Exploring Bikeability

Urban Infrastructure and Bicycle Transport

Dissertation

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Zusammenfassung

Die Nutzung des Fahrrades als Verkehrsmittel zeigt gegenüber anderen Modi Vorteile auf individueller sowie gesamtgesellschaftlicher Ebene und zeichnet sich durch geringe Externalitäten aus. Im Radverkehr ist die Infrastruktur von besonderer Bedeutung. Hier gibt es sowohl hinsichtlich der Eigenschaften möglicher Routen als auch bezogen auf die individuellen Präferenzen der Radfahrenden für diese Eigenschaften eine große Bandbreite. Dabei bestehen einerseits hinsichtlich der Wirkung dieser Infrastrukturen auf den Radverkehr sowie andererseits bezogen auf individuelle Präferenzen der Radfahrenden noch offene Fragen. Mit diesem Komplex befasst sich die vorliegende kumulative Dissertation.

Zum Einsatz kommt eine breite Kombination unterschiedlicher Methoden in einem integrierten Gesamtansatz. An die Herleitung der radfahrtauglichen Umgebung (Bikeability) über eine Literaturanalyse und einen interaktiven Expertenprozess schließen sich die Operationalisierung dieser Definition mittels offener Geodaten sowie die Bewertung der Einflüsse auf die Verkehrsmittelwahl in einem multinomialen Verkehrsmittelwahlmodell an. Darüber hinaus werden auf der detaillierteren Ebene der Routenwahl die einzelnen Einflussgrößen in einem diskreten Entscheidungsexperiment differenziert. Um die Interaktionen zu quantifizieren kommen dabei logistische Regressionsmodelle zum Einsatz. Des Weiteren werden Daten aus der Fahrradnavigation in einem Clusterverfahren genutzt um Routenpräferenzen ohne den möglichen Einfluss einer Befragungssituation zu analysieren.

Im Ergebnis zeigt sich ein konsensuales Verständnis von Bikeability unter Abbildung des Zusammenspiels der fünf wichtigsten infrastrukturellen Parameter (Radinfrastruktur an Hauptverkehrsstraßen, Kreuzungsdichte, Straßentypen, grüne Wege sowie Verleih- und Reparatureinrichtungen). Durch Nutzung offener Geodaten ist der entwickelte Ansatz uneingeschränkt räumlich übertragbar und thematisch adaptierbar. Das Verkehrsmittelwahlmodell belegt den stark positiven Einfluss der Bikeability auf die Wahl des Fahrrades

als Verkehrsmittel. Auf der differenzierten Ebene der Routenwahl bestätigt sich der besondere Einfluss der Radinfrastruktur an Hauptverkehrsstraßen. Die Ergebnisse zeigen dabei eine Abstufung im Nutzen für den Radverkehr, die dem Ausmaß der baulichen Trennung vom motorisierten Individualverkehr entspricht, sowie spezifische individuelle und strukturelle Implikationen. Neben Infrastrukturen an Hauptstraßen wird durch die angewandten Methoden auch die generelle Bedeutung von Nebenstraßen verdeutlicht und weiter differenziert. Die Ergebnisse zeigen dabei den enormen Nutzen von Fahrradstraßen aus Sicht der Nutzenden.

Die Erkenntnisse bieten spezifische Anknüpfungspunkte, sowohl für weitere Forschung als auch für Planung und Praxis, die in der Arbeit diskutiert werden.

Abstract

Using the bicycle as mode of transport has advantages on both the individual and the societal level. Compared to other modes, cycling shows low externalities. One important aspect of bicycle research is its interrelation with the infrastructure. Route characteristics, as well as individual preferences for specific routes, are diverse. Hence, there remain research gaps regarding individual route preferences of cyclists. In addition, the impact of specific infrastructure on cycling transport has not been sufficiently researched. The present study deals with this topic.

A broad combination of different methods is used in an integrated approach. First, the bike-friendliness of the urban environment (bikeability) is defined via a literature analysis in combination with an interactive expert survey. This definition of bikeability is then operationalized using open geodata, ensuring transferability. In addition, the effects of bikeability on mode choice are evaluated using a multinomial logit model. On the detailed level of route choice, the influencing parameters are further differentiated in a graphical online stated preferences survey. Mixed logit discrete choice models are then developed to quantify the trade-offs of interest. Furthermore, extensive data retrieved from a bike routing engine are clustered and analysed to reveal underlying route preferences, without the potential effects of an overt survey situation.

Results show a consensus in understanding of bikeability, as provided by experts. This is defined by a stable interaction of the components composing bikeability, in the following order of importance: cycle facilities along main streets, intersection density, road types, green pathways, and rental and repair facilities. The mode choice model proves the strong positive effect of high bikeability on choosing the bike as a mode of transport. On the detailed level of route choice, the particular influence of cycling infrastructure along main streets is confirmed, and differentiated according to the specific design. Aside from spe-

cific individual and structural implications, a greater separation from motorized transport generally corresponds with a higher utility for cyclists. Regarding side streets, the results reveal the general importance of minor roads and the enormous benefit of cycle streets prioritizing cyclists.

The presented findings may be used for further research and deliver recommendations for planning, which are discussed in the present study.

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Eidesstattliche Erklärung

Ich erkläre, dass ich die Dissertation selbständig und nur unter Verwendung der von mir gemäß § 7 Abs. 3 der Promotionsordnung der Mathematisch-Naturwissenschaftlichen Fakultät, veröffentlicht im Amtlichen Mitteilungsblatt der Humboldt-Universität zu Berlin Nr. 42/2018 am 11.07.2018 angegebenen Hilfsmittel angefertigt habe.

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1 Einleitung

1.1 Aufbau der Arbeit

Die vorliegende Arbeit wurde als kumulative Dissertation verfasst. Den Hauptteil bilden somit die in wissenschaftlichen Zeitschriften veröffentlichten bzw. zur Veröffentlichung vorgesehenen Beiträge der Kapitel 3 bis 5. Zunächst wird eine Einleitung in das Thema gegeben (1.2), der Stand der Forschung beschrieben (1.3) und die Gesamtfragestellung hergeleitet (1.4). Im Anschluss wird das methodische Konzept der Arbeit beschrieben (2). Dabei wird zum einen der übergeordnete Ansatz der Forschung erläutert und zum anderen die Zusammenhänge zwischen den einzelnen Modulen verdeutlicht. Darüber hinaus werden die methodischen Ansätze der Teilarbeiten kurz benannt, um den methodischen Gesamtzusammenhang zu verdeutlichen.

Die Arbeit schließt mit einer Zusammenfassung und Synthese der zentralen Erkenntnisse sowie einem Ausblick und Fazit (6). Unweigerlich gibt es zwischen den im Hauptteil aufgeführten Veröffentlichungen und den weiteren Abschnitten in Teilen Überschneidungen und Doppelungen. Dabei gehen die Beschreibungen der Kapitel 3 bis 5 deutlich stärker ins Detail, während die weiteren Ausführungen den Gesamtzusammenhang verdeutlichen sollen und auf einer gröberen Überblicksebene bleiben.

1.2 Ausgangssituation und Motivation

Der Mobilitätssektor, bestehend aus dem Transport von Gütern und Personen, weist zahlreiche negative Externalitäten auf (Profillidis, Botzoris, & Galanis, 2014). Diese bedingen negative Auswirkungen in verschiedenen Bereichen. Von besonderer Bedeutung ist der Klimawandel, der die aktuell größte Herausforderung der Menschheit darstellt (IPCC, 2018; Watts et al., 2020). Vor dem Hintergrund des sich verschärfenden Klimawandels sind CO_2-Emissionen besonders relevant (Nunez, Arets, Alkemade, Verwer, & Leemans, 2019; Sippel, Meinshausen, Fischer, Székely, & Knutti, 2020). Die CO_2-Emissionen im Transportsektor stiegen bis zuletzt weiter an, während in allen anderen Sektoren gegenüber 1990 Emissionen eingespart werden konnten (IPCC, 2018). Um die internationalen Pariser Vereinbarungen erfüllen zu können, müssen die Emissionen in allen Sektoren massiv sinken (Prognos, Öko-Institut, & Wuppertal-Institut, 2020). Innerhalb des Transportsektors stellt der Straßenpersonenverkehr nach wie vor den größten Emittenten dar (IEA, 2019).

Neben klimaschädlichen Emissionen werden Luftschadstoffe wie Stickoxide zu signifikanten Anteilen vom Straßenverkehr ausgestoßen (Anenberg, Miller, Henze, & Minjares, 2019). Hier zeigt sich zwar eine positivere Tendenz als bei den CO_2-Emissionen (Takeshita, 2011). Dennoch steht die massiv gesundheitsschädliche Wirkung dieser Emissionen außer Frage (Héroux et al., 2015; Pascal et al., 2013; Rovira, Domingo, & Schuhmacher, 2020).

Unabhängig von Emissionen wird ein Großteil des öffentlichen Raums in Städten durch den Flächenbedarf des motorisierten Individualverkehrs belegt (Jones, 2014; Roca-Riu, Menendez, Dakic, Buehler, & Ortigosa, 2020). Dabei wird die Flächenzuweisung der Bedeutung der jeweiligen Verkehrsmittel nicht gerecht (Gössling, Schröder, Späth, & Freytag, 2016; Will, Cornet, & Munshi, 2020). Untersuchungen der Flächengerechtigkeit können dabei als ein Teil der Debatte zu urbaner Umweltgerechtigkeit verstanden werden (Lakes, Brückner, & Krämer, 2014; Mohai, Pellow, & Roberts, 2009). Die Diskussion über eine gerechte Verteilung der Ressource Straßenfläche bzw. öffentlicher Raum ist in vollem Gange. Deutlich wird dies durch das in den letzten Jahren massiv steigende zivilgesellschaftliche Engagement (Becker & Renn, 2019; Schmidt, 2018) sowie eine steigende Anzahl von lokalen Projekten zur Flächenumwidmung und Neuverteilung (Aichinger & Frehn, 2017). Obgleich die oftmals geforderte Verteilung entsprechend den Modal-Split-Anteilen der einzelnen Modi zu kurz greift (Nello-Deakin, 2019), scheint der Status quo mit einem Fokus auf den motorisierten Individualverkehr und dessen Begründung nicht mehr angebracht. Insgesamt wurde der zusätzliche Flächenverbrauch des Verkehrs zwar gebremst, dennoch nimmt die für Verkehr benötigte Fläche deutschlandweit stetig zu

(Umweltbundesamt, 2020). Sicher ist, dass die Förderung und vermehrte Nutzung flächensparsamer Modi eine effiziente und gerechte Nutzung der begrenzten Flächenressourcen begünstigt.

Auf individueller Ebene steht Bewegungsmangel weltweit in Verbindung mit zahlreichen chronischen Erkrankungen und vorzeitigen Todesfällen sowie enormen volkswirtschaftlichen Kosten (Ding et al., 2016). Der Bewegungsmangel mit seinen Folgeerscheinungen stellt Gesellschaften und Gesundheitssysteme vor enorme Herausforderungen und wird als das größte Problem der öffentlichen Gesundheit des 21. Jahrhunderts bezeichnet (Blair, 2009; Bull et al., 2004)

Das Fahrrad stellt ein besonders nachhaltiges Verkehrsmittel dar. Verglichen mit anderen Modi erzeugt die Nutzung des Fahrrades nur einen Bruchteil der beschriebenen negativen externen Effekte (Ahrens, Becker, Böhmer, Richter, & Wittwer, 2013; Makarova, Mavrin, Magdin, Shubenkova, & Boyko, 2019; Watts, et al., 2020). Gegenüber den gesamtgesellschaftlichen Kosten des Autofahrens wird dem Radfahren sogar ein kilometerbezogener Nutzen beigemessen (Gössling, Choi, Dekker, & Metzler, 2019). Am Beispiel der Emission von Luftschadstoffen konnte gezeigt werden, dass eine gute Luftreinhalte-Policy und explizit gute Radinfrastruktur mit besserer Luftqualität einhergeht (Quarmby, Santos, & Mathias, 2019).

Radfahren als Form der aktiven Mobilität wirkt gesundheitsfördernd und präventiv gegenüber Herz-Kreislauf-Krankheiten (Grøntved et al., 2019; Mueller et al., 2015; Raustorp & Koglin, 2019; Schäfer et al., 2020). Die gesundheitsfördernden Effekte überwiegen mögliche Gefahren durch Verkehrsunfälle oder Exposition verschmutzter Luft dabei bei Weitem (Cepeda et al., 2017; Rojas-Rueda, de Nazelle, Tainio, & Nieuwenhuijsen, 2011; Sun et al., 2019). Auch auf Stress (Sattler et al., 2020) bzw. psychische Gesundheit (Leyland, Spencer, Beale, Jones, & Van Reekum, 2019; McCay, Bremer, Endale, Jannati, & Yi, 2019) sind positive Wirkungen belegt. Trotz zahlreicher ermutigender Studien sind die positiven Effekte nicht immer klar, wie ein aktuelles Review zur Wirkung auf Depressionssymptome zeigt (Marques et al., 2020).

In jüngster Vergangenheit zeigen sich zudem vor dem Hintergrund der Covid-19-Pandemie deutliche Veränderungen im Mobilitätsverhalten. Besonders die Motive für die Verkehrsmittelwahl und das Befinden in den öffentlichen Verkehrsmitteln spiegeln Befürchtungen vor Ansteckung wider (Nobis, Eisenmann, Kolarova, Winkler, & Lenz, 2020). Insbesondere Vorbehalte gegenüber dem öffentlichen Personennahverkehr mindern die Nutzung (Tirachini & Cats, 2020). Mit den verschobenen Motiven und Modal-Split-Anteilen wird die Bedeutung des Systems aktiver Mobilität aus Fuß- und Radverkehr als gesunde, sichere und umweltfreundliche Form der individuellen Mobilität deutlich (Dunning & Nurse, 2020; Kick, 2020). Gleichzeitig erfordern extrem gestiegene Radverkehrsmengen (Jacobs, 2020; Woods, 2020) eine zügige Umverteilung des öffentlichen Verkehrsraums, um eine aktive Mobilität auch unter Wahrung der Abstandsregelungen zu ermöglichen. Zahlreiche Städte haben mit der Einrichtung sogenannter Pop-up-Infrastruktur für den Radverkehr reagiert (Fahrradportal, 2020; Kraus & Koch, 2020; Carlton Reid, 2020). Es bleibt zu vermuten, dass sich das geänderte Nachfrageverhalten mit Abklingen der Pandemie nicht schlagartig ändert und neu geschaffene Routinen erhalten bleiben. Inwieweit der öffentliche Verkehr im urbanen Raum weiterhin die Grundlage einer nachhaltigen Mobilität im Umweltverbund bilden kann, scheint aktuell zumindest fraglich. So ist die Notwendigkeit, die Nutzung des Fahrrades als Verkehrsmittel zu unterstützen, um weitere substanzielle Teile der urbanen Mobilität verlagern zu können, aktueller denn je.

Wie beschrieben stellt das Fahrrad als Alternative ein besonders nachhaltiges Verkehrsmittel dar und zeigt gegenüber dem Auto deutliche Vorteile sowohl auf gesellschaftlicher als auch auf individueller Ebene. Die Entwicklung der Fahrradnutzung weist in den vergangenen Jahren bereits eine positive Tendenz auf. Insbesondere in den Großstädten steigt der Anteil des Fahrrades am Modal Split (Nobis, 2019). Dennoch werden insgesamt nur 11 Prozent aller Wege mit dem Fahrrad zurückgelegt (Nobis & Kuhnimhof, 2018). International zeigen sich enorme Unterschiede in der Fahrradnutzung zwischen verschiedenen Städten und Ländern (Buehler & Pucher, 2012). Dabei fallen einzelne europäische Orte wie Amsterdam und Kopenhagen mit besonders hohen Radverkehrsanteilen auf, die gleichzeitig über eine gut ausgebaute Fahrradinfrastruktur verfügen (de Lange & Feddes, 2019; Emanuel, 2019). Vor diesem Hintergrund ist es wichtig, infrastrukturelle Zusammenhänge im Radverkehr sowie präferierte Routeneigenschaften stärker wissenschaftlich zu untersuchen. Im Radverkehr umfasst dieser Infrastrukturbegriff eine Vielzahl von möglichen Eigenschaften jedes Streckensegmentes. Neben verschiedensten baulichen Varianten einer separaten Radinfrastruktur entlang bestehender Straßen sind weitere Routeneigenschaften im Mischverkehr bzw. abseits des motorisierten Verkehrs von Bedeutung für Radfahrende. Dieser Vielfalt an infrastrukturellen Eigenschaften des Raumes stehen aufseiten der Radfahrenden sehr unterschiedliche Präferenzen für Routeneigenschaften gegenüber. Dieser Komplex aus strukturellen Raumeigenschaften und individuellen Präferenzen für diese macht die Untersuchungen zu strukturellen Zusammenhängen und Routenpräferenzen im Radverkehr zu einer entscheidenden Forschungsrichtung. Gewonnene Erkenntnisse helfen einerseits, lokale Gegebenheiten und dahinterliegende Zusammenhänge sowie räumliche und individuelle Unterschiede im Radverkehr besser zu verstehen. Andererseits ermöglichen sie eine zielgerichtete Konzeption der Radverkehrsförderung. Durch das Umsetzen solcher Konzepte können entsprechende Arbeiten mittelbar zu einer vermehrten Nutzung des Fahrrades als Verkehrsmittel beitragen.

1.3 Stand des Wissens und Forschungslücke

Das individuelle Mobilitätsverhalten ist das Ergebnis eines multifaktoriellen Wirkkomplexes. Ein Einflussfaktor auf menschliches Verhalten sind dabei strukturelle Parameter. Im Spannungsfeld zwischen Mobilität und Raum- bzw. Infrastruktur stehen verschiedene etablierte Konzepte und methodische Ansätze zur wissenschaftlichen Analyse zur Verfügung. Im Folgenden wird der Stand der Forschung entsprechend der drei relevanten methodischen Ansätze aufbereitet und Forschungslücken benannt. Zuvor werden jedoch die zentralen Begriffe bestimmt und das für diese Arbeit maßgebliche gedankliche Modell menschlichen Verhaltens vorgestellt.

1.3.1 Zentrale Begriffe

Die Arbeit thematisiert Zusammenhänge zwischen Infrastruktur und Radverkehr im urbanen Raum. Der Begriff Infrastruktur, zusammengesetzt aus *infra* (darunter) und *Struktur* („Gefüge, das aus Teilen besteht, die wechselseitig voneinander abhängen; in sich strukturiertes Ganzes"(Dudenredaktion, o.J.)) kann etymologisch als darunterliegende Gesamtheit von Einzelteilen verstanden werden. Eine umfassende ökonomische Definition bietet Jochimsen (1966). Demnach meint der Begriff Infrastruktur die „Summe der materiellen, institutionellen und personellen Grundlagen einer Volkswirtschaft, die dazu beitragen, die Angleichung der Faktorenentgelte bei zweckmäßiger Allokation der Produktionsfaktoren, das heißt einen relativ hohen Integrationsgrad und das höchstmögliche Niveau der Wirtschaftsaktivitäten, zu ermöglichen" (H. Zimmermann, 1969). In dieser Dreiteilung ist die Verkehrsinfrastruktur dem Materiellen zuzuordnen. Darüber hinaus wirken die institutionelle (Regelungen und Normen) sowie personelle Infrastruktur (Humankapital) komplementär. Radinfrastruktur beschreibt dabei den Teil der Verkehrsinfrastruktur, der implizit oder explizit der Durchführung des Fahrradverkehrs dient. Dies umfasst also sowohl Radverkehrsanlagen zur exklusiven Nutzung durch Radfahrende wie (geschützte) Radfahrstreifen oder bauliche Radwege, also auch nutzbare Verbindungen auf Straßen und in Grünflächen. Ergänzend sind weitere Infrastrukturen wie Fahrradläden, Fahrradverleihsysteme oder Reparatureinrichtungen Teil der Radinfrastruktur. Bikeability wiederum meint die Eignung der Verkehrsinfrastruktur im Allgemeinen und der Radinfrastruktur im Speziellen für den Radverkehr. Dabei wird Bikeability in Anlehnung an Kellstedt et al. (2020) verstanden als Ausmaß, zu dem die tatsächliche und wahrgenommene Umgebung für das Radfahren förderlich und sicher ist (Kellstedt, Spengler, Foster, Lee, & Maddock, 2020). „Bikeability may be defined as the extent to which the actual and perceived environment is conducive and safe for bicycling." (ebd. S.2). Für die Operationalisierung in ergibt sich hieraus die abstrahierte Radfahrtauglichkeit eines urbanen Gebietes auf Basis von Geodaten. Dementsprechend wird die Expertenbefragung (3.1.3.1) eingeleitet mit „Bitte stellen sie sich eine urbane Umgebung vor, die generell zum Radfahren im Alltag einlädt."

Übergeordnet wird die Infrastruktur als *design* bereits in den Analysen von Cervero und Kockelman (1997) als Teil der Raumstruktur verstanden (Cervero & Kockelman, 1997) (vgl. 1.3.3). In der Folge werden auch Services im Sinne von *demand management* der Raumstruktur zugeordnet (R. Ewing & Cervero, 2010; Reid Ewing & Handy, 2009).

1.3.2 Theorie des geplanten Verhaltens

Theoretische Hintergrundfolie für die methodischen Anknüpfungspunkte dieser Arbeit bildet die Theorie des geplanten Verhaltens (Ajzen, 1985, 1991). Sie stellt eine Weiterentwicklung der Theorie der überlegten Handlung dar (Fishbein, 1979). Diese psychologische Theorie bildet die Entscheidungsbildung menschlichen Verhaltens im Zusammenhang zwischen Intention und Handlung modellhaft ab (siehe Figure 1-1). Basis ist der offensichtliche Zusammenhang zwischen Intention und Handlung. Der Theorie nach wirken sich Einstellungen und Normen jedoch nicht direkt auf das Verhalten, sondern auf die vorgelagerte Intention aus.

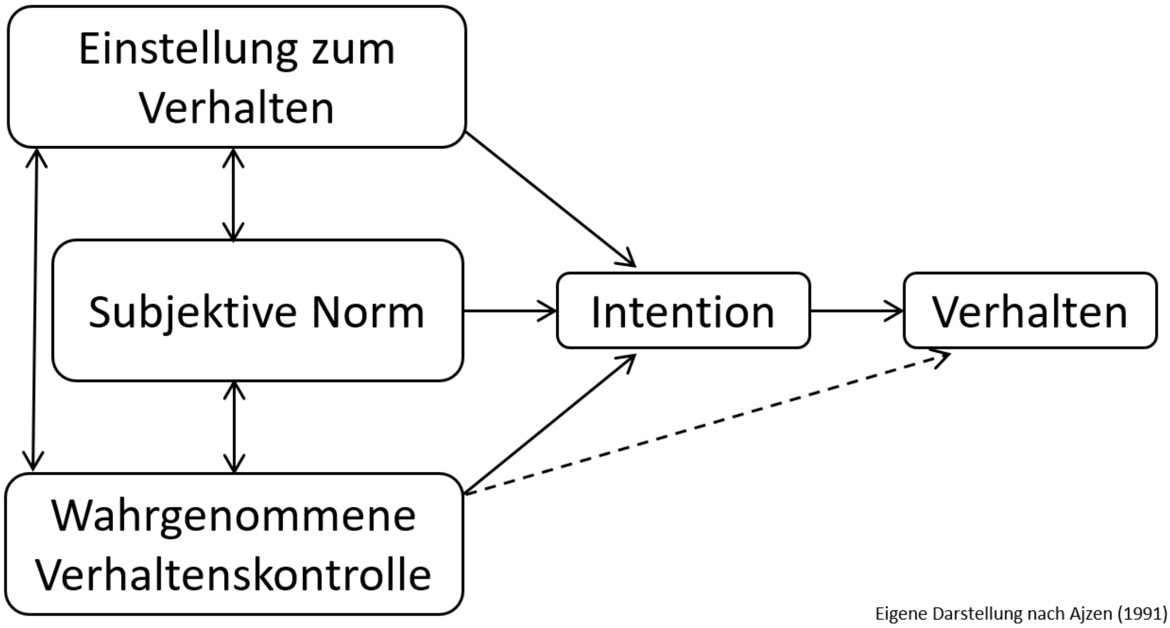

Figure 1-1. Theorie des geplanten Verhaltens

Die Intention wird demnach durch Einstellungen, subjektive Normen und wahrgenommene Verhaltenskontrolle gebildet. Diese wahrgenommene Verhaltenskontrolle stellt die entscheidende Weiterentwicklung gegenüber der vorausgegangenen Theorie der überlegten Handlung dar (Ajzen, 2020). Für die vorliegende Arbeit ist insbesondere diese wahrgenommene Verhaltenskontrolle von Bedeutung. Die Theorie des geplanten Verhaltens enthält in einer weiteren vorgelagerten Ebene auch eine Erklärung, wie Einstellungen, Normen und wahrgenommene Verhaltenskontrolle entstehen (Bamberg & Schmidt, 1999). Für die wahrgenommene Verhaltenskontrolle sind dies „Überzeugungen über verhaltensbezogene Ressourcen bzw. Barrieren" und „Verhaltenserleichterung durch diese Kontrollfaktoren", also die subjektive Einschätzung über interne und externe Ressourcen (Bamberg & Schmidt, 1999).

Entsprechend der behandelten Thematik sind hier die Bikeability der urbanen Umgebung (Kapitel 3) sowie entsprechende detaillierte Routeneigenschaften (Kapitel 4 und 5) zu verorten – bzw. deren subjektive Wahrnehmung. Frühere Forschung hat gezeigt, dass die Theorie des geplanten Verhaltens auch als Framework für Entscheidungsexperimente, wie in Kapitel 4 eingesetzt, dienen kann (Fujii & Gärling, 2003). Die Methode basiert auf der subjektiven Einschätzung und Bewertung von Alternativen. Zu beachten bleibt, dass die wahrgenommene Verhaltenskontrolle als einziger Einflussfaktor nicht nur auf die Intention, sondern auch direkt auf das Verhalten wirkt (Figure 1-1). Dennoch werden Eigenschaften der Infrastruktur einerseits immer subjektiv wahrgenommen; andererseits können entsprechende Unterschiede bzw. Interventionen im Bereich der externen Ressourcen die Einstellungen und Normen wiederum nur mittelbar und in geringem Ausmaß beeinflussen. Auch können verhaltensleitende indirekte Einflussfaktoren hier nicht beobachtet werden. Diese Einschränkungen erklären zum einen die maximal ermittelten statistischen Zusammenhänge mittlerer Stärke zwischen Pull-Maßnahmen und Verhaltensänderungen und zum anderen die Erkenntnis, dass nur ein begrenzter Teil der Bevölkerung überhaupt empfänglich für eine entsprechende Policy der Radverkehrsförderung ist (Cabral & Kim, 2020; Dill & McNeil, 2013).

Die Theorie des geplanten Verhaltens wird bereits seit Jahrzehnten erfolgreich in zahlreichen Kontexten angewandt (Bamberg, 1996; George, 2004; Godin & Kok, 1996; Yadav & Pathak, 2017; Yuriev, Dahmen, Paillé, Boiral, & Guillaumie, 2020). Das beschriebene Basisverständnis der Theorie des geplanten Verhaltens wird an verschiedenen Stellen der Arbeit um die entsprechenden theoretischen Konzepte, die den einzelnen angewandten Methoden zugrunde liegen, erweitert bzw. ersetzt. Dies wird im Einzelnen bei den jeweiligen Modulen angeführt.

1.3.3 Raumstrukturelle Analysen

Prinzipiell können räumlich verortete Geodaten zur Beschreibung der räumlichen Struktur mit empirischen Mobilitätsdaten aus verschiedenen Quellen wie beispielsweise städtischen Befragungen zusammengebracht und Zusammenhänge analysiert werden. Diese Analyse von Interaktionen zwischen Raumstruktur und Mobilitätsverhalten ist ein etabliertes Forschungsfeld (Aston, Currie, Delbosc, Kamruzzaman, & Teller, 2020; Cervero & Kockelman, 1997; Kagermeier, 1997; Meurs & Haaijer, 2001). Je nach Operationalisierung der Raumstrukturdefinition und Auswahl der abhängigen Variablen kommen Studien zu einer Vielzahl von Ergebnissen. Der Einfluss räumlicher Merkmale auf das Mobilitätsverhalten variiert dabei zwischen nicht vorhanden und sehr stark (R. Ewing & Cervero, 2010). Die Infrastruktur ist im Rahmen der *sechs D* (Density, Diversity, Design, Destination Accessibility, Distance to Transit, Demand Management) als Teil der Raumstruktur zu verstehen (R. Ewing & Cervero, 2010). Insgesamt scheinen raumstrukturelle Merkmale in dem Zusammenhang in Teilen eine notwendige, jedoch keine hinreichende Bedingung zu bilden (Scheiner, 2002). So ist beispielsweise eine Anbindung von Zielgelegenheiten an öffentliche Verkehrsmittel notwendig, um diese nutzen zu können, führt aber nicht zwangsläufig zu deren Nutzung.

Klassische Ansätze zur Analyse raumstruktureller Einflüsse auf das Mobilitätsverhalten aus dem US-amerikanischen Raum zielen in erster Linie auf die bessere Erklärung des motorisierten Individualverkehrs ab. In zahlreichen Studien gibt die Operationalisierung verschiedener Merkmale im Grunde die Unterscheidung zwischen dichter, urbaner und nutzungsgemischter Innenstadt gegenüber monofunktionalen suburbanen Bereichen wieder (R. Ewing & Cervero, 2010). In diesem Kontext spielt das Fahrrad als Verkehrsmittel oft keine Rolle. Buehler (2011) unternimmt einen frühen Vergleich zwischen Deutschland und den USA, um Unterschiede in der Verkehrsmittelnutzung auf der Basis von sowohl soziodemografischen als auch strukturellen Faktoren zu erklären (Buehler, 2011). Dabei wird zwar das Fahrrad als Verkehrsmittel explizit berücksichtigt, jedoch noch nicht die für das Radfahren relevanten infrastrukturellen Einflussfaktoren.

Weitere Ansätze bringen stadtweite Modal-Split-Angaben mit einfachen Daten zur Radinfrastruktur zusammen (Buehler & Pucher, 2011; Dill & Carr, 2003; Nelson & Allen, 1997). Dabei werden stark aggregierte Angaben zur Radinfrastruktur wie die Länge von Radwegen je Quadratkilometer oder je Einwohner verwendet. Trotz dieser stark vereinfachten Betrachtung weisen entsprechende Studien einen positiven Zusammenhang zwischen Radverkehrsinfrastruktur und Fahrradnutzung aus (ebd.). Dies ist insofern beachtlich, als Studien zeigen, dass nur ein begrenzter Teil der Bevölkerung – die *Interessierten, aber Besorgten* bzw. die *vorsichtige Mehrheit* – überhaupt sensibel für irgendeine Art der Policy im Radverkehr sind (Cabral & Kim, 2020; Dill & McNeil, 2013). Die positiven Effekte der Radinfrastruktur auf den Radverkehr wurden auch in mehreren Überblicksstudien belegt (Buehler & Dill, 2016; Yang, Wu, Zhou, Gou, & Lu, 2019).

Dennoch können diese Ansätze vor dem Hintergrund vielfältiger Einflussfaktoren kein integriertes Gesamtbild einer radfahrtauglichen Umgebung berücksichtigen. Jüngere Ansätze adressieren diese Herausforderung und entwickeln umfassendere Bikeability Indices bzw. Scores (Winters, Brauer, Setton, & Teschke, 2013; Winters, Teschke, Brauer, & Fuller, 2016). Diese bilden eine umfassendere Betrachtung. Einerseits erfolgt dabei jedoch die Auswahl der betrachteten Parameter entweder durch normative Setzungen der jeweiligen AutorInnen (Winters, et al., 2016) oder basierend auf einer singulären Voruntersuchung mit Probandinnen und Probanden (Winters, et al., 2013). Andererseits werden explizit Lücken benannt: So werden trotz zahlreicher integrierter Einflussfaktoren beispielsweise die fehlende Berücksichtigung weiterer Infrastrukturelemente wie Fahrradläden, Werkstätten oder Luftstationen (Handy, van Wee, & Kroesen, 2014) oder ein fehlendes Gesamtwirkgefüge der Einflussfaktoren (Buehler, Götschi, & Winters, 2016) kritisiert. Darüber hinaus schränkt die in den Ansätzen genutzte Datenquelle die Übertragbarkeit ein. Die Nutzung von städtischen Daten, proprietären Daten oder auf nationalen Erfassungen basierenden Daten begrenzt die Übertragbarkeit sowie Adaptierbarkeit und großräumige Vergleiche massiv. Entsprechend wird bereits von den AutorInnen angeregt, zukünftige Arbeiten unter Nutzung offener Geodaten durchzuführen (Winters, et al., 2016).

Vor dem Hintergrund dieser Forschungslücke haben sich zeitgleich mit der hier beschriebenen Forschung weitere AutorInnen des Themas angenommen und umfassendere Vorschläge zur Messung der Bikeability gemacht (Arellana, Saltarín, Larrañaga, González, & Henao, 2020; P. Gu, Han, Cao, Chen, & Jiang, 2018; Porter et al., 2020; Resch, Puetz, Bluemke, Kyriakou, & Miksch, 2020). Diese stellen eine wertvolle Weiterentwicklung dar und bieten oft umfassende Operationalisierungen der Bikeability (Arellana, et al., 2020; Nello-Deakin & Harms, 2019; Porter, et al., 2020). Jedoch basiert die Gewichtung der Einflussgrößen nach wie vor auf normativer Setzung (Winters, et al., 2016), einer singulären Vorstudie mit Probandinnen und Probanden (Arellana, et al., 2020) oder Modellierungsergebnissen selbst (Porter, et al., 2020). Nur in wenigen Studien zur Bikeability werden offene Daten verwendet (P. Gu, et al., 2018). Parallel werden noch immer Tools entwickelt bzw. weiterentwickelt, die die Realität zwar sehr detailliert wiedergeben können, aber auf der extrem zeit- und kostenintensiven individuellen Erfassung von Merkmalen im Feld (Cain et al., 2018; Kalvelage et al., 2017) bzw. auf nicht-automatisierter Bildinterpretation (Gullón et al., 2015) basieren.

Inhaltlich scheinen insbesondere das vermehrte Vorhandensein von Radinfrastrukturen (Bopp, Gayah, & Campbell, 2015; Buehler & Pucher, 2011; Dill & Carr, 2003; K. J. Krizek & Johnson, 2006; Pucher & Dijkstra, 2000) und eine höhere Kreuzungsdichte (Badland, Schofield, & Garrett, 2008; Cervero, Sarmiento, Jacoby, Gomez, & Neiman, 2009; Fan, Wen, & Kowaleski-Jones, 2014; Nielsen, Olafsson, Carstensen, & Skov-Petersen, 2013; Schoner & Levinson, 2014; Winters, Brauer, Setton, & Teschke, 2010) mit höherer Radnutzung in Verbindung zu stehen.

Insgesamt lässt sich feststellen, dass sich die Forschung zur Erfassung von für das Radfahren relevanten Faktoren in den letzten Jahren stark weiterentwickelt hat. Dennoch besteht angesichts der benannten Forschungslücken immer noch Bedarf an der Entwicklung einer konsensualen Definition von Bikeability (Buehler, et al., 2016; Kellstedt, et al., 2020), einer umfassenden Berücksichtigung der relevanten Faktoren (Handy, et al., 2014) und der Nutzung offener und ubiquitär verfügbarer Daten (Winters, et al., 2016).

1.3.4 Stated-Preference-Analysen

Methodisch gänzlich anders setzen sogenannte Stated-Preference- bzw. Stated-Choice-Studien an. In diesen geben Probandinnen und Probanden ihre Präferenzen direkt an (Kroes & Sheldon, 1988). Stated-Preference-Ansätze werden in der Verkehrsforschung seit Jahrzehnten eingesetzt (Ben-Akiva & Bierlaire, 1999; Hensher, 1994). Auch mit der Analyse von Routenwahlverhalten im Radverkehr befassen sich bereits diverse Studien (Aldred, Elliott, Woodcock, & Goodman, 2016). Im engeren Sinne werden dabei meist sogenannte diskrete Entscheidungsexperimente durchgeführt. Grundlage sind Konzepte zur Modellierung diskreter Entscheidungen auf Basis der Konzepte der Nutzenmaximierung und der Random Utility Theory (de Dios Ortuzar & Willumsen, 2011; McFadden, 1973; McFadden & Train, 2000). Demnach wählen Individuen aus einem Set an diskreten Alternativen diejenige mit dem für Sie höchsten Nutzen aus. In Entscheidungsexperimenten wählen Probandinnen und Probanden aus Alternativen von virtuellen Produkten. In der Forschung treffen die Befragten in der Regel Entscheidungen in mehreren aufeinander folgenden Entscheidungssituationen. Dabei werden die Alternativen bzw. die darin enthaltenen Merkmalsausprägungen variiert. Ein typisches Entscheidungsexperiment besteht beispielsweise aus acht Entscheidungssituationen mit je drei Alternativen, die sich in sechs Merkmalen mit jeweils bis zu vier Ausprägungen unterscheiden.

In der folgenden Modellierung werden diese Produkte in einzelne Eigenschaften mit verschiedenen Ausprägungen (Parameter) zerlegt. Mit Methoden der diskreten Entscheidungsmodellierung können dann Nutzenfunktionen mit Nutzwerten für diese Parameter geschätzt werden (Domencich & McFadden, 1975; McFadden & Train, 2000). Dabei wird aus der Gesamtheit der (je Individuum) erhaltenen Antworten unter Berücksichtigung aller gewählten und nicht gewählten Ausprägungen ermittelt, welchen Wert die jeweilige Ausprägung der Merkmale für die Befragten hat. Dabei können Interaktionen mit individuellen Merkmalen der Personen abgebildet werden. Vor dem Hintergrund breiterer Fahrradnutzung in der Bevölkerung, sich ausdifferenzierender Fahrzeugtypen am Fahrradmarkt und insbesondere eines Bedeutungsgewinns von Lastenrädern und Pedelecs (Eisenberger, 2020) werden die individuellen Differenzierungsmöglichkeiten jedoch noch nicht ausreichend genutzt. Auch großräumige Vergleiche in unterschiedlichem Kontext könnten mögliche weitere Zusammenhänge zwischen Radfahren, Routenwahl und strukturellen Einflussfaktoren aufzeigen.

Aufgrund der virtuellen Zusammenstellung der hypothetischen Alternativen bietet die Methode vielfältige Möglichkeiten bezogen auf Probandinnen und Probanden sowie untersuchte Merkmale. So können sowohl Personen, die nicht Rad fahren, als auch (bislang) nicht existierende Routeneigenschaften einbezogen werden. In den letzten Jahren hat es einige solcher Studien gegeben. Für Forschungsteilnehmende ist insbesondere die Art der Präsentation der Alternativen von Bedeutung. Einige Studien gehen dabei gänzlich ohne Visualisierung vor (Abraham, McMillan, Brownlee, & Hunt, 2002; Hunt & Abraham, 2007; Stinson & Bhat, 2003), was die Teilnahme insbesondere bei komplexen Experimenten erschwert. Demgegenüber werden die Routenalternativen teilweise über Originalfotos (Tilahun, Levinson, & Krizek, 2007), manipulierte Fotos (Clark, Mokhtarian, Circella, & Watkins, 2019; Mertens et al., 2016) oder abstrakte Visualisierungen (Vedel, Jacobsen, & Skov-Petersen, 2017) grafisch dargestellt.

Inhaltlich ergeben Stated-Preference-Ansätze meist eine deutliche Präferenz für getrennte Radinfrastruktur (Hunt & Abraham, 2007; Vedel, et al., 2017). Weniger häufig schneiden ruhige Nebenstraßen besser ab als Infrastrukturen an Hauptverkehrsstraßen (Sener, Eluru, & Bhat, 2009; Stinson & Bhat, 2003). Deutlich wird zudem, dass das Vorhandensein einer getrennten Infrastruktur wichtiger ist als sonstige Eigenschaften der Straße wie zulässige Höchstgeschwindigkeit, Verkehrsdichte oder Oberflächenbeschaffenheit (Mertens, et al., 2016; Stinson & Bhat, 2003; Winters & Teschke, 2010). Welche jeweilige Ausführung bevorzugt wird, unterscheidet sich je nach Studie und Operationalisierung (K. J. Krizek, 2007; Poorfakhraei & Rowangould, 2015; Tilahun, et al., 2007).

Wie beschrieben bietet die Methode Anknüpfungspunkte und ungenutzte Potenziale für großräumige Analysen unter Beachtung des jeweiligen Kontextes. Auch hinsichtlich der Analyse innovativer Infrastrukturmerkmale, die in der Mehrheit der Bevölkerung noch unbekannt sind, bestehen Forschungslücken.

1.3.5 Revealed-Preference-Analysen

Die Revealed-Preference-Theorie als eine der bedeutendsten ökonomischen Theorien geht davon aus, dass sich Präferenzen von Individuen durch die direkte Beobachtung ihres Verhaltens offenbaren (Samuelson, 1948). Entsprechende Studien stellen einen relevanten Forschungszweig dar (Varian, 2012; Vermeulen, 2012). Im Fall der Analyse von Routenwahlverhalten im Radverkehr werden dabei von Radfahrenden zurückgelegte Strecken analysiert. Für die Erfassung der Routen stehen verschiedene Methoden zur Verfügung (Pritchard, 2018). Im klassischen Ansatz wurden Routen der Probandinnen und Probanden ex post papierbasiert berichtet (Aultmann-Hall, 1996; Fitch & Handy, 2020; Howard & Burns, 2001; Kang & Fricker, 2013). Eine erste Weiterentwicklung stellt das webbasierte Berichten zurückgelegter Wege dar (Snizek, Sick Nielsen, & Skov-Petersen, 2013). Im Zuge der Verbreitung von mobilen Endgeräten und GPS-basierten Services werden in den letzten Jahren hauptsächlich effizientere Methoden der GPS-basierten Erfassung von Routen angewandt. Nach dem Einsatz von zu diesem Zweck verteilten GPS-Loggern (Dozza, Piccinini, & Werneke, 2016; Ghanayim & Bekhor, 2018; Prato, Halldórsdóttir, & Nielsen, 2018) kommen inzwischen im Wesentlichen Smartphone- Anwendungen zum Einsatz (Chen, Shen, & Childress, 2016; Heesch & Langdon, 2016; Skov-Petersen, Barkow, Lundhede, & Jacobsen, 2018; M. Zimmermann, Mai, & Frejinger, 2017). Häufig genutzt werden dabei Daten aus Anwendungen, die einen spezifischen Anwendungsfall (wie zum Beispiel Rennradtouren) adressieren (K. Lee & Sener, 2020; Still, 2020). Diese Apps richten sich speziell an sportlich orientierte Anwenderinnen und Anwender und zeigen gegenüber dem Alltagsverkehr massive Verzerrungen (Still, 2020). Mit dem starken Bedeutungsgewinn von Fahrradverleihsystemen ergab sich eine weitere wichtige Datenquelle. Hier konnten in junger Vergangenheit große Mengen an Nutzungsdaten aufgezeichnet werden (Eren & Uz, 2020). Diese stellen mittlerweile eine weitere wichtige Datenquelle dar (W. Li, Wang, Zhang, Jia, & Tian, 2020; Scott, Lu, & Brown, 2021). Aufgrund einer spezifischen Gruppe der Nutzenden sowie Nutzungsmuster (Ricci, 2015) sind auch hier Verzerrungen zu erwarten.

Einen qualitativen Sonderfall stellen sogenannte Bike-along-Interviews dar, bei denen Probandinnen und Probanden virtuell oder physisch beim Radfahren begleitet werden (Van

Cauwenberg et al., 2018). Diese Ansätze können mit dem Erfassen von Emotionen kombiniert werden und ermöglichen qualitative Analysen (Pánek & Benediktsson, 2017).

In der auf die Datengenerierung folgenden Analyse werden die gewählten Routen mit Alternativrouten verglichen und daraus Schlüsse gezogen (Prato, et al., 2018; Pritchard, 2018). Dieses Generieren von passenden Alternativen durch die Forschenden ist im Revealed-Preference-Ansatz von entscheidender Bedeutung, da die Ergebnisse maßgeblich auf den zur Verfügung stehenden und nicht gewählten Alternativen beruhen. Entsprechend können im Untersuchungsgebiet nicht vorkommende Eigenschaften nicht bewertet werden. Darüber hinaus können generierte Routen den Probandinnen und Probanden unbekannt sein oder aus anderen Gründen nicht in Frage kommen. Allerdings kommen einzelne neue Ansätze ohne das formale Generieren von Alternativrouten aus (M. Zimmermann, et al., 2017).

Inhaltlich zeigt sich, dass Radfahrende die Nähe zum motorisierten Individualverkehr meiden. Im Detail kommen die Studien zu unterschiedlichen Ergebnissen, welche Routeneigenschaften dafür bevorzugt gewählt werden. So wird einerseits eine Präferenz für ruhige Nebenstraßen ermittelt (Broach, Dill, & Gliebe, 2012; Stinson & Bhat, 2003; Winters, Teschke, Grant, Setton, & Brauer, 2010), während andere Studien separate Radinfrastruktur als erste Wahl sehen (Caulfield, Brick, & McCarthy, 2012; Winters & Teschke, 2010).

Die aufwendige Art der Datengenerierung einer Vielzahl der Studien dieses Ansatzes ermöglicht oftmals nur geringe Fallzahlen. Demgegenüber lässt die Nutzung von Daten aus speziellen Anwendungsfällen auf Verzerrungen durch eine sehr spezifische Nutzungsgruppe wie Sportlerinnen und Sportler oder Nutzende von Fahrradverleihsystemen schließen. Demgegenüber bietet die Nutzung von Daten aus Anwendungen für den Alltagsverkehr mit breiter Nutzung noch Potenziale.

1.3.6 Zusammenfassung und Fazit

Insgesamt ergibt sich inhaltlich aus der Zusammenschau der verschiedenen methodischen Ansätze der Forschungslandschaft ein konsistentes Gesamtbild. Inhaltlich stellen sich die Kernergebnisse in der Mehrzahl übereinstimmend dar. Dabei zeigt sich – wenig überraschend – ein deutliches Bild, wonach Radfahrende separierte Infrastruktur sowie ruhige Nebenstraßen bevorzugen. Dabei wird im Kleinraum versucht, den beschriebenen negativen Auswirkungen des motorisierten Verkehrs auszuweichen. Dennoch zeigen sich je nach eingesetztem Forschungswerkzeug inhaltlich unterschiedliche Tendenzen.

So wird beispielsweise in Stated-Preference-Ansätzen tendenziell eine Präferenz für separierte Infrastrukturen ermittelt (Hunt & Abraham, 2007; Vedel, et al., 2017). Bei Revealed-Preference-Ansätzen ist diese weniger deutlich – auch ruhige Nebenstraßen werden als erste Wahl gesehen (Broach, et al., 2012; Stinson & Bhat, 2003; Winters, Teschke, et al., 2010). Diese tendenzielle Diskrepanz wurde bereits in früherer Forschung aufgezeigt (Buehler & Dill, 2016). Diese Inkonsistenz zeigt den Bedarf an weiterer Forschung, um ein vollständiges Gesamtbild zu erhalten. Dabei bieten etablierte Ansätze noch ungenutzte Potenziale. So böten großräumig eingesetzte Entscheidungsexperimente in der Routenwahl unter Einsatz eines einheitlichen Designs die Möglichkeit, regionale oder strukturelle Unterschiede aufzudecken. Des Weiteren kann die Integration weiterer soziodemografischer Interaktionen einen wichtigen Mehrwert bezüglich zukünftiger Infrastrukturansprüche bieten. Zudem scheint im breiter verstandenen Revealed-Preference-Ansatz die Nutzung weiterer Datenquellen mit Fokus auf den Alltagsradverkehr vielversprechend.

Darüber hinaus zeigt der Stand der Forschung zu raumstrukturellen Analysen und Radverkehr auf einer vorgelagerten Ebene Lücken und Forschungsbedarf, der in früheren Studien explizit benannt wird. Dabei geht es in erster Linie um eine umfassende (Handy, et al., 2014) und konsensuale (Buehler, et al., 2016; Kellstedt, et al., 2020) Definition einer radfahrtauglichen urbanen Umgebung. Darüber hinaus würde die Nutzung offener Daten (Winters, et al., 2016) weitreichende neue Möglichkeiten der Übertragung und des Vergleichs von Forschungsergebnissen sowie großräumige automatisierte Analysen ermöglichen.

Insgesamt stellt sich die Analyse von Zusammenhängen zwischen Infrastruktur und Fahrradnutzung als relevantes und vielversprechendes Forschungsfeld dar. Trotz vielfältiger vorheriger Studien in diesem Feld bestehen noch Diskrepanzen und Forschungslücken. Etablierte und neue Ansätze bieten Anknüpfungspunkte auf mehreren Betrachtungsebenen: von der Herleitung und Operationalisierung von Bikeability auf der vorgelagerten Abstraktionsebene über Zusammenhänge mit der Verkehrsmittelwahl bis hin zur kleinräumigen Betrachtungsebene der Routenwahl. Stärker als bei jedem anderen Verkehrsmittel sind die Zusammenhänge vielfältig. Nutzende und Nutzungsmuster sind mit unterschiedlichen physischen Voraussetzungen, unterschiedlichen Fahrzeugtypen und individuellen Präferenzen äußerst heterogen. Dazu bietet eine Vielzahl unterschiedlicher Infrastrukturen verschiedene Rahmenbedingungen. Somit ergibt sich eine Vielzahl an möglichen Zusammenhängen und Forschungsansätzen.

1.4 Ziel der Arbeit und Fragestellung

Das Ziel der Arbeit zur Analyse von Zusammenhängen zwischen Infrastruktur und Radverkehr ergibt sich aus dem beschriebenen Forschungsstand und den abgeleiteten Forschungslücken und gliedert sich im Wesentlichen in zwei Hauptkomplexe und entsprechende zwei miteinander verbundene Fragestellungen:

Zunächst ist ein Ansatz zum Messen der Bikeability einer urbanen Umgebung zu entwickeln, dessen Operationalisierung drei Bedingungen erfüllt, die sich aus den Forschungslücken ergeben: Die Methode soll ein auf einem Konsens basierendes Verständnis der Einflussgrößen zugrunde legen (1), die relevanten infrastrukturellen Parameter berücksichtigen (2) und so umgesetzt werden, dass sie ubiquitär anwendbar ist (3). Beispielhaft ist der Nutzen der Methode zu untersuchen, indem der Einfluss dieser Bikeability auf das

Mobilitätsverhalten bzw. die Wahl des Fahrrades als Verkehrsmittel untersucht wird. Aus diesem Zielkomplex wird die folgende Fragestellung formuliert:

1. Wie lässt sich die Bikeability urbaner Infrastruktur unter Anwendung einer konsensualen Berücksichtigung der relevanten Einflussgrößen übertragbar operationalisieren und wie hängt diese mit der lokalen Fahrradnutzung zusammen?

Im zweiten Komplex ist zu klären, wie Infrastrukturpräferenzen von Radfahrenden charakterisiert sind. Hier zielt die Arbeit zum einen darauf ab, bisher ungenutzte Datenquellen aus der Fahrradnavigation zu erschließen, um durch einen weiteren Blickwinkel das in Teilen heterogene Bild zu vervollständigen. Zum anderen sollen Potenziale der etablierten Methode des Entscheidungsexperimentes ausgeschöpft und mögliche Unterschiede zwischen Personen- und Nutzungseigenschaften sowie räumlichen Kontexten ermittelt werden. Die entsprechende Fragestellung lautet:

2. Wie stellen sich Präferenzen hinsichtlich Routeneigenschaften im Radverkehr dar und welche Erkenntnisse liefern hierfür methodisch unterschiedliche Forschungsansätze?

2 Forschungsdesign und Methoden

Im Folgenden werden der methodische Ansatz und das Gesamtkonzept der Arbeit beschrieben. Das hier eingesetzte methodische Konzept zeichnet sich durch eine Kombination von verschiedenen Methoden für einzelne Module in einem breiten Methodenmix aus. Das Forschungsdesign ist grafisch in Figure 2-1 dargestellt.

Inhaltlich gliedert sich die Arbeit in drei Teile. Auf die unter den entsprechenden Kapiteln dieser Arbeit integrierten Veröffentlichungen ist in Figure 2-1 verwiesen. Dabei finden die Untersuchungen auf unterschiedlichen Betrachtungsebenen statt, die im Verlauf der Arbeit von gröber zu detaillierter verfeinert werden. Zunächst wird auf einer globalen, allgemeingültigen Abstraktionsebene ein generelles Verständnis von Bikeability entwickelt (2.1). Darauf aufbauend wird auf der Ebene der individuellen Verkehrsmittelwahl der Einfluss der vorab ermittelten Bikeability auf die Wahl des Fahrrades als Verkehrsmittel untersucht (2.2). Schließlich wird auf die noch feinere Ebene der Routenwahl für mit dem Fahrrad zurückgelegte Wege gewechselt (2.3). Hierbei werden die zuvor hinsichtlich ihrer Bedeutung für die Moduswahl des Fahrrades evaluierten Parameter auf der Ebene der Individuen weiter differenziert. Dabei werden zwei parallele Ansätze verfolgt, um sich der individuellen Routenwahl von Radfahrenden anzunähern: Einerseits wird ein diskretes Entscheidungsexperiment entwickelt und in der detaillierten, personenfeinen Analyse differenzierte Schlüsse gezogen (2.3.1). Andererseits wird mit der Analyse von Daten aus der Fahrradnavigation eine neue Datenquelle erschlossen, um das Gesamtbild methodisch umfassend zu vervollständigen (2.3.2). Dies dient auch dazu, vor dem Hintergrund beschriebener inhaltlicher Abweichungen früherer Forschung die Ergebnisse unterschiedlicher Methoden abzugleichen.

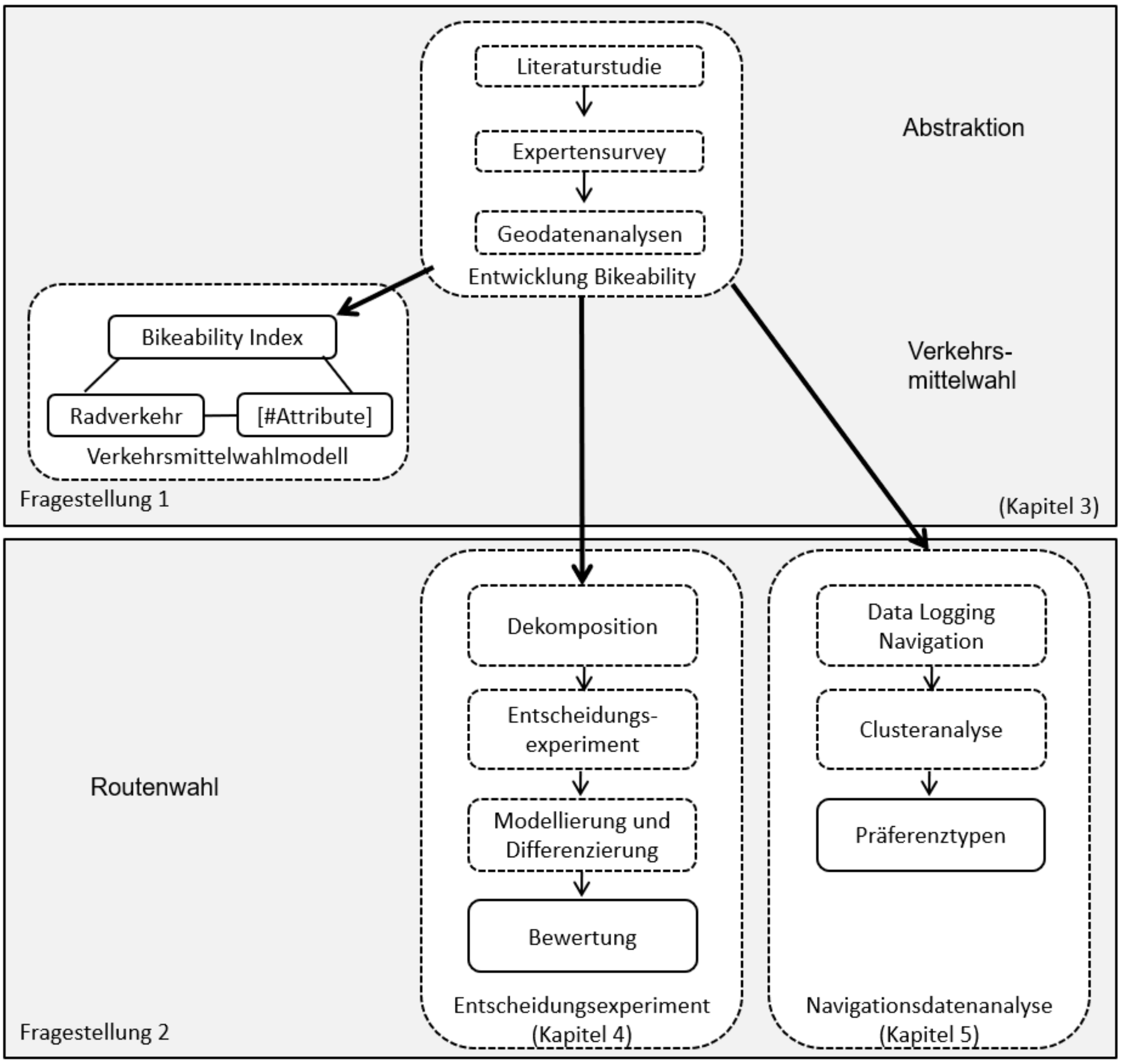

Figure 2-1. Forschungsdesign

Kapitel 3: More Than Bike Lanes – A Multifactorial Index of Urban Bikeability (S. 43)

Kapitel 4: Evaluating Cyclists' Route Preferences with Respect to Infrastructure (S. 76)

Kapitel 5: Assessing cyclists' routing preferences by analyzing extensive user setting data from a bike-routing engine (S. 110)

Im Folgenden werden die methodischen Ansätze der auf die jeweilige Teilfragestellung bezogenen drei Pakete im Einzelnen kurz skizziert. Im Detail sind die Methoden im jeweiligen Kapitel im Hauptteil beschrieben.

Vereinendes, jedoch nicht alleiniges Untersuchungsgebiet der Arbeiten ist Berlin. Berlin zeigt mit 18 Prozent an allen zurückgelegten Wegen einen deutlichen Anteil Radverkehr (Hubrich, Ließke, Wittwer, Wittig, & Gerike, 2019), eine langdauernde und intensive Nutzung der Fahrradnavigation (Rezic, 1999) sowie eine heterogene polyzentrische Stadtstruktur (Kulke & Suwala, 2015), die massive Unterschiede in der Infrastruktur bedingt. Damit sind Bedingungen für die Anwendung der einzelnen Bestandteile des methodischen Konzeptes gegeben.

2.1 Entwicklung des Bikeability Index

Wie in 1.3 beschrieben, weisen die bisherigen Ansätze im Wesentlichen drei Unzulänglichkeiten auf: eine fehlende konsensuale Definition der Bikeability, Lücken in der umfassenden Berücksichtigung der relevanten Einflussgrößen sowie Schwächen in der Übertragbarkeit.

Um diesen Mängeln begegnen zu können, wird eine Methodenkombination angewandt. Zunächst wird eine umfassende Literaturstudie durchgeführt, um relevante infrastrukturelle Einflussfaktoren auf die Radnutzung zu identifizieren. Diese werden im Anschuss geclustert und in einen Expertenprozess gegeben. Die Gruppe der 141 Expertinnen und Experten setzt sich zusammen aus internationalen Wissenschaftlerinnen und Wissenschaftlern, die zuvor thematisch relevant publiziert hatten, Mitgliedern des Forschungskreises des Nationalen Radverkehrsplans des Bundesverkehrsministeriums sowie weiteren anerkannten Expertinnen und Experten. Diese wurden per E-Mail kontaktiert und gebeten, mittels einer interaktiven Website die Bedeutung des jeweiligen Parameters zu bewerten. So können die Einflussgrößen in einen gewichteten Gesamtzusammenhang gebracht und ein konsensuales Verständnis von Bikeability unter Einbezug von Expertinnen und Experten entwickelt werden.

Im Anschluss daran werden für jeden Parameter raumbezogene Indizes berechnet. Dabei ist die Wahl der Datengrundlage von entscheidender Bedeutung, um eine überörtliche Anwendbarkeit und damit Übertragbarkeit und Vergleichbarkeit sicherzustellen. Hierbei stellt die offene Geodatenbank der OpenStreetMap eine ideale Datenquelle dar (Bertolotto, McArdle, & Schoen-Phelan, 2020). Dabei werden durch freiwillig Mitwirkende

Geodaten nach global gültigen Regeln erfasst und in einer frei zugänglichen Datenbank abgelegt. Mit enormen Zuwachsraten in den vergangenen Jahren (OpenStreetMap-contributers, 2020) ist eine umfassende weltweite Geodatenbank entstanden. Insbesondere in urbanen Gebieten weisen die Daten eine beeindruckende Detailtiefe und Aktualität auf. Dabei wurde auch für den expliziten Anwendungsfall der Radinfrastruktur die Genauigkeit und Aktualität der Daten belegt (Ferster, Fischer, Manaugh, Nelson, & Winters, 2020). Alle Informationen liegen als räumlich verortete Punkte und Linien mit Eigenschaften vor. Obwohl die Daten durch die Mitwirkenden nach einheitlichen Regeln abgelegt werden, bedingt es die Natur der Crowd-Sourcing-Daten, dass verschiedene parallele Varianten der Datenspeicherung existieren und die gelebte Praxis teilweise von den gültigen Regeln abweicht.

Unter Nutzung dieser Datenbasis werden für alle vorab definierten Parameter raumbezogene Indizes berechnet. Für jeden Parameter wird hierfür ein eigenständiges Vorgehen entwickelt. Dabei muss zum einen für eine valide Berechnung ein unterschiedliches Vorgehen der Mitwirkenden in der Erfassung der Daten berücksichtigt werden. Zum anderen sind verschiedene Geodatenanalysen zu implementieren, da die Topologie in den Daten nur implizit enthalten ist. Beispielsweise befindet sich im gesamten Raum eine enorme Vielzahl von Knoten, an denen sich Kanten schneiden. Um hieraus die tatsächliche Dichte von Straßenkreuzungen zu berechnen, ist eine sinnvolle Auswahl der Kanteneigenschaften zu treffen und ein geeignetes räumliches Clusterverfahren (Ester, Kriegel, Sander, & Xu, 1996) einzusetzen. Bei den Radverkehrsanlagen entlang von Hauptverkehrsstraßen kommt eine große Vielfalt möglicher baulicher Varianten mit prinzipiell unterschiedlichen Verfahren, diese in den Daten abzulegen, zusammen. Dieser Problematik wird mit unterschiedlichen konzeptionellen Ansätzen begegnet.

Schließlich werden die Indizes auf eine räumliche Relationsgröße bezogen. Mittels der im Expertenprozess entwickelten Gewichtung werden die Einzelausprägungen anschließend zu einem Gesamtwert der Bikeability zusammengeführt. Aus Gründen der Übertragbarkeit und Operationalisierbarkeit ist dieser Index auf eine gewisse Detailtiefe begrenzt.

2.2 Zusammenhang Bikeability und Mobilitätsverhalten

Um den Einfluss der Bikeability auf das Verkehrsmittelwahlverhalten zu ermitteln, wird ein Verkehrsmittelwahlmodell geschätzt. Da die genutzte Datenbasis nur Start- und Endpunkte der Wege enthält, ist zunächst für die knapp 74.000 Wege ein Routing durchzuführen und die Bikeability entlang der Route zu berechnen (Ahrens, 2009). Dann wird ein multinomiales logistisches Regressionsmodell definiert, in dem die Entscheidung zwischen einzelnen Klassen (hier Verkehrsmitteln) geschätzt wird. Hierbei wird im Rahmen der Nutzenmaximierung davon ausgegangen, dass jedes Individuum die Alternative mit dem größten individuellen Nutzen wählt (de Dios Ortuzar & Willumsen, 2011; McFadden, 1973). Zusätzlich zu den offensichtlichen Einflussfaktoren wie Zeit und Kosten der alternativen Verkehrsmittel wird die Bikeability als weiteres Attribut berücksichtigt.

Im Detail sind die Methoden und die Ergebnisse der Entwicklung der Bikeability und der strukturellen Zusammenhänge in der unter Kapitel 3 integrierten Veröffentlichung *More Than Bike Lanes – A Multifactorial Index of Urban Bikeability* beschrieben.

2.3 Differenzierung Bikeability

Auf der Ebene der Personen können die Präferenzen deutlich differenzierter analysiert werden, als dies auf der vorgelagerten globalen Abstraktionsebene unter Nutzung von Geodaten möglich und sinnvoll ist. Aus unterschiedlichen Gründen kann der entwickelte Bikeability Index kein sehr detailliertes Abbild der Realität schaffen: So muss der Index einerseits allgemeingültig sein und nach Möglichkeit den Großteil der für das Radfahren relevanten Merkmale für die Allgemeinheit wiedergeben. Darüber hinaus kann bei zu hoher Detailtiefe in der Regel kein Konsens für die Operationalisierung hergestellt werden. Nicht zuletzt steht ein zu feingranulares Vorgehen dem übergeordneten Ziel der Übertragbarkeit entgegen. Aus diesen Gründen bietet es sich an, die auf Geodaten basierenden Arbeiten auf der Ebene der Individuen weiter zu differenzieren.

Wird somit das individuelle Routenwahlverhalten von Radfahrenden untersucht, können weitere personen- oder raumbezogene Differenzierungen vorgenommen werden, die weiter gehende Unterschiede offenbaren. Im Einzelnen sind beispielsweise verschiedene Arten der (zuvor einheitlich betrachteten) Radinfrastruktur abzuwägen. Auch der Begriff der ruhigen Nebenstraßen lässt einigen Spielraum zur Differenzierung zu.

Zur weiteren Differenzierung der Infrastrukturpräferenzen werden wiederum zwei parallele Ansätze verfolgt: Zum einen werden (potenziell) Radfahrende in einem Entscheidungsexperiment nach ihren Präferenzen befragt (2.3.1). Hierbei ermöglicht die Ausweitung des Untersuchungsgebietes auf Griechenland neben individuellen auch strukturelle Analysen. So können die zu analysierenden Interaktionen methodisch einheitlich in sehr unterschiedlichen Kontexten betrachtet und verglichen werden. Griechenland zeigt dabei bezogen auf die Rahmenbedingungen einen besonders großen Kontrast zu Deutschland auf. Gegenüber Deutschland gibt es kaum substanziellen Radverkehr und fast keine Radinfrastruktur.

Zum anderen wird eine bislang nicht genutzte Datenquelle erschlossen und die in einer Anwendung zu Fahrradnavigation getätigten Abfragen analysiert (2.3.2). Dabei ist es von entscheidender Bedeutung für die Gesamtkonzeption, diese beiden methodisch gegensätzlichen Ansätze nebeneinanderzustellen. In 2.3.1 wird beschrieben, wie eine dem Stand der Wissenschaft und Forschung entsprechende Befragungsmethode angewandt und ein Entscheidungsexperiment für die konkrete Fragestellung entwickelt wird.

Unabhängig von der Qualität der wissenschaftlichen Umsetzung hat jeder methodische Ansatz spezifische Stärken und Schwächen (Boyle, 2003; Sanko, 2001). So hat beispielsweise jede Befragungssituation Einschränkungen hinsichtlich der hypothetischen Befragungssituation (Louvière & Timmermans, 1990), des Einflusses des Beobachters (McCarney et al., 2007) und des (vermeintlich) sozial erwünschten Verhaltens (Furnham, 1986). Darüber hinaus sind in der Regel Grenzen hinsichtlich Befragungszeitraum und der Anzahl von Probandinnen und Probanden gesetzt. Somit scheint es für ein schlüssiges

Gesamtbild sinnvoll, die Arbeiten zur Analyse des Routenwahlverhaltens durch den Einsatz methodisch unterschiedlicher Ansätze abzusichern.

Wie in 1.3 beschrieben, stellt neben den hier genutzten Ansätzen der Geodatenanalyse und der Stated-Preference-Befragung der Ansatz des offenbarten Verhaltens eine etablierte Forschungsrichtung dar. Auch bei diesem Revealed-Preference-Ansatz zur Analyse des beobachteten Verhaltens gibt es spezifische Schwächen. So besteht neben Einschränkungen in der maximal möglichen Fallzahl Ungewissheit über die jeweils zur Verfügung stehenden Alternativen. Diese werden durch die Forschenden normativ festgelegt und können den Teilnehmenden unbekannt sein. Einen vergleichsweise neuen Forschungsansatz stellt die Analyse von Daten aus Suchmaschinen dar. Diese wird aktuell für verschiedene Forschungsfragen eingesetzt (Adler et al., 2019; X. Li & Law, 2020; Vargas, Schiffman, Lam, Kim, & Mittal, 2020). Dass dabei das geplante Verhalten mit der Umsetzung in reales Handeln korreliert, ist neben den empirischen Erkenntnissen durch die Theorie des geplanten Verhaltens theoretisch hergeleitet worden (Ajzen, 1985).

2.3.1 Entscheidungsexperiment

Zur differenzierten Abfrage der Infrastrukturpräferenzen von Probandinnen und Probanden wird ein diskretes Entscheidungsexperiment entwickelt. Dabei werden den Probandinnen und Probanden vollständige Alternativen, bestehend aus verschiedenen Routeneigenschaften, zur Auswahl präsentiert. Jede Probandin bzw. jeder Proband wählt in einer Abfolge von acht Entscheidungssituationen jeweils die bevorzugte Routenalternative auf Basis der gegebenen Routeneigenschaften. Die Alternativen und deren einzelne Ausprägungen wurden konzeptionell entwickelt und deren Kombination nach einem Pretest softwaregestützt für einen möglichst hohen Erkenntnisgewinn optimiert (Bliemer & Rose, 2006; ChoiceMetrics, 2012).

Dabei werden neben der metrischen Reisezeit sechs Merkmale mit je bis zu fünf Ausprägungen differenziert. Die Dauer fungiert dabei als Quantifizierung und drückt die Zahlungsbereitschaft für bessere Routeneigenschaften aus. Aus diesen Kombinationen werden drei Blocks mit jeweils acht (insgesamt 24) Entscheidungssituationen zu je drei Alternativen (zuzüglich no-choice) generiert. Um das Experiment für die Teilnehmenden anschaulicher zu gestalten, werden alle 72 Alternativen neben der textlichen Beschreibung auch grafisch dargestellt. Verbreitet über Social Media und weitere Online-Kanäle konnten 4.775 Teilnehmende je acht und damit insgesamt 38.200 Beobachtungen liefern.

Da es wesentlich mehr deutsche Fälle als griechisch gibt, wird ein gewichtetes Subsampling eingesetzt. Dieses zieht aus der deutschen Stichprobe 350 Teilnehmende, die hinsichtlich Soziodemografie dem griechischen Sample ähneln. Wie in 2.2 bildet neben der Theorie des geplanten Verhaltens die Theorie der Nutzenmaximierung die Grundlage.

Mit den so gewonnenen Daten werden unter Nutzung von multinomialen logistischen Regressionsmodellen über Nutzenfunktionen Nutzwerte für die einzelnen Ausprägungen der Routeneigenschaften ermittelt (Ben-Akiva & Bierlaire, 1999; McFadden & Train, 2000). Dabei wird explizit berücksichtigt, dass die jeweils acht Antworten jeder einzelnen Probandin bzw. jedes einzelnen Probanden korreliert sind. Basierend auf gestützten Hypothesen werden verschiedene Interaktionen modelliert und schließlich drei Modelle hinsichtlich der Erklärungsgüte und der verwendeten Parameter vergleichen.

Die Arbeiten zum Entscheidungsexperiment sind in der Veröffentlichung *Evaluating Cyclists' Route Preferences with Respect to Infrastructure* in Kapitel 4 detailliert beschrieben.

2.3.2 Navigationsdatenanalyse als neue Datenquelle

In diesem methodischen Modul wird wie beschrieben eine weitere Datenquelle erschlossen, um die feinteiligen, individuellen Präferenzen der Radfahrenden auszumachen. Der Ansatz ist die Nutzung der Daten aus Anfragen für Fahrradroutennavigation (Rezic, 1999). Dabei werden die Log-Daten für das Berliner Stadtgebiet des Anbieters für ein volles Jahr aufgezeichnet und analysiert. In über 450.000 Fällen haben dabei Nutzende ihre spezifischen Präferenzen für Routeneigenschaften auf konkret geplanten Wegen angegeben.

Damit entspringen die Daten keiner Befragungssituation, sondern stammen aus den durch die Nutzenden für die durchgeführte Navigation getätigten Einstellungen.

Die detaillierten Einstellungen mit jeweils bis zu sieben Ausprägungen in den Kategorien *Straßentyp*, *Oberflächenqualität* und *Grüne Wege* resultieren in einer enormen Menge von möglichen Kombinationen. Diese Daten werden mit einem Clusterverfahren verdichtet, um somit darunterliegende typische Präferenzcluster zu ermitteln (Everitt, Landau, Leese, & Stahl, 2010). Im Einzelnen wird in der Clusteranalyse das Distanzmaß *asymmetric Manhattan* zur Berechnung der Distanzmatrix angewandt, das die enthaltene Information der ordinalskalierten Daten nutzt (Walesiak & Dudek, 2010b). Dazu wird ein hierarchischer Clusteransatz verwendet, der Lösungen für eine verschiedene Anzahl an Clustern ermöglicht. Als Clusteralgorithmus wird *complete-linkage* verwendet. Dieser ist vergleichsweise robust gegen Kettenbildung. Zur Auswahl der besten Clusterlösung wird schließlich einerseits das *Calinsky-Harabasz-Kriterium* genutzt. Dieses vergleicht die Kovarianz innerhalb der Cluster mit derjenigen zwischen den Clustern (Caliński & Harabasz, 1974). Andererseits wird das im Zuge der hierarchischen Clusterung erzeugte Dendrogramm verwendet. Dieses gibt den Prozess der Clusterung wieder und zeigt für jeden Schritt, welche Cluster zusammengefügt werden. Unter Beachtung beider Kriterien bietet sich eine Lösung mit fünf Clustern an. Diese bündelt die enorme Vielfalt an möglichen Kombinationen der Präferenzeinstellungen zu darunterliegenden Präferenztypen.

Diese Arbeiten sind in der Veröffentlichung *Assessing cyclists' route preferences by analyzing extensive data from a bike-routing engine* unter Kapitel 5 beschrieben.

3 Bikeability und strukturelle Zusammenhänge *(Preprint)*

Wie in 1.3.3 beschrieben, weisen frühere Ansätze zum Messen der Bikeability urbaner Gebiete methodische Unzulänglichkeiten auf. Dieser Artikel beschreibt die Entwicklung und Anwendung einer Methode, die diese Forschungslücke zu schließen versucht. Dabei bewegt sich der Ansatz zunächst auf einer vorgelagerten konzeptionellen Abstraktionsebene – die Entwicklung eines Bikeability Index ist global gültig und eine Nutzung für zahlreiche Anwendungsfälle denkbar. Anschließend wird mit der Verkehrsmittelwahl der offensichtlichste Anwendungsfall demonstriert und somit auf die Ebene der Verkehrsmittelwahl fokussiert.

Methodisch wird eine Literaturstudie zum Identifizieren der relevanten Einflussfaktoren durchgeführt. Diese werden im Anschluss in einem Expertenprozess gewichtet und somit in einen konsensualen Gesamtzusammenhang gebracht. Mit diesem Wissen werden unter Nutzung offener Geodaten räumliche Indizes sowie der Gesamtindex berechnet. Am Beispiel Berlins werden die resultierenden Daten zur Bikeability gemeinsam mit empirischen Mobilitätsdaten in einem Verkehrsmittelwahlmodell eingesetzt, um die Moduswahl von Individuen zu schätzen.

Dabei zeigen die Ergebnisse des Expertenprozesses ein stabiles Zusammenspiel der einzelnen Einflussfaktoren. Die Bikeability urbaner Gebiete lässt sich umfassend, konsensual und unter Nutzung uneingeschränkt verfügbarer Geodaten beschreiben. Die Ergebnisse des Verkehrsmittelwahlmodells zeigen einen signifikanten stark positiven Einfluss einer höheren Bikeability auf die Wahl des Fahrrades als Verkehrsmittel.

3.1 More Than Bike Lanes – A Multifactorial Index of Urban Bikeability

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Special Issue Transport Sustainability and Resilience in Smart Cities

In diesem Kapitel ist eine Preprint-Version des Artikels integriert. Die zitierfähige überarbeitete Postprint-Version nach Abschließen des Peer-Review-Prozesses ist dem verlinkten Artikel zu entnehmen.

Abstract: The present study aims to deduce bikeability based on a consensual understanding. The approach contains four steps and combines qualitative and quantitative methods in addition to using open data. First, findings from literature are condensed to determine relevant categories influencing bikeability. Second, an expert survey is conducted to estimate the importance of different categories to gain a common understanding of bikeability and merge various impacting factors. Third, open data are used in an automated workflow to calculate spatial indices. Fourth, the results are used in a multinomial logit mode choice model to evaluate the effects on mode choice behavior.

Results show a stable interaction between the components defining bikeability, linking specific spatial characteristics of bikeability and associated components. Applied components are, in order of importance, cycle facilities along main streets, intersection density, road types, green pathways and rental and repair facilities. The mode choice model shows a strong positive effect of a high bikeability along the route on choosing the bike as preferred mode. This confirms, that the bike friendliness on a route surrounding has a significant impact on the mode choice. Using universal open data and applying a stable consensual weighting renders the approach of assessing urban bike-friendliness fully transferable and the results comparable.

Keywords: bikeability, cycling, active transport, built environment, infrastructure

3.1.1 Introduction

Cycling as an active mode of transport has advantages at societal level in respect of CO_2, air pollutant and noise emission as well as space requirements (Ahrens, et al., 2013; Makarova, et al., 2019), and at individual level when considering physical inactivity as a risk factor for common diseases of affluence (I. M. Lee et al., 2012; Mueller, et al., 2015; OECD/ITF, 2013). Most recently, changing conditions in the transport sector caused by the covid-19 pandemic lead to a massive decline in public transport usage (Tirachini & Cats, 2020). As a consequence, a healthy and environmentally friendly system of individual mobility with low access barriers is even more important. Earlier research found, that more than half of the population can be defined as interested but concerned regarding using the bike as mode of transport (Cabral & Kim, 2020; Dill & McNeil, 2013). The choice of these people to use the bike is affected by according policies. One key factor for encouraging bike traffic is the implementation of a bike-friendly built environment, i.e. road infrastructure. Several studies aim to describe, categorize or investigate neighborhood characteristics to deduce the urban infrastructures bike friendliness (bikeability) of neighborhoods and analyze interrelations between the built environment and active travel (Nielsen, et al., 2013; Wahlgren & Schantz, 2014; Winters, et al., 2013; Winters, et al., 2016; Yang, et al., 2019). Others focus on evaluation accessibility (Vale, Saraiva, & Pereira, 2016). When considering high spatial resolution, studies may include considerable individual effort by raters in the field who collect associated data within an area (Cain, et al., 2018; Day, Rivera, Soler, Kent, & Kochtitzky, 2015; Sallis et al., 2015). Collected data are thematically similar overall but may be defined differently. Other studies follow a detailed data driven approach in local or regional case studies with specific operationalizations (Salon, Wang, Conway, & Roth, 2019; Teschke, Chinn, & Brauer, 2017). In contrast, numerous studies investigate interrelations between the built environment and (active modes of) transport at highly aggregated levels, such as the total length of bike lanes per square mile or per inhabitant, in respect of whole cities or nations (Buehler & Pucher, 2011; Dill & Carr, 2003; Nelson & Allen, 1997; Pucher & Dijkstra, 2000). In the latter cases, the secondary geodata used are specific data obtained from municipal or national sources (Buehler & Pucher, 2011; Winters, et al., 2016) or using specific software to gather data (Rybarczyk & Wu, 2014). Studies deliver valuable insight but it is often not possible to transfer methodologies to other regions and any comparison of results has its limitations. In addition, due to differences in data availability it is almost impossible to apply such detailed methodologies on a large-scale when crossing national borders. The lack of compatibility between such approaches highlights the importance of using a comparable and transferable index for the bikeability of urban neighborhoods using data with comprehensive coverage in different regions of the world (Winters, et al., 2016). Recent studies partly overcome this shortage by using open data but do not use a comprehensive definition of bikeability at the same time (Mueller et al., 2018; Schmid-Querg, Keler, & Grigoropoulos, 2021) while others elaborate a rather detailed research question and partly remain relaying on municipal data (Arellana, et al., 2020; Nello-Deakin & Harms, 2019; Porter, et al., 2020). Earlier studies identified further research gaps, such as using reliable data and different types of infrastructures (Forsyth & Krizek, 2010), integrating other kinds of infrastructure, such as bicycle shops or repair facilities (Handy, et al., 2014) and collecting data with systematic consideration of relevant factors (Buehler, et al., 2016). Unlike a coordinated and consensual consideration of impacting factors, various earlier studies improved our understanding significantly but use bike lanes as single parameters (Buehler & Pucher, 2011; Dill & Carr, 2003; Mueller, et al., 2018; Nelson & Allen, 1997; Pucher & Dijkstra, 2000). Other studies base weighting on single experiments (Arellana, et al., 2020; Winters, et al., 2013) or normatively determine an overall framework themselves (Winters, et al., 2016). As different types of infrastructure may have varying implications in different groups of cyclists (Damant-Sirois & El-Geneidy, 2015; Salon, et al., 2019) it is crucial to develop a consensual and integrative understanding of bikeability. To ensure applicability, the developed index should furthermore be fully transferable and applicable at any spatial level. Once having a workflow, a consensual index can be calculated for any spatial unit to enable evaluating the impacts of bikeability on cycling levels and other dependent variables in large-scale analysis and drawing comparisons between nations, cities and districts regarding the impacts of bikeability. Furthermore, policy makers of local and regional authorities in particular can profit greatly from this type of information as it provides a valuable basis for defining focal points of cycling strategies and determining investments and improvements in cycle infrastructure. The universal applicability in different spatial resolutions is thereby of main interest.

This paper addresses the challenge of developing such a procedure using open data. It also assesses the informative value of the resulting index by exemplary applying a multinomial logit mode choice model to describe the enhancements of bikeability on the decision of using bike as main transport mode in the city of Berlin.

3.1.2 Background: determinants of bikeability

It is crucial when deriving bikeability to identify relevant influencing factors. Methodologies vary widely and a growing number of studies are available. Findings are generally obtained from cross-sectional studies (Sallis, et al., 2015; Winters, et al., 2016), interventional studies (Ghosh, Arnold, Vingrys, & Ballis, 2016; Heinen, Panter, Mackett, & Ogilvie, 2015; Thakuriah, Metaxatos, Lin, & Jensen, 2012), stated preference studies (Aldred, et al., 2016; Caulfield, et al., 2012; Hardinghaus & Papantoniou, 2020; Hunt & Abraham, 2007), revealed preference studies (Broach, et al., 2012), and summarizing meta-analysis (Buehler & Dill, 2016; R. Ewing & Cervero, 2010; Humphrey, 2005; K. Krizek, Forsyth, & Baum, 2009; Wang, Chau, Ng, & Leung, 2016). In the following paragraphs, findings from previous research are grouped into five categories: road types, intersection density, cycle facilities along main streets, green pathways, and rental and repair facilities.

3.1.2.1 Road types

There are various ways to operationalize the predominance of motorized traffic on different roads. Previous studies, using the number of car lanes (Evans-Cowley & Akar, 2013), traffic volumes (Foster, Panter, & Wareham, 2011; Vandenbulcke et al., 2011; Wahlgren

& Schantz, 2014), permitted speed (Rowangould & Tayarani, 2016), road categories (Abraham, et al., 2002), or a combination of several characteristics (Birk et al., 2010), deliver varying results. Many interventional or cross-sectional studies prove the importance of calmer streets (Caulfield, 2014; Hou et al., 2010; Winters, Brauer, et al., 2010) while others do not (Cairns, Warren, Garthwaite, Greig, & Bambra, 2015). Some revealed preference studies verify the preference for local roads over arterials (Broach, et al., 2012; Winters, Teschke, et al., 2010) whereas other studies find diverging results (Aultmann-Hall, 1996) or no interrelations at all (Moudon et al., 2005). When questioning cyclists' route preferences in stated preference studies, giving priority to calmer streets over main streets appears obvious (Abraham, et al., 2002) even though the preference for dedicated cycle infrastructure or off-street paths might be stronger (Winters & Teschke, 2010).

3.1.2.2 Intersection density

Intersection density is an established infrastructural factor associated with mobility behavior (Cervero & Kockelman, 1997; Cervero, et al., 2009; R. Ewing & Cervero, 2010). Many studies prove the significance of higher intersection density on active transport routes (Badland, et al., 2008; Cervero, et al., 2009; Fan, et al., 2014; Nielsen, et al., 2013; Schoner & Levinson, 2014; Winters, Brauer, et al., 2010). When operationalizing intersection density as a directness of route in stated preference studies, low directness is found to be a hindering factor for cycling to work (Wahlgren & Schantz, 2014). Less confident cyclists on the other hand prefer a low number of junctions (Caulfield, et al., 2012).

3.1.2.3 Cycle facilities along main streets

Both stated preference (Caulfield, et al., 2012; Winters & Teschke, 2010) and revealed preference studies (Broach, et al., 2012; Garrard, Rose, & Lo, 2008; Ghanayim & Bekhor, 2018) conclude that cycle infrastructures are preferable to cycling in mixed traffic and can compensate for the adverse effects of busy streets. Many cross-sectional (Bopp, et al., 2015; Buehler & Pucher, 2011; Dill & Carr, 2003; K. J. Krizek & Johnson, 2006; Pucher &

Dijkstra, 2000) or longitudinal interventional studies (J. Gu, Mohit, & Muennig, 2017; Henao et al., 2015; H. Li, Graham, & Liu, 2017) also find correlations between the amount of cycle infrastructure and cycling frequency at different aggregation levels. In contrast, other cross-sectional (Cervero, et al., 2009) and revealed preference studies (Moudon, et al., 2005) refute such interrelations. One reason for inconsistent results is said to be not distinguishing adequately between different types of infrastructure in known studies (Forsyth & Krizek, 2010).

3.1.2.4 Green pathways

Findings related to cycling on green pathways appear inconsistent across all methodological approaches. Stated preference studies range from preferring off-street paths above all other routes (Winters & Teschke, 2010) to off-street paths being less attractive than paths along arterials (Abraham, et al., 2002). Similarly, revealed preference studies find no (Moudon, et al., 2005), low (Aultmann-Hall, 1996) or high (Broach, et al., 2012; Ghanayim & Bekhor, 2018; Winters, Teschke, et al., 2010) significance for choosing off-street paths. Cross-sectional studies provide contradictory findings ranging from a slightly positive (Parkin, Wardman, & Page, 2008) to no (Winters, Brauer, et al., 2010) or negative correlation (Fan, et al., 2014). This might be due to operationalization issues or to interrelations with other structural factors.

3.1.2.5 Rental and repair facilities

As the number of bike-sharing systems increases, it is becoming increasingly relevant to analyze their impact on bikeability and cycling mode shares. Previous studies concluded that bike-sharing has a positive influence on cycling levels but needs further measures to become effective (Midgley, 2011; Pucher, Dill, & Handy, 2010; Ricci, 2015). Few results illustrate the positive impact of other kinds of infrastructure, such as availability of repair facilities, air pumps or bicycle shops (Pratt, Evans, Levinson, & Turner, 2012; Pucher, et al., 2010). They are also mentioned as promising areas of interest and research subjects for further studies (Handy, et al., 2014).

3.1.3 Methodology

The approach combines different methods and contains four steps. First, literature is reviewed to determine factors influencing bikeability as described above. Second, an expert survey is conducted to rate the importance of deduced categories to arrive at a conceptual bikeability weighting. Third, open data are used to operationalize parameters for each influencing category and calculate individual values. Single parameters are merged to form an overall bikeability index by using the weighting determined. Fourth, using Berlin as an application example, a model is set up to evaluate enhancements using the bikeability index in a multinomial logit mode choice model.

3.1.3.1 Expert survey

A weighting is needed to merge different environmental parameters according to their specific importance to bikeability. Consulting the authors of many studies and other cycling-experts promises a more stable weighting than referring to a single element experiment. Therefore, an expert survey is conducted to gain a consensual understanding of bikeability.

The survey uses a website containing one main interactive module as shown in Figure 3-1. Each of the five influencing categories (see section Literature review: determinants of bikeability) is represented by a slider control. Moving the value of one category scales the other categories accordingly to add up to 100 percent. Participants are asked to apply the tool, specifying a general weighting based on their professional assessment of bikeability. Participants are also invited to add an impacting factor if they feel a category is missing.

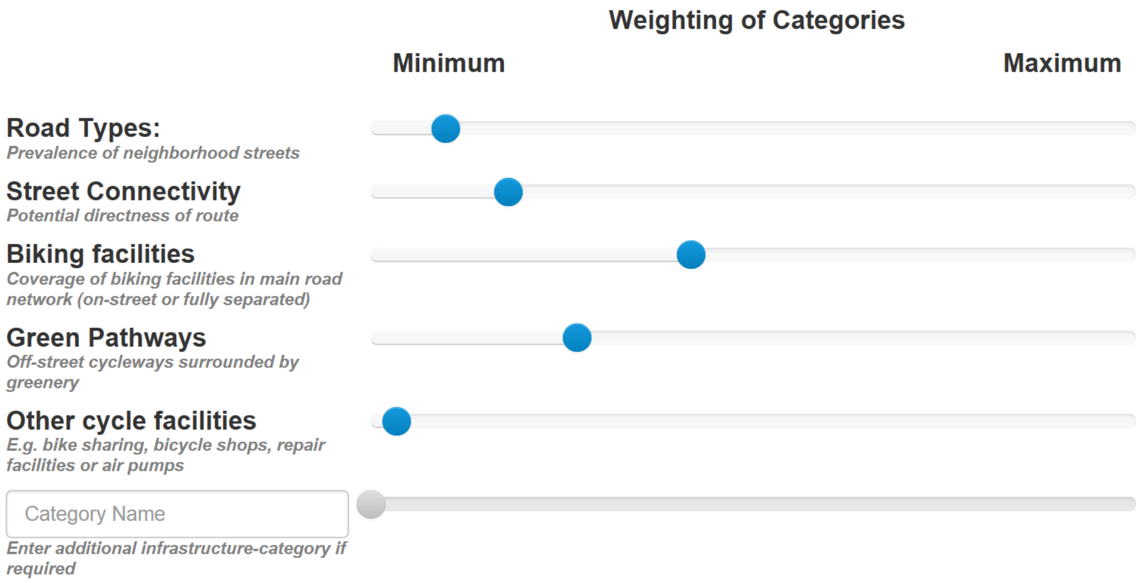

Figure 3-1. Interactive web module

A total of 141 experts were personally invited to take part in the survey. The experts were contacted by email between September 14 and September 19, 2016. Those invited were corresponding authors of the studies reviewed above (74) and published in the last four years, members of the research group of Germany's National Cycling Plan 2020 (32), and other well-known experts (35). Experts were assigned a personal code relating to a separate database containing information on the reason for selection, country of residence, profession (practical or research) and gender. When answering the survey, experts were asked to "imagine an urban neighborhood which generally invites bike riding in everyday traffic" and "weigh the importance of different elements of urban infrastructure for local bikeability". The goal was stated as calculating a bikeability index using spatial data.

3.1.3.2 Calculation of parameters

To ensure the transferability of the proposed method, data from OpenStreetMap (OSM) are utilized to calculate built environment parameters (OpenStreetMap-contributers, 2017). OSM represents an ideal basis for this methodology due to its standardization, comprehensive coverage, high level of detail and freedom from financial and legal constraints (Arsanjani, Barron, Bakillah, & Helbich, 2013; Haklay, 2010; Neis, Zielstra, & Zipf, 2012). Using OSM data, a workflow is set up to derive spatial parameters which can be calculated for any scale and extent. Each category is operationalized to a conclusive parameter allowing for various ways of tagging different types of infrastructure in the data. Different vector data sets, dividing the investigation area into grids or administrative zones (cells), can be loaded for spatial localization. Different administrative zones can also be extracted directly from OSM. Spatial indices are then calculated for each parameter. As the resulting values include different units and scales, they are standardized to permit unification into one overall bikeability index. Afterwards, the standardized values are merged using the weighting from the expert survey. Computing of individual indices for each category is described below.

To estimate **road types**, the road's importance indicated in the network for motorized traffic from motorway to traffic-calmed street is used. It is assumed that the road's importance to motorized traffic contrasts with the convenience of using that road by bicycle. This interrelation is implied in literature and the expert survey. All road segments are added up for each cell in the relevant category. The percentages of the three smaller road types (traffic-calmed, residential and tertiary streets) are added up to create an index and estimate the prevalence of small streets.

To estimate **intersection density**, intersections negotiable by bike are counted and the density per square kilometer is calculated. Each node in the data is analyzed. If a node is assigned to more than one highway, it is defined as a crossing street line. As intersections often contain a number of crossing street lines, a cluster algorithm based on the DBSCAN (Ester, et al., 1996) is used. Every cluster identified corresponds to one intersection.

To calculate the coverage of **cycle facilities along main streets**, the two main street categories usable by bicycle (primary and secondary) are analyzed. When calculating the coverage of biking facilities, both the variety of facilities that exist and different ways of tagging them are taken into account. Here, cycle lanes at street level and separated cycle tracks are considered by analyzing properties of the main street segment. Cycle tracks are also tagged as separate routes adjacent to the road when separated by grass or hedges. To capture these adjacent routes, a 10-meter buffer is placed around each street segment to identify cycle tracks running parallel to that segment. In each cell, the percentage covered by three types of facilities is calculated for both types of street and direction of traffic. When added, the result is the percentage coverage of main streets with cycle infrastructure.

To approximate the prevalence of **green pathways**, all public green areas accessible by bike are taken into account. In this case, differently tagged areas often overlap. For instance, small wooded areas within parks consist of two overlay polygons which are considered using an overlay algorithm. The area of public green spaces in each cell is added up and the percentage share of greenery in each cell is calculated. The actual length of trails is not taken into account as there is a significant difference between the density of tracks running through green spaces and local tagging behavior (mapping beaten tracks or only official pathways).

The category **rental and repair facilities** aggregates bike-sharing stations and bicycle shops providing repair or rental services in each cell. The amount is added up and the density per square mile is calculated.

3.1.3.3 Influence of the bikeability indicator on mode choice

In order to evaluate the influence of the calculated index on choosing the bike for a single trip a mode choice model has been applied. Basis of this analysis is the municipal household travel survey data (SrV) of the year 2008 which provides information about 73,667 valid trips within Berlin, 10,234 of them were covered by bicycle (Ahrens, 2009). In our case valid means that all trips start and end within the city border of Berlin, that they do not start and end in the same cell and that they do not include null values or values that are not plausible. The survey includes information about each trip (length, origin and destination area, trip purpose, main transport mode, etc.) and the conducting person (age, employment status, availability of a car or public transport ticket, etc.), aggregated to the spatial level of the 195 statistical units of Berlin (see Figure 3-2). Therefore, it is not possible to obtain the exact start and end points of single trips. Due to this limitation, center points of the respective districts have been calculated and used as origin and destination locations (see Figure 3-2a) as an approximation. Afterwards, a shortest path routing on the bike network has been applied between each pair of center points (see Figure 3-2b) and the obtained routes were subsequently intersected with the districts and associated bikeability values (see Figure 3-2c). Finally, the bikeability values of the crossed districts have been summed up and averaged for each trip.

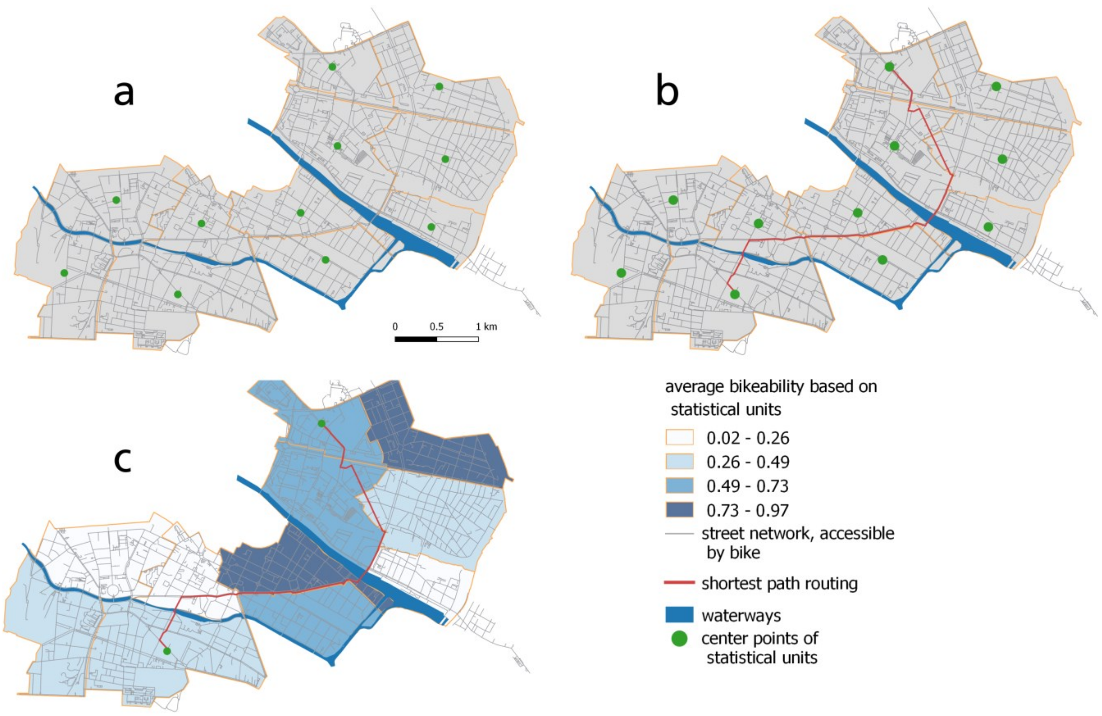

Figure 3-2. Process of averaging bikeability values of each trip.

The figure shows all statistical units of the district “Friedrichshain-Kreuzberg” as an example. In this illustration one of the 38,025 regarded trips is visualised. The process includes the calculation of area centroids (a), the routing bewteen one pair of centroids (b) and the averaging of bikeability values based on the crossed units (c). In this example the bikeability values of the regarded statistical units range between 0.02 and 0.97, the average value for the observed trip is 0.53.

In order to evaluate the influence of the calculated bikeability index on the choice of using the bike as primary mode instead of motorized transport for a respective trip a multinominal logit (MNL) model has been applied.

The MNL model is based on the assumption, that an individuum that faces a decision between distinct alternatives choses the alternative that comes with the highest utility. The Random Utility Theory, under the assumption of additive linearity, states, that the utility (U) of one alternative is the sum of their single components (X) and an independent and identically distributed (i.i.d.) error term (ε). The utility of one alternative can then be formulated as

$$U = X\beta + \varepsilon$$

where the parameters β are to be estimated and reflects the influence of the respective components x (de Dios Ortuzar & Willumsen, 2011; McFadden, 1973).

The dataset used for estimation includes all trips of the trip data described above, which are made by car, bike, public transport or foot as the corresponding main mode. From this, the dataset was cleaned by removing trips with implausible travel speeds (e.g. car trips faster than 100 km/h on average or walking trips over 7 km/h) and trips with distances less than 500 meters, which then reduces the dataset to a final of 48,825 observations. The dataset contains several properties of each conducted trip (the original route and mode), which were stated in the survey. As the model requires information on the alternatives which were not chosen, we calculated these respective route characteristics of the alternatives for each trip using the modes that were not chosen in the observed original trip (e.g. travel times and costs for public transport, car or bicycle).

The components of the utility function used for the estimation consists of trip attributes as well as person attributes. The former includes cost and travel time of the trip and the bikeability index for bike trips, the latter contains the age of the respondents and the availability of a public transport season ticket. The car availability of participants is considered in the availability of alternatives, i.e. a person without access to a car will not be given an alternative to drive. All attributes used are shown in Table 3-1, enhanced with a short description and the minimum, maximum and mean value. It is important to note, that the statistics are based on the values of all alternatives, including those, which were not chosen.

Table 3-1. Attribute Table

Attribute	Description	Min	Max	Mean
AGE	Age of the person observed in years	6	95	44.74
PT_TICKET	Public transport season pass available	0	1	0.48
COST PT	Costs of the trip with public transport in €	0.2	12.15	1.73
COST CAR	Costs of the trip by car in €	0.005	6.53	0.66
BIKEABILITY	Bikeability Index of the route	-0.87	0.97	0.18
TIME_BIKE	Travel time by bike in minutes	2.08	130.01	14.39
TIME_CAR	Travel time by car in minutes	1.13	111.11	19.75
TIME_TRAIN	Travel time by public transport in minutes	3.95	741.2	68.73
TIME_WALK	Travel time by foot in minutes	8.33	133.33	24.36

3.1.4 Results

3.1.4.1 Expert survey

With 57 valid responses, the return rate for the survey is 40.4%: one third from females and two thirds from males. 33 (58%) respondents are from Germany, 13 (23%) from other European countries and 11 (19%) from America. The profession for 44 (77%) participants is researcher while 13 (23%) are working in practice. One third of all respondents published at least one related peer-reviewed article in the last four years. Table 3-2 shows the results of the participants' assessment of bikeability. Cycle facilities along main streets are the most important component of bikeability but also show the highest variations in ratings. Further components are, in order of importance, intersection density, road types and green pathways. Rental and repair facilities are less important. Apart from assessing the described categories, one third of respondents (19) added and rated an individual category. Six respondents mentioned parking. Surface quality was also mentioned three times. Other categories were entered only once and were partly outside the scope of factors influencing infrastructure. When mentioned, both parking and surface quality attracted relatively high values (18.9 or 20.6 percent respectively on average).

Table 3-2. Expert survey: resulting interaction of components of bikeability [%]

	Road types	**Intersection density**	**Cycle facilities along main streets**	**Green path-ways**	**Rental and repair facilities**	**Addition-al catego-ry**
Mean	0.17	0.23	0.28	0.16	0.08	0.08
Median	0.14	0.24	0.27	0.16	0.07	0
Standard-deviation	0.10	0.90	0.11	0.09	0.06	0.16
Min.	0	0	0	0	0	0
Max.	0.45	0.45	0.52	0.36	0.25	1.00

3.1.4.2 Characteristics of parameters

Results are calculated using the example of Berlin, Germany, as proof of concept and to analyze intra-city characteristics and evaluate the methodology.

The structure of the network differs greatly when considering road types. Motorways and trunk roads form a loose network and are only present in a few districts. However, the percentage share of motorways in one particular cell is more than 45%. Primary streets appear as a star-shaped network with relatively low shares of 5% on average and a rather low variation. Secondary and tertiary streets account for substantial shares in the network with 17 and 11 percent respectively on average. Residential streets dominate most districts with 62% on average but ranging from 0 to 100%. Traffic-calmed streets account for low shares in many districts and also show dispersed distribution with high shares locally in a few districts. As shown in Table 3-3, small streets account for large shares in most districts. Table 3-3 shows the statistical characteristics of all input parameters for bikeability. All values range widely.

Table 3-3. Statistical key figures of individual parameters

	Small streets share (percentage share of all street km)	**Intersection density (intersections per km²)**	**Facilities along main streets (percentage coverage)**	**Greenery (percentage in area)**	**Rental and repair facilities (facilities per km²)**
Mean	0.76	37.6	0.65	0.18	0.91
Median	0.81	35.9	0.69	0.11	0.16
Standard-deviation	0.18	22.2	0.28	0.21	1.78
Min.	0	0	0	0.01	0
Max.	1	108.9	1	0.97	10.32

Figure 3-3 shows the spatial characteristics of the inner-city distribution of single values and the overall index based on Berlin. Darker colors indicate higher values. With regard to the individual parameters, the share of small streets (top left) shows a distribution with generally higher values in outer districts. The map of intersection density (top right) shows a centered distribution with the highest values in inner districts. The denser districts in the city center are characterized by a highly connected street network compared to lower intersection density in outer districts. The coverage of main streets with cycle facilities (middle left) appears in a highly dispersed distribution. The share of greenery (middle right) is highest in outer districts with the large green areas in the west and south east easily recognizable. The spatial density image of rental and repair facilities (bottom left) shows a clear centered distribution with very low values in large parts of the outer city. When considering the distribution of the merged overall bikeability index (bottom right), the highest values are seen in the eastern part of the city center as well as in certain other districts. The trend towards higher values in inner city districts is evident but there are dispersed characteristics as well.

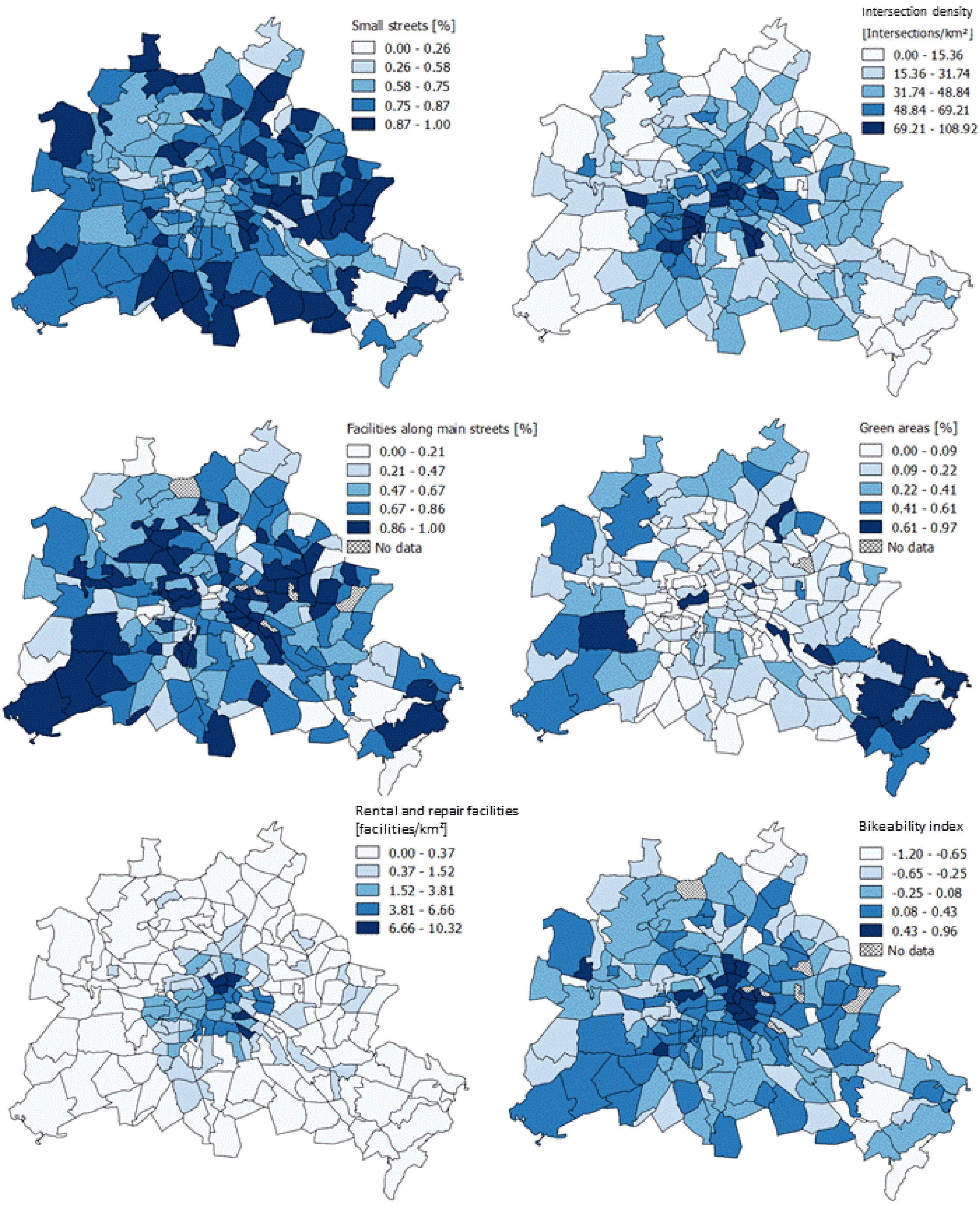

Figure 3-3. Inner-city spatial characteristics of individual distributions

3.1.4.3 Influence on mode choice

The estimation results of the applied mode choice model presented in section 4.3 are shown in Table 3-4 including the value of the estimator, the standard deviation and their respective t-value. The overall model performance shows a rho square of 0.403, while all results are significant at a 5 % level. Further, the parameter signs are as expected, i.e. parameter values for travel cost and travel times for all modes are negative. The age parameters indicate, that a person, the older he or she is, is more likely to choose car or bike or even walk as their preferred mode, rather than public transport. The availability of a seasonal public transport pass reduces the likelihood of using a car compared to the other modes, which meets our expectations. Taking a closer look to the travel time parameters, it can be stated, that the time riding a bike is perceived much more negative, than time spend on any other mode, followed by public transport, while the time spent walking or driving is perceived less negative.

Regarding the bikeability parameter estimated by the model, a strong positive effect of a high bikeability index along the route on choosing the bike as preferred mode, can be observed. This confirms, that the bikeability along a route has a significant impact on the choice of mode when making a trip. Furthermore, it shows, that the bikeability index derived in this paper performs well in collecting and representing the information which is crucial to describe bike friendliness along spatial areas.

Table 3-4. Model Results

Variable	Utility Equation	Estimator	Standard Deviation	t-value
ASC Bike	*Utility Alternative Bike*	**1.17**	*(0.0684)*	*17.1*
ASC Car	*Utility Alternative Car*	**0**	*(fixed)*	*fixed*
ASC Train	*Utility Alternative PT*	**1.87**	*(0.058)*	*32.4*
ASC Walk	*Utility Alternative Walking*	**-2.03**	*(0.0537)*	*-37.8*
Age Bike	*Utility Alternative Bike*	**0.0251**	*(0.00093)*	*27.1*
Age Car	*Utility Alternative Car*	**0.0254**	*(0.00091)*	*27.8*
Age Train	*Utility Alternative PT*	**0**	*(fixed)*	*fixed*
Age Walk	*Utility Alternative Walking*	**0.0151**	*(0.00083)*	*18.1*
Cost	*All Utility Alternatives*	**-0.839**	*(0.0291)*	*-28.8*
PT Ticket Bike	*Utility Alternative Bike*	**0.332**	*(0.0391)*	*8.49*
PT Ticket Car	*Utility Alternative Car*	**-0.245**	*(0.0352)*	*-6.96*
PT Ticket Train	*Utility Alternative PT*	**0**	*(fixed)*	*fixed*
PT Ticket Walk	*Utility Alternative Walking*	**2.31**	*(0.0349)*	*66.1*
Time Bike	*Utility Alternative Bike*	**-0.299**	*(0.00508)*	*-58.9*
Time Car	*Utility Alternative Car*	**-0.01**	*(0.0033)*	*-3.03*
Time Train	*Utility Alternative PT*	**-0.0324**	*(0.00109)*	*-29.8*
Time Walk	*Utility Alternative Walking*	**-0.00271**	*(0.00051)*	*-5.32*
Bikeability	*Utility Alternative Bike*	**0.518**	*(0.0623)*	*8.49*
Log-likelihood				**-37,466.51**

3.1.5 Discussion

In this study, an approach to assess the bikeability of urban infrastructures using open data is demonstrated. At the same time, the relevance of individual methodological components is evaluated. These components are built on each other and form the consistent overall framework of this approach. Thereby literature review, expert survey and operationalization of parameters are crucial to establish the index while the model demonstrates an example of application.

The results of the conducted expert survey confirm the relevance of parameters determined from the literature. Key insights from the survey are the weighting itself and the consistency of the determined weighting across different subgroups of participants. This stable weighting enables a consensual approximation of bikeability. In contrast to analyzing individual parameters (Buehler & Pucher, 2011; Dill & Carr, 2003; Nelson & Allen, 1997; Pucher & Dijkstra, 2000), the consensual integration of different parameters improves the approximation of bikeability and provides a more realistic overall picture – one main benefit of the present research. If the framework obtained in the expert survey is compared to recent integrative approaches, it is seen that the three most important categories (cycle facilities along main streets, intersection density and road types) are similar (Winters, et al., 2013) even with some differences in ranking and operationalizing values. Refining previous approaches (Winters, et al., 2016) and basing the calculation on broad expert consensus ensures an appropriate appraisal of bikeability.

Results of geodata analysis in Berlin show that OSM open data cover each part of the city sufficiently and are accurate enough as a basis for the analysis. The method of operationalizing categories to parameters also enables an approximation that characterizes the city well with regard to bikeability and its components. In combination with high accuracy and topicality of the data (Arsanjani, et al., 2013; Haklay, 2010; Neis, et al., 2012), it can be assumed that this approach allows transferability and consistency between municipalities and across national borders as desired by previous studies (Winters, et al., 2016). At present, limitations on data availability still exist, particularly in Asian countries. Using Berlin as an example, it can be seen that indices for individual parameters vary significantly within the city. Each index shows a specific statistical distribution and a characteristic spatial distribution. Remaining area-based, the method is appropriate for abstracting characteristics of points (rental and repair facilities, intersections), lines (road types and coverage of biking facilities) and polygons (green areas) and for merging different parameters at any district level in urban areas.

Overall, the mode choice model confirms the influence of the bikeability index on the choice of using the bicycle as a primary mode of transport for the example of Berlin. Thereby, the model performs quite good indicated by a rho square value of 0.403. This is especially valid against the background that choosing the bike as mode of transport generally has several impacting factors. Especially personal attitudes and preferences are difficult to model. Thereby, 56 percent of the population, the "interested but concerned" are seen to be the key target market to increase cycling and therefore accordingly sensitive for the impacts of a bike-friendly urban environment (Dill & McNeil, 2013). This conversely means: almost half of the population is not sensitive to differences in bikeability. Hence, modeling the usage of bike as based on spatial data is unlikely to show high coefficients of determination. Correspondingly, (Winters, et al., 2016) found coefficient of determination of about 0.35, (Dill & Carr, 2003) a range from 0.18 to 0.3.

With a closer look, all parameters in the model perform as expected in regard of their sign and value. This is true for both, cost and travel time parameters as well as additional parameters like the availability of a public transport season ticket. The negative parameter values for cost and travel time and the more negative perception of travel time when riding a bike or using public transport compared to driving a car, which can be explained by the effort needed for long bike rides and the discomfort of travelling with other people in crowded vehicles in public transport, are in line with other literature results (König, Axhausen, & Abay, 2004; Koppelman & Bhat, 2006).

According to the field of operation, there are various options to adopt the index: At present, different designs of cycle facility are analyzed in an aggregated way. Here, differently recorded infrastructures (i.a. bike lane vs. bike path) could be evaluated in detail. The parameter used for road categories indicates the importance of each road for motorized transport. In the present study, this parameter approximates the level of disturbance cyclists experience due to passing vehicles. Results show that the road network configuration differs between statistic units but extreme differences in the results are rare. Future research could take account of road construction standards, such as the number of lanes or speed limits, as shown in earlier studies described in the literature review section, and evaluate whether significant interrelations can be observed. It could also include parameters approximating bicycle parking and surface quality since these categories were mentioned in the expert survey. This information is not included in OSM in sufficient quantity at present. Due to exponential growth in OSM, the information may be available in the future. Regarding the parameters used, this index focuses on urban infrastructure that is adaptable to a certain extend. It is therefore meant to understanding bikeability that is in the responsibility of local or regional authorities. When aiming to draw a more comprehensive picture of bikeability than the scope of the present study, future research can easily integrate control variable like topography which may also be extracted from OpenStreetMap.

As main benefit the present approach enables assessing bikeability on any spatial level in large parts of the urbanized world. Hence, the present research lays the foundations for diverse large-scale analyses and may upgrade earlier results by refining the approximation of bikeability (Buehler & Pucher, 2011; Winters, et al., 2013; Winters, et al., 2016) and integrating comparable bikeability measures in cross-nation comparisons (Buehler, 2011).

3.1.6 Conclusion

A consensual and fully transferable approximation of bikeability has been developed. Gathering parameters in a comprehensive literature review and confirming as well as merging these components in an expert process ensures a broad consensus. Using open data only guarantees nearly unlimited transferability. The method lays the foundation for large-scale analyses evaluating the impact of bikeability on cycling mode shares and other dependent variables regardless of administrative borders and according limitations in data availability. Being able to assess bikeability with high spatial resolution in an automated process will make it possible to carry out comprehensive large-scale analyses on interrelations between bikeability and for example public health or collision rates. The example of

Berlin shows that the index adds a significant parameter with high impact when aiming to explain choosing the bike as mode of transport.

The method may also be a helpful tool for local and regional decision-makers. When rating bikeability while considering the interaction of components, the method may help municipalities to set priorities for cycling strategies based on detailed local conditions. Due to its granularity, the analysis may provide planning advice at local level by examining potential areas of intervention and local deficiencies in the overall framework. It will also reveal local discrepancies between observed active transport and bikeability and facilitate investigation of the reasons. The authors’ future research will implement large-scale analysis and investigate the impact of bikeability at an individual level by enhancing transport mode choice models.

3.1.7 Declarations

3.1.7.1 Conflicts of interest/Competing interests

The authors declare no conflict of interests.

3.1.7.2 Availability of data and material

The data that support the findings of this study are available upon reasonable request from the authors.

3.1.7.3 Funding

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3.1.8 References

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4 Routenwahl – Differenzierung mittels Entscheidungsexperiment

Nach Analysen auf der vorgelagerten konzeptionellen Abstraktionsebene zur Bikeability und Untersuchung der Effekte dieser Bikeability auf der Ebene der Verkehrsmittelwahl finden die nachfolgenden Analyseschritte auf der nachgelagerten feineren Ebene der Routenwahl statt. Wie in 1.3.4 beschrieben, bieten Stated-Preference-Ansätze ein etabliertes und geeignetes Instrument zur Analyse von Routenwahlverhalten. Im Radverkehr werden die Potenziale von Entscheidungsexperimenten jedoch noch nicht ausgeschöpft. Der folgende Artikel adressiert die Routenwahl unter sehr unterschiedlichen strukturellen Bedingungen.

Dafür wird ein einheitliches Entscheidungsexperiment in unterschiedlichem räumlich-lebensweltlichem Kontext durchgeführt. Dabei werden die Präferenzen im Routenwahlverhalten zwischen Deutschland, einem Land mit vergleichsweise gut ausgebauter Radinfrastruktur und substanziellen Anteilen des Radverkehrs am Modal Split, mit denen in Griechenland, einem Land mit sehr wenig Radinfrastruktur und kaum Radverkehr, verglichen.

Im Ergebnis stellen sich personenbezogene Unterschiede zwischen den Subgruppen stärker ausgeprägt dar als Unterschiede zwischen den zwei Ländern des Untersuchungsgebietes. Für spezifische Parameter wie Zeitsensitivität oder Geschwindigkeitsbeschränkungen zeigen sich dennoch deutliche Unterschiede nach Ländern. Damit belegen die Ergebnisse, dass bezüglich präferierter Routeneigenschaften selbst zwischen Regionen mit sehr unterschiedlichen Rahmenbedingungen trotz gewisser Abweichungen ein prinzipieller Konsens herrscht.

4.1 Evaluating Cyclists' Route Preferences with Respect to Infrastructure

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Abstract: Providing a sufficiently appropriate route environment is crucial to ensuring fair and safe biking, thus encouraging cycling as a sustainable mode of transport. At the same time, better understanding of cyclists' preferences regarding the features of their routes and their infrastructure requirements is fundamental to evaluating improvement of the current infrastructure or the development of new infrastructure. The present study has two objectives. The first is to investigate cyclists' route preferences by means of a choice experiment based on a stated preference survey. Subsequently, the second objective is to compare cyclist preferences in two countries with different cycling characteristics (both in infrastructure as well as cyclists' behavior). For this purpose, a graphical online stated preferences survey was conducted in Greece and Germany. Within the framework of statistical analyses, multinomial mixed logit discrete choice models were developed that allow us to quantify the trade-offs of interest, while distinguishing between the preferences of different user groups. In addition, user requirements in Greece, as a country with a low cycling share and very little dedicated bike infrastructure, were compared to the requirements in Germany, where cycling is popular and the infrastructure is well developed. The results over the whole sample indicate that subgroups value infrastructure differently according to their specific needs. When looking at country specifics, users from Greece are significantly more willing to accept longer travel times in return for higher-quality facilities. The utility of low speed limits in mixed traffic is also different. In Germany, low speed limits offset the disturbance caused by motorized traffic, but in Greece they do not. Consequently, the results help to asses which types of infrastructure are most sustainable from a user perspective and help to set priorities when the aim is to adapt the road infrastructure efficiently in a stable strategy.

Keywords: sustainable transport; active mobility; cycling; bike infrastructure, route choice survey; discrete choice experiment; route environment

4.1.1 Introduction

4.1.1.1 Background

Cycling in cities has positive impacts on public health (De Hartog, Boogaard, Nijland, & Hoek, 2010; Frank et al., 2006; Mueller, et al., 2018), space requirements, and noise and air pollution (Frank, et al., 2006) in several ways. At the same time, cycling rates are rising in many cities around the world, and a growing number of cities and municipalities are encouraging people to take up cycling. Enhancing the infrastructure is therefore of major importance, as insufficient infrastructure is a significant barrier. Consequently, infrastructure investments are the main focal point of municipal cycle strategies. To meet the demand of cyclists, it is crucial to have a good understanding of cyclists' route choice behavior. There are many different options possible when looking at bike routing. There are generally different types of infrastructure solutions that are practicable for main roads, as well as regulatory measures for both main and side roads. For example, protected bike lanes along main streets, as a rather new type of infrastructure, compete with cycle paths on the pavement or marked bike lanes (Monsere & McNeil, 2019). Alternatively, it appears desirable to cycle in mixed traffic along calm roads of different types. Cycle streets, however, did not exist in many countries or were used very rarely (Blitz, Busch-Geertsema, & Lanzendorf, 2020).

Knowledge of these route preferences with regard to the types of bikes used is essential. Previous research on route choice has increased our understanding, but, recently, the proportion of cyclists and public interest in cycling has increased dramatically. In addition, since there is an increasing division between areas with booming cycle traffic and those where cycling is stagnating at a low level, more knowledge about specific preferences and interactions is needed.

At the same time, we are experiencing several developments and recent dynamics that impact the field of research on this topic. In many urban areas in the global north, cycling as a mode of transport is being revived (Lanzendorf & Busch-Geertsema, 2014; Pucher & Buehler, 2017; Carlton Reid, 2017). In contrast, there are cities where cycling still does not play a significant role in everyday transport (Buehler & Pucher, 2012; Clark, et al., 2019; Morgan, 2019).

Based on the above, the present study had two main objectives. The first was to investigate cyclists' route preferences by means of a choice experiment based on a stated preference survey. Subsequently, the second objective was to compare cyclist preferences in two countries with different cycling characteristics. Accordingly, the study is conducted in Germany, as a country with relatively high cycle mode shares and a supply of cycle infrastructure, and Greece, a country with little cycle traffic and almost no dedicated bike infrastructure.

The manuscript is structured as follows. First, a brief overview of similar studies is provided. Second, the methodology of designing the experiment, gathering data, and modeling is described. Then, results are presented and discussed, while in the final step, conclusions are drawn.

4.1.1.2 Literature Review

This section provides an overview of research investigating cyclists' route preferences. There are different established approaches for investigating cyclists' route preferences and the impact of a corresponding road infrastructure.

- Cross-sectional studies use geodata and mobility data in different reference areas to analyze interrelations between cycling levels and properties of the road network (Sallis, et al., 2015; Winters, et al., 2016).
- In stated preference studies, participants are asked in hypothetical choice situations which type of infrastructure they prefer. Cyclists and non-cyclists may be surveyed, and the results are differentiated between socio-demographic factors (Clark, et al., 2019; Mertens, et al., 2016; Vedel, et al., 2017).

- Revealed preference studies gather data on actual roads taken by cyclists via GPS, e.g., from bike sharing or apps. Subsequently, conclusions are drawn regarding route choice behavior based on estimated alternatives (Broach, et al., 2012; Ghanayim & Bekhor, 2018; Prato, et al., 2018; M. Zimmermann, et al., 2017).

- Interventional studies designed to evaluate measures use case studies to investigate changes in cycling rates before and after infrastructural interventions (Ghosh, et al., 2016; Gössling, et al., 2019; Mölenberg, Panter, Burdorf, & van Lenthe, 2019; Thakuriah, et al., 2012).

- Meta-analysis or reviews on interrelations between transport and urban form summarize findings from previous studies (Buehler & Dill, 2016; R. Ewing & Cervero, 2010; Wang, et al., 2016). In addition, planning advice is offered based on a literature review (Forsyth & Krizek, 2010).

Regarding the methodological approach of the present study, the following literature review focuses on stated preference studies. These are a well-established method when researching individual preferences for defined alternatives, and in transport research, they have been applied in various settings in general (Ben-Akiva & Bierlaire, 1999; Hensher, 1994) and in the case of bike infrastructure preferences in particular (Aldred, et al., 2016). In recent years, there has been a growing body of empirical research on cyclists' preferences using stated preference methods, as summarized below.

In this context, most studies focus on road design and bike infrastructures. A study presented by Clark et al. (Clark, et al., 2019) investigates various types of bike infrastructure, number of car lanes, and car parking. Test persons are asked specifically about convenience, safety, and willingness to try the corresponding route. Vedel et al. included road characteristics and surroundings, the specific types of bike infrastructure, and operational measures of stops and bicycle crowding in Copenhagen, Denmark (Vedel, et al., 2017). Winters and Teschke conducted a similar study by varying several parameters of the road, and focused on differences regarding potential cyclists in Vancouver, Canada (Winters &

Teschke, 2010). A North-America-wide survey investigated various road characteristics with respect to the specific type of bike infrastructure, properties of the road, such as roadway class and parking as well as number, and types of crossings on the route (Stinson & Bhat, 2003). In a study by Sener et al. (Sener, et al., 2009), the influence of parking, type and width of facility, and number and type of crossings, as well as speed limits and traffic volume, are evaluated among cyclists in Texas. In a study conducted by Abraham et al. (Abraham, et al., 2002) in Calgary, a long list of attributes was included without using visualizations. Travel times on different route types were presented to the respondents to add up to the total travel time. The authors also included facilities such as changing rooms at the destination. A similar approach was used in Edmonton, Canada, including destination facilities (Hunt & Abraham, 2007).

Other studies focus on infrastructures as well, but do not take different road types or categories into account. A study conducted by Poorfakhraei and Rowangould (Poorfakhraei & Rowangould, 2015) in Albuquerque, New Mexico evaluates the willingness to pay for improvements regarding the implementation of cycle tracks, bike lanes, or street lighting. Videos of riding bikes on different types of infrastructures were shown to the probands. The research of Tilahun et al. (Tilahun, et al., 2007) is methodologically similar; it showed short video clips to test persons and used an adaptive stated preference survey in Minnesota. The authors investigated the impact of two types of infrastructure along streets, one off-street solution and parking. Mertens at al. conducted a study in Belgium with several road characteristics regarding design and condition as well as greenery and operational measures, such as speed limits and traffic density (Mertens, et al., 2016). Caulfield et al. varied only four attributes (plus travel time) in a study in Dublin, Ireland (Caulfield, et al., 2012). The authors investigated the type of infrastructure, number of crossings and traffic speed, and volume of cycle traffic.

Further studies increase the scope of specific research questions. The direct surroundings of public transport stations in Tianjin, China are evaluated by Liu et al. (Liu, Yang, Timmermans, & de Vries, 2020) in order to investigate which attributes are relevant for pedestrians and cyclists. Another study, based in Berlin, Germany, investigates the influence of different levels of street greening on cyclists' route choices (Nawrath, Kowarik, & Fischer, 2019). A study conducted in Santiago de Chile investigates reasons for bike commuters to ride on the sidewalk (Rossetti, Saud, & Hurtubia, 2019). The authors consider the existence and width of a bike lane as well as operational measures, such as the presence of pedestrians and buses, characteristics of the sidewalk, and surrounding land use.

Content-related prior research found mixed results. Here, only Stinson and Bhat (Stinson & Bhat, 2003) see residential roads as a first choice in comparison to arterial roads with separated facilities, while Sener et al. (Sener, et al., 2009) even see a negative impact for bike lanes in Texas, and argue this with the fact of being boxed in. However, in the majority of studies, the conclusion is a preference for separated facilities (Abraham, et al., 2002; Hunt & Abraham, 2007; Vedel, et al., 2017). Here, the existence of a separated facility is referred to as more important than the specific type of facility or other characteristics of the road, such as speed limits or traffic density (Mertens, et al., 2016). When differentiating the type of infrastructure, research results in a preference for bike lanes over cycle tracks (K. J. Krizek, 2007; Tilahun, et al., 2007) or cycle tracks over bike lanes (Poorfakhraei & Rowangould, 2015). When off-street cycle ways are included, some authors conclude that these routes are preferred over separated facilities along main streets (Winters & Teschke, 2010), while others conclude the opposite (Caulfield, et al., 2012) or find almost no difference between high-quality infrastructure and off-street paths (Clark, et al., 2019). Prior research agrees that a smooth surface is important, but several other factors of the route outweigh the impact (Mertens, et al., 2016; Stinson & Bhat, 2003; Winters & Teschke, 2010). The negative effect of on-street parking is verified by (Sener, et al., 2009; Tilahun, et al., 2007).

As is obvious, studies conclude that there is a willingness to avoid disturbances caused by nearby motorized traffic. Cyclists state that they mainly prefer either a separated cycling infrastructure or, less significantly, calm side roads in mixed traffic. The parameters considered vary. The main variable used for differentiating between the types of dedicated cycle infrastructures is accompanied in most cases by road type and surface quality. These are complemented by other specific variables. Except for Stinson and Bhat (Stinson & Bhat, 2003), all cited studies research an isolated local area under investigation. Differences between different regions or spatial locations are not evaluated. Furthermore, most studies are conducted in cities or regions with significant cycle mode shares.

4.1.2 Materials and Methods

Individual route choice behavior is influenced by several parameters of the route environment. At the same time, preferences for certain route characteristics differ strongly between individuals with respect to socio-demographics or bike types used. For this reason, a discrete choice experiment was used as the survey method, which allows differentiation between various factors. In this method, individual route characteristics were composed to create complete route alternatives. One major advantage of this stated preference approach is that cyclists as well as non-cyclists may be surveyed. Hypothetical and non-existent infrastructures can also be evaluated. The latter is particularly important when making a comparison between countries with a different infrastructure status.

4.1.2.1 Designing the Experiment

The questionnaire consisted of three parts. First, the method and objective were briefly described. Second, the actual discrete choice experiment was included. Third, additional questions were asked regarding the users' socio-demographics, mobility behavior, and spatial allocation.

Before proceeding to the core of the questionnaire, a brief description of the key targets of the survey was presented in the first part. The aim was to inform the participant about the scientific scope of the research and the expected results that relate to the development of appropriate municipal strategies on cycling. This introduction is provided in Appendix B. In addition, the following text was displayed during the whole discrete choice experiment (DCE) part of the poll, as guidance for the choice experiment: *On a day in May with good weather conditions, you would like to visit a friend. There are several alternative routes for this trip. Which route do you choose? All answers are your personal preference! There are no right or wrong answers.*

In the second part of the poll, the choice experiment was conducted. Before the experiment, we only asked whether the proband would be riding the bike on the road with children and which type of bike he or she would be using when choosing the following routes. This is to make sure the participants were aware of this difference from the beginning. The design of the actual experiment was extremely important. It included selecting attributes and levels, composing them to create complete alternatives, and combining the alternatives in choice sets. The attributes and levels were therefore defined in a workshop with experts in cycling science from two universities, a cycling advocacy group, a planning office for cycling strategies, non-university research institutions, and the federal environment agency. Based on the selection, a draft design that considered the expected interactions between the attributes was developed by hand. This design was tested and discussed in a focus group. Subsequently, a balanced design was created by hand. This pre-poll was implemented as an online survey using the software lamapoll (Langner, Maibaum, & Notev, 2018). Here, some combinations were omitted in order to obtain a realistic picture. In side streets, for example, there was no cycle infrastructure. Using this design, a pretest was carried out with 41 participants. To enhance the design efficiency, the data gathered in the pretest were used to develop a Bayesian efficient design using Ngene (Bliemer & Rose, 2006; ChoiceMetrics, 2012). In the final design, the duration of the trip as well as six properties of the road and its surroundings were differentiated. Each attribute had two to five possible levels (see Table 4-1). An experiment with eight choice situations, each consisting of three alternatives, was chosen. In order to allow for larger variations within the data collection, three blocks consisting of eight situations each were created. This resulted in a total of 24 choice situations, eight of which were shown to each proband. A no-choice option was also implemented for each choice situation. Each participant was randomly assigned to one of three blocks.

Table 4-1. Attributes and levels of the experiment

Attribute	Levels
Street type	**Arterial road** | Side street
Cycle infrastructure	**No cycle infrastructure** | Bike lane | Cycle path | Protected bike lane
Regulation	**Maximum speed: 50 km/h** | Maximum speed: 30 km/h / Zone 30 | Cycle street (residents only) | Living street
Surface	**Cobblestones** | Asphalt
Parking	No on-street parking | **On-street parking**
Trees	**No trees** | Trees
Travel time [minutes]	8 | 10 | 12 | 15

Bold indicates the reference scenarios. The description of the attributes and levels is included in Appendix A.

The choice situations were described in a tabular form and visualized with drawings (Figure 4-1). In addition, explanations were displayed for the infrastructure types "protected bike lane", "cycle street", and "living street" when hovering over the text. Earlier research proved that images in stated preference surveys are perceived subjectively (Hurtubia, Guevara, & Donoso, 2015). As a result, we did not have any control over features that were not explicitly included in the design, but are perceived by the test person (Hurtubia, et al., 2015); plain black and white drawings were chosen to display the alternatives. On a basic drawing with the same buildings and sidewalk, additional layers with drawings of streets of different sizes, different types of cycle infrastructure, signs indicating different regulations, uneven surfaces, trees, and parked cars were turned on and off to create the illustrations for the 72 different alternatives used.

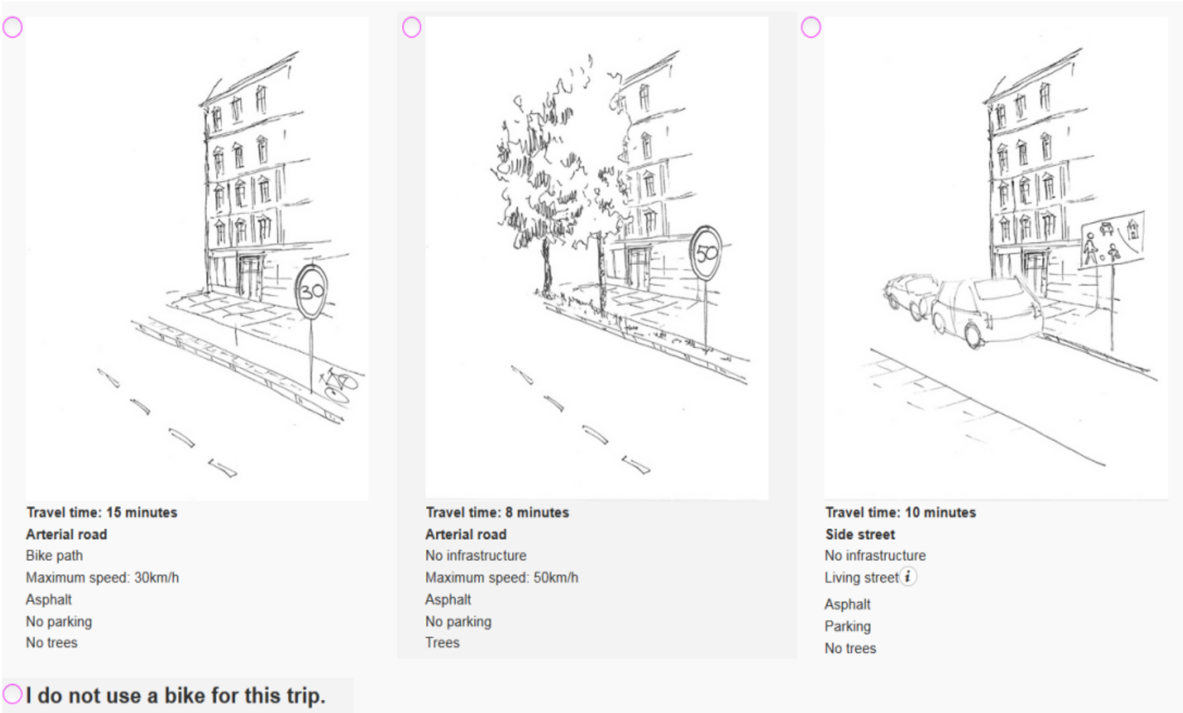


Figure 4-1. Exemplary choice situation

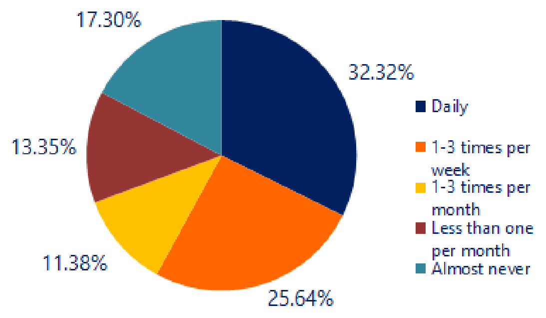
In the third part of the questionnaire, we collected additional information on the participants. These included mobility behavior (frequency of bicycle usage), socio-demographic information (levels of formal education, occupation, gender self-association, and age), and spatial information (country and postcode of permanent residence).

4.1.2.2 Recruitment, Sample, and Subsampling

The data were collected in autumn 2018 (Germany) and spring 2019 (Greece). Participants were recruited using internet, social media (mainly Twitter), cycling associations, universities, the German national cycle portal (nationalerradverkehrsplan.de), and Ecocity, a non-profit environmental organization in Greece. Thus, the sample is self-selective; however, several sample characteristics were evaluated during the survey in order to counterbalance the sample in several characteristics, as presented below.

Participants from other countries and those who filled in the poll with unrealistic speed were removed from the dataset. All incomplete returns were also deleted. After these steps, the dataset consisted of 4,775 individuals. With eight choice situations per individual, this results in 38,200 valid observations. Thus, 4,463 individuals with 35,704 observations were found in the German sample and 312 individuals with 2,496 observations in the Greek sample.

Due to the sampling method, the sample shows some bias in terms of socio-demographics. These distortions appear differently in the two countries under investigation. As is obvious, the German sample is also much larger than its Greek counterpart. We therefore draw a subsample from the German sample that approximates the distribution of socio-demographic variables in the Greek sample. Consequently, we use iterative post-stratification. By doing so, we match the marginal distributions of the German sample to the margins observed in the Greek sample. We use the distributions of the attributes of gender, age, and children. The latter specifies whether or not the participants use the bike with children. As a result, we obtain a German subsample of 350 observations, which approximates the corresponding distribution in the Greek sample. The total size of the dataset used is 662 individuals with 5,296 observations. Participants' characteristics indicate that there is a counterbalanced sample in terms of gender (60% males and 40% females), while with regard to age group, almost half of the participants belong to the 25–44 age groups (44%), with younger participants aged up to 24 years old accounting for 34% and older cyclists for 23% of the sample (Figure 4-2). Another interesting socio-demographic characteristic relates to the fact that 59% of the participants ride with their child. Finally, a similar counterbalance is achieved regarding how often participants ride their bicycle, as all options have similar percentages (highest percentage of daily cyclists).



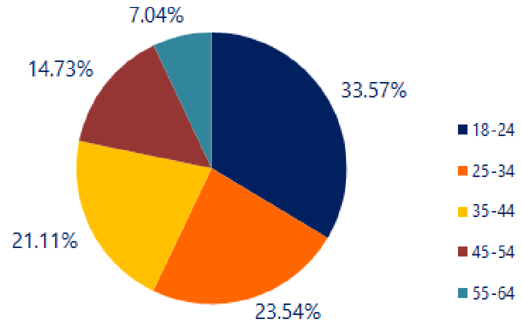


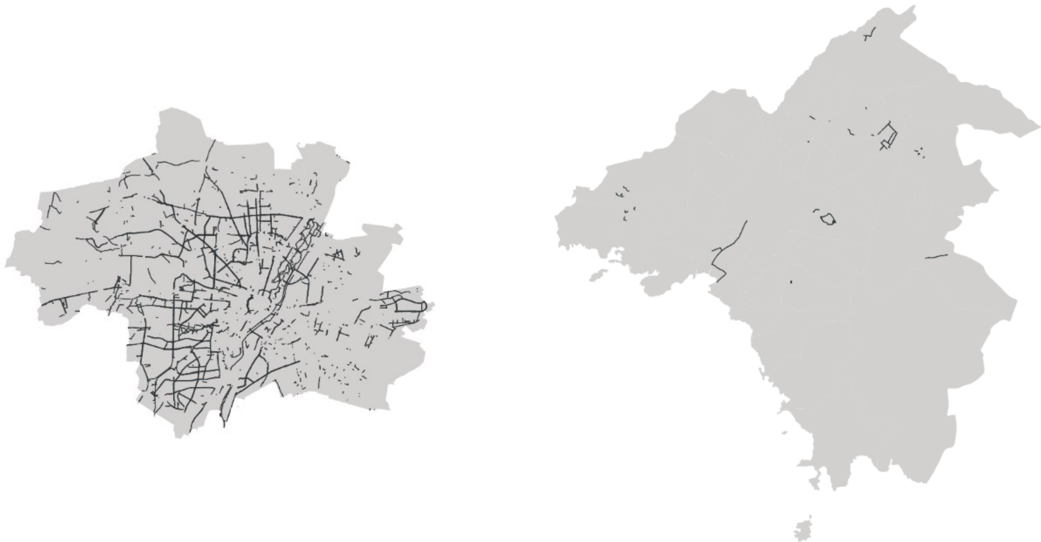
Figure 4-2. Sample characteristics: (**a**) Frequency of cycling; (**b**) age groups [years]

4.1.2.3 Area under Investigation

In Germany, the cycle mode share grew in metropolitan areas from 9% in 2002 to 15% of all trips in 2017, while it stagnated in rural areas (Nobis, 2019). The national cycle plan has formed the basis of cycle policies in Germany since 2002 (Bracher, 2016). In recent decades, many cities and regions have increasingly invested in cycling infrastructure and image campaigns to increase the cycle mode share (Lanzendorf & Busch-Geertsema, 2014). Most recently, starting with Berlin, bottom-up initiatives have been emerging in more and more cities. Initiated by these new actors, legally binding acts now specify high quality standards and wide coverage of the cycle infrastructure for the near future (Becker & Renn, 2019).

In Greece, cities are a hostile environment for cycling. Some of the most serious problems are narrow roads, very poor bike infrastructure, and lack of public transport. As a result, in spite of low-volume traffic flows, roads are congested and lose a lot of their capacity due to illegal parking. In many provincial streets, there are no pavements or they are exceptionally narrow, and general conditions are unsafe and discourage pedestrians. Today, mainly through programs funded by the Ministry of Transport and Ministry of the Interior, 27 Greek cities are equipped with cycling infrastructure, and there are also plans for several more (Vlastos & Bakogiannis, 2015). In addition, the implementation of the Sustainable Urban Mobility Plans in 160 Greek cities is another tool for improving cycling in Greece in the current decade.

Figure 4-3 provides an impression of the different conditions in the two countries under observation. The network of cycle tracks in the two cities, Munich in Germany and Athens in Greece, is displayed on a scale of 1:250,000. As can be seen, the city of Munich provides a dense network of cycle tracks, while in Athens, only a few isolated cycle tracks are available.



(a) (b)

Figure 4-3. Bike infrastructure: (**a**) Munich; (**b**) Athens

4.1.2.4 Model

The theoretical basis of choice experiments was provided with the random utility theory (Domencich & McFadden, 1975). Utility-maximizing behavior by the participants is assumed. The theory claims that people act according to their preferences. The inconsistency of choices that is often observed to some extent is explained by a random parameter. On this basis, the data are analyzed by applying mixed logit models using the software Biogeme (Bierlaire, 2018). We use mixed logit over multinomial logit in order to deal with the panel effect, as it allows the coefficient to vary for different decision-makers. Hence, these models take into account that the eight choices made by each subject are correlated, but heterogeneity exists between the subjects, and they are highly flexible (McFadden & Train, 2000). The choice probability of the mixed logit, as shown in Equation (1), is defined as an integral of logit probabilities over a density of parameters:

$$\boldsymbol{P_{ni}} = \int \left(\frac{\boldsymbol{e^{\beta' x_{ni}}}}{\boldsymbol{\sum_j e^{\beta' x_{nj}}}}\right) \boldsymbol{f(\beta) d\beta} \qquad (1)$$

Accordingly, the probability in the mixed logit is the weighted average (mixed function) of the logit provided by the density (mixing distribution). We also include normal error components for each alternative. The method allows the quantification of the benefit of an alternative compared to the defined reference. As reference, a main road without cycle infrastructure and without trees, with a maximum speed of 50 km/h and on-street parking, was chosen so that any change in the route characteristics represents an improvement for cyclists. Methods of discrete choice modeling were used to estimate utility functions based on the sum of the individual responses (Bierlaire, 2018). We aimed to compare three models: Model 0 evaluates the route attributes used in the DCE (see Table 3-1), model 1 includes socio-demographic interactions (see 4.1.2.2), and model 2 develops interactions regarding the two parts of the area under investigation by adding dummies (see 4.1.2.3).

For model 0, we estimated the extent to which the specific route characteristics influenced the decision for a route using a mixed logit model.

To estimate systematic differences between groups of participants, socio-demographic interactions are implemented in model 1. Here, we proceeded iteratively. First, we explored a large number of possible interactions regarding socio-demographic attributes and combinations of these attributes in the whole sample. For this, we used multinomial logit models due to performance issues. Second, we tested all interactions that were significant in the whole sample, consisting of the two national samples in the nations' samples, separately. Third, we included only those interactions that were significant in all three cases (whole sample and both separate nations' samples). In this case, these are the interaction terms for surface*rarely, which indicates the interaction of a smooth surface with a stated usual frequency of using the bike less than once per week. Fourth, with this specification, we estimate the final model using a mixed logit approach; slow_kids indicates the interaction of the living street and cycle street regulations (slow) with stating cycling with children.

To finally analyze country specifics, in model 2, we estimate systematic heterogeneity between Greece and Germany by testing country dummies. Similarly to model 1, in a first step, we tested many relevant interactions. In a second step, we included only significant interactions. In model 2, these are the interaction of the living street and cycle street regulations (slow) with the country dummy for Greece, and the interaction of the time parameter with the dummy for Greece. For this final model, we used the mixed logit approach.

The utility (U) for a route for an individual (n) as an alternative (j) in a choice situation is specified as the sum of the values of the coefficients (β) and the random error term for the agent effect (EC):

$$U_{nj} = ASC_j + (\beta\_time_n + \beta\_time\_s_n \times Triang) \times time_{nj} + \beta\_slow\_greece_n \times slow\_greece_{nj} + \beta\_time\_greece_n \times time\_greece_{nj} + \beta\_surface\_rarely_n \times surface\_rarely_{nj} + \beta\_kids\_slow_n \times kids\_slow_{nj} + \beta\_sidestreet_n \times sidestreet_{nj} + \beta\_path_n \times path_{nj} + \beta\_protected_n \times protected_{nj} + \beta\_lane_n \times lane_{nj} + \beta\_no\_IS_n \times no\_IS_{nj} + \beta\_living_n \times living_{nj} + \beta\_cycle_n \times cycle_{nj} + \beta\_v30_n \times n30_{nj} + \beta\_v50_n \times v50_{nj} + \beta\_surface_n \times surface_{nj} + \beta\_parking_n \times parking_{nj} + \beta\_trees_n \times trees_{nj} + EC_{nj} \quad (2)$$

The description of the coefficients is included in Appendix A.

Equation (2) is presented using the example of model 2. In model 1 and model 0, the interaction parts are omitted with regard to socio-demographics and socio-demographics with country specifics, respectively. All mixed logit models used for the final estimations were estimated using 700 draws. Thus, the time parameter was distributed triangularly in order to obviate positive values in the distribution. We performed chi-square-based likelihood ratio tests to compare the models.

4.1.3 Results

The estimation results are presented in Table 4-2. Model 0 takes only route characteristics into account, while model 1 also includes socio-demographic interactions, and model 2 extends model 1 by adding country dummies.

Table 4-2. Estimation results

	Model 0		Model 1		Model 2	
Parameter	**Est. value**	**t-value**	**Est. value**	**t-value**	**Est. value**	**t-value**
ASC_1	4.04	8.49	3.71	8.23	3.48	8.09
ASC_3	4.16	8.71	3.82	8.47	3.60	8.33
ASC_2	3.97	8.34	3.64	8.08	3.42	7.92
β_lane	1.39	14.4	1.39	14.48	1.37	14.32
β_path	1.90	18.7	1.91	18.88	1.89	18.81
β_protected	2.57	24.89	2.58	25.07	2.56	25.05
β_sidestreet	0.64	6.32	0.62	6.12	0.60	5.94
β_time	−0.14	−12.78	−0.14	−12.95	−0.17	−13.33
β_time_s	0.28	4.28	0.25	3.71	0.20	2.62
SIGMA_1	−0.06	−0.51	−0.04	−0.35	−0.02	−0.18
SIGMA_2	−0.01	−0.12	−0.01	−0.12	−0.01	−0.09
SIGMA_3	−0.00	−0.05	−0.00	−0.02	−0.01	−0.08
SIGMA_4	2.40	9.25	2.13	8.94	2.13	9.21
β_cycle	1.88	17.8	1.73	15.07	2.15	17.84
β_kids_slow	-	-	0.29	3.57	0.38	4.62
β_living	0.85	12.05	0.71	8.28	1.12	12.24
β_v30	0.30	6.92	0.30	7.11	0.30	7.02
β_parking	0.54	14.75	0.54	14.87	0.55	14.90
β_slow_greece	-	-	-	-	−1.13	−13.39
β_surface	1.26	16.22	1.58	16.51	1.69	17.38
β_surface_rarely	-	-	−0.74	−6.41	−0.92	−7.86
β_time_greece	-	-	-	-	0.07	5.06
β_trees	0.29	8.73	0.29	8.80	0.30	9.12
Model fit						
LL (null model)	−5803.38		−5804.39		−5709.11	
LL(final)	−5684.28		−5658.25		−5537.18	
Est. parameters	19.00		21.00		23.00	
Rho square	0.02		0.022		0.03	
LL ratio test (initial model)	238.21		292.28		343.86	

Gray values are not significant at the 95% level. The description of the coefficients is included in Appendix A, and comprehensive results are in Appendix C.

The results indicate that all parameters show the expected sign and plausible values. This means that all improvements in road characteristics compared to the reference are assigned higher utilities for the user, while travel time has a negative utility. For all route attributes under consideration, a significant impact on route choice is demonstrated. In addition, the alternative specific constants (ACS) show similar values for the three alternatives in all three models. This is most plausible, as all proposed route alternatives vary randomly over the alternatives. Regarding the error term, the results show insignificance for alternatives one to three. Only the no-choice option (4) differs significantly. This can be explained by some individuals choosing not to cycle at all several times, while the majority almost always chose a defined alternative.

The route attributes are organized along the topics of dedicated bike infrastructure (bike lane, bike path, and protected bike lane), regulation (living street, cycle street, 30 km/h), other factors of the road (side street, on-street parking, surface, and trees), and travel time. In addition, model 1 includes socio-demographic interactions (slow_kids and smooth_surface_rarely). Model 2 includes both socio-demographic interactions and country dummies (time_greece and slow_greece). Regarding dedicated bike infrastructure, values for the different types vary substantially. The values for the three types of dedicated bike infrastructure show that cyclists value the alternatives very differently. The highest utility over all parameters is presented for bike lanes that are protected from motorized transport by bollards. This coefficient shows very high values of more than 2.5. A physical bike path (1.9) and a painted bike lane (1.39) show high but clearly lower utilities. Regarding different types of regulation, it is seen that a cycle street, as a street type with priorities for cyclists, shows a very high utility (1.88). Apart from dedicated infrastructure, a cycle street is the most popular attribute. With a value of 0.85, a living street has a much lower utility. The utility for a reduced speed limit of 30 km/h (0.297) is very low by comparison. Regarding other factors of the road, a smooth surface shows a high utility (1.26), while a side street instead of a main street (0.643), absence of on-street parking (0.539), and trees along the street (0.288) are less important for route choice. With a value of 0.14, a longer travel time has a clear disutility.

The socio-demographic interactions implemented in model 1 show two fundamental trends. Firstly, low speed limits (living street and cycle street) are much more beneficial for those travelling with children. The interaction term has a value of 0.288, which is added onto the values for the living street and cycle street in model 1. Secondly, the utility of a smooth surface is lower for people stating that they cycle only rarely (less than once per week). The term of −0.739 indicates that a smooth surface means a much lower utility for people who state that they cycle only rarely.

In model 2, the country specifics are evaluated. The results indicate that higher travel time is linked to significantly less disutility in Greece than in Germany. The interaction term of time_greece has a value of 0.673. Compared to the global value of the time parameter in model 2 (−0.171), this indicates a major difference between the two countries under investigation. Furthermore, in the Greek sample, the utility of cycling in slow mixed traffic (living street and cycle street) is much lower than in Germany (−1.13).

Values for both rho-square and log likelihood increase in the more complex models 1 and 2, while the likelihood ratio tests are positive at the 95% level, proving the increased goodness of fit of both models.

4.1.4 Discussion

The present study had two main objectives. The first was to investigate cyclists' route preferences through a choice experiment based on a stated preference survey. Subsequently, the second objective was to compare cyclist preferences in two countries with different cycling characteristics (both in infrastructure as well as cyclists' behavior), Greece and Germany.

Regarding the first objective, the results indicate that dedicated bike infrastructure along main streets as well as good surface quality are highly beneficial to road users. Thus, the utility increases with the level of separation. Protected bike lanes are most desirable. Here, the current research is in line with the recent results of Clark et al. (Clark, et al., 2019). In mixed traffic, cycle streets that give priority to cyclists were perceived as much more beneficial than living streets, which are defined by a very low speed limit. The utilities for using a side street instead of a main street, no parked cars, and a lower speed limit (30km/h) are relatively low. Interestingly, in this study, a reduced speed limit of 30 km/h is less beneficial to cyclists than the absence of parked cars. When taking the state of research into account, it is assumed that the utility of dedicated infrastructure is lower in real life. This means that cyclists tend to prefer separated infrastructure, but do use calm streets without facilities more often when comparing the results to revealed preference surveys (Buehler & Dill, 2016). Finally, significant positive utility from street greening can be measured, even though it is comparatively very low, a statement that is supported by Nawrath et al. (Nawrath, et al., 2019). In the present research, the utility for trees along the street is almost the same as that for a speed limit reduced to 30 km/h.

Furthermore, the data show several fundamental trends when evaluating interactions. Utilities of low speed limits in mixed traffic are much higher when cycling with children. This is very plausible, as the need for safety is higher when on the road with children (Bakogiannis, Siti, Vassi, Christodoulopoulou, & Eleftheriou, 2014). In addition, when cycling with slow kids, very low speed limits certainly do not slow cyclists any further, as they are already cycling slowly anyway. Interestingly, these interrelations are not seen to a large extent for dedicated bike infrastructure. Another insight relates to the importance of surface quality. This is of much less utility for respondents who state that they cycle on an irregular basis. This can be verified by the impression that cycling on uncomfortable cobblestones may be acceptable for a sporadic trip, but not for regular commuting. Interestingly, unlike earlier research, we did not find any consistent impact of gender (Aldred, et al., 2016).

A unique contribution of the present research refers to the comparison of two countries, Germany and Greece. As described above, cycling mode shares as well as the amount and quality of the infrastructure are very different in Germany and Greece. To analyze whether these differences are interrelated with different route choice behaviors, several interactions with country dummies were tested. Model 2 indicated two significant interactions. Firstly, it can clearly be seen that the utility for low speed limits is much less in Greece. This shows that for Greek respondents, low speed limits reduce the disturbances by motorized traffic to a much smaller extent. It is assumed that this is connected to the perception of the safety-in-numbers effect, which means that accidents increase less than proportionally to the traffic volume of cyclists (Elvik & Bjørnskau, 2017). With fewer cyclists present in traffic, motorists tend to pay less attention. This interrelation can also be explained by less willingness to obey traffic rules generally in Greece (Vlastos, 2007). A corresponding interrelation regarding dedicated bike infrastructure cannot be found. Apart from that, the time parameter is significantly less negative in the Greek sample. This means that travel time is perceived less negatively here. Consequently, cyclists would accept longer detours in order to account for better route characteristics. Both country-specific interaction terms, the one for slow speed limits and the one for travel time, show high magnitudes. This shows that the differences between the two countries under observation are great.

Considering some limitations of the present study, the research is based on a self-selective distorted sample in two countries. Thus, a varying amount of social media visibility was necessary to obtain returns. This implies a bias in the data. The parent population for this research is not the whole population of the country, but people who are at least interested in cycling as a mode of transport. Hence, a representative sampling would not be beneficial. As we draw a weighted subsample for the German part and test for individual interactions, including controlling thereof, distortions between the two countries under observation are assessed as unproblematic. Furthermore, most studies cited above do not use representative samples (Abraham, et al., 2002; Caulfield, et al., 2012; Hunt & Abraham, 2007; Liu, et al., 2020; Mertens, et al., 2016; Nawrath, et al., 2019; Poorfakhraei & Rowangould, 2015; Rossetti, et al., 2019; Sener, et al., 2009; Stinson & Bhat, 2003; Tilahun, et al., 2007; Vedel, et al., 2017).

In the choice experiment, all characteristics except for the travel time were represented graphically. This may lead to this component being considered differently, as well as to a potential under-estimation of the negative utility implied by the time parameter. In addition, there are levels of attributes that are not currently common in the observation area. These particularly account for protected bike lanes and cycle streets. Some users may be inexperienced regarding these infrastructures. On the other hand, researching nonexisting alternatives and hypothetical decisions is a major strength of the stated preference approach (Hurtubia, et al., 2015).

Finally, as a proposal for further research, a predictive platform market can be used instead of a questionnaire survey. On the predictive markets, platform users try to predict the probability of certain events. This is the result of asking participants not only to perceive reality, but also to estimate the probability of the event appearance on the market. The advantage of predictive markets is the so-called wisdom of the crowd, which leads to the use of diversified knowledge (Czwajda et al., 2019).

4.1.5 Conclusion

The present study uses a questionnaire survey (discrete choice experiment) in two countries with different cyclists' characteristics, both in terms of infrastructure and significance of the bike as mode of transport in everyday traffic. Subsequently, three models were implemented: One considering only route characteristics, a second also including socio-demographic interactions, and a third adding the country dummies. Overall, the proposed methodological approach improves knowledge and provides new insights regarding the cyclist's preferences in route choice.

The main findings of the research are presented below:

- Dedicated bike infrastructure, referring especially to protected bike lanes, indicates stable high utilities across subgroups and the different countries, highlighting that providing dedicated space for bicycles is effective in creating places that appeal to cyclists.
- Route preferences do not generally differ between Greece, as a country with low cycling shares and a less developed bike infrastructure, and Germany, as a country with much cycle traffic and a comparatively well-developed infrastructure. Moreover, differences in subgroups regarding socio-demographics or mobility behavior are limited. Both statements indicate that the selection of the route for a cyclist is

not, in general, affected by the regional characteristics of riders, but is based on independent characteristics of the route.

- On the other hand, for particular characteristics, preferences between the countries appear quite differently. These are in line with the perception of different mobility cultures in the investigation areas. For instance, low speed limits in mixed traffic are much less beneficial in Greece than they are in Germany, highlighting the different users' behaviors that exist in the countries examined.

Based on the key findings above and the overall research results, the following practical recommendations, which are crucial for both stakeholders and policy makers, may be extracted:

- Implementing dedicated bike infrastructure along main streets appears to be a stable strategy, regardless of individual and local characteristics. From the user's perspective, the separated bike infrastructure, which brings order and predictability to streets, is preferred across all subdivisions. In this way, expanding a network of preferably segregated infrastructure appears to meet stable demand, always considering that this requires smart investment and careful planning.
- With regard to the alternative strategy—integrating cyclists into mixed traffic by lowering speed limits—no general statements can be made. Here, preferences appear more diverse regarding both socio-demographic characteristics and regional particularities. The results show that requirements for several subgroups can be met by such a strategy, but it is less of a one-size-fits-all approach. Consequently, good knowledge of local particularities is crucial to ensuring that such a strategy will be widely accepted and, in particular, supports the needs of vulnerable groups.

4.1.6 Declarations

4.1.6.1 Author Contributions

M.H.: Conceptualization, data curation, formal analysis, methodology, visualization, writing—original draft, writing—review and editing; P.P.: Data curation, funding acquisition, investigation, writing—review and editing.

4.1.6.2 Funding

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4.1.6.4 Conflicts of Interest

The authors declare no conflict of interest.

4.1.7 Appendix A.

Table 4-3. Survey parameters

Attribute	Level	Description	Coefficient
Street type	Arterial road	Wide road with two lanes for motorized traffic in each direction. Road has a center marker.	-
	Side street	Narrow street without markings for motorized traffic.	β_sidestreet
Cycle infrastructure	No cycle infrastructure	There is no dedicated cycle infrastructure. Bikes and cars share use the same roadway in mixed traffic.	β_no_IS
	Bike lane	Marked lane or cyclists on street level.	β_lane
	Cycle path	Path on the sidewalk level.	β_path
	Protected bike lane	Protected bike lanes are located on street level. They are separated from motorized vehicles by bollards.	β_protected
Regulation	Maximum speed: 50 km/h	The maximum permitted speed for motorized traffic is 50 km/h. The right of way is regulated by traffic signs.	β_v50
	Maximum speed: 30 km/h	The maximum permitted speed for motorized traffic is 30 km/h. In arterial roads: The right of way is regulated by traffic signs. In side streets: Right over left, as is standard.	β_v30
	Cycle street	Cycle streets give priority to cyclists. Access for residents in motorized vehicles is allowed, with a speed of up to 30 km/h. Cyclists must not be endangered or hindered. If necessary, vehicles have to slow down further. Cycling side by side is allowed.	β_cycle
	Living street	Maximum speed is walking pace. Pedestrians and playing children may use the full width of the road. Pedestrians must not be endangered or hindered. If necessary, vehicles have to wait. Pedestrians must avoid unnecessarily obstructing vehicle traffic.	β_living
Surface	Cobblestones	The surface is bumpy and consists of cobblestones.	-
	Asphalt	The surface is smooth and consists of asphalt.	β_surface
Parking	No on-street parking	No cars are parked.	β_parking
	On-street parking	Cars are parked at the side on street level.	-
Trees	No trees	There are no trees along the street.	-
	Trees	Trees line the street at sidewalk level.	β_trees
Travel time	8 | 10 | 12 | 15	The travel time for the alternative in minutes.	β_time
Interaction terms			
		Cycle street or living street	slow
		Cycling on the road with kids	kids
		Less than once per week	rarely
		Country dummy for Greece	greece

4.1.8 Appendix B.

Welcome to the cycling route choice survey

In recent years, the proportion of bicycle trips has increased significantly. Simultaneously, cities and municipalities aim to support increased cycling. To allow for appropriate municipal cycle strategies, knowledge on cyclists route choice behavior is crucial. Against this background, the Institute of Transport Research at the German Aerospace Center is carrying out a study on route preferences.

Therefore, your statements as road user are of fundamental importance.

Based on the results, we give recommendations for the future expansion of the cycle infrastructure.

I have read the privacy policy and accept it.

Note: You can only participate in the survey if you accept the privacy policy.

Yes No

continue ›

Survey instructions:
In the next questions you will see three different alternatives for a cycling route.
The individual routes may seem similar but have several different street characteristics. The alternatives also **vary in travel duration due to differences in route distance.**

All route characteristics are illustrated in the pictures, except for travel time, which is written under each picture. When pointing on *i* additional information is provided.

Please select one of the displayed cycling routes that you would choose.
The survey method requires comparing a variety of similar choice situations, therefor you will be questioned in **eight choice situations**.

Please imagine the following situation:
On a day in May with good weather conditions you would like to visit a friend. There are several alternative routes for this trip. Which route do you choose?

All answers are your personal preference! There are no right or wrong answers.

continue ›

Figure 4-4. Introduction and survey instructions

4.1.9 Appendix C.

Table 4-4. Model estimation results

	model 0			model 1			model 2		
Parameter	Value	t-test	Std err	Value	t-test	Std err	Value	t-test	Std err
ASC_1	4.04	8.49	0.476	3.71	8.23	0.451	3.48	8.09	0.431
ASC_3	4.16	8.71	0.478	3.82	8.47	0.452	3.6	8.33	0.432
ASC_2	3.97	8.34	0.477	3.64	8.08	0.451	3.42	7.92	0.431
β_lane	1.39	14.4	0.0966	1.39	14.48	0.0962	1.37	14.32	0.0954
β_path	1.9	18.7	0.102	1.91	18.88	0.101	1.89	18.81	0.1
β_protected	2.57	24.89	0.103	2.58	25.07	0.103	2.56	25.05	0.102
β_sidestreet	0.643	6.32	0.102	0.621	6.12	0.102	0.601	5.94	0.101
β_time	−0.14	−12.78	0.0109	−0.141	−12.95	0.0109	−0.171	−13.33	0.0129
β_time_s	0.283	4.28	0.0662	0.254	3.71	0.0684	0.196	2.62	0.0747
SIGMA_1	−0.0582	−0.51	0.114	−0.0426	−0.35	0.121	−0.0299	−0.18	0.164
SIGMA_2	−0.00891	−0.12	0.0757	−0.00896	−0.12	0.0742	−0.00676	−0.09	0.073
SIGMA_3	−0.0044	−0.05	0.0969	−0.00225	−0.02	0.0999	−0.00893	−0.08	0.106
SIGMA_4	2.4	9.25	0.259	2.13	8.94	0.238	2.13	9.21	0.231
β_cycle	1.88	17.8	0.106	1.73	15.07	0.115	2.15	17.84	0.121
β_kids_slow	-	-		0.288	3.57	0.0806	0.383	4.62	0.083
β_living	0.853	12.05	0.0708	0.706	8.28	0.0852	1.12	12.24	0.0918
β_v30	0.297	6.92	0.0429	0.304	7.11	0.0427	0.299	7.02	0.0426
β_parking	0.539	14.75	0.0365	0.54	14.87	0.0363	0.546	14.9	0.0366
β_slow_greece	-	-	-	-	-	-	−1.13	−13.39	0.0842
β_surface	1.26	16.22	0.078	1.58	16.51	0.0956	1.69	17.38	0.0975
β_surface_rarely	-	-	-	−0.739	−6.41	0.115	−0.924	−7.86	0.118
β_time_greece	-	-	-	-	-	-	0.0673	5.06	0.0133
β_trees	0.288	8.73	0.033	0.289	8.8	0.0328	0.301	9.12	0.033
model fit									
LL (null model)	−5803.381			−5804.387			−5709.107		
LL(final)	−5684.278			−5658.247			−5537.178		
Est. parameters	19			21			23		
Rho square	0.017			0.022			0.026		
LL ratio test (initial model)	238.206			292.279			343.858		

Gray values are not significant at the 95% level.

4.1.10 References

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5 Routenwahl – Differenzierung mittels Navigationsdatenanalyse als neue Datenquelle

Nach der Analyse des Routenwahlverhaltens mittels des etablierten Werkzeugs des diskreten Entscheidungswahlexperiments wird im Folgenden auf der Ebene der Routenwahl verblieben, jedoch ein anderer methodischer Ansatz angewandt. Wie in 1.3.6 beschrieben, weisen die Ergebnisse verschiedener methodischer Ansätze gewisse Diskrepanzen auf. Der folgende Artikel versucht hier, das Bild zu vervollständigen und abzurunden, indem eine weitere Datenquelle erschlossen wird.

Dafür werden die Daten einer Software zur Navigation im Radverkehr genutzt. Dabei werden für ein Jahr die durch die Nutzenden getätigten Einstellungen zu gewünschten Routeneigenschaften für die jeweilige Strecke aufgezeichnet. Damit können eine sehr große Datenmenge und Eingaben ohne Befragungssituation gewonnen werden. Die Daten werden geclustert, um darunterliegende Präferenztypen zu ermitteln.

Es zeigen sich fünf stabile aus der Vielzahl der möglichen getätigten Einstellungen herausgehende Präferenzcluster. Inhaltlich stärken die Ergebnisse die Rolle ruhiger Nebenstraßen als Fahrradrouten. Damit vervollständigen die Ergebnisse das Bild und ergänzen insbesondere die Ergebnisse der Stated-Preference-Ansätze.

5.1 Assessing cyclists' routing preferences by analyzing extensive user setting data from a bike-routing engine

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Routenwahl – Differenzierung mittels Navigationsdatenanalyse als neue Datenquelle

Abstract: Many municipalities aim to support the uptake of cycling as an environmentally friendly and healthy mode of transport. It is therefore crucial to meet the demand of cyclists when adapting road infrastructure. Previous studies researching cyclists' route choice behavior deliver valuable insights but are constrained by laboratory conditions, limitations in the number of observations, or the observation period or relay on specific use cases. The present study analyzes a dataset of over 450,000 observations of cyclists' routing settings for the navigation of individual trips in Berlin, Germany. It therefore analyzes query data recorded in the bike-routing engine BBBike and clusters the many different user settings with regard to preferred route characteristics.

Results condense the large number of routing settings into characteristic preference clusters. Compared with earlier findings, the big data approach highlights the significance of short routes, side streets and the importance of high-quality surfaces for routing choices, while cycling on dedicated facilities seems a little less important.

Consequentially, providing separated cycle facilities along main roads – often the main focal point of cycle plans – should be put into the context of an integrated strategy which fulfills distinct preferences to achieve greater success. It is therefore particularly important to provide a cycle network in calm residential streets as well as catering for short, direct cycle routes.

Keywords: active travel; bicycle route choice; navigation data; preference types

5.1.1 Introduction

Regarding negative external effects, the bicycle is an attractive mode of transport. In recent years, many western cities have seen an increase in cycling rates (Lanzendorf & Busch-Geertsema, 2014; Nobis, 2019; Woods, 2020). Most recently, due to the covid-19 pandemic bicycle use increased strongly while utilization of public transport declined (Nobis, et al., 2020; Tirachini & Cats, 2020; Woods, 2020). This stresses the long-term importance of supporting the bicycle as alternative mode of transport and as feeder to boost public transport (Geurs, La Paix, & Van Weperen, 2016). One important measure aimed at supporting the uptake of cycling is adapting the urban infrastructure to meet the demand of cyclists. Accordingly, cyclists' route choice behavior and preferences are highly relevant in planning and practice. To assess this behavior, previous studies are based mainly on two research approaches:

- In revealed preference studies (RP), the actual behavior is observed. Most recent studies track cyclists and compare the route chosen to potential alternatives to evaluate the impact of route characteristics on route choice (Bernardi, La Paix Puello, & Geurs, 2018; Broach, et al., 2012; Ghanayim & Bekhor, 2018; Prato, et al., 2018).

- In stated preference studies (SP), participants take decisions based on a set of hypothetical alternatives. In an interview setting, probands choose between defined route descriptions which normally differ in route characteristics and travel time (Caulfield, et al., 2012; Hardinghaus & Papantoniou, 2020; Mertens, et al., 2016; Vedel, et al., 2017).

Apart from these two main research paradigms, studies differ widely from each other when looking at the parameters under observation. Different investigation areas also vary in terms of the local significance of bicycle transport or the network as is. The latter is very important when defining alternatives in revealed preference studies. In general, earlier research found that short travel times and routes avoiding disturbance by motorized transport were more preferred (Broach, et al., 2012; Caulfield, et al., 2012; Vedel, et al., 2017). Studies with different contexts therefore deliver varying findings when it comes to the importance of route characteristics that ensure fewer disturbances. For instance, some studies see calm side streets as a first choice (Broach, et al., 2012; Winters, Teschke, et al., 2010) while others conclude that separated facilities are preferred (Caulfield, et al., 2012; Winters & Teschke, 2010). The importance of smoother pavements or paved over unpaved road is demonstrated (Prato, et al., 2018) but, in the context of other route characteristics, their importance is limited (Winters & Teschke, 2010). These prior studies related to two different approaches (RP and SP) enabled to gain a good understanding of the complex route choice behaviour. [1]

Although using well developed and broadly accepted methods, any overt survey situation involves response biases, such as the observer bias (McCarney, et al., 2007) or social desirability bias (Furnham, 1986), which potentially distort the results. In addition, the observation periods and sample sizes are limited due to extensive and costly data collection. Both paradigms (RP and SP) also have individual strengths and limitations (Boyle, 2003; Sanko, 2001). The hypothetical nature of choice experiments often leads to an overestimation of the willingness to pay (Murphy, Allen, Stevens, & Weatherhead, 2005). In addition, by the example of recreation research other limitations like the perception or image of the alternatives as well as the estimation of context effects in relation to the range of levels provided are shown (Louvière & Timmermans, 1990). Researching route choice behavior also reaches limits because stated choice sets can only present single route segments. In real-life, a route is normally composed of several varying route segments, including real-life constraints. For instance, a route along side streets is usually more complex than cycling along a main road, which cannot always be captured by standard measures of detour or expenditure of time. On the other hand, revealed preference studies depend heavily on the given network in the observation area. It is not possible to evaluate infrastructure elements that are not present as attractive alternatives to the participants. Likewise, the research may include alternatives that may be unknown to the participants. Either way, the individual choice of a certain route may have other reasons that are not observed. In recent years, big data methods are being applied in cycling research (Ma, Xu, Meng, & Cheng, 2020; Romanillos, Zaltz Austwick, Ettema, & De Kruijf, 2016). While these approaches are mainly focused on bike sharing, further promising data sources on every day cycling have the potential complete the picture of route preferences.

This paper uses requests of a bike-routing engine to derive cyclists routing preferences from user settings in the context of bike navigation. This refers to individual settings which are stated by the user to specify the navigation according to the users' desires for each individual trip regarding various route characteristics. The objective of this study is therefore to

[1] For a detailed overview of all studies cited, regarding framework conditions of the area under investigation and variables included in the model see **Table 5-3** in the appendix.

deliver insights into the desired routing characteristics of urban cycle journeys following a different approach than classical RP or SP studies. It analyzes cyclists' recorded settings when performing routing requests in a clustering procedure to derive typical types of routing preferences. They are based on the large variety of possible combinations of user settings as users may specify graduated routing preferences in the input fields *street category*, *surface quality* and *green pathways*. Accordingly, appropriate routes are suggested for the origin-destination relations based on these settings. Based on the data, the number of requests for each preference type is analyzed in order to evaluate its importance. This enables us to derive recommendations for planning and practice.

Recently, search engine data (mainly Google Trends or internet search queries) is being used for various research questions like estimating future tourism demand (X. Li & Law, 2020), modelling suicide rates (Adler, et al., 2019) or evaluating the perception of mental health in the context of mass shooting events (Vargas, et al., 2020). Using these data in the present approach allows us to validate results derived from classical approaches by researching route searching behaviour. The approach has advantages compared to SP or RP studies: first, there are no laboratory conditions or any survey situation when gathering the data. The queries raised by regular users are recorded in the back end. These real-life conditions promise a rather realistic picture since they include given interrelations between different characteristics as well as side-effects, such as a less direct route when intentionally avoiding main roads. Second, the sample size of the analyzed dataset is large. The data collection method enables us to record and analyze a full sample of users of the bike-routing engine with almost half a million queries. Third, the observation period is long. The data is collected over a whole year. Finally, the structure of the data means that we can use a relatively simple analysis method. Compared with rather complex modelling approaches, when looking at stated preference studies or difficulties when generating alternatives in revealed preference studies, the present approach uses simple hierarchical clustering.

On the other hand, the present method does not allow for quantifying trade-offs e.g. between travel time and route characteristics. Due to the nature of the data, individual users remain unknown. It is assumed that the requests concern mainly sporadic trips and trips in unknown areas. In addition, there is no tracking which could proof the user drove the proposed route. Most precisely, the approach refers to route searching behaviour which has been proven to closely interrelate with preferences (Chorus & Timmermans, 2008). The findings therefore emerge from a specific sample and pertain to trips rather than to individuals. The research is conducted in Berlin using the bike-routing engine BBBike (Rezic, 1999).

This is an appropriate case, as the local bike-routing engine has a long history and high usage level. In addition, standing at 18 percent in 2018, Berlin has a substantial mode share of cycling (Hubrich, et al., 2019).

5.1.2 Methods

The methodological approach contains five steps. First, data is gathered by recording the request in the bike-routing engine. Second, the data is preprocessed and transformed to a consistent geographical reference system. Third, the data is explored and compared with municipal household survey data. Fourth, a hierarchical clustering is performed to derive preference types. Finally, preference types are described and the importance of each preference type is evaluated.

5.1.2.1 Data basis

The main component of the present study is analyzing data recorded by BBBike. BBBike is a bike-routing engine for cyclists. The initial version was developed in 1999 for the city of Berlin (Rezic, 1999). It is now available in many towns and cities. The software is accessible via web browser and as a mobile app. BBBike searches cycle routes between two points. After choosing for origin and destination of the trip, the setting menu opens. Users are encouraged to specify routing preferences with various settings as shown in Table 5-1. After confirming the settings, the route is calculated.

Table 5-1. Characteristics available for routing requests in the BBBike bike-routing engine (http://www.bbbike.de)

Variable	Value
Speed	Free field, default is 20km/h
Street category	No preference
	Prefer residential roads [calm]
	Use only residential roads [calm*]
	Prefer main roads [main]
	Use only main roads [main*]
	Avoid main roads without cycle paths/bus lanes [infra]
	Avoid main roads without cycle paths [infra*]
Surface quality	No preference
	Avoid cobblestones and bad surfaces [smooth]
	Use only very good surfaces (suitable for racing bikes) [smooth*]
Avoid traffic lights	No
	Yes
Avoid unlit streets	No
	Yes
Green pathways	No preference
	Prefer green pathways [green]
	Strongly prefer green pathways (may result in longish routes if there are no suitable routes surrounded by greenery available, so use with caution) [green*]
Use unknown streets	Allow routing through "unknown" streets (streets which are not yet researched for cyclist usage)

The proposed route is described, can be displayed on an interactive map and exported in various formats. The interactive map can display cycle paths, surface quality, public transport, greenery and other data and can also show current weather conditions. The bike-routing engine uses the OpenStreetMap (OSM) road network for routing (OpenStreetMap-contributers, 2017). The street network in the investigation area is diverse. With regard to the total length of the street network, our own calculations based on the OSM describe the infrastructure as follows: 69 percent is assigned to residential roads and 17 percent to main roads. Of the main roads, 39 percent of the length is covered by a cycle infrastructure, while 27.5 percent of the municipal area is green area. In the side street network, a significant number of streets have cobblestones or bad surfaces. Residential roads almost never have any cycle infrastructure.

Based on the differences in the road network and the level of detail the routing engine provides, the suggested routes vary widely from each other depending on the preference settings. Based on the routing preference settings, the routes for the same origin-destination relation can be up to one third longer compared with the shortest route (the default setting). Accordingly, routes under different settings may overlap completely or not have any segment in common (see Figure 5-1). Figure 5-1 shows different routes for the origin-destination relation between two university locations in Berlin. These routes are between 6,573 and 7,440 meters long; the overlap with the shortest route under default settings ranges from 20 to 76 percent. For a detailed overview of the length and overlap of different routes for varying settings, see Table 5-4 and figures in the appendix. These provide an impression of the sensitivity of the routing algorithm. These routes display one specified routing preference per alternative. Since the routing preferences in the individual categories can be combined the resulting variety of proposed routes in very large.

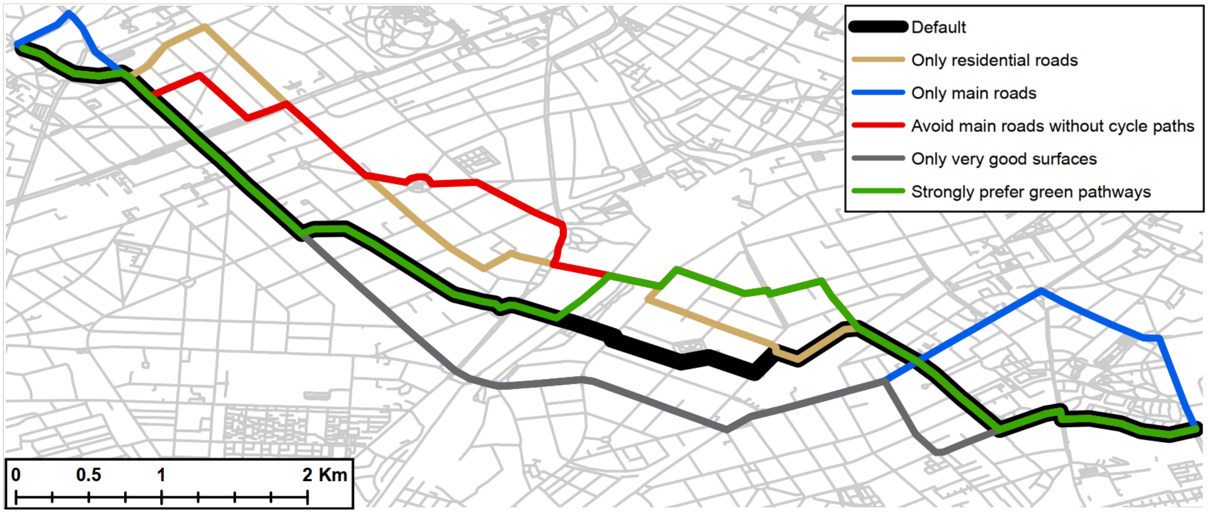

Figure 5-1. Different routing suggestions for the origin-destination relation between two university locations in Berlin. The routes are between 6,573 and 7,440 meters long; the overlap with the default route ranges from 20 to 76 percent.

For this study, all requests in the city of Berlin were logged over a period of one year (the whole of 2017), including the timestamp of the request, start and end point coordinates, addresses and postcodes as well as all user settings regarding the routing preferences for the individual trip. In total, the observation period covers 461,170 valid requests, an average of approximately 1,263 per day.

Due to methodological reasons, the sample does not show representative data for all trips travelled by bicycle. As shown in Figure 5-2, compared with the municipal household travel survey data (SrV) (Ahrens, 2014), the BBBike data does not show strong morning and afternoon peaks. In contrast, BBBike requests start later in the day and the number per hour remains similar during the daytime. Regular journeys like work, education or childcare require no repeated routing, so such trips are underrepresented in the data but account for a large proportion of the volume of cycle traffic.

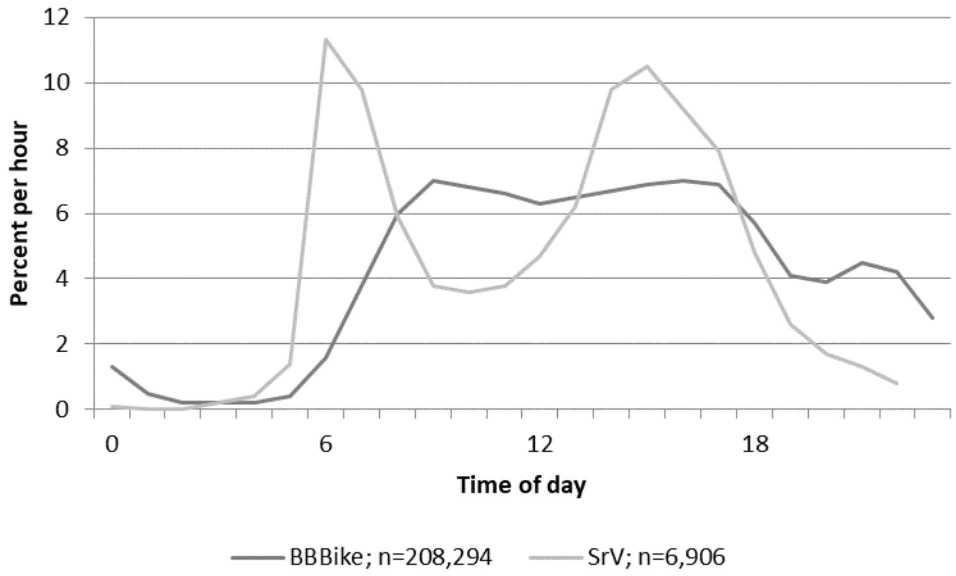

Figure 5-2. Distribution of BBBike requests over the course of the day compared with the municipal survey. Both curves show the average for weekdays Tuesday to Thursday.

With regard to the distribution over the course of the week, on average there are about fifteen percent less requests on the weekend compared with weekdays. In traffic counting data, this decrease in cycling on weekends is much greater and shows a difference of 40.3 percent over all counting stations in the whole year 2017 (Günter, 2018).

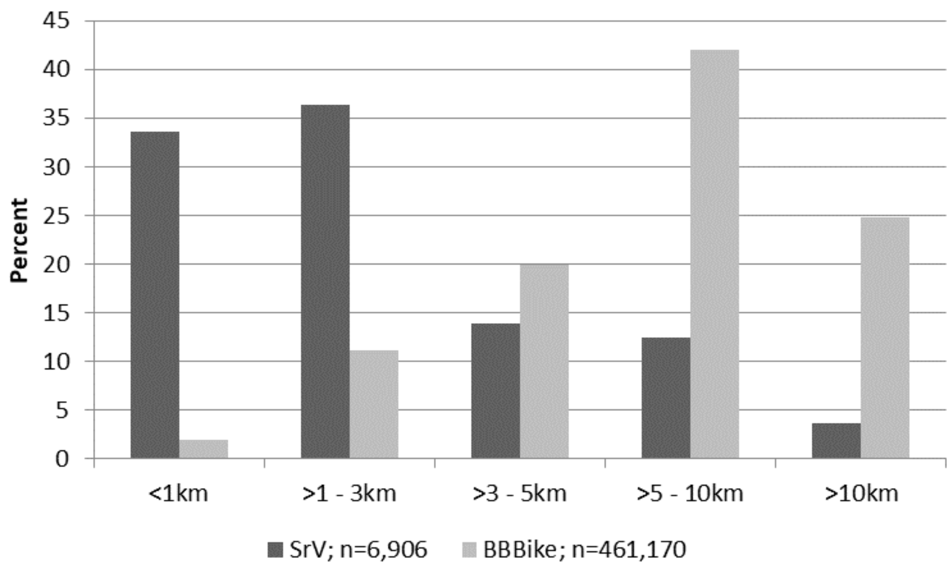

Figure 5-3. Distances of BBBike requests compared with the municipal survey. The values describe the percentage of each length category on all trips in the respective dataset.

In addition, the distances in BBBike requests are much longer than those of all cycle journeys reported in the municipal survey (see Figure 5-3). The mean distance for BBBike requests (7.9 km) is more than twice that for journeys reported in SrV data (3.3 km). This difference in distribution indicates that the tool is being used for longer and possibly unknown routes where routing is helpful. With regard to the spatial distribution and time of year, the requests in BBBike and trips in the representative municipal household travel survey data are distributed similarly (see Figure 5-4). The bike-routing engine is not designed for specific use cases like fitness cycling but for everyday traffic. Consequently, it is neither being used by a specific user group, nor does it include any gamification elements distorting the results. Overall, an extensive cross-sectional dataset is gathered over a long period of time. These data do not rely on any artificial situation that might potentially affect the individual. The enormous number of cases and the data collection, unnoticed by the user, are the primary advantages of the data. Nevertheless, the data has two main limitations: first, there is no information about the individual user who is performing the request. Second, as users are not tracked, there is no information as to whether the requesting user took the suggested route or even made the trip at all. To some extent, users search for the ideal route by making more than one request with different settings for the origin-destination relation within five minutes. This relates to 10,662 requests. The service should therefore be seen as an information tool. Given the high number of requests, the data reveals interesting insights into cyclists' routing preferences. It therefore opens up the opportunity for an innovative approach which aims to investigate route search behavior.

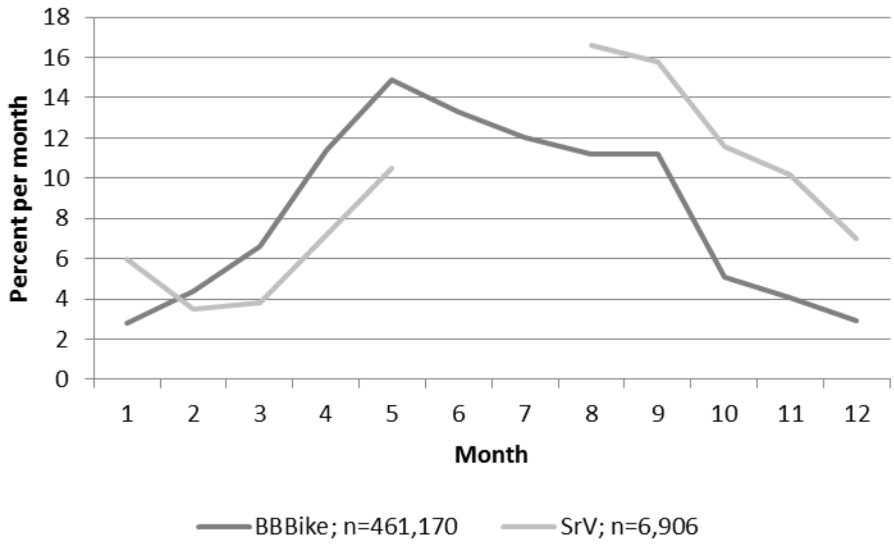

Figure 5-4. Distribution of BBBike requests over the course of the year compared with SrV. In SrV, trip data are not collected during summer holidays.

Analysis of the routing preferences required data preparation which aimed to build a geo-database from the log files provided by BBBike. The large volume of data was processed using Python scripts and PostgreSQL queries. This meant re-projecting the data, which initially referred to an internal coordinate system of BBBike, to the destination system WGS84. Using these coordinates, a geometry was assigned to each start and end point and visualized in QGIS.

5.1.2.2 Cluster analysis

The bike-routing engine allows for several different specifications of desired route characteristics in different categories. This results in a wide range of possible combinations. A hierarchical cluster analysis is performed to condense these into characteristic preference types. A hierarchical cluster analysis divides data into clusters that are as different from each other as possible and merges similar cases together into one cluster (Everitt, et al., 2010). The goal is to determine a solution which on the one hand consists of as few clusters as possible, and on the other hand represents the structure of the data without losing information. The cluster analysis is structured into eight steps as shown by (Hansen & Jaumard, 1997). The process of the cluster analysis is illustrated in Figure 5-5.

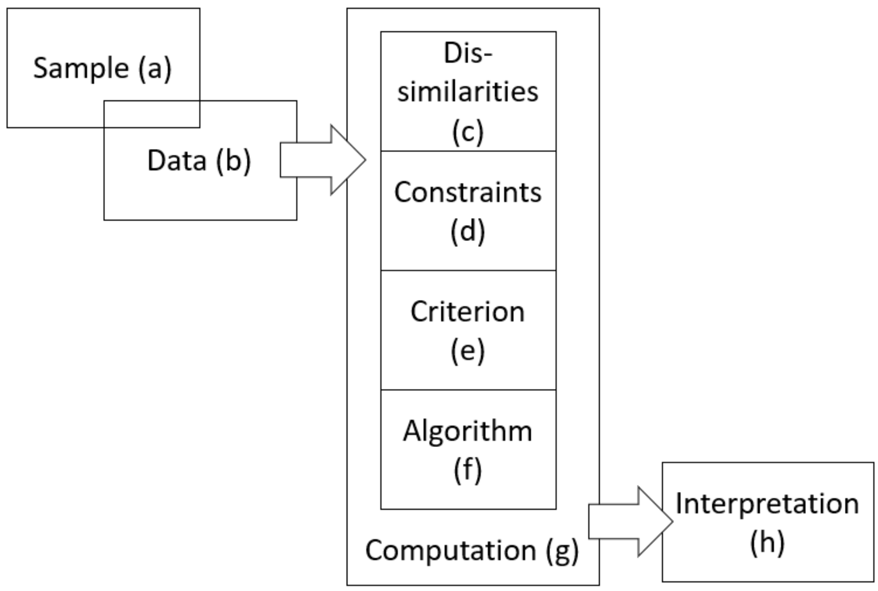

Figure 5-5. Process of the cluster analysis

Sample (a): The dataset described in 5.1.2.1 is used as the sample for clustering.

Data (b): The characteristics of the entities on which the clustering is based are the preferences for various route attributes. These routing preferences are present as nominal data indicating preferences for various road types, surface quality and green pathways. These data include ordinal information as *no*, *weak* and *strong* preference are stated for each street type as well as for surface quality and greenery. To make this information usable, the preference settings are transformed into five ordinal variables defining the desired usage of side roads, main roads, main roads without cycle infrastructure, smooth road surfaces and green pathways with three values each. That means for all requests there is the information if no preference [0], preference [1] or strong preference [2] for each according category (residential roads, main roads, no main roads without infrastructure, avoid cobblestones, green pathways) is stated.

Dissimilarities (c): The asymmetric Manhattan method as proposed by (Walesiak & Dudek, 2010a) is used to calculate a distance matrix for the specific case of ordinal data. In order to do so, the relative distance between every pair of observations in the dataset is calculated and organized in the distance matrix. To do this, the scale for the distance measure is treated as an interval. According to (Kaufman & Rousseeuw, 2009), the majority of authors do this so as not to lose information, even though the differences between the single values cannot be known in detail and may be different.

Constraints (d): The hierarchical approach is chosen as the clustering method. In hierarchical cluster analysis, objects are merged together into clusters step by step. For each step, similarity matrices are calculated as described in (c) and objects are assigned to the cluster which fits best. Thus, the analysis produces results for a variety of cluster solutions according to the number of resulting clusters. Hierarchical clustering can thus deliver criteria to specify the optimum number of cases, while partitioning algorithms need the number of groups as input a priori. With regard to constraints, there is no need for normalization as the range and relations are identical for all variables integrated in the clustering.

Criterion (e): Various measures of homogeneity exist for different types of data and approaches. By evaluating such measures, it is possible to determine the optimal number of cases in the process. The Calinski-Harabasz criterion (CHC) is used (Caliński & Harabasz, 1974). The CHC combines two important measures for evaluating each cluster solution. The total within-cluster covariance shows how compact each cluster is. A low value is preferred. The between-cluster covariance defines how different the clusters are from each other. The Calinski-Harabasz criterion is defined as

$$VRC_k = \frac{SS_B}{SS_W} \times \frac{(N-k)}{(k-1)},$$

where SS_B is the overall between-cluster variance, SS_W is the overall within-cluster variance, k is the number of clusters, and N is the number of observations.

Algorithm (f): The complete-linkage method is applied as the cluster algorithm to identify similar clusters. Complete-linkage measures the farthest pair of points to calculate similarity. As agglomerative hierarchical clustering, the algorithm starts from each element representing one cluster. The clusters are successively merged together until all elements are united in one cluster. This approach allows the dendrogram to be interpreted as graphical output of the clustering process (see Figure 5-7). The dendrogram illustrates the tree of cluster solutions produces by the algorithm. The algorithm is relatively robust against chaining and builds rather compact clusters.

Computation (g): The algorithm (f) is applied to the distance matrix (c).

Interpretation (h): Interpretation and choosing the number of clusters that fits best is based on two separate evaluations. First, the CHC as described in (e) is evaluated. For the combined CHC, the best cluster solution has the highest value (Caliński & Harabasz, 1974).

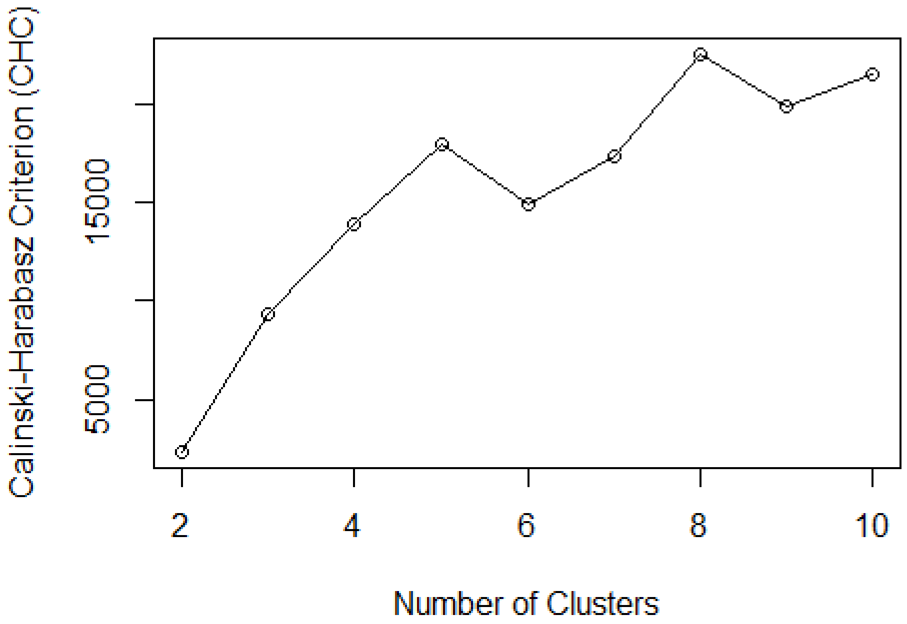

Figure 5-6. Calinsky-Harabasz criterion for different number of clusters in the data

The CHC offers solutions with five or eight clusters (see Figure 5-6).

Second, the dendrogram (Figure 5-7) is evaluated. Complete-linkage allows the dendrogram to be used in graphical interpretation to choose the number of clusters that fits best (see Figure 5-7). The dendrogram works as a tree diagram and displays the clustering in accordance with the sequence of the process (in which step clusters are merged together) and the distance where merging occurs (indicated by the height as shown in the Y-axis of the dendrogram). Taking the steps of merging and the high of standardized distance (Y-axis in the dendrogram) into account, a solution of five or eight clusters would be possible based on the dendrogram.

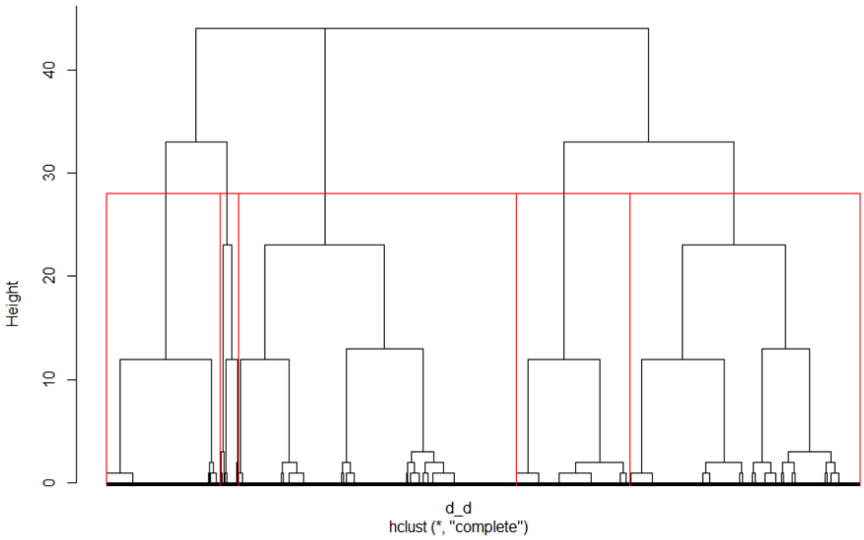

Figure 5-7. Dendrogram of the hierarchic cluster analysis

To achieve the goal of preferably few clusters, we decided for a cluster solution with five clusters to represent the data. This clustering result is indicated by red squares around each cluster in Figure 5-7. The height displays the relative distance between the merged clusters in the process. It refers to the value of the according distance matrix. Interpretation of the chosen cluster solution in respect of content is described in the results section.

5.1.3 Results

Now we present the results for routing preferences. First, we present a descriptive overview. Then, we carry out data processing and apply filters before applying the methodology. Groups and subsets are analyzed over time. We draw comparisons with the cycle traffic in Berlin using the official municipal household travel survey data of SrV 2013 (Ahrens, 2014). Subsequently, we analyze preferences and present the results of the cluster analysis to describe preference types and related route characteristics.

5.1.3.1 Overview

The mean distance in BBBike requests shows a strong peak during summer. With regard to the spatial distribution of requests in terms of start and destination locations, we can observe a concentration in the inner city. The heatmap of destination locations does not differ substantially from this picture. Figure 5-8 compares the spatial distribution of starting locations of BBBike requests to the starting locations of cycle trips according to SrV and the population density in Berlin. In addition, we compare the frequency distributions of BBBike and SrV. As seen in Figure 5-8, these distributions appear similar in general. As assumed, the starting locations of both datasets, BBBike and SrV peak in the inner city. Both distributions also show more trips in western outskirts than in eastern districts. More precisely, BBBike routing requests seem to interrelate stronger to population density than the bike trips in SrV data do. Hence, BBBike requests clearly peak in dense inner-city districts. The frequency distributions of BBBike and SrV are very similar.

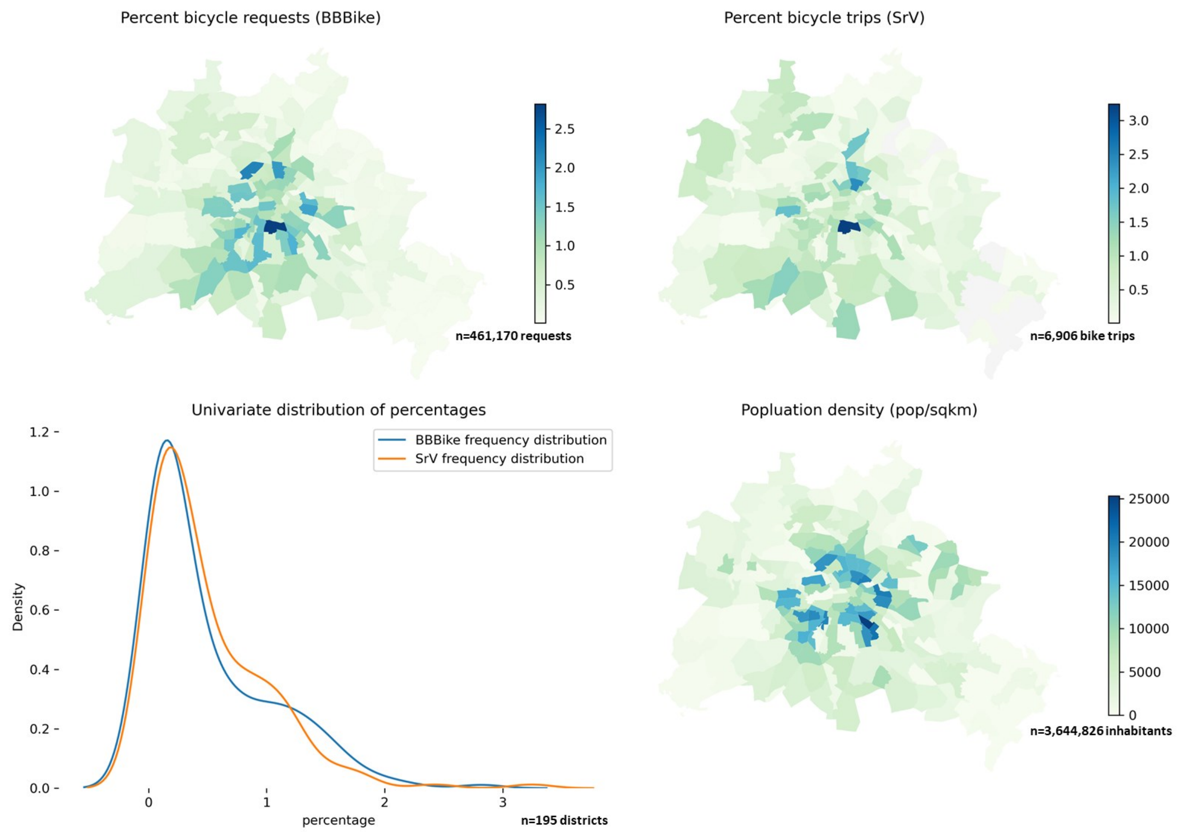

Figure 5-8. Spatial distribution of the proportion of BBBike requests in a certain district in regard to all requests (top left), the proportion of SrV trips starting in a certain district in regard to all trips (top right),), frequency distribution of percentages of BBBike and SrV across all districts (bottom left) and population density (bottom right)

To gain insights into routing preferences, we analyzed BBBike-routing preferences as seen in Table 5-1. When examining the data, we see a high proportion of default requests. The request is defined as default when only the origin and destination are given but no routing preference is stated in any of the settings. These default requests make up 36.1 percent or 166,341 observations. It can clearly be seen that much lower rates of default requests occur on weekends than weekdays and in summer over winter as shown in Figure 5-9. Accordingly, trips using the default settings have a shorter distance than those with indicated preferences (6,877.3 vs. 7,487.7 on average). BBBike gives the shortest route whenever no preference is specified.

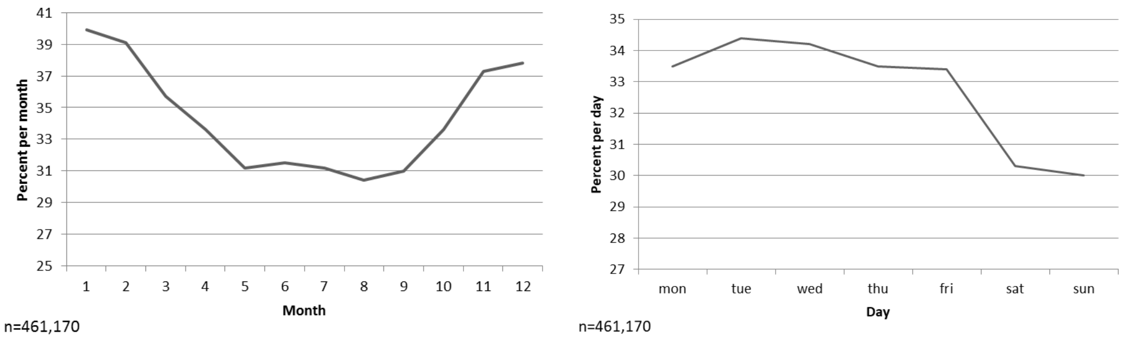

Figure 5-9. Share of default requests in all requests over the course of the year (left) and the course of the week (right)

The distribution of other preference settings differs over the course of the year. The preference for main roads makes up only two percent in May and reaches the maximum of 4.3 percent of all requests in January.

Figure 5-10 summarizes the ten most frequently used combinations of settings for individual requests. The default requests, clearly dominating the individual settings, are not displayed. The six most common requests either include the preferred use of side roads or display a simple preference for either green pathways or smooth surfaces. Accordingly, when any routing preference is specified by the user (no default queries), the most common individual preference is related to surface quality (29,657 requests).

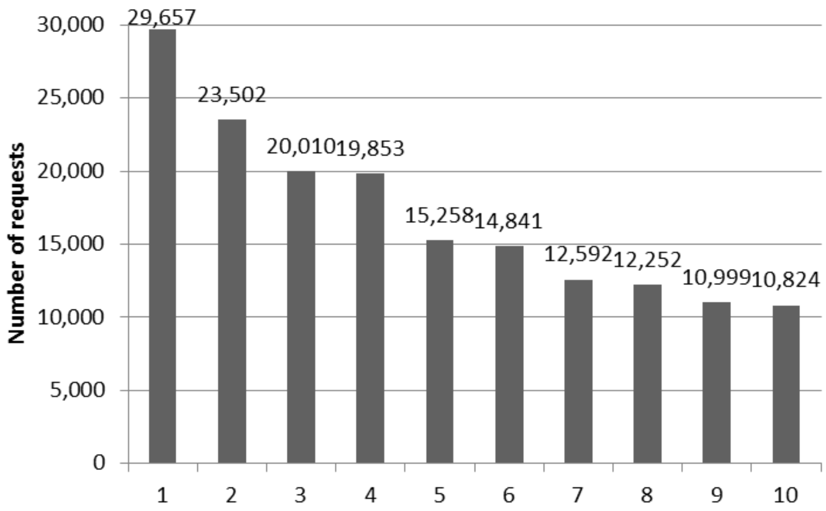

Figure 5-10. Top ten most common preference settings (without default queries):

1: Avoid cobblestones and bad surfaces
2: Prefer residential roads, prefer green pathways, avoid cobblestones and bad surfaces
3: Prefer green pathways
4: Prefer residential roads, avoid cobblestones and bad surfaces
5: Prefer residential roads
6: Prefer residential roads, prefer green pathways
7: Avoid main roads without cycle paths, avoid cobblestones and bad surfaces
8: Avoid main roads without cycle paths, prefer green pathways, avoid cobblestones and bad surfaces
9: Avoid main roads without cycle paths/bus lanes, avoid cobblestones and bad surfaces
10: Prefer green pathways, avoid cobblestones and bad surfaces

Figure 5-11 illustrates the interrelations between preferences for road categories and preferences for other characteristics like greenery or surface quality. In the flow diagram the size of the bars indicate the overlap between the characteristics on left side of the diagram and the road categories on the right side of the diagram. It therefore illustrates the structure of the data. We can grasp the importance of the interrelations between specific characteristics from this. For example, a preference for green pathways is often stated solely (lowest red bar linking "Green" to "No Preference") or together with a preference for calm side roads (top red bar). On the contrary, the joint preference for green pathways and smooth surface mainly goes together with a preference for calm side roads (top blue bar) and a preference for infrastructure (second blue bar linking "Green-Smooth" to "Infra"). A preference for main roads is mainly linked to no additional preference (third green bar) and preference for smooth surfaces (third purple bar) while interrelations to any setting preferring greenery are limited (red and blue bars). As obvious, by far the largest interaction is shown by the default queries with combine no stated routing preference for both, road categories and other characteristics (vast green bar). For a detailed list of all intersected preferences including the exact quantification see Table 5-2 in the appendix.

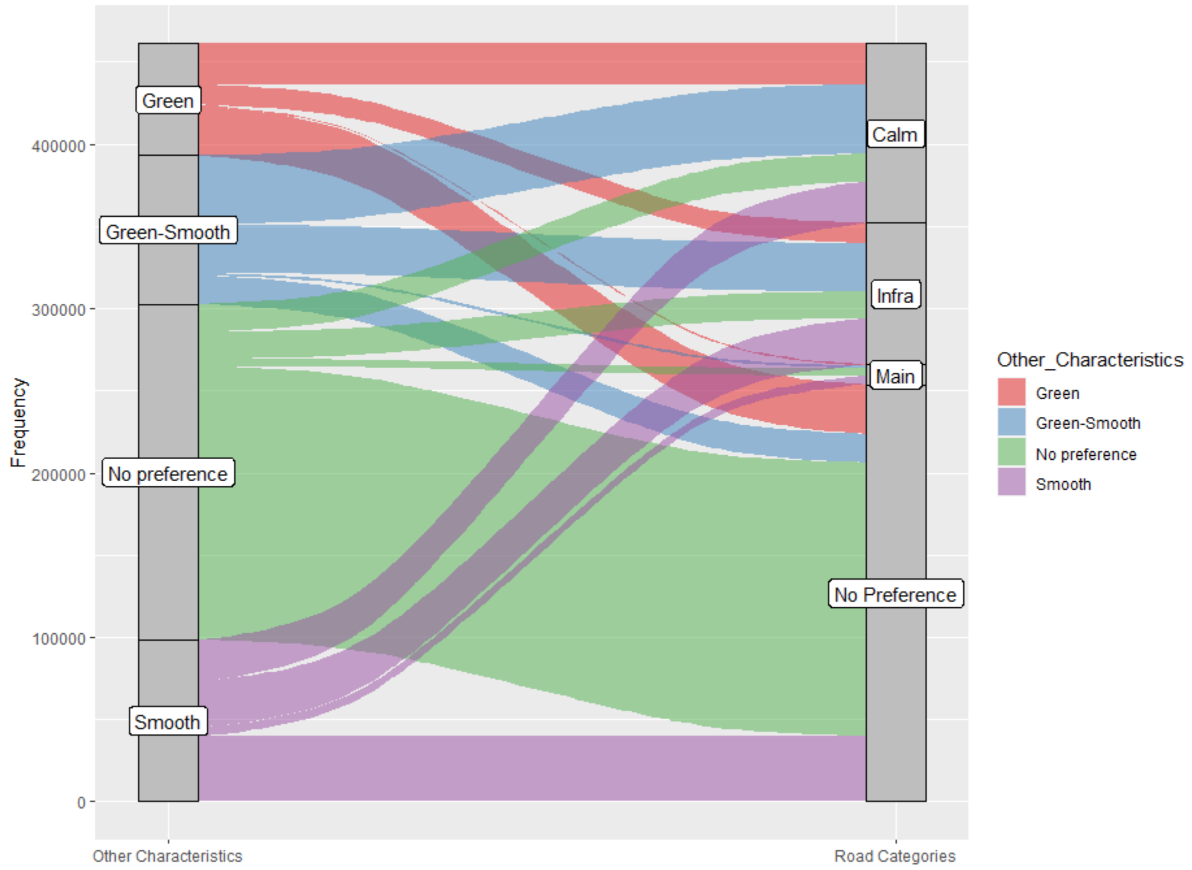

Figure 5-11. Interrelations between preferences for other characteristics (left column) and road categories (right column)

Other characteristics: prefer green pathways (Green), avoid bad surfaces (Smooth), prefer green pathways and avoid bad surfaces (Green-Smooth);
Road preferences: prefer calm residential roads (Calm), avoid main roads without cycle infrastructure (Infra), prefer main roads (Main); simple and strong preference summed up.

Comparing preference settings between city regions, it is seen that green pathways and calm roads are requested less in the inner city than in outer parts of the city. More precisely, requests preferring green pathways in the center account for nine percentage points less than in outer parts. The difference with regard to calm roads in the inner city is three percentage points. In contrast, requests searching for the shortest route occur more often. Other preferences do not show noticeable differences.

For a detailed overview of the length and overlap of different routes for varying settings in different urban contexts, see Table 5-4 and figures in the appendix. These provide an impression of the sensitivity of the routing algorithm and the different routes provided for different routing preferences.

5.1.3.2 Results of the cluster analysis: Preference types

The cluster analysis as described in 5.1.2.2 results in five clusters. These clusters characterize the preferences observed in the requests and may be described as content-related. Figure 5-12 gives an overview about the distribution of routing preferences in each cluster and shows the number of requests per cluster.

In the cluster **Comfort,** avoiding disturbances caused by bad surface quality is determinant. All requests wish to avoid bad surfaces with 81 percent aiming to avoid cobblestones and bad surfaces and 19 percent wishing to use only very good surfaces. In addition, 50 percent of the requests wish to avoid main roads without cycle path (or bus lanes). Green pathways are less relevant than on average with 30 percent preferring and 10 percent strongly preferring them.

The clusters **Relax** and **Park** show preferences for combining calm side roads and green pathways. In the cluster **Relax,** the request for side roads dominates. Also, in **Relax,** a preference for smooth surfaces is given in 80 percent of the requests, while in **Park** smooth surface is not requested at all. In **Park** the preference for green pathways is seen in all requests.

The cluster **Bike Path** shows a low preference for green pathways, while all requests wish to avoid main roads without cycle path (or bus lanes). Here, smooth surface is not requested at all.

By far the smallest cluster **Fast & Easy** shows a preference for cycling along main roads regardless of the existence of cycle infrastructure. The importance of green pathways is the lowest of all clusters. The preference for smooth surfaces is above average.

In addition to the results of the cluster analysis, the **Default** queries represent the largest group. Here, the users did not state any routing preference and did confirm the default setting of the bike-routing engine. According to BBBike, in these requests the shortest bike route is provided. The detailed characteristics of each cluster are shown in Figure 5-12. The figure shows the distribution of preference settings, which the users of the bike-routing engine chose in each cluster (see Table 5-1). This summarizes the main results of the cluster analysis.

Three major results are particularly interesting: first, a preference for green pathways is seen in all clusters to some extent. Second, smooth surface plays a major role in three clusters. Third, two clusters combine preferences for greenery and calm side roads.

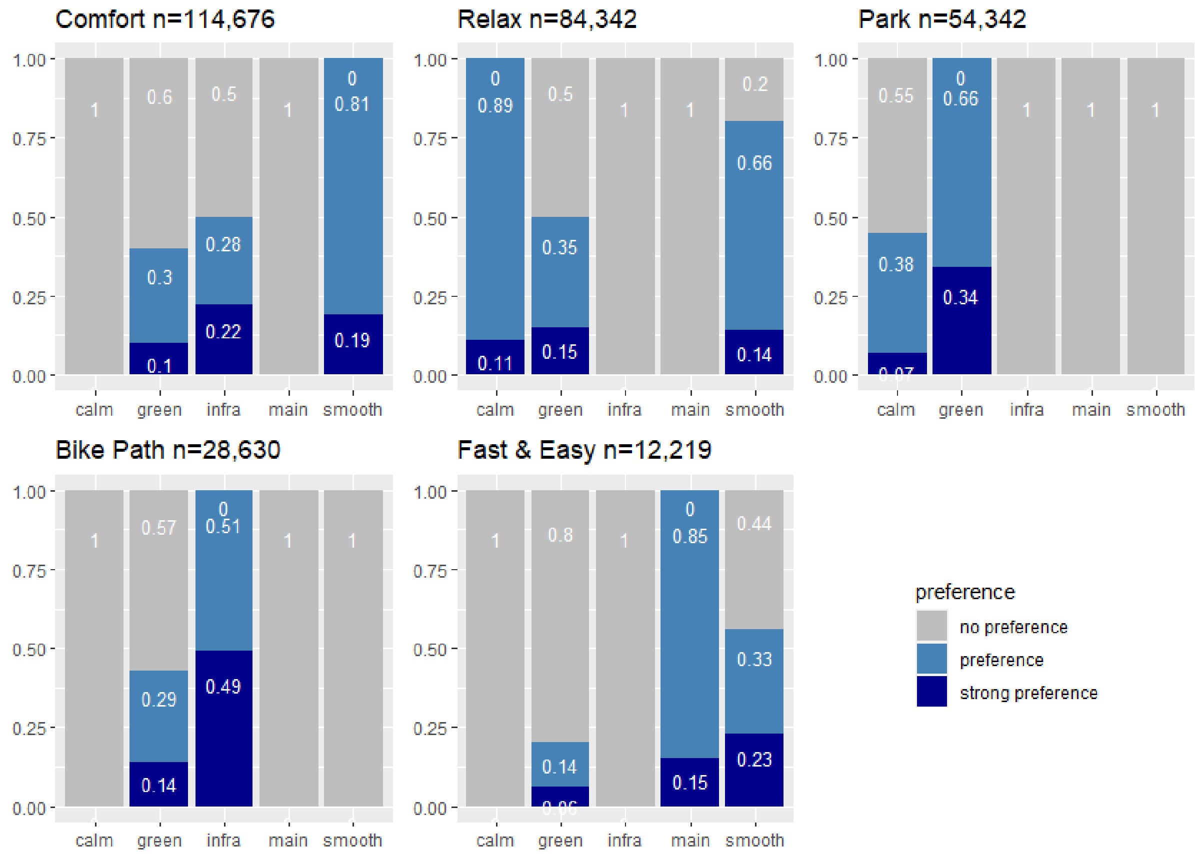

Figure 5-12. Percentages of preferences in resulting clusters

5.1.4 Discussion

This study analyzes the detailed requests of a bike-routing engine. In contrast to conventional methodologies like SP or RP studies, a non-personalized big data basis has been clustered in order to generate routing preference types that make it possible to infer the importance of road characteristics to cyclists from a user's perspective. The outcomes show stable clustering results and clear preferences towards certain infrastructural facilities (see 5.1.3). Earlier research found that analyzing recorded data on search behavior may generally be used to estimate consumer preferences (Chorus & Timmermans, 2008). The present approach has several advantages. Due to the efficient way that data is collected, it is possible to gather a very large dataset of almost half a million cases over a long observation period of one year. It therefore becomes possible to use a full sample of the requests in the bike-routing engine without being potentially distorted by a survey situation. This eliminates several disturbing influence factors like the social desirability bias, the observer bias or the non-response bias. In addition, we do not rely on a conceptual choice experiment or the normative generation of alternatives. As shown in the literature section, previous research does not always come up with clear and consistent results. Against this background, this approach provides findings from a different point of view, which help to assess the integrated overall view of route choice behavior in the context of validating earlier results. These main issues are presented below.

At around one third, a very large proportion of requests were executed in default mode. To some extent the large number of default requests might be explained by users who do not read the explanation and do not change the default setting due to a lack of attention. The settings used for the request are displayed in drop-down menus after typing origin and destination and have to be confirmed before the route is calculated. When used on purpose, these requests represent a preference for the shortest route. Searching for the shortest route is more important in the winter months than in summer and on weekdays compared with weekends. As described, it is assumed that the requests pertain largely to leisure and sporadic trips. Earlier research found that on repeated and especially on non-leisure trips, cyclists tended to choose the shortest route more often than on routes for other purposes (Bernardi, et al., 2018). Accordingly, disutility of the absence of bike infrastructure appears lower on commuting trips (Broach, et al., 2012). This suggests that the preference for the shortest route may even be stronger than the sample reveals. It should be clarified that this is especially true for male frequent cyclists (Bernardi, et al., 2018). In this matter, researching route preferences mainly on leisure trips may reveal more information on desired route characteristics, as time constraints are less important and influence route choices to a lesser extent. It is assumed that when differentiating route choice behavior between trips with different purposes, the pivotal factor is time pressure rather than differences in desired route characteristics.

If any routing preference is specified, the most important setting (more than half of all requests) is to avoid bad surfaces. Avoiding bad surfaces is the most frequently used individual setting and accompanies all preferred road categories. A slightly lower preference on main roads might be explained by the fact that there are few main roads with bad surface quality in Berlin. The results therefore clearly demonstrate the dominant significance of smooth surfaces. This has to be seen within the context of the investigation area in Berlin. As explained, a number of residential streets, are paved with cobblestones and have bad surfaces. Consequentially, the fact that participants in Berlin are highly aware of surface quality and the existence of methodological differences may explain the discrepancy in respect of earlier stated preference studies which concluded that surface quality had limited importance compared with other factors (Mertens, et al., 2016; Winters & Teschke, 2010).

Compared to earlier results, in this study more requests show a preference for cycling in mixed traffic on calm roads over separated facilities (Broach, et al., 2012; Caulfield, et al., 2012; Hardinghaus & Papantoniou, 2020; Vedel, et al., 2017; Winters & Teschke, 2010; Winters, Teschke, et al., 2010). With a difference of five percentage points, prioritizing calm roads is more common than accepting routes which include segments on main roads with cycle infrastructure. The latter are classified in the cluster *Bike Path* and partly in *Comfort*. This discrepancy may be partially explained by well-designed images of cycle infrastructures in stated preference studies compared with a rather more moderate design and condition of such infrastructures in Berlin since large parts of the bike infrastructure originate from the 80th when different design standards were applicable.

In terms of the relevance of off-street cycling facilities, i.e. green pathways, the results are in line with several earlier studies revealing their strong effect (Broach, et al., 2012; Buehler & Dill, 2016; Vedel, et al., 2017; Winters & Teschke, 2010).

On the whole, the cluster analysis shows that specific combinations of different preference settings are more common than others. For example, calm roads are often used together with a preference for green and/or smooth routes as seen in the clusters *Relax* and *Park*, while main roads are combined with smooth surfaces but very rarely with green routes. The cluster solution identifies the interrelation by condensing 63 possible settings into five preference types plus the default cluster which probably presents a preference for the shortest route. The clustering shows a stable solution and represents combinations of preferences with clear priorities in each cluster. Accordingly, characteristic desires can be condensed into just a few combinations of settings. These individual preference types are reflected by the clusters *Relax* and *Park* combining calm roads with green pathways, *Comfort* and *Bike Path* looking for smooth surfaces and (partly) avoiding main roads without cycle infrastructure, *Fast & Easy* desiring main roads regardless of cycle infrastructure and *Short* with the search for the shortest route using the default settings. These clusters show preference settings which differ strongly from each other, illustrating that there is no ideal route and no 'one-size-fits-all-approach', but rather distinct individual and trip-related preferences that determine route choices.

As described, Berlin is seen as a suitable case study. Given the nearly half a million observations recorded and the long history of the bike-routing engine in Berlin, it may capture a sufficient picture of bicycle transport in Berlin considering the limitations described below. More recently, the bike-routing engine has become available in many other cities which will make it possible to verify to what extent resulting clusters can be generalized.

The limitations of the present study are discussed below. Individual users are unknown due to the methodological approach and the way the data is recorded. So, unlike previous studies, we cannot evaluate the routing preferences in groups based, for example, on socio-demographic features or level of cycle confidence (Aldred, et al., 2016; Broach, et al., 2012; Caulfield, et al., 2012; Winters & Teschke, 2010). The participants of this study, and accordingly the results, cannot be regarded as representative of the municipal population but should reflect cyclists in the investigation area with an affinity to ICT. Most importantly, we are researching the people who already cycle and the conclusions drawn can only be based on them. Given the methodological approach, we can only research the users of the bike-routing engine. In addition, other than modelling approaches (RP or SP) we cannot quantify trade-off e.g. between travel times and route characteristics.

As we do not know the individuals behind the requests, the resulting preference types pertain to trips rather than to individuals. Accordingly, it is possible that an individual user shows different routing preferences for different occasions. Also, as the bike-routing engine provides routes but does not track cyclists, it is not known to what extent using the tool actually results in traveling the proposed route. Most precisely, the data reflects route searching or planning behavior rather than route choice behavior. Nevertheless, earlier research justifies the main idea of the approach (Chorus & Timmermans, 2008). As described, in a limited amount of cases users even try different settings for the same origin-destination relation. With regard to the temporal aspect, we cannot prove for certain whether requests for a specific trip are made immediately before this trip. However, the distribution of the requests over the course of the day, week and year appears plausible. If we assume a close time connection between request and planned starting time of the trip, these distributions indicate primary but not sole use for leisure and sporadic trips. In addition, the tool's purpose for navigation beyond known routes or a well-known neighborhood narrows the representative nature of the data. It is obvious that no repeated navigation is needed for commuting trips or short trips in the neighborhood. Thus, the navigation is used for much longer trips than the mean distance for cycling trips according to the municipal data (SrV). As a result, there is less information on journeys cycled on a regular basis as well as short trips which do, however, account for large proportions of the road traffic.

Finally, the analysis carried out in this paper can only research preferences based on choosing alternatives from the predefined options the tool provides. Any further preferences remain hidden. For example, all types of infrastructure along main roads like bike lane, bike path or protected bike lane create one category. The type of bicycle infrastructure is not differentiated in the data. In that context, the interpretation of the default settings matters. According to BBBike, in the default setting the shortest bike-routing is computed. From a user's perspective, this is understandable since every additional preference specified potentially leads to longer trips. The observation of significantly less default queries both in summer and on weekends compared to winter and weekdays suggests the interpretation of using default for the shortest path since the share of these queries declines when time constraints and weather conditions are likely to allow for longer bike trips. Hence, we assume that the default queries pertain to a preference for the shortest route. The importance of short trips is plausible as travel time is major impacting variable in transport research (Jain & Lyons, 2008; König, et al., 2004). Nevertheless, it is also possible that parts of the users do not pay attention to the possible routing settings and confirm the default setting displayed be the tool for no specific reason. This has to be kept in mind when interpreting the concluded desire for shortest trips.

5.1.5 Conclusion

The present study provides insights into cyclists' route preferences by analyzing an extensive dataset of requests with according routing preference settings collected in the bike-routing engine BBBike. Compared with previous studies, this study uses a different type of data and a different approach. The findings gathered under different circumstances show in particular that:

- Diverse routing preferences can be condensed into six trip-related preference types which differ strongly from each other.

- The largest of these routing preference types is defined by the default settings of the routing engine and therefore searches for the shortest route without limitations on route specifics.
- Compared to prior findings, in the present study with the according setting, surface quality and using side roads appear to be more important than separate cycle infrastructure along main roads.
- For a small proportion of trips, cyclists prefer main roads irrespective of cycle infrastructure.

When providing recommendations for designing a bike-friendly city, the following key messages become apparent:

- Given the dominant preference for the shortest route as indicated by the default queries, there is a strong need for short cycle connections through the city. On one hand, this strengthens the potential for cycle super-highways or express routes for cyclists as these enable fast transit. On the other hand, it shows a need for a dense network ensuring direct cycle connections through the city.
- Providing a well signposted coherent network of cycle connections on calm side roads combined with well-maintained surface quality appears to be a key point. A strategy such as this satisfies a greater demand than providing a network of separated cycle facilities along main roads. Given the opposing preferences, an integrated strategy should take both into account.
- When planning cycle routes, specific preference types need to be considered to consistently meet the demand. For example, combining segments on calm side roads with segments through parks fulfills connected preferences, while combining cycle facilities on main roads with green segments does not.

5.1.6 Declarations

5.1.6.1 Availability of data and material

The data that support the findings of this study are available upon reasonable request from the authors.

5.1.6.2 Funding

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5.1.6.3 Acknowledgement

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5.1.8 Appendix

Table 5-2. Distribution of preferences for road categories (x-axis) intersected with preferences for other characteristics (y-axis)

		Calm	Infra	Main	No Preference	Overall
Green	n	24,887	12,260	876	30,075	**68,098**
	% in column	22.8%	14.3%	7.2%	11.9%	14.8%
	% in row	36.5%	18.0%	1.3%	44.2%	100.0%
	% in total	5.4%	2.7%	0.2%	6.5%	14.8%
Smooth	n	25,161	27,993	5,317	39,951	**98,422**
	% in column	23.0%	32.6%	43.5%	15.7%	21.3%
	% in row	25.6%	28.4%	5.4%	40.6%	100.0%
	% in total	5.5%	6.1%	1.2%	8.7%	21.3%
Green-Smooth	n	42,164	29,347	1,547	17,385	**90,443**
	% in column	38.6%	34.1%	12.7%	6.9%	19.6%
	% in row	46.6%	32.4%	1.7%	19.2%	100.0%
	% in total	9.1%	6.4%	0.3%	3.8%	19.6%
No preference	n	17,017	16,370	4,479	166,341	**204,207**
	% in column	15.6%	19.0%	36.7%	65.6%	44.3%
	% in row	8.3%	8.0%	2.2%	81.5%	100.0%
	% in total	3.7%	3.5%	1.0%	36.1%	44.3%
Overall	**n**	**109,229**	**85,970**	**12,219**	**253,752**	**461,170**
	% in column	100.0%	100.0%	100.0%	100.0%	100.0%
	% in row	23.7%	18.6%	2.6%	55.0%	100.0%
	% in total	23.7%	18.6%	2.6%	55.0%	100.0%

Road preferences: prefer calm residential roads (Calm), avoid main roads without cycle infrastructure (Infra), prefer main roads (Main); other characteristics: prefer green pathways (Green), avoid bad surfaces (Smooth), prefer green pathways and avoid bad surfaces (Green-Smooth); simple and strong preference summed up. **Reading example:** the first cell shows that 24,887 requests combine a preference for calm roads (column) with that for green pathways (row). The percentage values show that 22.8 percent of requests which give a preference for calm roads (column) also prefer green pathways (row). At the same time, in 36.5 percent of requests preferring green pathways, there is also a preference for calm roads. In total, the combination preferring calm roads and green pathways makes up 5.4 percent of all requests.

Table 5-3. Overview of cited studies

Author	Year	Variables used in the model	Type of analysis	Country	Investigation area	Local cycle mode share
Bernardi, La Paix Puello, Geurs	2018	Link type [type of road or bike infrastructure], Link quality, Link beauty, Link traffic nuisance	Revealed preference	Netherlands	countrywide	Not stated
Ghanayim, Bekhor	2018	Total route length, Route length on streets with bike paths, Route length on urban arterials and highways, Average street length, Dwelling units / m, Route length "near sea", Route length "near park"	Revealed preference	Israel	Tel Aviv metropolitan area	1,6%
Prato, Halldórsdóttir, Nielsen	2018	Distance, Wrong way, Left turns, Right turns, Bicycle infrastructure type, Bicycle facility type, Cumulative elevation gain, Surface type, Number of intersections, Motorized road type, Motorized free speed, Number of motorized traffic lanes, Land-use designations	Revealed preference	Denmark	Copenhagen	37% commuting trips
Vedel, Jacobsen, Skov-Petersen	2017	Road environment, Cycle track, Green surroundings, Crowding (other cyclists on the route), Stops (on the route), Route length	Stated preference	Denmark	Copenhagen	35% of all trips
Aldred, Elliott, Woodcock, Goodman	2016	Varying	Review on stated preference surveys	Varying	Varying	Varying
Buehler, Dill	2016	Varying	Review	World	Varying	Varying
Mertens, Van Dyck, Ghekiere, De Bourdeaudhuij, Deforche, Van de Weghe, Van Cauwenberg	2016	type of cycle path, speed limit, speed bump, vegetation, evenness of the cycle path surface, general upkeep, traffic density	Stated preference	Belgium	Flanders	14 % of trips shorter than 5 km
Winters, Teschke, Brauer, Fuller	2016	Bike Score (10-unit change), Destinations/Connectivity Score, (10-unit change), Bike Lane Score (10-unit change), Hill Score (10-unit change), Bike Score (categorical), City	Cross-sectional	US/ Canada	24 cities	1,9% (mean) commuting trips
Nielsen,	2013	Distance to retail concentration, Train station within 1 km, Population density with-	Cross-	Denmark	Denmark	23%

Olafsson, Carstensen, Skov-Petersen		in 1.5 km, Public transport departures within 500 m, Retail jobs/resident within 500 m, Topology as elevation range within 1.5 km, Intersection pr. Network dist. within 1.5 km, Intersection pr. Network dist. within 500 m (Ln), Residence is a flat, Copenhagen or Frederiksberg (Place dummy), City of Odense (Place dummy), Respondent has driver's license, Occupation: student, Occupation: full time employment, Education: medium, Education: long (academic), Family type: single, Household income/adult, Personal income, Gender	sectional			Individuals who cycle
Broach, Dill, Gliebe,	2012	Bridge with on-street bike lane, Proportion of route along links with [varying] upslope, Distance of route, Path size, Left turn without traffic signal and parallel [varying] traffic volume, Proportion of route on designated bicycle boulevard, Proportion of route on off-street, regional bike path, Proportion of route on streets with [varying] traffic volume without a bike lane, Left turns and straight movements through traffic signals per mile, Turns or straight movements through stop signs per mile, Left and right turns per mile, Right turns at unsignalized intersections with cross traffic volume 10,000+ per day, Left turns and through movements at unsignalized intersections with [varying] cross traffic volume	Revealed preference	USA	Portland	Not stated
Caulfield, Brick, McCarthy	2012	Adjacent traffic speed (km/h), Type of infrastructure, Travel time (min), Number of junctions on route, Cycle traffic on route	Stated preference	Ireland	Dublin	Not stated
Buehler, Pucher	2011	Bike share of commuters, Bike commuters per capita, Bike lane supply, Bike path supply, Cycling safety, College students, Car access, Sprawl index, Public transport supply, Gasoline price, Hot weather, Cold weather, Annual precipitation	Cross-sectional	USA	90 cities	0,8% (mean) Commuting trips
Winters, Teschke	2010	major streets, residential streets, rural roads and highways, off-street paths, cycle paths next to major roads but physically separated from traffic, road markings, bicycle lanes, traffic calming, route surfaces, car parking	Stated preference	Canada	Vancouver metropolitan area	~2%
Winters, Teschke, Grant, Setton, Brauer	2010	gross population density, % of land area with green cover, average air pollution (ppb NO2), variation in elevation, % of road segments >10% slope, traffic calming features, stencils, bike route signs, traffic crossings with bike activated signals, ratio of 4 way intersections: all intersections, *% of land area with use: (*agriculture, commercial, education, entertainment, industrial, office, park, single family residence, multifamily residence, land use mix)	Revealed preference (shortest)	Canada	Vancouver metropolitan area	1,7% for work trips
Garrard, Rose, Lo	2008	Type of bicycle facilities (path, lane, no)	Observing	Australia	Melbourne	1,2%
Hunt, Abra-	2007	Availability of showers at destination, Availability of secure parking at destination,	Stated pref-	Canada	Edmonton	Not stated

ham		Minutes riding on roadways in mixed traffic, Minutes riding on designated bike lanes on roadways, Minutes riding on bike paths shared with pedestrians	erence			
Moudon, Lee, Cheadle, Collier, Johnson, Schmid, Weather	2005	Age in years, Gender, Race, Marital status, General health, Income, Own a bicycle?, Number of cars in household, Vehicle miles traveled per month, Exercise at home?, Use transit?, Work hours per week, Vigorous activity, Number of facilitators of cycling mentioned, Total household location factors -Proximity to recreational destinations, Perceived presence of, Benefits of physical activity, Presence of amenities for cycling and jogging in the neighborhood, High social support for walking and cycling in the neighborhood, High visual quality of the neighborhood, Presence of destinations in neighborhood, Presence of auto-oriented facilities in the neighborhood, Problems related to automobiles in neighborhood, Percentage of streets lined with bicycle lanes, Distance to the closest trail, Number of parks within the 3 km buffer, Number of destinations within the closest NC6 (sports facility and school), Size of the closest NC3 (grocery and restaurant), Area of convenience stores within the 3 km buffer, Number of parcels within the closest NC10 (office, fast food, and clinic/hospital)	Cross-sectional	USA	King County, Washington	<1%
Stinson, Bhat	2003	Roadway class, Parallel parking permitted, Bicycle facility type, Bridge type, Hilliness, Riding surface, Travel time, Facility continuity, Number of stop signs per mile, Number of red lights, Number of major cross-streets	Stated preference	USA / Canada	countrywide	varying
Abraham, McMillan, Brownlee, Hunt	2002	total cycling time including stops at red lights and stop signs, time on arterial roads, time on arterial roads with wide curb lane, time on arterial roads with bicycle lane, time on residential roads, time on bike route consisting of residential roads, time on bicycle pathways alongside arterial road, time on bicycle pathways in park area, Parking facility available at destination, Cost for parking facility, Other facilities available at destination, Cost for other facilities	Stated preference	Canada	Calgary	Not stated
Aultmann-Hall	1996	Turns, Turns per km, Signals, Signals per km, Major signals, Proportion of movements between a major and minor road with a signal, Proportion of movements from a minor/path to a minor/path with a signal, Proportion of route on arterial roads, Proportion of route on collector roads, Proportion of route on local roads, Proportion of route off-road, Road bridges, Travel on grade (km), Level railway crossings	Revealed preference (shortest)	Canada	Guelph, Toronto, Ottawa	Not stated

Table 5-4. Comparison of length and overlap for exemplary routes

Relation	**Inner city route** **[City center east/ Alexanderplatz – City center west/ Breitscheidplatz]**		**Edge of town route** **[Freie Universität Lankwitz/ Malteser-str – Freie Universität Dahlem/ Thielplatz.]**		**Edge of town to city center route** **[Humboldt Universität Adlershof/ Rudower Chaussee – Humboldt Universität Mitte/ Unter den Linden**	
[km]	Length	Length identical with default	Length	Length identical with default	Length	Length identical with default
Default	6.25	6.25	6.57	6.57	14.31	14.31
Prefer residential roads [calm]	6.63	2.38	6.75	2.37	15.83	7.50
Use only residential roads [calm*]	7.39	0.83	6.92	2.82	16.91	0.94
Prefer main roads [main]	6.39	4.19	7.11	1.82	14.93	4.07
Use only main roads [main*]	6.39	4.19	7.44	1.33	15.19	3.09
Avoid main roads without cycle paths/bus lanes [infra]	6.46	4.14	6.83	2.53	14.53	11.35
Avoid main roads without cycle paths [infra*]	6.34	3.60	6.83	2.53	14.55	11.52
Avoid cobblestones and bad surfaces [smooth]	6.25	6.25	6.75	2.75	14.31	14.31
Use only very good surfaces [smooth*]	6.25	6.25	6.75	2.75	14.32	13.98
Prefer green pathways [green]	7.47	0.00	6.57	6.57	17.27	6.20
Strongly prefer green pathways [green*]	7.54	0.00	6.76	4.98	18.93	2.11

For a clearer overview, only strong preferences are displayed on the maps.

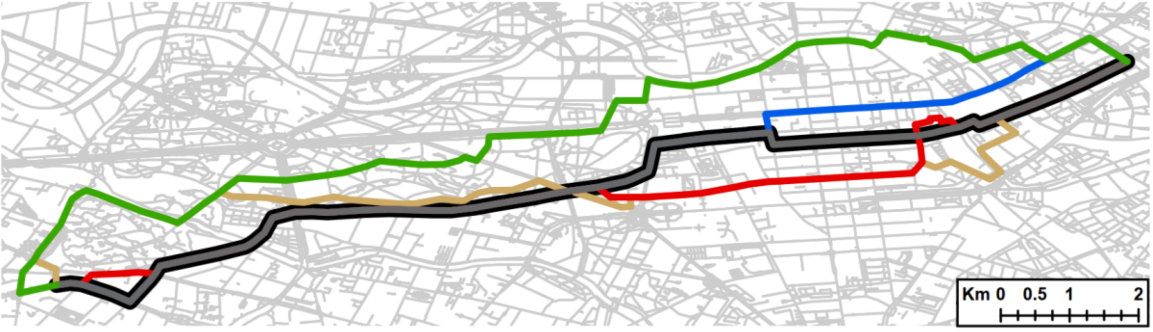

Figure 5-13. Inner city routes

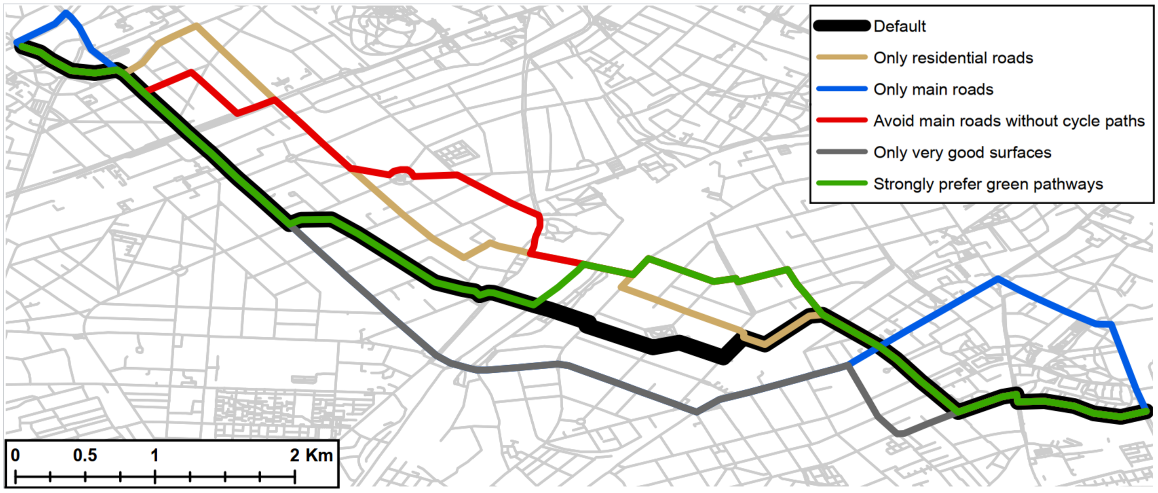

Figure 5-14. Edge of town routes

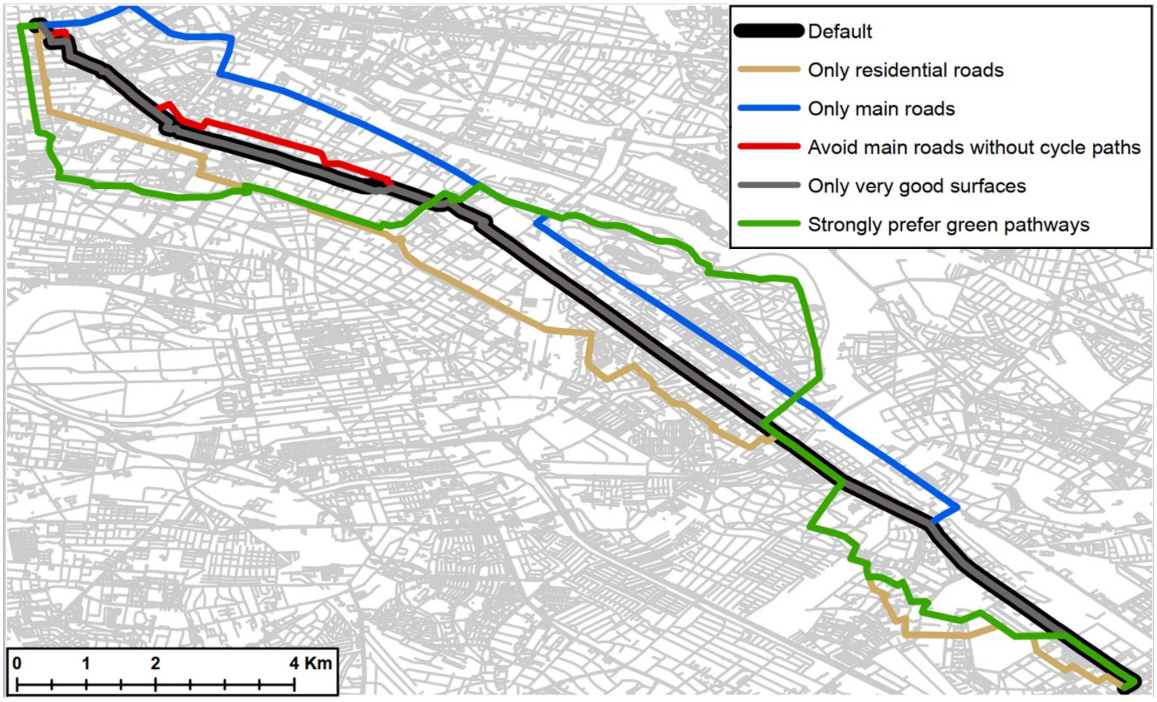

Figure 5-15. Edge of town to city center routes

6 Synthese

6.1 Zusammenfassung zentraler Erkenntnisse

Das übergeordnete Ziel dieser Arbeit ist es, die Forschung zu infrastrukturellen Zusammenhängen und Routenwahlverhalten im Radverkehr voranzubringen. Wie beschrieben sind diese Untersuchungen sowohl für das Verständnis des Systems der aktiven Mobilität als auch für zielgerichtete Förderung nachhaltiger Mobilität von besonderer Bedeutung. Zur Fokussierung wurde der Stand der Forschung aufbereitet und so besonders relevante Forschungslücken entdeckt. Dabei zeigte sich einerseits, dass frühere Ansätze zur Analyse der Bikeability urbaner Gebiete Einschränkungen aufweisen. Andererseits bleiben auf der nachgelagerten Ebene der Routenwahl teilweise Fragen unbeantwortet und Potenziale werden nicht ausgeschöpft.

Aus diesem Bild leiteten sich die Forschungsfragen in den zwei Hauptkomplexen der Arbeit ab. Um diese zu beantworten, wurde für die Arbeit ein breiter Mix von Methoden entwickelt. Diese wurden zielgerichtet in einzelnen Modulen im Sinne der Gesamtfragestellung eingesetzt. Die theoretische Hintergrundfolie für die Arbeiten bildet die Theorie des geplanten Verhaltens. Diese besagt im Kern einen Zusammenhang zwischen Intention und menschlicher Handlung. Für diese Arbeit ist dabei insbesondere die subjektiv wahrgenommene Ressource Infrastruktur von Bedeutung, die entsprechend dem theoretischen Modell über die *wahrgenommene Verhaltenskontrolle* sowohl auf die Intention als auch auf das Verhalten wirkt. Somit wird ein Teil des Entscheidungsprozesses abgebildet.

Im Folgenden wird auf die spezifischen Fragestellungen und die hierzu gewonnenen Erkenntnisse eingegangen.

> Forschungsfrage 1: Wie lässt sich die Bikeability urbaner Infrastruktur unter Anwendung einer konsensualen Berücksichtigung der relevanten Einflussgrößen übertragbar operationalisieren und wie hängt diese mit der lokalen Fahrradnutzung zusammen?

Die Frage adressiert mit der konsensualen Grundlage, der integrierten Betrachtung und dem Fokus auf Übertragbarkeit und offene Daten drei ermittelte Mängel früherer Ansätze. Mit dem Komplex befasst sich die in Kapitel 3 integrierte Veröffentlichung *More Than Bike Lanes – A Multifactorial Index of Urban Bikeability*. In dem zugrunde liegenden Artikel wurde ein dreistufiger Ansatz zur Entwicklung eines Bikeability Index erarbeitet. In einem vier-ten Schritt wurde dieser Index am Beispiel Berlins auf Effekte auf den Radverkehr getestet. Inhaltlich ergeben sich aus dem methodischen Komplex zwei Kernerkenntnisse:

Die erste relevante Erkenntnis lieferte der interaktive, onlinebasierte Expertenprozess auf Basis einer vorgeschalteten Literaturanalyse. Dabei zeigt sich, dass trotz des heterogenen Hintergrundes der beteiligten Expertinnen und Experten hinsichtlich des räumlichen Kontextes der Tätigkeit und des wissenschaftlichen vs. praxisorientierten Schwerpunktes weitgehende Einigkeit darüber herrscht, was eine radfahrtaugliche urbane Umgebung ausmacht.

Unabhängig davon, dass die Operationalisierung der einzelnen Merkmale teils vorbereitender Analysen und Kombinationen verschieden konstruierter Geodaten bedarf, lässt sich die Radfahrtauglichkeit dabei mittels fünf Parametern abbilden. Von besonderer Bedeutung sind die Ausstattung von Hauptverkehrsstraßen mit Radverkehrsanlagen, gefolgt von der Kreuzungsdichte, welche direkte Routen ermöglicht. Darüber hinaus haben der Anteil ruhiger Nebenstraßen an allen Straßen sowie grüne Wege abseits des motorisierten Individualverkehrs mittlere Bedeutung. Schließlich sind Verleih- und Reparatureinrichtungen von geringer aber signifikanter Bedeutung. Somit wird eine Kombination verschiedener Qualitäten für den Radverkehr abgebildet. Die Merkmale zielen dabei auf ein Ermöglichen des sicheren Radfahrens an Hauptverkehrsstraßen, das Vorhandensein ruhiger bzw. attraktiver Alternativrouten, geringe Umwege und ergänzende Angebote wie Verleih- und Reparatureinrichtungen ab. Insofern vereint der Bikeability Index verschiedene situative bzw. individuelle Anforderungen und Präferenzen von Radfahrenden.

Zweitens zeigt sich in der Modellierung der Verkehrsmittelwahl am Beispiel Berlins, dass dieser entwickelte Index einen signifikanten und stark positiven Einfluss auf die Wahl des Fahrrades als Verkehrsmittel hat. Die entsprechend dem entwickelten Vorgehen lokal abstrahierte Radfahrtauglichkeit korreliert also deutlich mit der individuellen Entscheidung, das Fahrrad als Verkehrsmittel zu wählen. Anzumerken bleibt, dass diese kurzfristige Entscheidungsebene in gewissem Maße von mittel- und langfristigen Entscheidungen wie der individuellen Wohnstandortwahl in ein radfahrtaugliches Gebiet überlagert sein kann.

In Bezug auf die Fragestellung lässt sich festhalten, dass das vorgeschlagene Vorgehen methodisch als geeignet angesehen werden kann, die adressierten Mängel des Forschungsstandes zu beheben. So wird ein konsensuales Verständnis zugrunde gelegt, das sicherstellt, die relevanten Parameter zu berücksichtigen. In der Umsetzung wurde ein Arbeitsablauf basierend auf offenen Geodaten realisiert. Am Berliner Beispiel konnte zudem belegt werden, dass eine höhere Bikeability und die Wahl des Fahrrades als Verkehrsmittel stark positiv interagieren. Die Konzeption kann also auch inhaltlich die implizierte Hypothese belegen, dass eine höhere Radfahrtauglichkeit mit mehr Radverkehr einhergeht.

> Forschungsfrage 2: Wie stellen sich Präferenzen hinsichtlich Routeneigenschaften im Radverkehr dar und welche Erkenntnisse liefern hierfür methodisch unterschiedliche Forschungsansätze?

Die Frage adressiert einerseits ungenutzte Potenziale in etablierten Forschungsansätzen. Andererseits zielt sie auf den Bedarf ab, weitere, bisher ungenutzte Datenquellen zu erschließen. Die zugrunde liegende Thematik wurde in den Kapiteln 4 und 5 behandelt.

Die Ergebnisse des in Kapitel 4 (Veröffentlichung *Evaluating Cyclists' Route Preferences with Respect to Infrastructure)* beschriebenen Entscheidungsexperiments zeigen für verschiedene Eigenschaften der Straße einen sehr unterschiedlichen spezifischen Nutzen für Radfahrende. Dabei ergeben sich stabile Präferenzen über die Subgruppen mit einer großen Bedeutung von separierten Radinfrastrukturen an Hauptstraßen. Differenziert nach Infrastrukturtyp schneiden die Ausführungsvarianten mit stärkerer baulicher Trennung besser ab. So werden mit Pollern geschützte Radfahrstreifen besser bewertet als bauliche Radwege. Diese schneiden wiederum besser ab als markierte Radfahrstreifen bzw. Schutzstreifen. Gegenüber Hauptverkehrsstraßen mit Radverkehrsanlagen fällt der Nutzen von Nebenstraßen als Radrouten geringer aus. Einen sehr hohen Nutzen zeigen diese für die Radfahrenden erst, wenn sie als Fahrradstraße mit expliziter Priorisierung des Radverkehrs ausgeführt sind. Fast so positiv wie eine Basisradinfrastruktur in Form einer reinen Markierungslösung entlang einer Hauptverkehrsstraße wird eine glatte Straßenoberfläche als Komfortmerkmal bewertet. Auch die Abwesenheit parkender Kraftfahrzeuge sowie das Vorhandensein von Straßenbäumen haben einen klar positiven Nutzen. In der personenbezogenen Differenzierung zeigt sich insbesondere, dass Radfahrende mit Kindern geringeren Geschwindigkeiten des motorisierten Individualverkehrs einen deutlich höheren Nutzen beimessen. Dies wird neben der noch stärkeren Präferenz für Fahrradstraßen insbesondere durch die stärker positive Bewertung von verkehrsberuhigten Bereichen, in denen Schrittgeschwindigkeit gilt, deutlich. Zudem sinkt der positive Nutzen glatter Oberfläche mit sinkender Häufigkeit der Fahrradnutzung.

Neben den individuellen, personenbezogenen Analysen wurden die Präferenzen in Deutschland mit denen in Griechenland verglichen. Dieser Vergleich ist deshalb besonders interessant, weil Griechenland – ganz anders als Deutschland – kaum über Radverkehr und kaum über ausgebaute Radinfrastruktur verfügt. In dieser strukturellen Differenzierung unter verschiedenen Rahmenbedingungen zeigt sich einerseits, dass der Nutzen geringerer zulässiger

Höchstgeschwindigkeiten im griechischen Sample viel kleiner ausfällt als im deutschen. Darüber hinaus wird der Zeitparameter in Griechenland weniger negativ bewertet. Es werden also generell längere Umwege für bessere Routeneigenschaften in Kauf genommen. Hier zeigt sich der Einfluss des jeweiligen Kontextes, der in Kapitel 4 näher beschrieben und interpretiert ist. Die von der deutschen Perspektive abweichende Bedeutung von Geschwindigkeitsbegrenzungen und der Zeitkomponente sind vor dem Hintergrund einer anderen Mobilitätskultur, generell geringerer Regelkonformität und einer nach wie vor gelebten Dominanz des Autos zu sehen.

Einen anderen Blickwinkel bieten die Ergebnisse der in Kapitel 5 (Veröffentlichung *Assessing cyclists' routing preferences by analyzing extensive user setting data from a bike-routing engine)* beschriebenen Analysen der Daten aus der Fahrradnavigation. Zunächst wurde gezeigt, dass sich die Vielzahl der in der Radnavigation getätigten Einstellungen für bevorzugte Routeneigenschaften zu wenigen Präferenzclustern kondensieren lässt. Dadurch wird deutlich, dass sich die auf Einzelwege bezogenen Routenpräferenzen heterogen und teilweise konträr darstellen. Es ergeben sich in der Rangfolge der Klassenbesetzung sechs Präferenzklassen. Diese weisen Präferenzen für die kürzeste Route (1), eine Route mit glatter Oberfläche und dem Meiden von Hauptstraßen ohne Radinfrastruktur (2), eine Route mit glatter Oberfläche auf Nebenstraßen und grünen Wegen (3), eine Route auf Nebenstraßen und grünen Wegen (4), eine Route mit Meiden von Hauptstraßen ohne Radinfrastruktur (5) und eine Route auf Hauptstraßen ungeachtet von Radinfrastruktur (6) auf. Mit Blick auf die primäre Auswahl von Radverkehrsanlagen an Hauptstraßen gegenüber ruhigen Nebenstraßen zeigen sich zwei fast gleich große Lager. Darüber hinaus wird in der größten Klasse simpel die schnellste Route gewünscht. Dabei ist zu beachten, dass diese Auswahl der Voreinstellung entspricht. In der mit Abstand kleinsten Klasse werden ungeachtet der Radinfrastruktur nur Hauptstraßen gewünscht. Letztere ist in der Einstellung der Nutzenden klar von der schnellsten Route zu unterscheiden.

Die Routenpräferenzen im Radverkehr stellen sich also in mehrerer Hinsicht differenziert dar. Insgesamt ist eine Präferenz für vom motorisierten Verkehr getrennte Radinfrastrukturen zu erkennen. Diese Infrastrukturen scheinen umso wertvoller, je stärker die bauliche Trennung vom motorisierten Individualverkehr ausgestaltet ist. Daneben spielen ruhige Nebenstraßen eine große Rolle. Hier bieten Geschwindigkeitsbeschränkungen und besonders eine explizite Bevorzugung des Radverkehrs (Fahrradstraßen) einen deutlichen Mehrwert. Je nach Eigenschaften der Person oder des Weges zeigen sich gewisse Abweichungen. So werden beim Radfahren mit Kind, von weiblichen sowie älteren Radfahrenden eine Trennung vom motorisierten Verkehr sowie geringere zulässige Höchstgeschwindigkeiten stärker positiv bewertet als in der Gesamtheit. Auch bei Gelegenheitsnutzenden zeigen sich Unterschiede, beispielsweise hinsichtlich der Bedeutung der Oberflächenqualität. Des Weiteren zeigt das Beispiel des Präferenzclusters der ausschließlichen Nutzung von Hauptverkehrsstraßen, dass auch diskrepante Präferenzen bestehen. Darüber hinaus ergeben sich Zusammenhänge mit strukturellen Einflüssen und lokalen Partikularitäten, wie der Vergleich zwischen Deutschland und Griechenland zeigt. Dabei bleiben die Routenwahlentscheidungen – wie immer in der Verkehrsmodellierung – eine Abwägung gegenüber Zeitvorteilen.

6.2 Fazit

Die Ergebnisse der einzelnen Kapitel beantworten die Fragestellungen. Vor dem Hintergrund des Forschungsdesigns der Gesamtkonzeption im Zusammenspiel der einzelnen methodischen Module ergeben sich weitere entscheidende Erkenntnisse. Im Hinblick auf den Stand der Forschung bringt die Synthese der Ergebnisse der unterschiedlichen methodischen Ansätze einen relevanten Mehrwert. Von besonderer Bedeutung ist der im Verlauf der Arbeit verfeinerte Fokus, der durch die Verschiebung von der globalen Abstraktionsebene auf die Ebene der Moduswahl und schließlich die Ebene der Routenwahl unterschiedliche Blickwinkel und damit eine integrierte Gesamtbetrachtung ermöglicht. Aus der Vielzahl der methodischen Werkzeuge, Betrachtungswinkel, inhaltlich-thematischer Differenzierungen und den daraus resultierenden Erkenntnisbausteinen können im Wesentlichen vier übergeordnete Schlüsse gezogen werden.

Radverkehrsanlagen an Hauptverkehrsstraßen sind von herausragender Bedeutung. Inhaltlich weisen die Ergebnisse trotz methodischer, individueller und struktureller Vielfalt diese übereinstimmende Tendenz in Hinblick auf das Kernergebnis auf. Alle eingesetzten Methoden sehen hierin die wichtigste Bedingung für den Radverkehr. Bei der Messung der Bikeability urbaner Gebiete stellt dieser Parameter nicht nur die wichtigste Einflussgröße dar, auch ist sich die heterogene Gruppe der Expertinnen und Experten darin einig. Im Entscheidungsexperiment schneiden hochwertige Radinfrastrukturen entlang von Hauptverkehrsstraßen trotz einer Vielzahl an getesteten, individuell und strukturell definierten Subgruppen in jeder Teilgruppe am besten ab. Damit ist die Einigkeit nicht nur zwischen den methodischen Ansätzen gegeben, sondern auch zwischen den untersuchten Subgruppen der Nutzenden. Im Zuge der zunehmenden Fokussierung im Verlauf der Arbeit zeigt sich zudem die Abstufung und weitere Differenzierung innerhalb des zuvor aggregiert betrachteten Parameters *Radinfrastruktur an Hauptverkehrsstraßen*. Dabei wird zum einen die

Bedeutung und Rangfolge dieser Merkmale bestätigt, zum anderen werden die Erkenntnisse um die relative Bewertung analog zur Stärke der physischen Trennung vom motorisierten Individualverkehr ergänzt. Auch in der Analyse der Navigationsdaten stellen Abfragen unter Beachtung der Infrastruktur an Hauptverkehrsstraßen gegenüber den ruhigen Nebenstraßen die etwas größere Gesamtgruppe dar.

Auch weitere Routeneigenschaften sind wichtig. Trotz der herausragenden Bedeutung einer separierten Infrastruktur entlang von Hauptverkehrsstraßen sind auch weitere Elemente von Bedeutung. Diese inhaltlichen Schattierungen der Ergebnisse werden durch den Einsatz verschiedener methodischer Ansätze offenbart. Im Entscheidungsexperiment erfolgte innerhalb der Nebenstraßen eine Ausdifferenzierung entsprechend den Bedingungen für den Radverkehr bei unterschiedlicher straßenverkehrsordnerischer Regulierung. Dabei zeigte sich insbesondere der enorme Nutzen von Fahrradstraßen. Das Spiegeln dieser Differenzierung durch den methodischen Ansatz der Analyse von Navigationsdaten gleicht die Ergebnisse des hypothetischen Entscheidungsexperiments mit der unter realitätsnahen Bedingungen aufgezeichneten Routensuche ab. Bei dieser Analyse schnitten die Nebenstraßen insgesamt besser ab als im Entscheidungsexperiment. Vermutlich sind die im Entscheidungsexperiment visualisierten, den Regelplänen entsprechenden Ausführungen der Radinfrastruktur im Mittel deutlich hochwertiger als die in der Realität anzutreffenden Lösungen. Insofern kann die eingangs beschriebene tendenzielle Diskrepanz zwischen den Ergebnissen unterschiedlicher methodischer Ansätze nicht ausgeräumt werden. Insgesamt zeigen individuell unterschiedliche Ausprägungen der Präferenzen im Entscheidungsexperiment und konträre Präferenzcluster kleinerer Teilgruppen in der Navigationsdatenanalyse auch abweichende Bedürfnisse. Die erkennbare Bedeutung von grünen Wegen und besonders ruhigen Routen entspringt dabei möglicherweise einer anderen Motivlage als die mutmaßlich durch Sicherheits- und Zeitaspekte geleitete Wahl geschützter Infrastrukturen. Von Interesse sind dabei auch die aus der Navigationsdatenanalyse resultierenden typischen Kombinationen präferierter Routeneigenschaften. So sind beispielsweise Präferenzen für ruhige Straßen besonders stark mit Präferenzen für grüne Wege verknüpft. Gegenüber dem Auto sind Radfahrende nah am Äußeren, ohne einen umgebenden privaten Raum. Dadurch werden äußere Eindrücke viel stärker wahrgenommen. Anders als im Auto kommen neben der Zeitkomponente weitere Einflussgrößen ins Spiel. So können gegenüber reinen Transiträumen auch die Aufenthaltsqualität und Attraktivität der Route eine Rolle spielen. Demgegenüber kann das Beispiel der Präferenz für Hauptverkehrsstraßen im kleinsten Cluster der

Navigationsdatenanalyse mit Einfachheit und Klarheit der Route erklärt werden. Dies wiederum spricht für den Bedarf an einer guten Beschilderung und intuitiven Führung von Radrouten. Die verschiedenen Ansprüche sind vor dem Hintergrund der eingangs beschriebenen großen Vielfalt im Radverkehr bezogen auf Nutzende, Nutzungsmuster und Fahrzeugtypen nicht überraschend. Im Hinblick auf die stärkere Verbreitung und weitere Ausdifferenzierung unterschiedlicher Fahrzeugtypen wie Lastenräder und Pedelecs ist auch in der Art der Nutzung und den damit einhergehenden Präferenzen ein Verfestigen und Ausdifferenzieren zu erwarten.

Vulnerable Gruppen profitieren stärker von einem radfahrtauglichen Umbau der Infrastruktur. Wie die Ergebnisse der Entscheidungsmodellierung zeigen, bewerten Alltagsradfahrende mittleren Alters verschiedene Routeneigenschaften nicht substanziell anders als spezielle Teilgruppen. Das Beispiel des Radfahrens mit Kind zeigt, wie entsprechende Verkehrsteilnehmende ruhige bzw. geschützte Routen noch stärker positiv bewerten als die Allgemeinheit. Gleiches gilt analog für ältere Radfahrende. Für Gelegenheitsradfahrende, ältere Menschen und Menschen mit Kindern wiegen die Vorteile hochwertiger Routen also noch stärker. Gleichzeitig zeigen diese Gruppen geringere Radnutzung, sodass noch größere Potenziale für Zuwächse zu erwarten sind.

Individuelle Unterschiede sind stärker ausgeprägt als strukturelle. Bei beiden auf der Ebene der Routenwahl eingesetzten Verfahren ergibt sich mit Blick auf die personenbezogene Differenzierung eine größere Spannweite als bei der räumlichen Differenzierung. So zeigen sich einerseits starke soziodemografische Interaktionen im Entscheidungsexperiment und andererseits ganz unterschiedliche Präferenztypen in der Navigationsdatenanalyse. Beide Unterschiede korrelieren nicht mit Teilräumen. Dies ist ein weiterer Beleg dafür, dass sich Präferenzen für und Bewertungen von Radinfrastrukturen wenig in der räumlichen, wohl aber in der (subjektiven) personenbezogenen Differenzierung unterscheiden. Die individuellen Unterschiede sind vor dem Hintergrund der bereits erwähnten großen Heterogenität der Radfahrenden bezogen auf zahlreiche Eigenschaften zu sehen. Dennoch zählt der spezifische Kontext, wie die beschriebenen Besonderheiten des griechischen Samples zeigen. Dabei scheint bei einer in Griechenland vorherrschenden generell geringeren Regeltreue der Nutzen von Streckenbeschränkungen deutlich kleiner. Demgegenüber ist die Bereitschaft, für hochwertige Routen Umwege in Kauf zu nehmen, in Griechenland analog zur geringen Verfügbarkeit hochwertiger Radinfrastrukturen klar höher. Da sich die Präferenzen sonst nicht substanziell unterscheiden, ist zu vermuten, dass eine Basisausstattung an Infrastruktur als notwendige Bedingung für den Radverkehr bislang fehlt, um einen Mobilitätswandel einzuleiten.

6.3 Ausblick

6.3.1 Zukünftige Forschung

Mit den beschriebenen Erkenntnissen hilft die Arbeit, das Gesamtbild in der Forschungslandschaft zu infrastrukturellen Zusammenhängen im Radverkehr zu vervollständigen. Das ermöglicht zum einen Empfehlungen an die Planung und Praxis. Zum anderen wird weiterer Forschungsbedarf adressiert und Möglichkeiten diesbezüglich eröffnet.

Die Arbeiten bilden die Grundlage, die Bikeability urbaner Gebiete in jedem denkbaren Maßstab messen zu können. Dies eröffnet weitreichende Möglichkeiten der Verschneidung mit weiteren Daten aus anderen Quellen. So könnten großräumige Analysen unter Nutzung empirischen Mobilitätsdaten die Effekte der Bikeability in unterschiedlichen Kontexten validieren. Darüber hinaus sind Einsätze für verschiedene weitere Fragestellungen denkbar. So könnten Analysen mit Bikeability und Gesundheitsdaten Aussagen zu Zusammenhängen zwischen *public health* und radfahrtauglicher Umgebung zulassen. Eine Verschneidung mit Sozialstrukturdaten könnte zum einen Gerechtigkeitsaspekte in der Versorgung mit Radinfrastruktur in der Gesellschaft adressieren. Zum anderen wären in der Analyse des Zusammenspiels beider Thematiken Aussagen zur Radinfrastruktur als möglicher Treiber von Gentrifizierung denkbar. Darüber hinaus ist die Messmethode an sich adaptierbar und ließe sich mit anderen Parametern auf weitere Fragestellungen anwenden, beispielweise zur fußgängerfreundlichen oder kindgerechten Stadtgestaltung.

Auch methodisch bieten sich Ansätze, die Messung der Bikeability weiter zu verfeinern. Die oben beschriebene großräumige Messung der Bikeability in Kombination mit Mobilitätsdaten böte eine Datengrundlage, den Index selbst datenbasiert zu optimieren und die Ergebnisse des Expertenprozesses zu überprüfen. Liegen ausreichend georeferenzierte Datenpunkte für den lokalen Radverkehr sowie die Bikeability und die zugrunde liegenden Parameter vor, kann ein adaptives Verfahren des maschinellen Lernens die Gewichtung der Einflussparameter hinsichtlich der Erklärungsgüte des Radverkehrs optimieren. Darüber hinaus bietet das hier nachgelagerte Entscheidungsexperiment die Möglichkeit, insbesondere die Parameter Radinfrastruktur und Nebenstraßen im Index weiter auszudifferenzieren. Dabei könnten innerhalb des Parameters Radinfrastruktur die unterschiedlich bewerteten Ausführungen unterschiedlich stark gewichtet werden. Gleiches gilt für verschiedene Regulierungen auf Nebenstraßen.

Die umfangreichen Daten aus dem Entscheidungsexperiment bieten die Möglichkeit weiterer Differenzierungen. So scheinen insbesondere Routenpräferenzen unter Nutzung verschiedener innovativer Fahrradtypen wie Lastenrad oder Pedelec relevant. Da die Verbreitung dieser Fahrzeugtypen stark zunimmt, kann eine entsprechende Analyse zukünftige Infrastrukturanforderungen aufzeigen. Auch bieten sich weitere, großräumige Vergleiche unter verschiedenen Rahmenbedingungen an. Diese Arbeiten laufen derzeit. Darüber hinaus hat sich mit Inkrafttreten der Elektrokleinstfahrzeugeverordnung im Juni 2019 eine fundamentale Änderung ergeben: Erstmals werden neue, motorisierte Fahrzeugtypen auf der zuvor exklusiven Radinfrastruktur zugelassen. Vor diesem Hintergrund ist einerseits von Interesse, wie sich Routenpräferenzen bei zunehmender Anzahl und Ausdifferenzierung von Fahrzeugtypen generell ändern. Andererseits sind die spezifischen Routenansprüche von Nutzenden neuer Mikromobilitätsverkehrsmittel (insbesondere E-Tretroller) als weitere Adressaten der Infrastruktur relevant.

Schließlich kann das quantitative Forschungsparadigma die Frage des *Warum* nur sehr begrenzt beantworten. Die Modellierbarkeit von menschlichem Verhalten hat deutliche Grenzen und die Ergebnisse haben zumeist nur eine mittlere statistische Erklärungsgüte. Weitere schwer quantitativ messbare, aber sehr wichtige Einflüsse wie Routinen, Lebens- und Mobilitätsstile beeinflussen das Verhalten. Vor diesem Hintergrund scheinen qualitative Ansätze wie beispielsweise die genannten *bike-along*-Interviews eine geeignete Ergänzung zu sein. Diese können Motive für oder gegen das Radfahren bzw. für oder gegen eine bestimmte Route tiefergehend untersuchen und auch darunterliegende Emotionen offenlegen. Dies ist insbesondere vor dem Hintergrund der Erkenntnis im Zuge der Covid-19-Pandemie relevant, dass sich zuvor stabile Rahmenbedingungen und Zusammenhänge unerwartet und schnell ändern können.

6.3.2 Implikationen für Planung und Politik

Die Ergebnisse liefern wichtige Hinweise für die Planung und Praxis. Zunächst belegen sie, dass eine höhere Bikeability klar mit mehr Radverkehr zusammenhängt. Diese Erkenntnis liefert also ein Argument, dass Investitionen in eine radfahrtaugliche Umgebung nicht nur die bereits Radfahrenden belohnen, indem sie den vorhandenen Radverkehr sicherer, komfortabler oder schneller machen. Ein entsprechender Ausbau geht demnach auch mit mehr

Radverkehr einher. Vor dem Hintergrund der beschriebenen individuellen, gesellschaftlichen und umweltbezogenen Vorteile zahlen sich Investitionen in den Radverkehr also aus, sodass eine klare Empfehlung für diese ausgesprochen werden kann. Wie beschrieben profitieren dabei vulnerable Gruppen besonders stark. Hierfür sind insbesondere die Erkenntnisse bezogen auf Kinder- und Familienmobilität wichtig. Das Sicherstellen einer aktiven und nachhaltigen Mobilität ist in diesen Gruppen entscheidend. Spätestens mit dem Eintritt ins Familienleben wird häufig ein privater Pkw angeschafft. Ein gutes infrastrukturelle Angebot kann dazu beitragen, junge Familien im System der aktiven Mobilität zu halten. Dies ist auch vor dem Hintergrund von Mobilitätsbiografien von großer Bedeutung. Demnach ist es langfristig entscheidend, wie Kinder bezogen auf Mobilität sozialisiert werden. Darüber hinaus kann eine kindgerechte Stadt eigenständige Mobilität der auf den Fuß- und Radverkehr angewiesenen Kinder und Jugendlichen ermöglichen. Gleiches gilt für das Sicherstellen von Mobilität und sozialer Teilhabe älterer Menschen – nicht zuletzt vor dem Hintergrund der nachholenden Mobilität älterer Frauen ohne Führerschein.

Sämtliche methodischen Ansätze zeigen die überragende Bedeutung von Radverkehrsanlagen entlang von Hauptverkehrsstraßen. Dabei zeigt sich, dass für hochwertige, vom motorisierten Individualverkehr getrennte Infrastrukturen hohe und über sämtliche Teilgruppen stabile Präferenzen vorherrschen. Aus Sicht der Nutzenden sollten solche Lösungen demnach der Kern einer städtischen Strategie sein. Auch Radverkehrsführungen auf Nebenstraßen sind von hoher Bedeutung. Hier zeigt sich ein heterogeneres Bild hinsichtlich Teilgruppen und Räumen, sodass in der Planung ein genauerer Blick lohnt. Die detaillierten Ergebnisse der Entscheidungsmodellierung bieten durch die Quantifizierung über die akzeptierte Reisezeit die Möglichkeit, Trade-offs für unterschiedliche Führungsvarianten im Einzelnen zu bestimmen. Klar wird, dass als Fahrradstraßen mit expliziter Priorität für den Radverkehr ausgewiesene Nebenstraßen eine besondere Wirkung entfalten und daher vermehrt eingesetzt werden sollten. Vor dem Hintergrund von Aushandlungsprozessen im Zuge der Flächenumverteilung im öffentlichen Raum sind hier geringere Konflikte zu erwarten als auf Hauptverkehrsstraßen. Wie gezeigt wurde, kommt ein deutlich geringeres Geschwindigkeitsniveau insbesondere Familien mit Kindern zugute. Ein Basisnetzwerk an verkehrsberuhigten Zonen könnte somit einen zusätzlichen Mehrwert schaffen.

Weiterhin zeigen die Ergebnisse, dass nicht nur fließender, sondern auch ruhender motorisierter Individualverkehr negative Wirkungen auf den Radverkehr hat. Dies ist im Zuge einer integrierten Strategie der urbanen Mobilität bei anstehenden Flächenumverteilungen zu berücksichtigen. Darüber hinaus sollte eine radfahrtaugliche urbane Umgebung mehrere

Qualitäten vereinen. Unterschiedliche Bewertungen und konträre Präferenzcluster können nur in einer vielfältigen Stadt befriedigt werden. Neben baulichen und regulatorischen Lösungen in Haupt- und Nebenstraßen scheinen dabei Merkmale wie Begrünung einer anderen Motivlage zu entsprechen. Demnach sind Aufenthaltsqualität und Attraktivität von Routen neben dem Anwenden von ingenieurstechnischen Regelplänen zu berücksichtigen, um die radfahrtaugliche Umgebung zu vervollständigen.

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