current field surveys and the current cycling experience to attempt to explain or partially explain the modal share of cycling in 2008. Again, if more current travel behavior study data was available, the issues caused by the large difference in time between the variable in question and the factors used to study it could have been greatly diminished.

Finally, this qualitative method of field surveys is inherently biased by the sole observer, the author of the thesis. In order to be able to make more causal inferences between aspects of the built environment and the modal share of cycling, a survey to cyclists across the city would need to be conducted. Hearing directly from the cyclists themselves about what impacts their decision to cycle or not would be a useful expansion of this study. Knowing what people base their decisions off of could be helpful in determining the changes in the built environment the city should pursue to more reliably grow the rate of cycling in Munich.

6.2 Synthesis of Results and Conclusions

Despite the limitations of this study described in the previous section, associations between the various aspects of the built environment investigated by both the quantitative and the qualitative study can be made.

This thesis attempted to answer the question, *"What elements of the built-environment influence cycling in Munich, how, and to what degree?"*.

The results of the various multiple regression results of the quantitative study and the experiences cycling through Munich of the qualitative study can be joined to answer the six specific questions which make up the answer to the main research question.

1. *Are there elements of the built environment's design or land-use diversity, independent of a district's density, which encourage cycling?*

According to the results of the second stepwise multiple regression process, the street network's composition and the ratio of developed land devoted to buildings are both associated with the modal share of cycling in a district. From the qualitative study, these results can be confirmed, as the experiences cycling along major (primary and trunk) roads was significantly different than cycling along secondary and tertiary roads. Areas with more space dedicated to buildings than service or transport areas felt much more aligned with the human scale and provided a positive feeling of enclosure.

2. *Does the presence of more green areas (parks, meadows, forests, etc.), specifically those with cycleways through them, encourage cycling?*

To answer this question, the shortcomings of the quantitative study, specifically the variables used to measure the prevalence of cycleways through green areas, prevent any sort of statistical association. However, according to the author's experience cycling through parks and natural areas throughout the city, it is hard to believe that these do not in some way influence residents' decisions to cycle for certain trips. It should also be noted that the variable measuring the median distance to the nearest park or natural area was associated with the modal share of cycling in the initial stepwise multiple regression process as seen in Figure 4.3, which implies that more parks and natural areas dispersed throughout the city might encourage more people to cycle for more trips.

3. *What impacts, if any, do the street network and the cycle network have on the rate of cycling in the city?*

Reviewing the multiple regression results from the second stepwise multiple regression process and the initial individual regressions with each variable it is clear there may be some connection between the prevalent types of streets in a district and the rate of cycling, but no real associations can be drawn other than as was described above. As for the cycling network, the rate of cycleways along streets and the rate of signposted cycle routes per developed land area also seem to show some positive connection with the cycling rate across the city, but no real associations can be drawn both of these variables dropped out during the variable trimming and stepwise multiple regression processes.

The variables related to streets which were open to cycling show a closer relation with the modal share of cycling, however. Both bicycle streets (Fahrradstrassen) and those open to contraflow cycling show a strong association with the modal share of cycling, but only the contraflow one-way street variable dropped out during the variable trimming process. The variable representing the prevalence of bicycle streets in a district did remain until the final iteration of the initial stepwise multiple regression process.

The experiences gathered during the qualitative study show that the presence of clearly marked cycle lanes, well-designed cycle paths, and dedicated cycle paths (especially in green areas) were the more comfortable, secure-feeling, safe and pleasant to use than any other type of infrastructure for cyclists. Shared and contraflow one-way streets were also noticed as useful and comfortable cycling infrastructure, but only when they were clearly marked. Therefore, combining these two studies, it can be said that the cycling infrastructure network can have a significant impact on cycling, depending on the quality of said infrastructure. The main criteria which impact the quality of the cycling infrastructure, according the qualitative study are tidiness, and legibility, and human scale. Those cycleways which feel new, clean, or well-maintained, are easy to figure out at a normal cycling speed, and feel properly sized for the cyclist and surround conditions to feel safe and secure probably do encourage cycling, or at least using them over other routes.

4. *Do the presence of offices, retail, restaurants and bars, other amenities, or the diversity of these land-uses influence the rate of cycling in a district?*

As the destination accessibility variables were the strongest dimension measured by the individual regressions with each variable and a variable representing this dimension (*culturalsocial_1km*) remained in both final variable sets from both stepwise multiple regression processes, it can be said that having these cultural and social destinations within easy access range of a cyclists (one to three kilometers) is strongly positively associated with the modal share of cycling. It can also be said that easy cycling access to the other types of common destinations which were highly collinear with the *culturalsocial_1km* variable is also associated with higher cycling rates throughout Munich.

Looking at this question through the experiences of the qualitative study, it can be said that the cycling experience was generally more pleasant in areas with more human activity and complexity – both aspects of the built environment which correlate with a high amount of shops, restaurants, bars, and other amenities. It also simply makes sense that those who do not have many options within an easy cycling range would more likely not choose to cycle to these destinations, and the results of the quantitative and qualitative study seem to support this.

5. *Does access to public transport or a specific type of public transport (bus, tram, U-Bahn, or S-Bahn) affect the rate of cycling in a district?*

The most interesting result of the quantitative study in answering this question comes from the variables of interest analysis, within which the median distance to a tram station variable (*med_tramdist*) was added back into the simplified regression equation from Section 4.2.3. The variable actually became more significant than the *culturalsocial_1km* variable, which normally always remained after being found to be collinear with another, less significant variable. This means that, at the least, areas with more prevalent access to the tram network also show increased rates of cycling. Looking at the collinearity of this factor with other density and destination accessibility variables, it seems that this is simply a correlation without any causation, however. More central and dense districts are simply more likely to have higher rates of cycling and higher levels of accessibility to public transport.

Using the qualitative study to complement this finding, it seems even more likely that this is simply correlation. Tram tracks actually make streets more of a barrier to cross for cyclists and passengers exiting and entering the tram can often form obstacles for cyclists trying to cross an intersection or simply ride down the road. However, it can be said that streets with trams on them do have a certain pleasant enclosed feeling to them and are usually busier and more complex, making them more engaging to cycling through.

6. *What might the City of Munich do to continue to increase the modal share of cycling further?*

Reviewing the answers to the previous questions, and the results of both studies, this thesis can recommend a few improvements which could further encourage cycling throughout the city and help Munich reach its goal of a 20% modal share of cycling city-wide.

- Further extension of the signposted cycle route network, and the development of a pavement marking system which matches the directions posted on the signs to help guide cyclists to the route they which to follow.
- Improving access to common destinations in outer areas of Munich. Simply having easy cycling access to large supermarkets, retail shops, and other kinds of shops and amenities seems to encourage cycling.
- Fixing or redesigning poor cycling infrastructure. Especially in the outer areas of the city, cycling can feel a little unwelcome in centers of activity, whether it be from a lack of cycling infrastructure or due to poor conditions of the existing cycle lane or path.
- Planning, building, and extending continuous green areas within districts. The impacts that the strip of mostly uninterrupted green and/or forested areas along the Wurm river in Pasing, the central park area of Berg am Laim, or the forested areas along the Isar in Sendling and other districts adjacent to the river have on the cycling experience cannot be understated. The ability to simply ride without having to stop at intersections or worry about cars on the road is a freeing experience that only these long green areas can provide. They impart a very human-scale cycling experience enclosed by the trees, a transparent pathway where obstacles and possible conflicts can be seen from a distance, and a tidy built environment which feels pleasant and separate from the city surrounding the area.
- Shifting signposted cycle routes off of major roadways and onto secondary and tertiary roads or side streets. Major roadways, especially the federal highways (Bundesstrassen), had some of the worst cycle lanes and paths of any kind of roadway. The Mittlerer Ring, the B304, and Heinrich-Wieland-Straße in Berg am Laim, the B11 (Plinganserstraße) in Sendling, Josef-Frankl-Straße, Lerchenstraße and Dülferstraße in Feldmoching-Hasenbergl (in the town center), and other major roadways outer and middle districts often had poor cycling conditions. Improving these would make cycling feel much safer and more secure throughout the city.
- Expanding and improving the red-filled cycle lanes in intersections throughout the city. Some intersections in the city with cycle lanes are filled in with red paint to bring the cycle lane to the attention of motorists. This practice should be expanded everywhere possible, and also improved to include the crossing points for cycle paths emanating from the sidewalks. Having this stark marking on the pavement not only makes motorists more aware, but lets the cyclists know that they are welcome, and that motorists really should be giving way to them. These markings make for much safer and more confident cycling though busy and congested streets.

The City of Munich has come a long way in supporting cycling since its recognition as a mode with unique needs began in 1986. The city often tops lists of the most bike-friendly cities in the world online, but still, much can be done to take the city to the next level and make cycling a very common mode of transport among all demographic and social groups.

6.3 Recommendations for Future Research

In light its findings and the limitations of this study, several opportunities for further research which expand upon this thesis arise.

To improve on the quantitative study, using more discrete data (disaggregate or smaller aggregations) would be ideal, as this would help to remove the modified areal unit problem with this thesis. Studies conducted with more accurate or more complete data on some of the variables would also improve upon the findings of this study. A longitudinal study following the changes to the built environment and the changes in the modal share of cycling over time would be very useful in forming causal connections between the built environment and the modal share of cycling throughout the city.

As to the problems with ecological fallacy, future qualitative research which could help to understand people's decision to cycle or not could be:

- Surveys of cyclists and non-cyclists intended to discover their decision making process and motivations.
- Studies into the effects of the increased visibility of cycling in the city. With all of the new infrastructure and marketing programs for cycling popping up throughout the city in the past decades, what are the impacts of these elements being in the public eye on the modal share of cycling? Does the fact that cycling has been made more visible encourage cycling?
- As Munich's marketing efforts through programs like the Radlhauptstadt take root, what sort of culture around cycling is developing in the city? How do these programs, and the changes to the built environment, change the public's perspective on cycling?

As more and more research into the built environment and its relationship with cycling in Munich is conducted, the stronger the evidence for the city's actions to support the mode of transport become. With congested roadways, S-Bahn trains seemingly breaking down weekly, and several U-Bahn lines operating at capacity, people are looking for alternatives. Cycling has long been the answer for many of them. This thesis shows that what the city has done in the past has certainly supported those who might want to switch to cycling as their main mode of transport. Still, more can be done to keep help the city's modal share of cycling rise further. With the findings of this thesis and other research following it, the city can further focus its efforts to more efficiently and effectively grow the share of cycling in Munich.

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8 APPENDICES

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