Bridging the gap: Measuring and valuing integrated accessibility

November 2025

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NZ Transport Agency Waka Kotahi research report 738

Contracted research organisation – Principal Economics Limited

NZ TRANSPORT AGENCY WAKA KOTAHI

Te Kāwanatanga o Aotearoa New Zealand Government

ISBN 978-1-991311-20-7 (electronic)
ISSN 3021-1794 (electronic)

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Torshizian, E., & Isack, E. (2025). *Bridging the gap: Measuring and valuing integrated accessibility* (Report 738). NZ Transport Agency Waka Kotahi.

Principal Economics Limited was contracted by NZ Transport Agency Waka Kotahi in 2023 to carry out this research.

Keywords: Multi-dimensional accessibility; value of access; welfare analysis.

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Please note: This research was conducted under a previous policy context. For example, the research was developed and/or undertaken under the 2021–2024 Government Policy Statement on Land Transport. Consequently, references contained in the report may be to policies, legislation and initiatives that have been concluded and/or repealed. Please consider this in your reading of the report and apply your judgement of the applicability of the findings to the current policy context accordingly.

[1] This research was conducted October 2023 to June 2024.

Acknowledgements

We would like to thank the members of the steering committee for this project:

- Dr Malcolm Menzies (chair), Chris Vallyon, Rowan Selwood-Eyes, Sandy Fong and Tom Beard from NZTA.
- Shrividya Ravi from the Ministry of Transport.

We also highly appreciate Ernest Albuquerque's input as an observer of the steering committee.

We want to acknowledge the inputs of Phil Donovan for his technical assistance with the required data and Dr Saeid Adli's input in the first stage of this project.

We would also like to thank the peer reviewers Professor Arthur Grimes, Senior Fellow at Motu, and Professor Ahmed M. El-Geneidy (McGill University, Canada).

Abbreviations and acronyms

API	application programming interface
BFCA	balanced floating cost accessibility
DEM	digital elevation model
DPPA	daily potential path area
EDF	equivalent doorstep frequency
FOS	feasible opportunity set
GC	generalised cost
GDAL	Geospatial Data Abstraction Library
GIS	geographic information system
GPS	Global Positioning System
GSS	General Social Survey
GTFS	General Transit Feed Specification
HTS	Household Travel Survey
IDI	Integrated Data Infrastructure
MAUP	Modifiable Areal Unit Problem
MBCM	Monetised Benefits and Costs Manual
MNL	multinomial logit
MTUP	Modifiable Temporal Unit Problem
OSM	OpenStreetMap
OTP	OpenTripPlanner
PCA	principal component analysis
PPA	potential path area
PTAL	public transport accessibility level
RP	revealed preference
SA	statistical area
2SFCA	two-step floating catchment area
SP	stated preference
STP	space-time prism
TAZ	traffic analysis zone
TLA	territorial local authority
WTA	willingness to accept
WTP	willingness to pay

Contents

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Executive summary

Access is about potential interaction opportunities and is among everyday life's most important factors. After all, what would life be worth without access to opportunities? In urban economics, access is recognised as the most important factor in the value of land. Despite its critical role in our lives, the analyses of accessibility are incomplete due to various reasons, including lack of data, biased measurement and disconnection with welfare. Various papers construct accessibility measures without considering the usefulness of these measures. The others that focus on the welfare aspect often lack the details on measurement. Almost none of the available studies consider all these aspects together and conclude the value of access.

To address this knowledge gap, Principal Economics was contracted by NZTA in 2023 to carry out this research project to:

- review national and international data and methodologies for constructing a multi-dimensional accessibility measure and explain the use of live and static General Transit Feed Specification (GTFS) files to inform spatial accessibility
- use modal reach curves to quantify how far people are willing to travel in different New Zealand contexts to reach different destination types
- develop appropriate weighting for integrating different destination types into measures that account for and represent the 'value' of reaching different destination types for various population groups.

Measuring person accessibility is critical to inform integration of land use and transport decisions

Efficient investment in our land transport system connects people and businesses quickly and safely, supporting economic growth and creating social and economic opportunities, including access to land for housing growth.

The common (cumulative) accessibility measures are constructed based on the reach of a destination (typically jobs) within a time or a simple distance measure. This measure is mostly administrative (defined by an analyst and not based on a tested definition of access). It does not consider various dimensions of access that may matter to social welfare. The danger is using these untested measures for transport planning that may have unintended consequences. Accessibility considers how transportation infrastructure integrates with land use, impacting the ease with which people can reach desired locations.

Person accessibility is a data-heavy and computationally intensive task but is rapidly growing

While we identified a range of barriers to the use of accessibility measures, particularly due to lack of data and time-consuming methodologies, the rapid change in the available technologies and the use of multi-dimensional accessibility measures in transport appraisals indicate the importance of considering these measures, identify best methods for their construction and develop robust methods for using them. To enhance this, our research project provides a toolkit for constructing accessibility measures. Also, our parallel project on alternative appraisal methodology identified a comprehensive and credible approach for using the identified measures to inform decision making.

Constructing accessibility measures

We constructed over 2,900 measures of access disaggregated by nine travel destinations, four travel times, four travel modes, four age groups and five income quintiles.

As shown in Figure E.1, we undertook extensive modelling and data analysis, including estimating 4,800 regressions to obtain decay factors by dimensions of accessibility measures. In addition to the individual accessibility measures, we constructed a range of aggregate measures using principal component analysis (PCA) methodology. As shown in Figure E.2, accessibility measurement involves constructing impedance, deterrence and saturation functions using the identified methods.

Figure E.1 Constructing accessibility measures

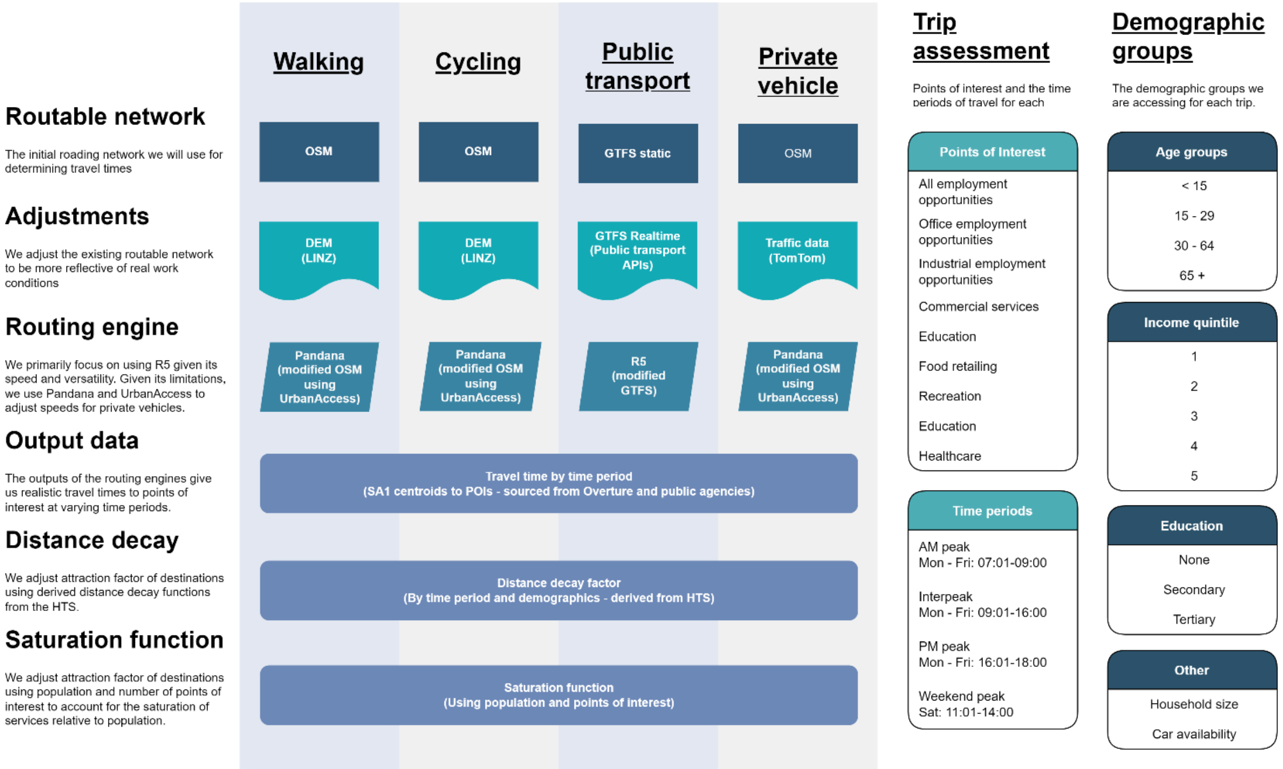
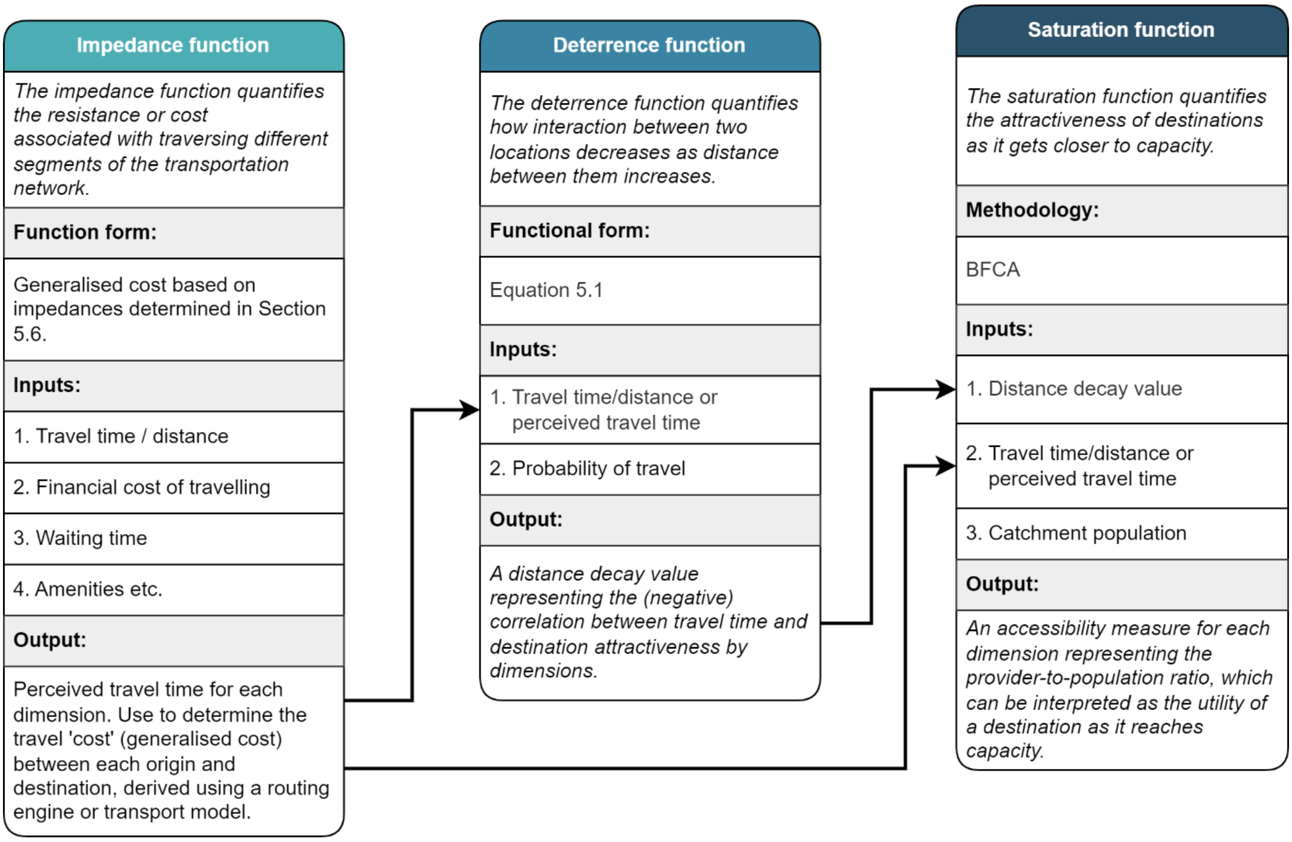


Figure E.2 Accessibility measurement process



Using accessibility measures

The measures are useful to illustrate various dimensions of access clearly. For example, this can highlight, the best available modes for reaching healthcare during the PM peak period for the median-income working-age population. However, there are too many measures to investigate, and it is unclear if they matter to an effective improvement of access. For example, if private vehicle travel time was improved due to an investment in roads, the measure of access may show that driving access to a destination is higher but there is no information on whether that translates into any benefits to society. It is unclear if driving was the best mode for improving access and if the lack of access (and its improvement) is considered a benefit by population groups at all. Hence, we tested the measures of access against the welfare of individuals and identified the most critical measures of access to Auckland and Wellington communities. The combined measure of access to school and entertainment using public transport during the PM peak is the best individual measure of access in correlation with social welfare. After controlling for other factors, we tested the correlation between all identified access and life satisfaction (our welfare measure). The results suggested that most individual measures do not explain welfare.

Our estimated value of overall access varies between $14,266 (willingness to obtain higher access) and $46,448 (compensation for giving up access)

We identified the combination of aggregate accessibility measures correlating with welfare by purpose. Then we estimated willingness to pay (WTP) and willingness to accept (WTA) for these measures. For this, we considered our estimate of the correlation between welfare and income and the best available estimate from international studies. We compared the results with the latest studies available and identified the estimated values using our sensible income parameter. Accordingly, the $ value column shows the 2023-dollar value for a unit change in the combined accessibility measure. Accordingly, the overall value of access is between $14,266 (WTP) and $46,448 (WTA) per household per annum as illustrated in Table E.1.[2]

Table E.1 Dollar value of 1% increase in normalised aggregated accessibility measures – 2023 real prices

Measure (mode, purpose, time)	$ WTP	$ WTA
Food	$7,090	$15,637
School	$1,878	$9,075
Education	$974	$8,944
Retail	$1,178	$8,076
All industries	$1,430	$1,537
Health	$1,033	$1,452
Other	$283	$1,087
Industry	$128	$475
Recreation	$165	$272
Total	$14,266	$46,448

[2] It should be noted that a change in overall accessibility is practically a significant improvement in transport and land use. For example, the PCA measure for all purposes is equal to 34 in Albany. A 10% increase in that measure would be equal to the access levels estimated for Birkenhead in Auckland. According to Table E.1, the 10% improved access level will be valued at $142,660 for a household. A comparison between the two suburbs' available public transport, travel times and available services shows that improving access by 10% is very costly. It is less tangible to give examples of a 1% difference in access for people who are unfamiliar with those suburbs, but to clarify further, Northcote Point's access is 1% smaller than Northcote. Northcote has many shops around and a functional transport network. Its neighbouring suburb, Northcote Point, is surrounded by water on the south and east.

We further disaggregated the value of access for different income quintiles

We first tested the variation in the estimated impact of PCA measures across (adjusted) income quintiles – the lowest quintile (Q1) to the highest quintile (Q5). The results showed that the parameters do not change (Table E.2). This is likely due to the endogeneity of access with respect to location choice, which leads to a spatial wellbeing equilibrium. We recommend that a future study explores this further.

Table E.2 Dollar value of 1% increase in normalised aggregated access measures to different income quintiles – 2023 real prices using New Zealand General Social Survey income impact estimate

Measure (mode, purpose, time)	WTP					WTA				
	Q1	Q2	Q3	Q4	Q5	Q1	Q2	Q3	Q4	Q5
Food	$1,065	$2,111	$3,003	$4,983	$14,585	$1,065	$5,393	$7,671	$12,732	$29,754
School	$359	$712	$1,013	$1,726	$3,929	$1,736	$3,440	$4,893	$8,119	$18,977
Education	$186	$369	$525	$871	$2,036	$1,711	$3,389	$4,821	$8,002	$18,700
Retail	$226	$447	$635	$1,010	$2,463	$1,545	$3,061	$4,353	$7,226	$16,886
All industries	$520	$1,030	$1,465	$2,432	$5,684	$599	$1,187	$1,688	$2,802	$6,548
Health	$291	$575	$828	$1,365	$274	$3,209	$534	$759	$1,259	$2,979
Other	$54	$107	$152	$252	$590	$207	$411	$585	$972	$2,271
Industry	$25	$49	$69	$115	$268	$91	$180	$256	$425	$993
Recreation	$3	$7	-	$10	-	$4	$8	$12	$20	$11
Total	$2,729	$5,407	$7,690	$12,764	$29,829	$10,167	$17,603	$25,038	$41,557	$97,119

An aggregate measure of access alone does not meaningfully explain welfare – we identified a combination of accessibility measures that best explain social welfare

We then tested the usefulness of common cumulative accessibility measures, particularly the number of jobs accessible within 30 minutes of driving and 45 minutes of travel using public transport during the AM peak. Our results indicated that the impact of these measures on welfare is equal to zero – statistically insignificant. Our aggregate accessibility measures provide a robust estimate of the value of access in the presence of cumulative accessibility measures. The cumulative accessibility measures are still useful administrative tools, and their relationship with welfare needs to be investigated in future studies.

Suggestions for future research

- The role of accessibility in agglomeration economies, a concept central to economic theory, is not as clearly understood as needed. Agglomeration economies refer to the benefits firms and individuals obtain by locating near each other (in spatial and industrial clusters). We suggest the main reason for the lack of evidence in this space is the underdeveloped accessibility measurement, which is now addressed in this report. We suggest using our identified accessibility measures and further investigating the relationship between access and land values in a future study that also needs to consider the impact of digital accessibility.
- We suggest further research into the impact of reliance on cars on accessibility in New Zealand. While the literature mostly agrees that increased accessibility is associated with less car usage, a few recent articles discuss that reliance on the motor vehicle in US cities mostly leads to greater accessibility compared to the European cities.
- Public transport patronage and private vehicle driving were subject to significant changes during and after the COVID-19 pandemic. Since the data used for public transport and driving is live data, the vehicle kilometres travelled and public transport patronage may already have bounced back as is evident

from the national data. However, the results may still be affected by the aftermath of COVID-19 if we are not yet back to equilibrium.

- With the increase in work-from-home opportunities and the uptake of various technologies, access has been considered differently by population groups. In a future study, it is critical to further investigate the integration between virtual and physical accessibilities.
- There is a need to collect real-time GTFS for other regions. We collected real-time GTFS for Auckland, Canterbury and Wellington.
- Developing a behavioural survey of walking and cycling to inform logsum analysis and impedance function could improve analysis of cycling and further consider the increased role of ebikes, which flatten out a city so that hilliness is no longer an issue for ebike riders. This will likely have important implications for the distance decay function in our study, which considers slope a negative factor for the likelihood of cycling.
- We used the available information from OpenStreetMap (OSM) and spatial data for walking. Given the broad scope of our report (at the national level), it proved difficult to collect information on other attributes that contribute to walking access such as sidewalk width. While OSM has fields for these attributes, there is no information included in those fields. We suggest that practitioners could calculate and update accessibility measures for smaller, mainly urban areas.
- In our analysis of distance decay, we have not controlled for chained trips. This should be further investigated in the future using the Household Travel Survey dataset.

Abstract

This report comprehensively reviews the available methods and data sources for constructing multi-dimensional accessibility measures for New Zealand and then estimates their value. We used a combination of OpenStreetMap, TomTom, GTFS static and GTFS Realtime together with a range of data from Stats NZ, the Ministry of Transport Household Travel Survey and spatial information from LINZ to construct accessibility measures at the granular statistical area 1. For the routing engine, we used R5 and Pandana. We obtained 80 distance decay curves for each purpose of travel. Disaggregated by nine travel destinations, four travel times, four age groups and five income quintiles, we constructed 2,899 accessibility measures. To summarise these measures and provide accessibility measures useful for decision making, we used principal component analysis and constructed 10 combined accessibility measures by purpose. We then fitted this into a regression analysis of welfare using Stats NZ's General Social Survey and Census data. After applying sample weights, we derived over 10 million sample population in Auckland and Wellington and applied valuation methodology to derive willingness to pay and willingness to accept estimates for the aggregated accessibility measures (by purpose). The results indicated a willingness to pay (for access gain) of $14,266 per household per year and a willingness to accept (for access loss) of $46,488. We further disaggregated these values for income quintiles. Our results suggest that the common administrative (cumulative) accessibility measures fail to explain social welfare. The multi-dimensionality of access requires considering different aspects of access in decision making. The project outputs provide helpful information for accessibility-based appraisal methodologies focusing on land use and transport integration. In addition to its methodological contribution, the report provides a toolkit for constructing accessibility measures.

1 Research context and structure

1.1 Accurate accessibility measurement is critical for informing difficult transport and land-use decisions

Efficient investment in our land transport system connects people and businesses quickly and safely, supporting economic growth and creating social and economic opportunities, including access to land for housing growth. There is a growing body of research investigating transit accessibility (El-Geneidy et al., 2016; Owen & Murphy, 2020; Stewart, 2017; Welch, 2013; Yan et al., 2022).

This report investigates the following gaps in the research on accessibility:

- Most previous studies consider a single destination type such as job opportunities, overlooking other destinations such as healthcare, education and social facilities provided in a city.
- Studies tend to focus on specific modes such as public transport and do not factor in other modes and possible integration between modes.
- Temporal variations in transit services due to departure times and service frequency have been underemphasised.
- The accessibility measures tend to focus on the current conditions of transport systems, and future investment and scenario testing have not been investigated thoroughly.

These gaps highlight the importance of the topic of the current report on developing a multimodal, multi-destination spatio-temporal accessibility measure to replace vehicle mobility-based measures. The methodology will be applicable to both the current conditions of transport accessibility and scenario testing for evaluating different options. Our methodology predominantly leverages open datasets. This report also provides a comprehensive review of methodologies and tools used in international studies, pinpointing gaps in datasets that need attention and refinement.

1.2 This report identifies and implements multimodal, multi-destination spatio-temporal accessibility metrics

Accessibility measures hold an important place in the assessment and selection of transportation plans and projects. They represent the extent to which commuters can reach desired destinations and are useful for capturing the effects of both the transportation system and land use. The purpose of this research project is to develop a comprehensive methodology for an integrated multimodal, multi-destination spatio-temporal accessibility metric. The methodology will be versatile and adaptable, with the capacity to effectively evaluate accessibility under existing transportation conditions while serving as a dynamic tool for scenario testing.

Until recently, accessibility has most commonly been analysed as a static phenomenon. All conventional accessibility measures are cross-sectional and give only a representation of a snapshot in time (Miller, 2018). This static approach needs to pay more attention to the complexities surrounding how people adapt to changing conditions within the transport and land-use system. One such aspect relates to unimodal, bimodal, intermodal or multimodal combinations and how people tend to draw on a variety of these combinations in meeting their travel needs (Groth, 2019; Jonsson et al., 2014; Oostendorp et al., 2019).

Our approach provides a conceptual framework and a quantitative methodology to analyse accessibility, focusing on a mixture of place-based and person-based accessibility approaches. This enhances the precision and applicability of accessibility measures, thereby providing a more insightful and evidence-based foundation for transportation and urban planning decisions. The outcome of this research contributes to the development of sustainable, efficient and equitable transportation systems that are better aligned with the diverse and evolving needs of communities and strategic government transport objectives.

Currently, the research team leads parallel work on an alternative transport appraisal methodology, which might be an accessibility-based one. The current report provides useful information for that work on accessibility-based appraisal methodology.

1.3 Accessibility measurement has been limited and inconsistent

NZTA annually conducts high-level spatial accessibility assessments that, while valuable, have certain limitations when it comes to informing local planning and investment decisions. The existing methodologies, whether applied nationally or at the local level, predominantly emphasise access to jobs and, to a lesser extent, the availability of various social amenities such as access to primary healthcare within a 15-minute radius or striving for the concept of an 'x-minute city'. However, these assessments are inherently limited in scope as they predominantly revolve around the notion of commuting, which is more based on assumptions of the analyst rather than the user perspective. Given that the supply of transport services varies across the day, this variation could affect not only accessibility levels but also the capability of individuals to use a wider variety of transport modes and options.

As discussed in our parallel research project on alternative transport appraisal methodology, accessibility-based appraisals are linked closely with the requirements of an alignment between land use and transport. This highlights the importance of accurate measurement of accessibility that will be useful for appraisals.

Another factor is the multi-destination aspect of transport. According to the Ministry of Transport (2022) Household Travel Survey (HTS), travel to jobs accounts for merely 30% of trips. This narrow focus overlooks the broader spectrum of mobility needs and opportunities within communities. Consequently, there is a gap in the absence of a comprehensive composite measure that effectively encompasses all transportation modes and types of destinations to provide a more holistic evaluation of accessibility.

The absence of a unified, nationally consistent approach to measuring accessibility has resulted in the widespread utilisation of ad hoc methodologies. These divergent approaches have had varying impacts on individuals within the transportation system, causing disparities, inconsistencies and an array of challenges such as the different approaches taken in configuring overcrowded data. The inconsistencies in measuring accessibility lead to biased comparison of benefits and hence prioritisation of projects.

To address these shortcomings, NZTA initiated this research project with the primary objective of developing a robust methodology for constructing a multimodal, multi-destination spatial accessibility metric. The creation of such a metric plays a pivotal role in identifying regions endowed with abundant transportation access, thereby indicating their suitability for urban densification. Simultaneously, it will spotlight transport-deprived neighbourhoods, particularly those heavily reliant on private vehicles, where targeted interventions could eliminate accessibility barriers, fostering more inclusive transport systems. Furthermore, this comprehensive metric will be instrumental in guiding decisions related to potential areas for future urban development.[3]

This research is not limited to the status quo but also extends to anticipating future developments and innovations both in the short and long term that have the potential to significantly influence accessibility. This forward-looking approach recognises that unforeseen advancements or disruptions could have profound impacts on the accessibility landscape.

[3] For example, by considering how new subdivisions affect vehicle kilometres travelled.

1.4 Project objectives to construct accessibility measures based on frontier methodologies and available datasets

Given the inherent uncertainties surrounding future developments and technological shifts, this research was executed in two distinct stages. The first stage determined the feasibility of deriving an accessibility measure to support the shift from mobility-based to accessibility-based transport planning. At the culmination of the initial stage, a critical decision was made regarding the feasibility of pursuing the remaining objectives, considering the insights and findings from the first stage.

Stage 1 of this research project consists of several key objectives, each designed to address critical aspects of the field. This initial stage is dedicated to conducting a thorough literature review, identifying essential datasets, exploring active-mode network analytics and investigating the use of General Transit Feed Specification (GTFS) files for spatial accessibility assessment. In the second stage, we used the findings of the first stage to construct the measures.

Objectives of stage 1

A. Review national and international literature and experience of accessibility measures in transport.
   Addressing objective A: Our literature review adopts a three-fold approach. We delve into the strategic context of transport accessibility in section 1.5. In section 2.1, we explore the significance of a paradigm shift in planning, transitioning from a focus on mere mobility to embracing accessibility. In chapter 3, we examine various transport accessibility measures and methods that can facilitate this essential paradigm shift.

B. Identify typical accessibility datasets and tools used in urban areas worldwide that may not be readily available within New Zealand and suggest other approaches to measurement that may be adopted in the short and long term.
   Addressing objective B: Chapter 3 focuses on the use of different datasets such as the Stats NZ IDI and artificial intelligence (AI)-generated data alongside existing datasets such as Census, GTFS, traffic data and network data.

C. Identify how active-mode network analytics could consider levels of service and desirability of links given the datasets currently available in New Zealand.
   Addressing objective C: In chapter 4, we investigate the potential of using AI with satellite imagery for generating data on traffic, safety and comfort for walking and cycling networks. We also explore the integration of other relevant databases such as Auckland Transport's asset management data, which includes information on bus stop shelters and other amenities.

D. Explain the various ways live and GTFS static files have been used overseas and in New Zealand to inform aspects of spatial accessibility (with more of a focus on connectivity rather than public transport performance analytics).
   Addressing objective D: Chapter 4 explores the methodologies for measuring the impact of public transport travel time inaccuracy and variability on spatial accessibility using GTFS Realtime data.[4]

Objectives of stage 2

E. Identify weighting and calibration factors for saturation curves to quantify the diminishing additional benefit of reaching more destination types.
   Addressing objective E: Chapter 5 defines a saturation function with the property of decreasing marginal rate of return and one parameter for opportunities for different trip purposes.

[4] GTFS static data may underestimate public transport accessibility by an average of 1.5%. However, it is noteworthy that, in certain regions, the estimates of accessibility can deviate significantly, with some areas experiencing overestimations or underestimations of more than 40% (Braga et al., 2023).

F. Use modal reach curves to quantify how far people are willing to travel in different New Zealand contexts to reach different destination types.
Addressing objective F: Chapter 4 uses HTS data to estimate the attractiveness of destinations for different socio-economic groups in various areas.

G. Develop appropriate weighting for integrating different destination types into measures that consider the price of land and transport and represent the value of reaching different destination types for different population groups.
Addressing objective G: We use multi-criteria analysis to factor various dimensions of accessibility (land use, destination types, land price, transportation costs and value of reaching different destination types for each population group) and assign weights to each criterion based on their relative importance.

H. Inform production of a toolkit (being developed in parallel by NZTA) that will enable assessment and measurement of accessibility based on a wide range of measures, in addition to access to employment, at all levels of the transport system.
Addressing objective H: We use the latest advances in transport accessibility tools to convert the proposed measure of accessibility to a solution that NZTA's data science team can use for various applications of transport accessibility analysis.

The objectives outlined in this research project are structured to provide a comprehensive understanding of accessibility measures in transportation.

1.5 Accessibility plays a key role in the transport system

Given the overlapping effects of transport, housing and taxing policies, a comprehensive policy framework must consider all these elements and provide for an integrated land-use and transport system. While policy objectives are not the driver of the choice of a methodology, it is helpful to understand how accessibility aligns with current and previous policy objectives. As discussed in our parallel research report on accessibility-based appraisal methodology, the accessibility framework provides a holistic framework for appraising land-use and transport policies. Hence, the current report's investigation of accessibility measurement is critical for robust land-use and transport decision making, considering economic and productivity outcomes and social welfare.

Improved economic growth and productivity and creating value for money are among the four strategic priorities of the latest Government Policy Statement on Land Transport. Accessibility has a critical role by improving transport and land-use integration, ultimately leading to improved economic growth. The multi-dimensional aspect of accessibility ensures demand and supply are aligned and investments are prioritised to achieve optimal economic, environmental and social outcomes. Improving accessibility can also contribute to emissions reduction by promoting efficient vehicle use through improved transport planning and infrastructure, which will optimise traffic flow and reduce congestion (and associated emissions).

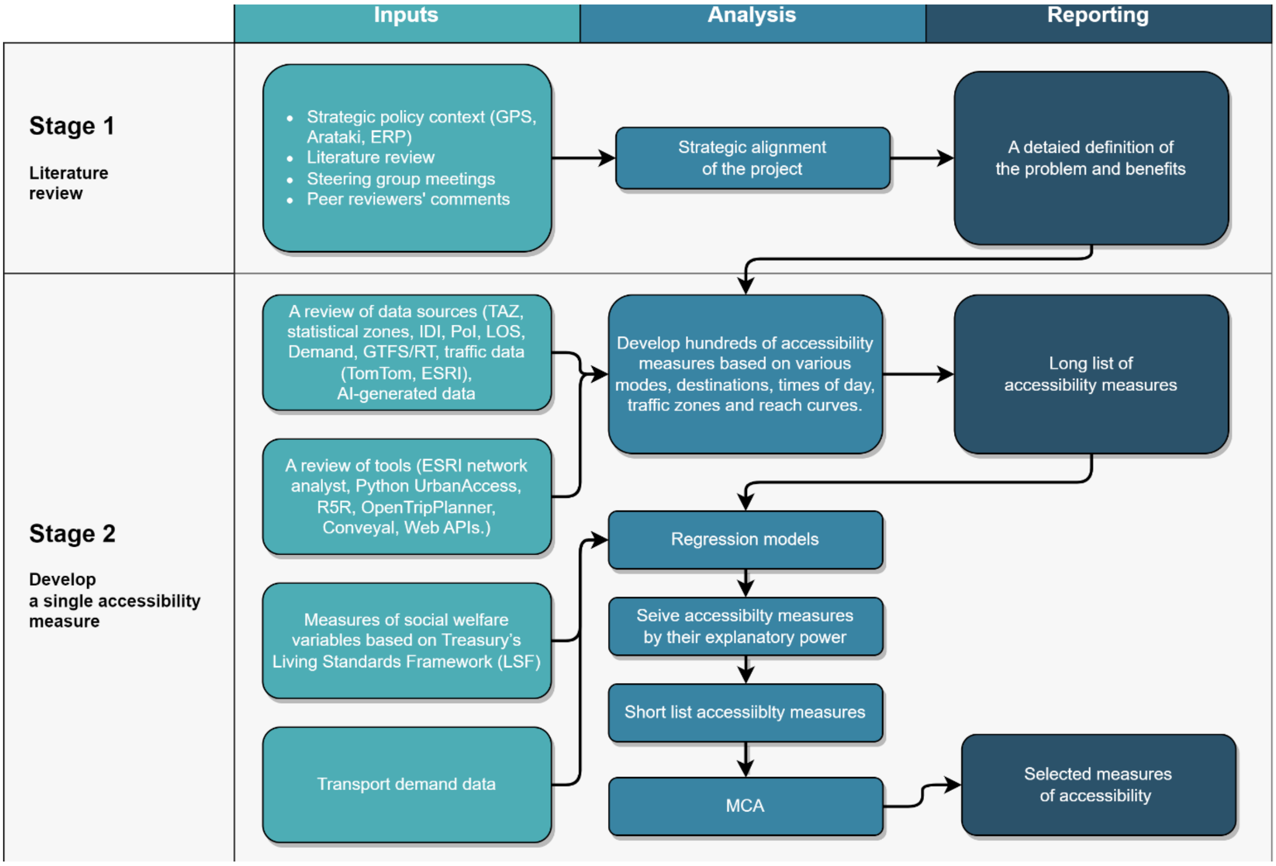
1.6 Our approach is developed using an extensive literature review in collaboration with the experts

At a high level, our approach to this research is based on collaboration with the frontier researchers working on this topic across different jurisdictions and undertaking a systematic literature review of the academic and grey reports,[5] guided by comments of the project steering committee and peer reviewers at the beginning and end of each milestone. We present our methodology for the literature review in the following sections.

[5] Given this is a frontier topic, we suggest the grey literature is an important input.

Technically, a useful measure of accessibility should provide the highest predictive (explanatory) power for social welfare. To establish this, we will identify measures of social welfare and test the explanatory power of the measures of access against them. Our approach is illustrated in Figure 1.1. First, the models of transport accessibility are used to generate a long list of accessibility measures based on the mode of transport, granularity of spatial distribution (zone sizes), time of day, type of destinations, different reach curves (definition of near and far) and other factors. The long list of accessibility measures are then evaluated against different social welfare variables to generate a short list of measures based on their explanatory power. This methodology is consistent with other approaches taken to identify various measures/functional forms (Kinigadner et al., 2021; Torshizian, 2017; Torshizian & Grimes, 2014, 2021). Finally, a multi-criteria analysis approach is used to combine the short list of accessibility measures into one accessibility measure based on success factors such as simplicity, sensitivity and policy alignment.

Figure 1.1 High-level methodology



Source: Principal Economics

The methodology is built upon existing research, the most recent advances in accessibility research and tools (El-Geneidy et al., 2016; Pereira & Herszenhut, 2023) and recent experience of other agencies in OECD countries (Statistics Canada, 2023). These studies provide valuable insights on data and methods of accessibility measures to enhance technical outcomes and align them closely with policy objectives. We commence with established theories and frameworks in mobility and accessibility research to form a foundational theoretical framework for our study. This approach allows us to systematically interpret our findings in the context of these theories, ensuring that our research is anchored in a robust conceptual understanding of the subject matter.

2 Moving from transport planning for mobility to transport planning for accessibility

This chapter provides the basics for accessibility measurement through consideration of the definition and usefulness of accessibility measurement. We review the reasons for the shift in planning paradigms from mobility to accessibility. The chapter describes traditional economic appraisal methodology in transport, which often focuses on mobility objectives such as time savings, and argues for a more holistic perspective that captures the transformational impacts of transport projects.

The chapter tackles the complexities of defining and assessing transport accessibility. It introduces the concept of the space-time prism (STP) as a tool to understand the temporal and spatial constraints on individual movement and how these affect access to opportunities. This concept is crucial for creating inclusive and effective transport policies that cater to communities' diverse needs.

The chapter also discusses the challenges of managing urban transport as a public service, highlighting its unique complexity compared to other public services. It addresses difficulties in coordinating multiple modes of transport, dealing with a wide range of stakeholders and the necessity for context-specific solutions.

In addition to these discussions, Appendix B considers the difference between managing transport and other public services and provides further information about the complexities of measuring accessibility.

2.1 Access is a key component in urban economics through its role on agglomeration economies

Infrastructure economics is primarily focused on agglomeration benefits, taking into account the impacts of transport exposure on local employment and productivity. There are various economic models simulating productivity outcomes of improved access. Conceptually, land values would be all equal if the level of access was the same (assuming amenities priced equally). We need to ask what is this access urban economists have been so focused on and how to measure it. We then need to rethink how to use that measure of access for appraising land use and transport projects. This project will focus on the measurement of access, and a parallel project will further expand on the use of accessibility for appraising projects.

2.2 Mobility is focused on the capability of movement, and accessibility is about the potential interaction opportunities

Understanding transport accessibility and mobility is crucial in transportation planning as they are distinct concepts leading to divergent transport outcomes. Mobility – a core aspect of transportation planning – signifies the capability for movement and the ease of travelling from one point to another. This concept is primarily about the movement potential within the transport system. In contrast, accessibility is about the potential opportunities for interaction with geographically dispersed destinations, going beyond mere spatial separation. It concerns how easily individuals can access different locations and services within the transport network (Handy, 1996; Hansen, 1959):

- **Mobility measurement:** Mobility is typically assessed through metrics such as volume-to-capacity ratios, reflecting how efficiently the transport system facilitates movement. Lower ratios indicate better mobility, characterised by faster travel times and smoother movement. However, this focus on mobility often leads to strategies aimed at enhancing system efficiency such as expanding road networks and increasing capacity, primarily to meet increasing travel demands.

- **Accessibility measurement:** Accessibility measures incorporate factors such as impedance, which accounts for the time and cost involved in reaching a destination, and decay, which assesses the desirability of potential destinations. This broader view includes the 'cumulative opportunities' measure, quantifying the number of destinations reachable within a given time or distance (Handy & Niemeier, 1997). The implication of accounting for these factors is that an accessibility measure accounts for the integration between land use and transport system.
- **Shift in planning paradigms:** Traditional transportation planning has predominantly focused on improving mobility. While this approach aims to facilitate accessibility by easing the reach to destinations, it often leads to urban environments heavily dependent on automobiles, ironically decreasing overall accessibility. In contrast, planning that emphasises accessibility focuses on the end goals – easy access to destinations – and considers both the travellers and the wider system. This perspective encourages a broader range of strategies, including land-use policies, and fosters environments where people have the choice to engage in urban activities without relying solely on driving (Handy, 1993). Alternative transport planning is mostly gathered around transport-oriented development ideas. This approach is epitomised by transport-oriented development, which promotes denser, mixed-use and walkable developments around transit hubs, diminishing the reliance on driving. Transport-oriented development aims to provide residents with more options for engaging in urban life without the necessity of a car (Calthorpe, 1993; Dittmar & Poticha, 2004; White & McDaniel, 1999).
- **Challenges and criticisms:** However, the accessibility-focused approach is not without its challenges. Critics such as Lucas (2006) point out that accessibility analyses can be resource intensive and context specific, often leading to reluctance in data collection and assessment due to the time and effort required. This issue has been largely addressed by the recent developments of more efficient tools and more powerful computers. Furthermore, while planning for accessibility may reduce the need for driving, it does not necessarily diminish actual driving, as individual travel preferences vary. Factors such as travel time and the availability of destinations may not uniformly influence people's choices, with some still preferring to drive (Salomon & Mokhtarian, 1998). Both of these issues are addressed in this report.
- **Policies to reduce driving:** Policies are being developed to directly reduce driving utility. These include strategies that limit mobility such as auto-restricted zones, gas taxes, parking fees and congestion pricing. However, advocating for enhanced accessibility tends to be more favourable than limiting mobility given the high value placed on freedom of movement and the general unpopularity of restrictive measures.

In conclusion, transport accessibility and mobility are interconnected yet distinct elements in transportation planning. Understanding their nuances is key to developing effective strategies that balance the need for efficient movement with the goal of easy access to diverse destinations, ultimately leading to more sustainable and equitable urban environments.

2.3 Person-based accessibility is primarily focused on ease of access to reach locations and services

Transport accessibility is the ease with which individuals and businesses can access others for a variety of purposes, including social, economic and information exchange, both physically and virtually. This underscores the essential role of transportation systems in facilitating engagement in activities, distributed across both space and time.

Despite its central role, defining and measuring transport accessibility has been challenging. It encompasses not just the physical distance or travel time to destinations but also the quality, availability of transportation options and possibility of virtual access to the destinations. Accessibility considers how transportation infrastructure integrates with land use, impacting the ease with which people can reach desired locations.

Spatial economic theory (Alonso, 1964) posits that location choices, whether residential, business or for activities, are a balance between accessibility levels and other factors.[6] Agglomeration economies refer to the benefits that firms and individuals obtain by locating near each other (in spatial and industrial clusters). The impact of digital accessibility on these economies is still evolving. The emerging ‘science of cities’ suggests that these economies scale with city size, primarily due to increased social and physical network interactions. However, the explicit demonstration of these effects remains underdeveloped.

Addressing these complexities requires well-designed visualisation tools and effective communication strategies. Interactive displays that allow individuals to explore the impacts of various transportation policies on their neighbourhood’s accessibility can be instrumental. Moreover, context-sensitive storytelling that non-technically explains how transportation policies could enhance or hinder neighbourhood accessibility is crucial. Such approaches help in making the concept of accessibility more tangible and relevant to everyday life.

In transportation planning and policy making, understanding and effectively applying the concept of transport accessibility is vital. It guides decisions not only on infrastructure development but also on urban planning, economic development and environmental sustainability. Effective accessibility planning can lead to enhanced quality of life by providing more equitable access to essential services and opportunities.

Transport accessibility is a multifaceted concept that plays a critical role in connecting people and places. While it is a fundamental aspect of transportation systems, its practical application in planning and policy making faces challenges due to its complex nature. These complexities have been increased by introduction of virtual accessibility as a mode. Addressing these challenges requires a combination of robust theoretical understanding, practical measurement approaches and effective communication and visualisation tools.

2.3.1 Accessibility is the ease of reaching diverse locations and services

In brief, accessibility is defined as the ease of reaching diverse locations and services, integrating considerations beyond physical movement to encompass opportunities for interaction and engagement within the transport network.

The concept of accessibility is a multifaceted and crucial component in the realm of urban planning and transportation systems. It is contingent upon the intricate interplay of the spatial distribution of activities and the availability of transportation infrastructure. Accessibility, in this context, delineates the maximal realm of opportunities or the highest level of attainable access that individuals can secure within a given geographical area. However, the realisation of this maximum accessibility is contingent upon a set of parameters, which, in the broadest sense, are considered as resources.

These resources encompass various dimensions such as time, costs, cognitive efforts, discomfort or even feelings of insecurity that are required for individuals to traverse distances. In order to ascertain a maximum level of accessibility, it is necessary to establish a general, predefined framework that encompasses the ability to overcome spatial separation based on these resources. This framework is vital for understanding the limitations and potentials within an urban environment. Individuals often encounter barriers and limitations that curtail their ability to fully access the opportunities within their environment. These limitations are often attributed to personal factors, which can include but are not limited to a person’s financial means, physical mobility and cognitive capabilities.

[6] This theory suggests that the value of land and buildings (their ‘bid rents’) reflects these trade-offs and the competition for locations with varying levels of transportation advantage. Techniques such as hedonic pricing (which is a revealed preference approach) can be used to estimate the value of accessibility.

Hence, the capability of an individual to overcome spatial separation is a pivotal determinant in defining the subset of opportunities that are genuinely available to them. In this context, accessibility serves as a gauge of the potential for interaction and engagement within a given geographical area. It can be quantified in terms of its volumetric or quantitative aspects, offering a tangible measure of how accessible a location or region is to its inhabitants.

In summary, to comprehend accessibility in its entirety, one must consider two primary dimensions: contextual factors and personal attributes. Contextual elements encompass the built environment, including land-use patterns and the quality and availability of transportation systems. These factors, in essence, define the infrastructure that facilitates accessibility. Meanwhile, personal attributes encompass an individual's characteristics such as vehicle ownership, income level, physical abilities and cognitive capabilities. These attributes play a crucial role in determining an individual's capacity to access the opportunities available within a specific geographic context.

The context encompasses not only the "spatial distribution of activities" as elucidated by Hansen (1959) but also the transportation systems that potentially link individuals to these activities. These transportation systems encompass a diverse array of infrastructures and services designed to facilitate spatial mobility, including but not limited to roads, public transit and associated amenities. The efficiency and reach of these systems directly influence the capacity of an individual to overcome spatial barriers.

However, it is essential to recognise that this capacity is substantially shaped by a multitude of individual attributes spanning from economic status and gender to access to personal vehicles and knowledge of the transportation network as well as one's place of residence, household composition and physical capabilities. This confluence of personal attributes contributes to a wide spectrum of potentialities, leading individuals to experience distinctly varied levels of accessibility.

Kaufmann et al. (2004) illuminate the dynamic nature of an individual's ability to overcome spatial separation by emphasising the critical role of one's active engagement in the pursuit of movement possibilities. In essence, the capacity to transcend spatial limitations is not an inherent, unchanging trait but rather a quality that necessitates active cultivation through the act of travel itself. As individuals accumulate experience in utilising transportation systems to access activities dispersed across geographic space, their accessibility progressively expands.

See Appendix A for further discussion of the meaning of accessibility.

2.3.2 We are focused on person accessibility (and not place accessibility)

Scholars frequently draw a distinction between the concepts of person accessibility and place accessibility, which, while often used interchangeably, are distinct in their underlying definitions. It is imperative to elucidate this disparity in order to gain a comprehensive understanding of these critical concepts (Kwan, 1999; Miller, 2007; Pirie, 1979).

Person accessibility pertains to an individual's capability to reach and interact with specific locations. In essence, it denotes whether an individual possesses the means to access a designated set of places. Conversely, place accessibility refers to the attribute of a location, particularly an activity-based location, and its openness or inaccessibility to a specified group of people or from specific origins.

These two facets of accessibility are intrinsically intertwined and can be perceived as the reciprocal of one another. Person accessibility underscores an individual's inherent ability to undertake actions, aligning closely with the emphasis on personal agency. The term 'accessibility' will be used in place of 'person accessibility', which is the experience of individuals in their interactions with the built environment.

The conceptualisation of accessibility as a potentiality underscores the nuanced nature of this concept, highlighting its capacity to exhibit variations in terms of magnitude, extent or volume. In essence, individuals can encounter differing degrees of accessibility. Hansen's (1959, p. 2) definition emphasises that the accessibility experienced by an individual is contingent upon a complex interplay of two factors: the specific context and the attributes of the individual. We will address these in our methodology.

2.4 Transport planning adopts accessibility to achieve an integrated land-use and transport system

Accessibility measures incorporate a wider array of factors, including the quality and availability of transportation options and the integration of transport infrastructure with land use. This section provides a brief introduction to the usefulness of accessibility to transport planning. Our parallel project on alternative appraisal methodology provides further technical discussion of the usefulness of accessibility to transport appraisal (Torshizian et al., in publication).

The consideration of land use and transport integration in accessibility measurement is the key factor for improving the economic and productivity outcomes of the transport network. Transport planning's shift towards accessibility aligns with broader societal goals of enhancing social welfare (Kahn & Juster, 2002; Manderson, 2005), as emphasised by various entities from the New Zealand Treasury to the OECD (Boarini et al., 2006). Accessibility to services, whether physical or digital, enables residents to engage with urban life in multifaceted ways – from work and education to healthcare and social participation. This is not just about facilitating movement but ensuring that movement leads to positive societal outcomes.

Much of transport policy and planning has been historically rooted in economic principles such as cost-benefit analysis, focusing predominantly on mobility objectives such as time savings. However, this focus may overlook the broader benefits of accessibility. While time savings from transport investments are valued for reducing travel disutility and allowing time for beneficial activities (Mackie et al., 2001), this assumption is increasingly questioned. People derive varied satisfaction from travel, and saved time does not necessarily translate into wellbeing-enhancing activities and improved social welfare (Mokhtarian & Salomon, 2001).[7]

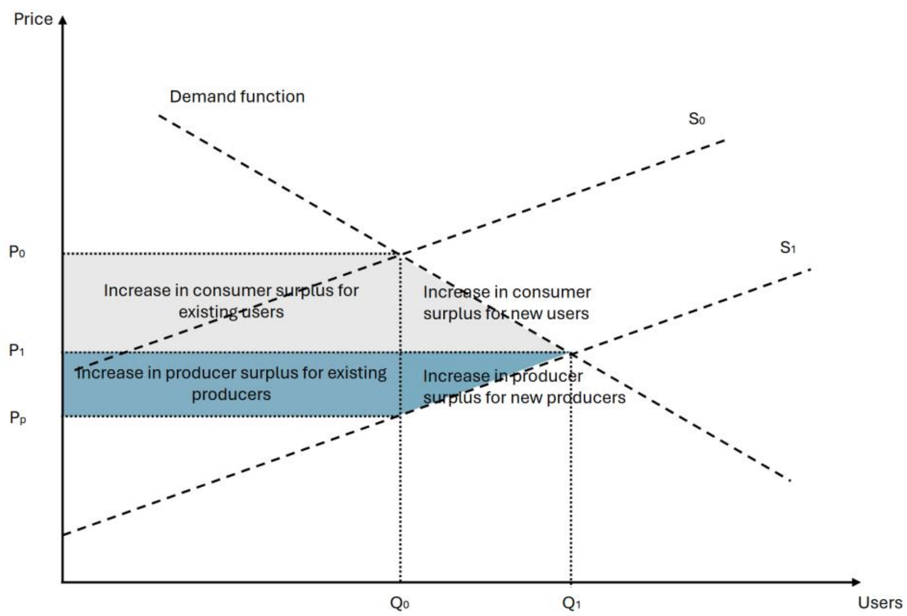
Traditional economic evaluation in transport often emphasises decision utility – the value given to outcomes like time and cost savings – yet this overlooks experienced utility – the actual happiness or unhappiness resulting from those outcomes (Kahneman et al., 1997). There is growing scrutiny over whether the benefits projected from transport choices truly reflect the wellbeing derived from them (Ettema et al., 2010; Kahneman et al., 1997).

Focusing solely on monetised travel time savings can undervalue projects that offer significant psychological benefits, especially to disadvantaged individuals. Projects that enhance mobility may primarily benefit those who are already highly mobile, overlooking individuals with restricted mobility such as non-drivers or low-income groups who might benefit disproportionately from increased accessibility (Lucas et al., 2009; Stanley et al., 2011).

[7] The concept of quality of life (QoL), developed by the World Health Organization, has been used in transport studies to blend objective indicators with subjective attitudes. However, the definition and measurement of QoL can vary, often intersecting with subjective wellbeing (de Groot & Steg, 2006; Steg & Gifford, 2005). The most significant influences on psychological wellbeing are poverty/unemployment, meaningful relationships and health, all of which are directly impacted by transport accessibility. Transport projects that improve accessibility can potentially lift households out of poverty, reduce barriers to social relationships and minimise health impacts (Banister & Bowling, 2004; Jones et al., 2003; Vemuri & Costanza, 2006).

Alongside accessibility gains, it's important to consider welfare gains or consumer surplus in transport evaluation (Figure 2.1). This involves measuring the benefits received from transport choices, factoring in the willingness to pay for these benefits. However, traditional models like the rule of a half,[8] while useful, may not fully capture the complex relationship between cost and demand in transport (Cherchi & Ortúzar, 2006). The gap between the rule of a half and choice model approaches widens in situations with substantial variations in travel costs. This suggests that the rule of a half may tend to overestimate changes in consumer surplus (Guzman et al., 2023).[9]

Figure 2.1 Consumer surplus



Source: Principal Economics
Note: The intersection of the demand function with various marginal cost functions (S_x) is shown. Policy implementations can enhance the initial supply function (S_0), shifting it to S_1. This causes the demand curve to meet a new, lower equilibrium price (P_1), increasing demand from Q_0 to Q_1. The benefits to both existing and new users, illustrated by the shaded area between S_0 and S_1, are quantified using the rule of a half.

The choice of accessibility measures is critical. Simple place-based indicators may not accurately reflect the needs of those who could benefit most from improved accessibility. A comprehensive measure that considers both infrastructure and human aspects of transport is needed.

Adopting accessibility as a focal point in transport planning is essential for aligning transport policies with the overarching goal of improving social welfare. This approach recognises that transport is not just about moving people but enabling them to lead fulfilling lives. By prioritising accessibility, transport planning can better address the diverse needs of all community members, contributing to more equitable, sustainable and thriving societies.

[8] The rule of a half (Tressider et al., 1969) is a concept used in transport economics to estimate the benefits or costs to consumers resulting from changes in transport services such as fare reductions or improvements in travel times. It is based on the assumption that the demand curve for travel is linear between two points, typically before and after a change in transport conditions.

[9] For overall welfare change, we must consider the change in producer surplus in addition to the change in consumer surplus.

2.5 Accessibility measurement is a data-heavy and computationally intensive task

Measuring transport accessibility is complex, encompassing various dimensions that add to its intricacy (Lee, 2009; Mavoa et al., 2012; Murray et al., 1998). Firstly, it needs to be multimodal (Liao & van Wee, 2017), considering different transportation methods. This is coupled with the requirement to provide access to multiple destinations (Levinson & Krizek, 2005), which varies throughout the day (Bhat et al., 2000; Burns, 1979), adding another layer of complexity.

The measurement must be spatial, accurately reflecting the geographical distribution of transport accessibility (Miller, 1999; Shen, 1998b). The social dimension is also critical as different socio-economic groups have diverse requirements for accessibility services (El-Geneidy & Levinson, 2006; Huisman, 2005; Weibull, 1980). This necessitates a dual focus on both the supply and demand of transport accessibility (Ni et al., 2019). Furthermore, factors such as the quality of transport and service levels are essential components of comprehensive accessibility evaluation (Handy, 1992). Finally, the model must not only assess current conditions of the transport network but also project future scenarios.

All these requirements underscore the need for a data-intensive and computationally demanding approach. The outcome’s focus, whether on spatial details or socio-economic factors, influences the type of data required, each bringing its own limitations. For instance, a model focusing on spatial details might lack in capturing detailed travel behaviour and social nuances, while one emphasising socio-economic aspects requires sample datasets such as travel diaries, which may not offer the same spatial detail.

3 Methods for accessibility measurement

This chapter presents various methods for measuring accessibility, highlighting their applications in different contexts and discussing the interplay of different components such as land-use, transportation, temporal and individual aspects (which fits within objective A of this report).

The chapter begins with a review of national perspectives, detailing methodologies used in New Zealand such as NZTA's location-based accessibility analysis and the work by Abley and Halden (2013) using utilitarian and human capability approaches. It then transitions to international perspectives, examining accessibility measures in Canada, Germany, Edinburgh, Sweden and London. These sections offer insights into different models and tools used globally such as the Spatial Access Measures used by Statistics Canada and the Technical University of Munich (TUM) Accessibility Atlas.

Subsequent sections provide details on the concepts of place-based and person-based accessibility measures, discussing characteristics, applications and limitations, and a discussion on methodological issues and biases in accessibility analysis such as boundary effects, modifiable areal unit problems and starting point effects. It explores the use of deterministic and stochastic models for shortest path problems. We also highlight the role of stated and revealed preference in measuring person-based accessibility, incorporating factors such as demand, safety, comfort and attractiveness of destinations and modes. This chapter includes an examination of impedance, deterrence and saturation functions in accessibility analysis. We discuss the various applications of multinominal logit models in accessibility measures and its equivalency with the gravity model.

Finding the shortest path between two points on a network is a fundamental problem in graph theory. The technical measurement issues are further presented and discussed in Appendix D.2. The choice between deterministic and probabilistic algorithms for shortest path problems depends largely on the nature of the network and the specific requirements of the application. While deterministic algorithms offer consistency and certainty, probabilistic algorithms provide flexibility and efficiency in complex and dynamic environments. The ongoing evolution of hybrid and AI-driven approaches indicates a future where the strengths of both deterministic and probabilistic methods are leveraged for optimal network pathfinding. To avoid lengthy technical discussions here, these topics are further discussed in Appendix E.

Overall, the chapter offers a detailed and nuanced approach to understanding transport accessibility, integrating location-based assessments with considerations of human capability and demographic variations. It provides a comprehensive framework for measuring accessibility across various contexts.

3.1 A review of national and international perspectives on transport accessibility

In reviewing transport accessibility, it is crucial to consider national and international perspectives as they provide valuable insights into different approaches and challenges encountered across diverse contexts. This comparative review highlights the varying strategies and priorities in addressing accessibility within transportation systems globally.

3.1.1 Nationally, the most relevant study is NZTA's accessibility analysis methodology and the most relevant work is Project Monty

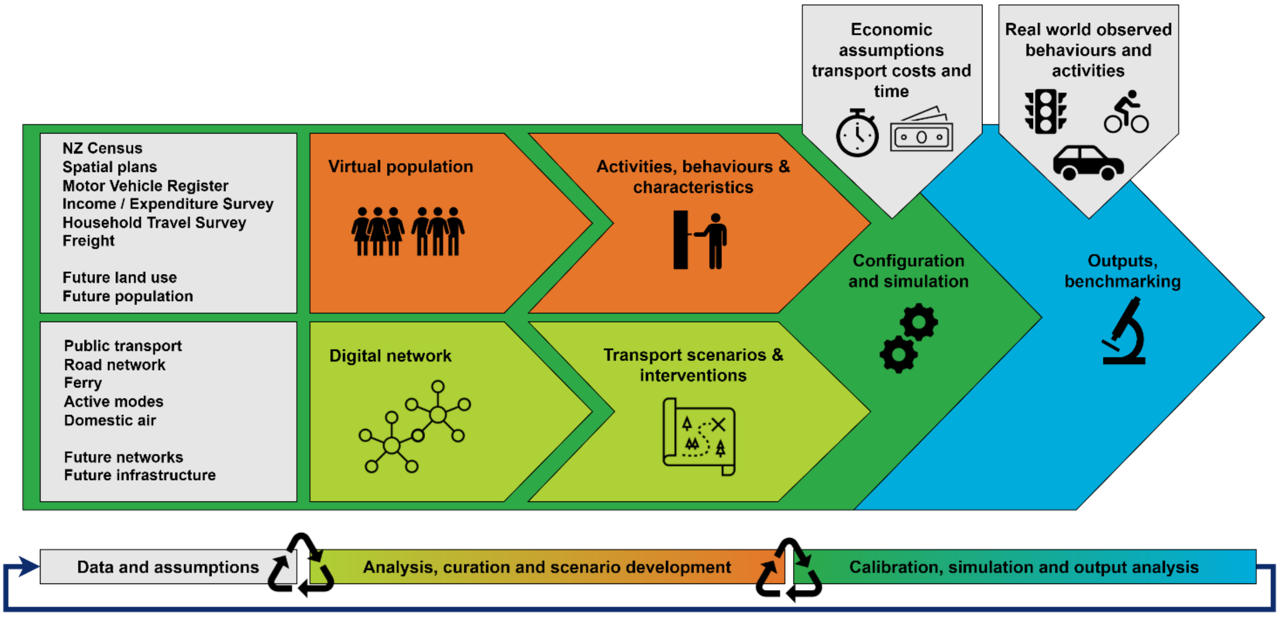
Since 2019, NZTA has been systematically evaluating annual transport accessibility across New Zealand. This includes a location-based accessibility analysis (a contour measure of accessibility, also known as cumulative accessibility). The methodology involves calculating 45 minutes of travel time from the centre of each statistical area 1 (SA1) in New Zealand during morning peak hours. It quantifies the total number of jobs accessible for each SA1 via walking, cycling and public transport. For driving, a 30-minute travel time is considered, with an additional 15 minutes factored in for parking and walking to the final destination. The result of this analysis is a heatmap that visually represents job accessibility during the morning peak hours.

The most relevant work on accessibility in New Zealand has been limited to a previous study on developing a methodology for accessibility analysis and the technical modelling work on developing an agent-based model. In an earlier NZTA research report on New Zealand accessibility analysis methodology, Abley and Halden (2013) combined a utilitarian and human capability approach to define and measure accessibility. The report developed accessibility maps for specific destinations such as supermarkets, healthcare facilities and educational institutions. The method used is a combination of cumulative opportunity and gravity measures that are more commonly used in the literature (El-Geneidy & Levinson, 2022). For the cumulative opportunity approach, Abley and Halden propose a measure of access to destinations that provide the services residents need (primary schools, retail groceries, doctors' surgeries, sports grounds) by all modes, and for the human capability approach, they propose the accessibility measure is disaggregated for residents with differing abilities and needs. Their report uses a comprehensive approach to accessibility measures with these key elements:

- **Accessibility measures:** The methodology uses a mix of location-based accessibility and the human capability approach. This includes considering various travel modes (walking, cycling, public transport, private vehicle), travel behaviour and destinations.
- **Population groups:** Population groups are categorised based on age. Different weights are assigned to transportation modes and activities for different age groups, recognising that accessibility needs vary with age. For example, certain age groups might prioritise access to healthcare facilities, while others might focus on educational institutions or workplaces.
- **Destinations:** The methodology incorporates a range of destinations into its accessibility assessments. These include healthcare facilities, educational institutions, supermarkets, convenience stores and employment locations. Each destination type is weighted differently based on its perceived importance to various age groups.
- **Time of day:** The report acknowledges the time of day as a factor in accessibility. However, the specifics of how time of day is integrated into the methodology are not detailed in the sections reviewed.
- **Location-based accessibility:** The approach considers the geographic distribution of facilities and services, analysing how easily they can be accessed from different locations. This includes an assessment of the transportation network and the travel time required to reach various destinations.
- **Human capability approach:** The methodology incorporates aspects of the human capability approach by considering the varying abilities and resources of different demographic groups. For example, it acknowledges that not everyone has access to a private vehicle or is able to drive, which impacts their ability to access certain locations.

One of the most recent developments in transport planning in New Zealand is Project Monty. The Ministry of Transport has developed a national-scale, agent-based model (ABM) to provide forecasts of travel behaviour at both micro and macro levels. For residential travel, Project Monty links travel behaviours from the HTS to New Zealand's Census data and roading network. It simulates the travel choices made by each agent (virtual person) in undertaking their daily transport activities (travel to work, school, shopping). The modelled choices are additionally affected by travel costs and travel time for different travel modes (Arup, 2020). Project Monty does not directly assess accessibility. However, its results contribute to evaluating accessibility. The behavioural aspects of transportation inform the logit model, which is essential for assessing a transport system's utility. Figure 3.1 illustrates the high-level data inputs and methodology used in Project Monty.

Figure 3.1 Schematic overview of Project Monty



Source: Ministry of Transport

3.1.2 Accessibility measurement is being investigated and developed across different jurisdictions

Quantification and measurement of accessibility has been approached in several studies using different methods and tools (Adhvaryu et al., 2019; Halden, 2002; Leishman & Rowley, 2012).

The main methods of measuring accessibility on a macro scale are:

- cumulative opportunity measures (Dovey et al., 2017; O'Sullivan et al., 2000)
- gravity measures (Bocarejo & Oviedo, 2012; Karou & Hull, 2014)
- utility measures (Ben-Akiva & Lerman, 1985)
- distance measures (Talen & Anselin, 1998; Yenisetty & Bahadure, 2020).

We provide a review of the international perspective on accessibility measurement in Appendix C. The tools presented in that appendix illustrate a significant advancement in measuring and analysing accessibility in urban and regional planning. They collectively highlight the importance of location-based accessibility measures, providing valuable insights for planners and policy makers.

However, a recurring theme across these tools is the lack of integration of human capability approaches that consider individual needs and abilities in accessing services and amenities, which is central to the purpose of accessibility measurement – to capture capability of individuals to reach destinations. Future developments in this field could benefit from incorporating these aspects, ensuring a more holistic and inclusive approach to accessibility. Additionally, balancing geographical accessibility with individual and socio-economic factors could lead to more equitable and effective urban planning strategies.

Table 3.1 summarises these tools, comparing the strengths and limitations of each methodology.

Table 3.1 Overview of international transport accessibility tools

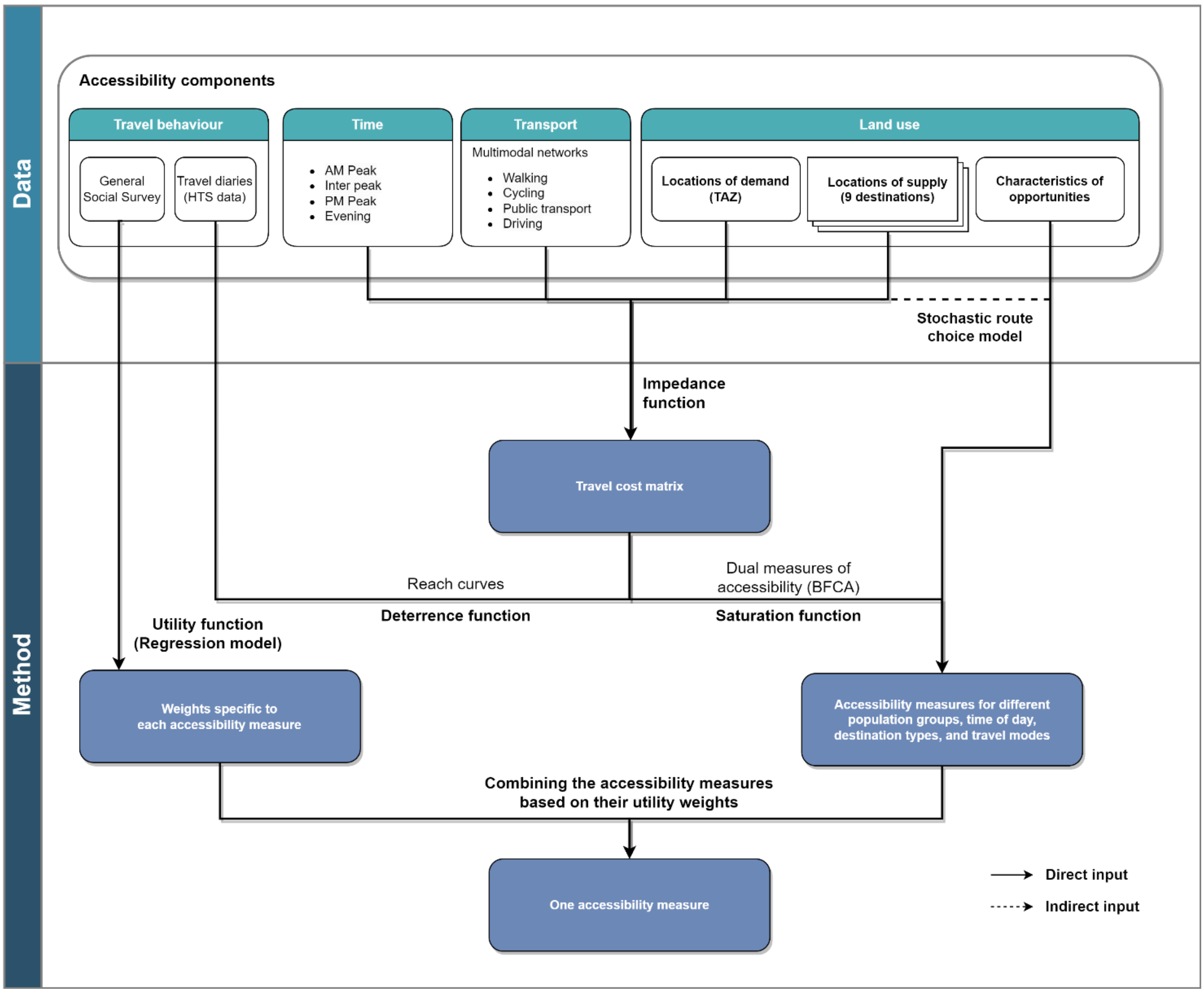
Measure/tool	Developed by/for	Region/country	Description and features	Pros	Cons
PTAL (Public Transport Accessibility Level)	Transport for London	London, UK	Rates locations by proximity to frequent public transport services. Used for urban planning and construction decisions.	Clear focus on public transport. Widely recognised and used in London. Direct urban planning implications.	Limited to public transport. Does not represent multimodal accessibility. Does not represent access to destinations.
TUM Accessibility Atlas	Technical University of Munich	Munich Metropolitan Region, Germany	A multimodal GIS-based tool for decision making. Includes thematic datasets (costs, emissions etc.) and assesses accessibility from regional to local scales.	Comprehensive multimodal approach. Includes diverse datasets (costs, emissions etc.). Applicable from regional to local scales.	Complexity may limit user-friendliness.
Accessibility Tool for Västra Götaland	Unknown	Västra Götaland, Sweden	Focuses on travel time analysis for road and public transport. Specific details about features and usage are not provided.	Specific focus on travel time analysis for road and public transport.	Lack of detailed public information on features and applications.
MaReSi SC (Maximum Recommendable Size of Shopping Centres)	Planning authorities in Oslo	Oslo, Norway	Method for determining the maximum recommendable size of shopping centres, considering transport accessibility factors.	Tailored for shopping centre development. Integrates accessibility into urban development planning.	Highly specific use case (shopping centres). Limited applicability outside of retail planning.
Spatial Access Measures	Statistics Canada and Infrastructure Canada	Canada	Set of spatial measures assessing access to various amenities using active and public transportation modes. Includes seven amenity categories and four transportation mode variants.	Broad coverage of amenities and transport modes. Supports sustainable and resilient transportation systems.	Complexity in data collection and analysis. May be too detailed for certain practical applications.

Source: Principal Economics

3.2 The dimensions of accessibility include land-use, transportation, temporal and individual aspects

Accessibility in transportation planning is a multifaceted concept influenced by various factors that interact to shape an efficient transport network. These factors are broken down into four primary components: land-use, transportation, temporal and individual aspects (Geurs & van Wee, 2004). Each of these components plays a crucial role in determining the level of accessibility experienced by individuals and communities (Figure 3.2).

Figure 3.2 Relationships between components of accessibility



Source: Principal Economics inspired by Geurs and van Wee (2004)

Land-use aspect

- **Supply and demand of opportunities:** This aspect deals with the quantity, quality and spatial distribution of opportunities such as jobs, healthcare facilities, educational institutions and recreational spaces. It also considers the demand for these opportunities at origin points such as residential areas.
- **Interaction between supply and demand:** The interaction between supply and demand leads to competition for resources, impacting accessibility. For example, limited availability of school spaces or job openings in an area affects the level of access to these opportunities.

Transportation aspect

- **Characteristics of the transportation system:** This encompasses factors related to the journey from an origin to a destination, including travel time, waiting time, parking, expenses and effort required. It also considers the reliability, comfort and safety of different modes of transportation.
- **Supply and demand in transportation:** The supply side includes infrastructure features such as road capacity, public transport schedules and travel costs, while the demand side includes the volume and nature of both passenger and freight travel.

Temporal aspect

- **Availability of opportunities:** This component addresses the availability of opportunities at different times, acknowledging that access to services and activities is not constant throughout the day or week.
- **Individual time constraints:** It also considers the time individuals have available for various activities, acknowledging that personal schedules and commitments significantly affect accessibility.

Individual aspect

- **Personal abilities:** Individual characteristics such as age, income, educational level, household situation and physical condition significantly affect a person’s ability to access different modes of transportation and the opportunities available in their vicinity.
- **Opportunity distribution and accessibility:** Factors such as income level, travel budget and educational qualifications influence the distribution of accessible opportunities. For instance, job accessibility studies (Cervero & Kockelman, 1997; Geurs & Ritsema van Eck, 2001; Shen, 1998a) show that occupational matching is a significant factor in accessibility metrics.

An effective accessibility measure should integrate all these components, recognising the interdependencies and cumulative impact they have on overall accessibility. This comprehensive approach ensures that the measure reflects the true accessibility landscape, capturing the nuances and complexities of how people interact with and are served by transportation systems.

Understanding these components is essential for developing a transport measure for effective transportation policies and infrastructure. By considering the land-use, transportation, temporal and individual aspects, transportation planning can be more responsive to the diverse needs of communities, leading to improved accessibility and, consequently, enhanced quality of life.

3.3 Measuring place-based and person-based accessibility

This section provides a review of measures available for place-based and person-based accessibility. Further technical notes are provided in Appendix C.

3.3.1 Place-based accessibility measures

Person-based accessibility focuses on how accessible various services and destinations are from specific locations. Place-based measures are capable of examining accessibility at a granular level (meshblocks for every parcel level), providing insights into the spatial distribution and availability of services across an area.

Place-based measures consider various services, including public transport options, road networks and pedestrian paths, thereby providing a comprehensive view of accessibility. These measures incorporate spatial and temporal factors, acknowledging that accessibility varies not just by location but also over time. The measures are multimodal, considering different forms of transportation, including walking, cycling, public transport and private vehicles. These measures recognise the importance of multi-destination accessibility, acknowledging that individuals travel to various types of destinations.

Best practice for place-based accessibility uses the gravity model, which is instrumental in understanding the likelihood of travel between different locations based on distance and the availability of services. However, place-based accessibility assigns identical accessibility levels to different individuals within the same zone, disregarding variations in their actual experiences. These traditional indices, being integral measures tied to a single reference location such as home, overlook the fact that many trips contributing to individual accessibility occur within the context of a person's daily activity sequence. Also, these measures neglect the impact of spatio-temporal constraints that may limit an individual's ability to reach numerous opportunities in the urban environment (Kwan, 1998).

3.3.2 Person-based accessibility measures

Person-based accessibility measures evaluate how easily different population groups can access transport services. Person-based accessibility measures are social, temporal, multimodal and multi-destination but they are mostly limited in their spatiality.

The common source of information for human accessibility analysis is HTS data (Guzman et al., 2023). Unlike place-based accessibility, the HTS data runs on a sample usually ranging from 3–5% of the population. These surveys are instrumental in gathering data but come with limitations such as lack of representativeness and potential biases.

Household travel surveys conducted in various countries offer data on travel patterns, modes of transport and accessibility to different demographics. These surveys typically gather information on the frequency, duration, purpose and modes of trips made by individuals within a household. This data is instrumental in understanding how accessible transportation is for different segments of the population.

Since the HTS data includes a detailed travel diary, they are ideal candidates for logsum models – for details on logsum models, see Appendix D.1.2. The results tend to show the impact of accessibility and transport investment on mode choice and among different socio-economic groups.

HTS data records travel diaries but does not include travel path. The HTS data is required to be complemented with data from routing engines. The logsum model can be calibrated using HTS data, implementing the data enrichment paradigm (Louviere et al., 1999). The combined data enables the evaluation of preferences toward new alternatives and reducing the bias associated with the hypothetical nature of the stated preference data.

Person-based accessibility measures are essential for understanding and improving travel behaviour. While current methodologies provide valuable insights, there are significant gaps and limitations that future research needs to address. Enhancing the spatial detail of studies, improving survey techniques and developing more sophisticated models are key areas for future development to inform policy.

3.3.3 Gravity and logit model equivalency

Two main models that incorporate the accessibility functions to deliver an accessibility measure are gravity and logit models. While these models have been mentioned in different contexts of accessibility measurement, the equivalency between the two model formulations is rarely remarked upon. This is possibly largely due to disciplinary silos. Geographers typically work within a gravity framework, often seemingly unaware of the connections of their models to random utility. Random utility modellers (often economists or engineers) typically tout their models as behaviourally superior to gravity models, often seemingly unaware of the gravity model's solid foundations in information theory (Miller, 2020).

Anas (1983) demonstrated that gravity/entropy and random utility-based multinomial logit (MNL) models are mathematically identical. Miller (2020, pp. 11–14) has described this equivalency.

3.3.4 Bridging the person-based and place-based accessibility measures

Considering the complementary feature of person-based and place-based accessibility measures, it is possible to combine them to create a more comprehensive accessibility measure that can address the research objectives. For our analysis, we use HTS data for assessing how individuals access various services and facilities and aim to estimate the utility of diverse accessibility aspects. This evaluation is pivotal in comprehending the varying travel patterns and preferences across different areas.

Data available through Stats NZ IDI provides more granular and frequent information, which is useful for identifying the most useful measure of accessibility by considering wellbeing and other factors of utility at the granular individual level.

We incorporate the gravity model, a staple in spatial analysis, to develop place-based accessibility measures (social, temporal, multimodal and multi-destination). The gravity model, by considering distance and mass factors such as distance decay, demand and level of service, enables us to quantify the accessibility of different locations. This model plays a crucial role in our assessment, allowing us to encapsulate geographical and infrastructural elements in our accessibility analysis.

A critical aspect of our methodology is the application of outputs derived from the logsum model.[10] Predominantly used in transportation economics, this provides a quantitative measure of the utility from a set of travel choices. We utilise the output of this model as weights to combine different temporal, multimodal and multi-destination accessibility measures. This allows us to harmonise the various accessibility measures into a consolidated framework, offering a multi-dimensional perspective on overall accessibility.

By amalgamating these methodologies, our report presents a comprehensive and nuanced understanding of accessibility, blending people-based and place-based factors. This approach underscores the multifaceted nature of accessibility and opens avenues for targeted improvements in both policy and practice.

3.4 Nine destination types are identified

Until recently, accessibility was often viewed as a static concept, with traditional measures offering only a snapshot of conditions at a specific time (Miller, 2018) and failing to account for the dynamic nature of individuals' travel experiences and needs. In Appendix D.3.1, we explore how to segment the STP into various time intervals. This section delves into the association between accessibility variations throughout the day and the commuting times of different groups, including the impact of individuals' time flexibility on commuting decisions, and draws upon spatio-temporal data from real-world activities such as travel surveys.

Minnen et al. (2016) pointed out the prevalence of non-standard working hours arising from self-directed work schedules or rigid shift patterns, with part-time work more common among women and overtime more frequent among men. Distribution of these hours across the day and week significantly influences commuting patterns and travel times. Studies suggest that local, non-work accessibility metrics are more useful predictors of physical activity (Chudyk et al., 2015; Frank et al., 2013; Krizek & Johnson, 2006; Nathan et al., 2012), healthcare services (Brondeel et al., 2014; Mao & Nekorchuk, 2013), local trip making (Krizek, 2003; Merlin, 2014), traffic exposure (Houston et al., 2013) and land values (Rauterkus & Miller, 2011).

Traditional place-based approaches did not consider these realities. For instance, the cumulative opportunity measure, which calculates the maximum reachable opportunities within a fixed travel time, may inaccurately represent individual access levels due to varying time values (Fayyaz et al., 2017). Jonsson et al. (2014) criticised the static view for ignoring how people adapt to changes in transportation and land use. Järv et al.

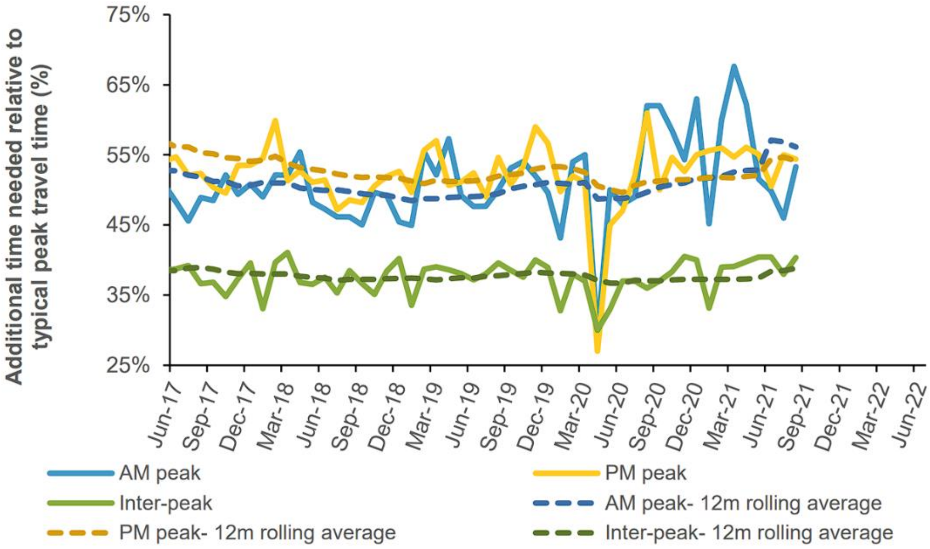
[10] In an MNL model, the logsum component serves as an accessibility measure, representing the natural logarithm of the MNL probability denominator. For technical details, see Appendix D.1.2.

(2018) proposed a dynamic accessibility model, demonstrating how static models can overestimate accessibility and underestimate inequalities. Furthermore, adding consumer surplus to the equation increases variability (El-Geneidy et al., 2016), which affects different groups' access to transportation modes and can lead to segregation within the STP (Abbasi et al., 2021; Kwan, 2013; Wang et al., 2012).

Recent advancements in analytical tools and open data sources have enabled more-nuanced dynamic accessibility analyses (Pereira et al., 2021; Stępniak et al., 2019). Early work (Lei & Church, 2010; Farber et al., 2014; Xu et al., 2015) highlighted the spatio-temporal variability in accessibility, particularly for public transport. Lee and Miller (2018) measured the impact of public transport services on space-time accessibility in an underserved area, although their approach had limitations in fully capturing temporal dynamics.

Analysis of travel survey data reveals disparities in public transport and driving provision, influencing accessibility and travel mode choice among various socio-demographic groups. For instance, in Figure 3.3, August 2021 data showed a 53% longer travel time during the AM peak compared to typical travel times, indicating significant fluctuations in travel reliability over different periods.

Figure 3.3 Additional travel time needed relative to typical travel time (reliability) (adapted from Auckland Transport, 2022, p. 18)



Note: This shows the difference between typical (median) and 85th percentile travel time on the combined arterial and motorway network for the AM peak, interpeak and PM peak. This is a measure of reliability – a percentage of how much variation a driver would experience from their day-to-day journey time in addition to a typical experience (median travel time). The smaller the percentage, the better the reliability. Less than 50% additional travel time is regarded reliable in view of a driver's experience, 50–70% is considered unreliable but tolerable and above 70% is deemed totally unreliable.

The development of non-work destination types relies on past literature, stakeholder input and researcher judgement. These considerations include their general consistency with trip purposes typically described in travel surveys (revealed preference and stated preference). Cui and Levinson (2020) propose seven non-work destination categories – stores, restaurants, schools, colleges, recreation facilities, religious sites and other opportunities – to match with the travel diary records. McCahill (2018) proposes nine non-work destination categorised based on HERE facility types. These studies show the number of destinations and how they are categorised is mostly contextual and based on data availability and objectives of the accessibility measures. Table 3.2 shows the destinations that we considered for the accessibility measure and their description. We chose these destinations based on the availability of data (in particular from the HTS) and the usefulness to policy and available models based on the inputs of the research steering committee. These destinations are adaptable and can be modified to align with future requirements.

Table 3.2 Nine destination types considered

	Destination	Description
1	Jobs	The number of all jobs in each traffic analysis zone (TAZ)
2	Office	The number of office jobs in each TAZ
3	Industries	The number of industrial jobs in each TAZ
4	Commercial	Number of shops in a cell, excluding grocery stores, fresh produce, delis and bakeries
5	Food	Grocery stores, fresh produce, delis and bakeries
6	Education	Primary, intermediate and secondary schools
7	Recreation	Parks, gyms, pools and sports centres
8	Entertainment	Museums, theatres, cinemas, community centres, libraries and nightclubs
9	Healthcare	Hospitals and general practitioners, including urgent medical care

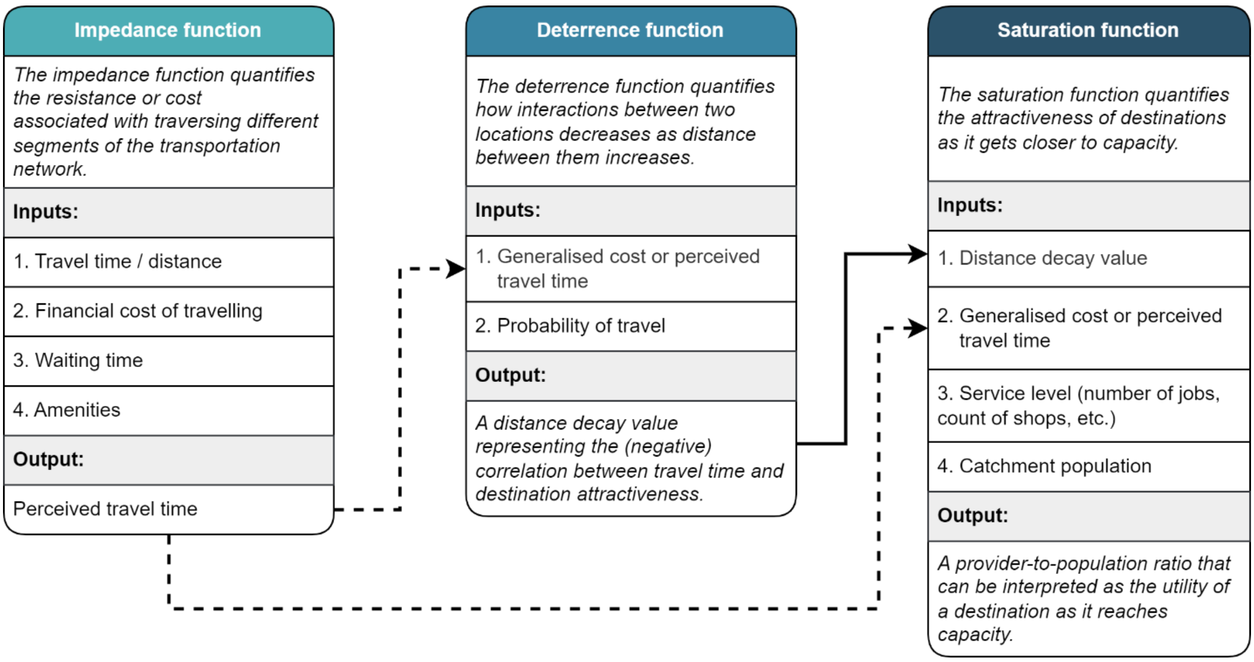
Source: Principal Economics inspired by McCahill (2018)

From a person-based accessibility approach, perceived accessibility is based on the individual's preferences and abilities rather than objective references. Therefore, the choice of which shop to go to for groceries at what time of day by what mode (including virtual access) and the options the individual has the ability to use largely affects their perceptions of accessibility (Lättman et al., 2018).

3.5 Constructing accessibility measures

There are different accessibility functions for different travel options – modes, destinations, abilities, periods and so on. Translating these into concrete measures of accessibility requires a few further assumptions – defining how to measure how near or far one point is from another (**deterrence function**), the cost of travel from one point to another (**impedance function**) and the marginal value of added destinations (**saturation function**). Figure 3.4 provides a summary of these functions and their inputs and outputs.

Figure 3.4 Overview of accessibility functions



Source: Principal Economics

Perception and evaluation (weighting) of impedance, saturation and deterrence functions vary from agent to agent depending on the agent's cognitive abilities, tastes/preferences, personal experiences and personal (and household) constraints. The ability of people to exploit a given physical context of access and attraction will also vary depending on their financial, cognitive and physical capabilities.

To capture user preferences, these separate functions are defined for different socio-economic groups, spatial locations, times of day, modes of transport and destinations. This means sets of hundreds of accessibility measures. These functions are also complementing each other. The impedance function outcomes feed the deterrence function, the deterrence function also feeds the saturation function. This modular design allows for independent design and calibration of each function.

3.5.1 Impedance function summarises the factors of travel cost as a measure of travel time (duration)

Impedance functions play a pivotal role in modelling and understanding transport accessibility as they quantify the resistance or cost associated with traversing different segments of the transportation network. Accessibility measures use time for the (generalised) cost at each link in the network, including travel cost, travel time and distance. However, impedance does not provide information about user preferences. The MNL model (see Appendix E.2) provides an understanding of resistance by replacing travel time with perceived travel time, which includes level of service factors such as slope and weather. The resistance in each link is also different for each mode and time of day. Equation 3.1 shows a general impedance function:

$$A_{ij} = f_{m,t}(C_{ij}) \quad \text{(Equation 3.1)}$$

where A_{ij} is the access from i to j, $f_{m,t}$ is a function of access for mode m and time t and C_{ij} is the perceived travel time between origin i and destination j. Simply, impedance summarises the factors of travel cost as a measure of travel time (duration) or travel distance.

3.5.2 Deterrence function estimates the likelihood of travelling at different levels of travel duration

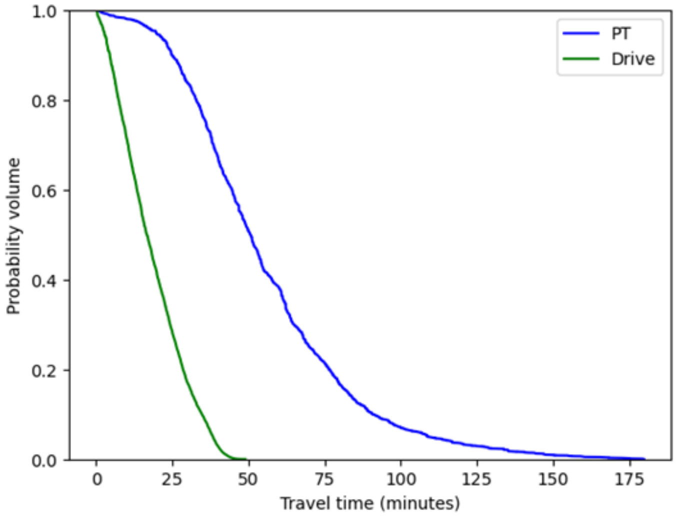
The concept of distance decay describes how interactions between physical or socio-economic entities diminish as the distance between them increases (Wang, 2014). Fotheringham (1981) indicated that, in well-developed regions with extensive road networks, the impact of distance or 'distance friction' is less pronounced. Distance decay typically implies that the intensity of interactions decreases with distance although factors such as the significance, size or mass of locations can enhance interaction intensity. The nature of this relationship can be complex, often stemming from the method and shape used to model the decrease. To approximate this relationship, three approaches are commonly employed: multiple linear functions, polynomial curves and transformed functions (Halás et al., 2014). Research by Paez (2016) and Viegas and Martínez (2016) has explored the use of reach curves in analysing accessibility, highlighting their effectiveness in capturing subtle variations in accessibility levels.

Different conceptualisations of distance decay exist such as continuous functions, discrete patterns (either binary or multiple discrete levels based on travel time or distance ranges) or a combination of these forms (Wang, 2012). The continuous form itself can take various shapes, including negative exponential (Wang et al., 2018), power (Jia, 2016; Wang et al., 2020), Gaussian (Dai, 2010; Guagliardo, 2004), log-logistic (Delamater et al., 2013) and others (Taylor, 1983).

The concept of revealed accessibility pertains to the actual use of a service whereas potential accessibility refers to the probable use of a service (Khan, 1992). Determining the most appropriate distance decay function and its coefficients requires analysing real-world usage patterns. In essence, actual service use demonstrates revealed accessibility and the statistical patterns identified by a distance decay function help to define potential accessibility, which can be viewed as the anticipated or projected level of accessibility (Wang, 2021).

In this report, we use a data-driven and empirical distance decay function based on revealed preference to measure various spatial behaviours to represent actual patterns most accurately. We use the complementary cumulative distribution method to measure distance decay (Taylor, 1983). We use the HTS to calibrate an S-shaped deterrence function to estimate the attractiveness of destinations for different socio-economic groups in various areas. We calibrate the S-shaped distance decay function uniquely for various territorial local authorities (TLAs) across New Zealand. This approach enables us to accurately capture the spatial distribution of the distance decay function throughout the country (Figure 3.5).

Figure 3.5 Distance decay function for travel to work in Auckland



Source: Principal Economics
Note: This illustrates an S-shaped distance decay function for travel time, comparing public transport and driving. It highlights that the likelihood of travel to work significantly reduces to nearly zero after 50 minutes of driving. In contrast, the number for public transport (PT) is 180 minutes of travel time.

3.5.3 Saturation function sums up the information from other functions together with the level of access information

The saturation function accounts for the competition in the accessibility measures by incorporating both the level of demand and the level of service. The floating catchment area family of methods are a popular tool for the saturation function. The two-step floating catchment area (2SFCA) model proposed by Luo and Wang (2003) is commonly used in academic and practical accessibility measurements (Bauer et al., 2017; Fujita et al., 2017; McGrail & Humphreys, 2009; Shah et al., 2016). This method involves two steps:

1. **Determining level of service at a provider:** This step focuses on calculating the level of service at a given destination. It does so by considering the supply (such as number of doctors) and the estimated demand from the surrounding population within a certain catchment area. This step results in a local provider-to-population ratio.
2. **Aggregating level of service for population centres:** In this step, the level of service is aggregated for each population centre. This involves ‘floating’ the catchment areas to these centres and calculating accessibility as the weighted sum of the level of service at each facility within its catchment area.

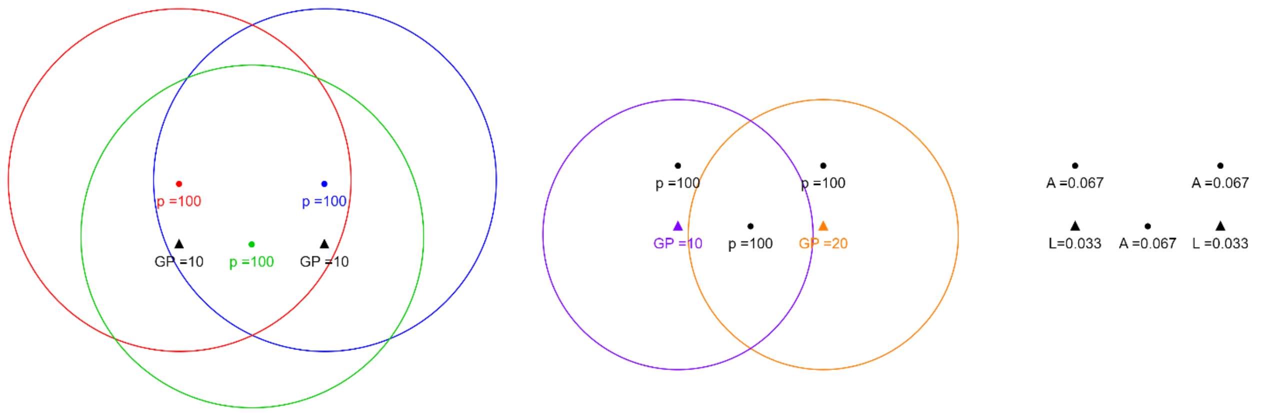
The 2SFCA method has certain limitations such as the potential inflation of demand and level of service (Delamater, 2013; Wan et al., 2012). This issue arises because 2SFCA assumes uniform demand within a catchment area and equal access for all individuals, which may not reflect real-world scenarios. Additionally, it might overestimate the level of service, particularly in densely populated areas.

To address these issues, several enhancements to the 2SFCA method have been proposed (Paez et al., 2019):

- **Variable catchment sizes:** Adjusting catchment sizes based on population density or transportation networks provides a more realistic assessment of accessibility.
- **Differentiating service levels:** Accounting for different destination types, their capacity and respective demands can improve the accuracy of the model.
- **Incorporating travel time:** Replacing simple distance measures with the distance decay function better reflects the actual effort required to access services.
- **Weighting population demand:** Applying different weights to different segments of the population according to their specific needs can refine demand estimates.

These adjustments make the 2SFCA method more nuanced and reflective of real-world conditions, enhancing its utility in planning and policy making.

Figure 3.6 Levels of service of two clinics and accessibility of three population centres (adapted from Paez et al., 2019)



Note: Triangles are clinics, dots are population areas, coloured circles are segments of catchment areas. Each circle represents 100 people and each triangle includes 10 doctors. Left diagram shows catchments for each population area. Middle diagram, shows catchments for each GP. Based on the binary 2SFCA method, the level of service for each facility is 0.033 and total level of service provided to each population centre is 0.067.

4 Data and methods for accessibility measurement

Accessibility analysis leans heavily on open data sources, real-time information and emerging technologies to reveal the dynamics of movement within urban environments. The datasets considered for accessibility consist of socio-economic and land-use data merged with various geographic overlays providing information on the network and transport modes.

This chapter is organised as follows:

- The geographic definition used for the analysis of accessibility is described in section 4.1. This is important for ensuring all identified data sources will be available at the appropriate geographic level.
- Section 4.2 describes the sources of data for socio-economic, land use, travel behaviour and network. These datasets will be used for identifying the accessibility measure groups.
- Sections 4.3 and 4.4 describe the methods and models used for different functions of the accessibility measure. Appendix I provides and examines the wider data and tools commonly used to assess transport accessibility, encompassing a wide range of open data sources and emerging technologies.

4.1 Our geographic boundaries are defined at the SA1 level

Stats NZ (2022) uses various statistical zones to disseminate data. A meshblock, the smallest unit in the hierarchy, typically contains around 80–120 dwellings. Aggregations of meshblocks (SA1s) typically contain around 400–1,000 people. They offer a broader view of population demographics and are often used for analysing housing affordability, educational attainment and employment patterns. The larger size of an SA1 compared to a meshblock may mask underlying inequalities within the area, requiring careful interpretation of data. Another consideration is the usefulness of the definition of geographic boundaries for policy analysis and its consistency with available modelling frameworks. Based on our conversation with the project steering committee, we concluded that the SA1 geographic boundary provides a reasonable level of granularity that is consistent with other modelling frameworks. Hence, we consider the SA1 geographic level suitable for the construction of accessibility measures.

In our analysis of points of interest as destinations, SA1 is used to aggregate these to simplify the analysis. For instance, the total number of offices can be aggregated to one destination at the centroid of an SA1.

4.2 An extensive range of data sources were used for capturing different measurement dimensions

4.2.1 Socio-economic data is obtained from Census 2018 and the HTS

We used Census 2018 data for population information at SA1 level. The information age groups were sourced from the HTS, which covers the period 2014–2020 and provides information about 2,967 individuals and 128,282 trips. For further details on available socio-economic data sources, see Appendix H.1.

4.2.2 Land use data is sourced for different destination types

Traditionally, the assessment of transport accessibility focused primarily on the daily commute to work, with an emphasis on connecting individuals to employment opportunities. As discussed, a paradigm shift in accessibility analysis has recognised that urban life is much more multifaceted and accessibility is not confined to the workplace alone. In this evolving landscape, points of interest have emerged as crucial destinations that offer a richer and more comprehensive perspective on accessibility.

This shift in perspective signifies a more inclusive approach to accessibility. Rather than solely measuring the ease of reaching jobs, accessibility analysis now acknowledges that urban residents require access to a wide array of essential services, facilities and places of interest. Based on the literature review, we identify nine categories of destinations: jobs, office, industries, commercial, education, entertainment, healthcare, bars and restaurants, and recreation. Details about the source of data for these destinations are provided in Table 4.1. By considering points of interest as essential destinations, accessibility analysts gain a comprehensive understanding of the demand for access.

Table 4.1 Destination types and data sources for accessibility analysis

Destination	Description	Source
Jobs	The number of all jobs in each TAZ	Business employment data (Stats NZ)[11]
Office	The number of office jobs in each TAZ	
Industries	The number of industrial jobs in each TAZ	
Commercial	Number of shops in a cell, excluding grocery stores, fresh produce, delis and bakeries	Overture Maps[12]
Food	Grocery stores, fresh produce, delis and bakeries	
Education	Primary, intermediate and secondary schools	LINZ – NZ Facilities[13]
Recreation	Parks, gyms, pools and sports centres	Overture Maps
Entertainment	Museums, theatres, cinemas, community centres, libraries and nightclubs	
Healthcare	Hospitals and general practitioners, including urgent medical care	LINZ – NZ Facilities

Source: Principal Economics

Different sources are used for destination data for accessibility analysis. The main sources used to create the land-use dataset are the business employment data and Census employment data. Data from the New Zealand Government's open data portal is used to identify destinations such as healthcare and education.

The shift towards considering points of interest instead of jobs as destinations in accessibility analysis is a fundamental revaluation of how we view urban mobility. It underscores the importance of enriching urban life beyond the workplace and signifies a commitment to fostering equity and inclusion in our cities. As we continue to develop our urban landscapes, including points of interest as essential destinations will be central in shaping transportation infrastructure catering to holistic needs and aspirations of urban residents.

4.2.3 Travel behaviour data is sourced from GSS and HTS

We used two data sources for consideration of travel behaviour and utility of accessibility:

- The New Zealand General Social Survey (GSS) provides information on the welfare of New Zealanders aged 15 years and over. It covers a wide range of social and economic outcomes.
- The HTS is representative of New Zealand's population and daily travel demand. It measures travel by asking everyone in randomly selected households to record their travel over 2 days.

[11] We have used SA1 level employment data, which is not publicly available.

[12] Overture Maps (https://overturemaps.org) provides open geospatial data, including comprehensive data for 54 million points of interest worldwide. OpenStreetMap is the best resource for identifying parks, reserves and general open green spaces. OpenStreetMap data has been incorporated as part of the Overture Maps points of interest dataset. We use Overture Maps as our source of green spaces to avoid duplication.

[13] https://data.linz.govt.nz/layer/105588-nz-facilities/

We used the GSS data together with the identified accessibility measures to identify the measures with the highest explanatory power for the welfare of New Zealanders. This methodology is consistent with the approaches that Kinigadner et al. (2021), Torshizian (2017) and Torshizian and Grimes (2014, 2021) take for identifying various measures/functional forms. We provide a brief introduction to these surveys below. Descriptive statistics for GSS are provided in chapter 6 and details for the HTS are provided in section 5.4.

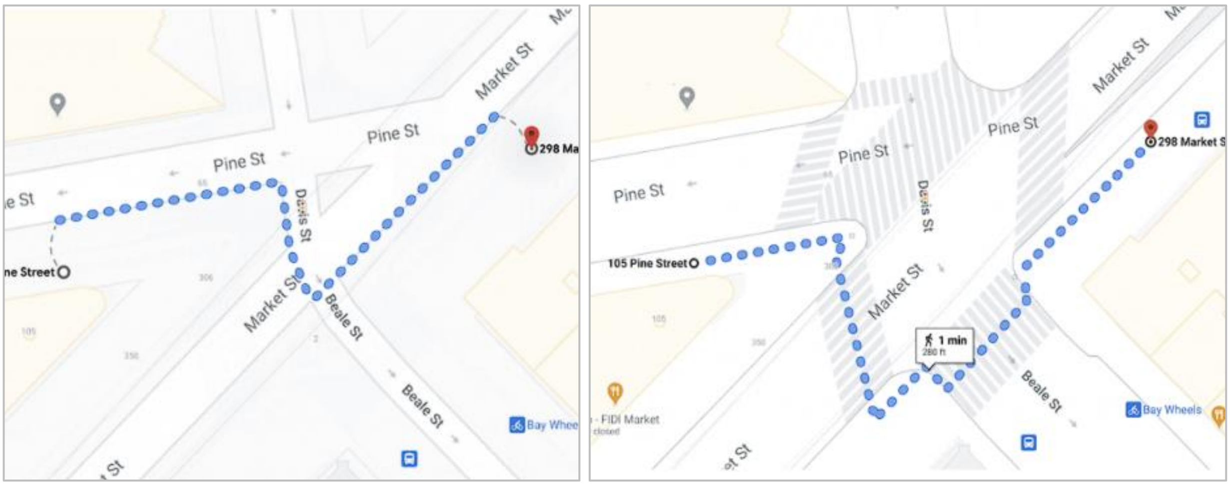
4.2.4 Network data is collected from OpenStreetMap (OSM) and other sources

Given its granular nature, the most useful network data is available from live data sources. In this section, we provide details on the available data for walking, cycling, driving and public transport.

4.2.4.1 Walking data is dominantly based on OSM

Walking is a fundamental part of accessibility measures. It often connects different modes of travel, forms first/last mile of a journey or serves as the sole means of transport. A routing application programming interface (API) such as Google, HERE and OSM typically uses road centrelines to map walking paths. This approach benefits from simplicity and readily available data. However, it lacks precision in detailed aspects of pedestrian access such as modelling crosswalks at intersections.

Figure 4.1 Current pedestrian network based on road centrelines (left) and proposed network that can identify sidewalks and crossings (right) (reprinted from Dicker, 2021)



We present the potential usefulness of computer vision and aerial imagery using tile2net in Appendix H.2 to capture the crossing formation that could complement the walking data. However, the use of tile2net was computationally intensive, requiring the processing of over several terabytes of satellite imagery. This was impossible to accomplish within the timeframe of the current project.

4.2.4.2 Cycling data is based on OSM and available spatial layers

Like the walking network, the cycling network can be seen as serving the first/last mile of a journey or constituting an entire trip on its own. In New Zealand, 17% of household car trips (trip chains) are under 2 km long and almost half (48%) are less than 6 km long (Waka Kotahi NZ Transport Agency, 2010). We take a similar approach to previous studies and use the OSM data for cycling (Bres et al., 2023; Knap et al., 2023; Vierø et al., 2023).

Another important factor for the cycling network is the hilliness of the links as it can impact the accessibility measure’s impedance function. The slope of each link is measured using the New Zealand 1 metre digital elevation model (DEM).[14] It is important to note that slope is not too relevant to ebikes – we discuss this in chapter 8. We identified other data available from council data to complement this information and present that in a table in Appendix H.3. The use of this complementary information will be recommended for future studies.

4.2.4.3 Driving information is collected from TomTom

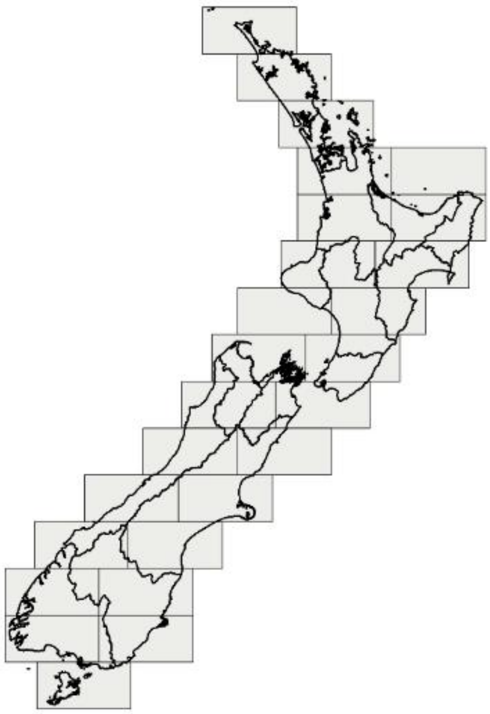
TomTom data, renowned for its comprehensive and current street network database in New Zealand, is a valuable asset for driving network research. It includes detailed information about speed limits and turn restrictions. NZTA holds a licence for TomTom data, ensuring its accessibility for research purposes.

Access to TomTom's routable network (TomTom Multinet) is conditional on the licensing agreement and is not available for use by third parties. Historical vehicle travel speeds can be queried via the TomTom Traffic Stats web user interface or API – albeit with a limit to the area extent of each query. While these two datasets can be linked without access to the TomTom Multinet, we merge the TomTom traffic statistics with OSM using spatial approximations for matching historical travel speeds with the OSM routable network.

To mitigate for area-based query limits with the TomTom Traffic Stats API, it is possible to construct identical queries set below the area limit looping over each. This can be achieved by checking the extent of New Zealand into 26 areas and merging the subsequent API responses while deleting any duplicate roads.

This provides historical travel speeds for the entire New Zealand roading network recorded by TomTom. We show the bounding boxes we use to disaggregate the extent of New Zealand in Figure 4.2.

Figure 4.2 TomTom data extracted via the TomTom Traffic Stats API using 26 queries



Source: Principal Economics

[14] A 2020 map of the national cycling network is available at https://spatial.nzta.govt.nz/portal/apps/experiencebuilder/experience/?id=f08560df63014613868127771b1e4677.

4.2.4.4 For public transport, we use GTFS Realtime and GTFS static

Over the last two decades, transport accessibility models have become more sophisticated and easier to use, especially after the creation of the GTFS data format (Farber & Fu, 2017; Pereira, 2019). The GTFS standard has allowed the emergence of several transport routing models and accessibility tools that account for door-to-door travel time estimates in complex multimodal transport networks (Pereira et al., 2021; Higgins et al., 2022). Recent studies assess trip-level or even person-level accessibility based on fine-grained standard data like GTFS and smartcard ticketing data (Arbex & Cunha, 2020; Batty, 2013; El-Geneidy & Levinson, 2006; Lee & Miller, 2018).

Several relational database tables comprise the GTFS static data, specifying the transit system's stops, trips, routes, arrival and departure time and other schedule information (Google for Developers, 2022b). The public transport network based on GTFS data can be combined with walking and/or cycling networks to create a multimodal system. The network data can further be enriched by including amenity information such as shelter, light, bench, rubbish bin, arrival sign, shade, footpath and bike lane. (For details on GTFS static files and how they can be related to each other using the key fields, see Appendix H.2.)

We collected GTFS Realtime data for Auckland, Wellington and Canterbury. For other regions, we used GTFS static. We collect data for all trip status updates on Tuesday for weekday peaks and Saturday for weekend peaks. Trip delays are aggregated by time period, stop_id and trip_id, which are used to modify GTFS static datasets.

4.3 A range of methods used for constructing accessibility functions depending on data availability

Data collection, manipulation and analysis required for constructing measures of accessibility is extensive – accessibility data is possibly one of the most complex in big data analysis. As presented in the previous chapter, the accessibility measure is constructed based on the deterrence and saturation functions, with impedance as an input to both. At a high level, these components are combined to derive the single measure of accessibility. In this section, we describe the source of data for each component.

4.3.1 Impedance function constructed for walking, cycling, driving and public transport

Network desirability is an instrumental component in the analysis of transport accessibility. This metric provides insights into the quality and performance of transportation networks. To measure commuters' preferences on their travel behaviour, studies use stated preference and revealed preference data to develop a choice model. A popular choice model recommended in this research is the logit model.

Olszewski and Wibowo (2005) proposed the notion of equivalent walking distance to gauge the effects of walking facility attributes on generalised walking cost, which can be used as an indicator of walking accessibility performance. Similar approaches are proposed by Allan (2001).

Expanding on Olszewski and Wibowo, we recommend a similar approach and propose perceived time instead of travel time to develop the generalised cost function. This allows for including demand and desirability into the accessibility measure.

4.3.1.1 Walking accessibility measures are constructed using the estimates available from earlier studies, but we will need to collect a wider range of information for New Zealand

Studies have revealed the close associations between pedestrian choice behaviours and attributes of the walking environment.

Liang et al. (2023) have classified these into three categories:

- Neighbourhood-level attributes, including land-use pattern, coverage of points of interest, topological design, socio-economic characteristics of people who work or reside in the neighbourhood.
- Street-level facility attributes that affect the walking experience such as road crossing facilities, traffic flow, sidewalk width and slope.
- Other exogenous and uncontrollable attributes such as the weather.

The walking network data has the information on environmental attributes of each link in the walking network. A questionnaire survey data will be useful to collect data on how commuters perceive walking to their destinations. A utility-based walking accessibility measure can be used to combine street-level facility attributes and pedestrians' behavioural responses. The perceived time can replace travel time in the impedance function (generalised cost function) for the walking network.

In absence of the survey data, we use the results of Liang et al. (2023) as shown in Table 4.2. The stated preference results column shows the estimated parameter using a fixed effects regression analysis. The sidewalk distance equivalent converts the walking attributes of different facilities to an equivalent sidewalk distance, measured in metres.[15]

Table 4.2 Sidewalk distance equivalent for different walking attributes

Walking attributes	Stated preference results	Sidewalk distance equivalent
Walking distance (m)	-0.008	1.00
Restaurant/store	0.191	–23.60
Street lighting	0.065	−8.09
Sidewalk width (>5 m)	0.042	−5.16
High pedestrian crowdedness	-0.120	14.91
Cover/roof	0.094	−11.61
Slope (>5%)	-0.257	31.82
At-grade crosswalk	0.016	−1.98
Over/underpass with lift	0.065	−7.98
Over/underpass with stairs	-0.054	6.74
Over/underpass with escalators	-0.026	3.22
Extra waiting time (min)	0.200	24.80

Source: Liang et al. (2023, p. 9)

4.3.1.2 Cycling accessibility measures are constructed using the estimates available from earlier studies, but we will need to collect a wider range of information for New Zealand

Studies on the relationship between the built environment and travel behaviour are more concerned with bad and good (design and implementation) practices (Sun et al., 2017) rather than with eliciting user preferences. Our focus is to measure preferences/choice behaviour as a function of attributes of the built environment (and a set of covariates).

[15] It can also be interpreted as the marginal substitution rate between that attribute and the sidewalk walking distance. More specifically, sidewalk distance equivalent is defined as the equivalent sidewalk distance a pedestrian perceives as they walk through a certain walking facility attribute.

> *The literature shows that a wider range of attributes have been included in studies of route choice of walkers and related to cyclists. Not only road-related attributes (e.g., sidewalk presence, sidewalk width, presence of traffic lights, presence of zebras), but also buildings height, presence of public lighting, have been studied, but also functional aspects such as presence of retail frontage and greenery … Sidewalk width/bike lane width, public lighting, crossing facilities and vehicle traffic volume are important factors with a significant influence on walking/biking.* (Liu et al., 2020, p. 2)

There is a gap in data on how cyclists perceive the cycling facilities. Since New Zealand does not have a travel behaviour survey specific to this context, we can approximate perceived travel times by referring to analogous studies such as Liu et al. (2020). This approach is akin to how we handle walking network data. The attributes that we could include in our analysis are cyclist distance and presence of retail shops. This low number of attributes available for the network means less variation in the cycling accessibility measures. The modular structure of our code ensures that, once local New Zealand data becomes available, it can be seamlessly integrated with minimal modifications.

Table 4.3 Cycle distance equivalent for different attributes

Cycling attributes	Stated preference results	Distance equivalent
Cyclist distance (m)	-0.006	1.00
Retail shops	0.04	-6.67
Traffic lights	-0.028	4.67
Separation fences	0.104	-17.33
No bicycle crossing facilities	-0.288	48.00
Wider than 2.5 m	0.349	-58.17
2.5 to 1.5 m	0.105	-17.50
Below 1.5 m	-0.076	12.67
No cyclist path	-0.378	63.00
Almost no car or bike in the streets	0.316	-52.67
Not crowded	0.219	-36.50
Somewhat crowded	-0.025	4.17
Very crowded	-0.51	85.00
Greenery	0.246	-41.00
No lights	-0.21	35.00

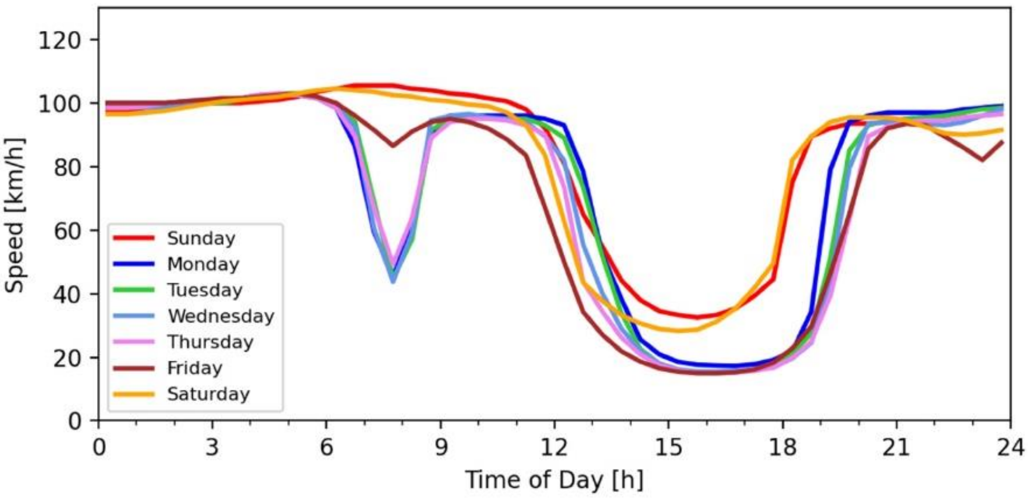
Source: Liu et al. (2020)

4.3.1.3 Driving information is collected from TomTom

Research on the differences between perceived and actual driving travel times has yielded mixed results. Earlier studies like the one by Abdel-Aty et al. (1997) focused on factors affecting driving route choices before the widespread use of smart routing technologies. In contrast, more recent work (Razo & Gao, 2013) emphasises the impact of real-time traffic information, available through advances in telecommunications and mobile technology, on driving route choice. Given the minor discrepancies between actual and perceived travel times, we rely on historical travel time data for driving analysis.

The main source of historical travel time is TomTom's Multinet data because it is available at NZTA. Historical driving data can be adopted for use by converting TomTom's Multinet routable network with minimal efforts. TomTom speed profiles are derived by aggregating and processing trillions of anonymous GPS measurements from millions of devices that reflect actual consumer driving patterns. Speed profiles enable navigation and routing algorithms to find the fastest routes in complex road networks, predict travel times accurately and suggest alternative routes or time to travel. The product provides average speeds per road element per direction of traffic for every 5 minutes of each day of the week for the complete road network. Figure 4.3 shows real driving speeds recorded on one highway across different times of the day and different days of the week.

Figure 4.3 A sample of TomTom speed profiles data (reprinted from Meinck, 2021)



4.3.1.4 Public transport information is collected using GTFS Realtime and GTFS static

GTFS Realtime is a feed specification that allows public transportation agencies to provide real-time updates about their fleet to application developers. It is an extension to GTFS, an open data format for public transportation schedules and associated geographic information.

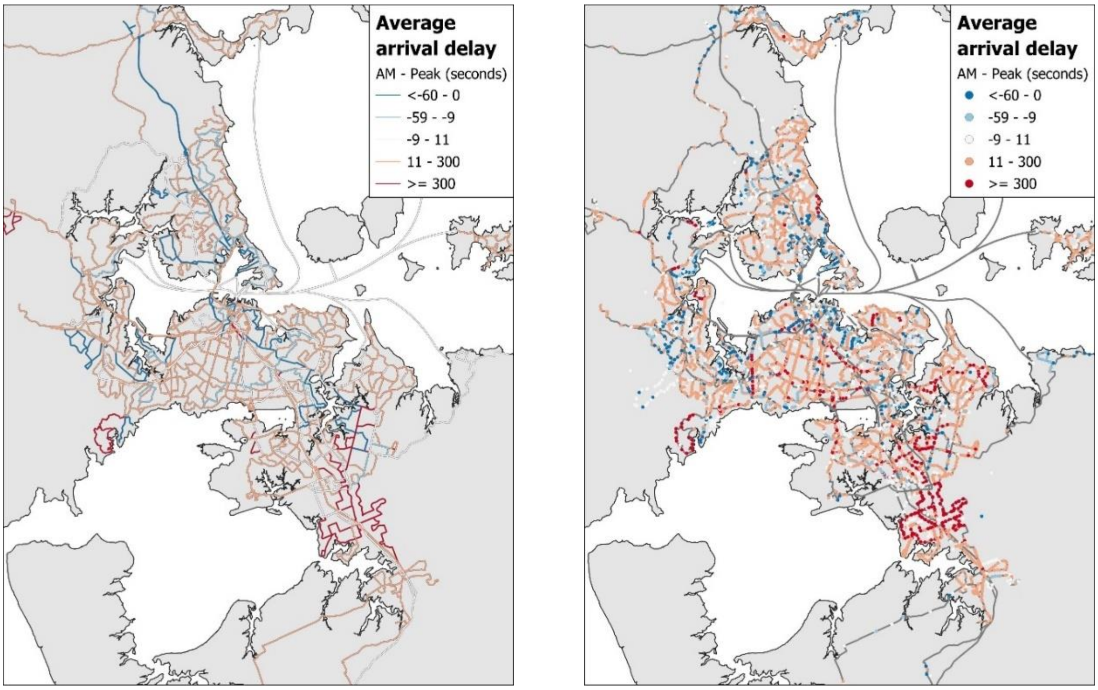
Recent studies have developed methodologies to correct scheduled GTFS timetables with GTFS Realtime data and improve accessibility accuracy (Liu et al., 2023; Wessel et al., 2017; Wessel & Farber, 2019). The findings show significant accessibility differences across neighbourhoods and socio-economic groups.

Braga et al. (2023) analysed the impact of day-to-day travel time variability on accessibility by comparing GTFS Realtime P50 to GTFS Realtime P85.[16] Their results show, on average, ignoring day-to-day travel time variability can lead to an overestimation of accessibility by up to 50%, with an observed range of 34–67%.

Figure 4.4 shows a snapshot of the distribution of bus service delays in Auckland (for 18 March 2024). The data is collected from Auckland Transport's GTFS Realtime feed. The delays are the difference between the GTFS Realtime data and static public transport schedule. As shown, the distribution of delays is not homogeneous and some areas are disproportionally affected by bus service delays. It is evident that the GTFS data should be corrected by the real-time information before being used for an accessibility measure. The identified areas with higher delay likelihood seem to be the areas with either high-density or low-density levels. (For the structure of GTFS data, see Appendix H.4.)

[16] P50 and P85 refer to different levels of probability or confidence in the accuracy of the estimate.

Figure 4.4 Delays in Auckland's public transport network at link level (left) and same data at (bus) stop level (right) at AM peak (7–9am)



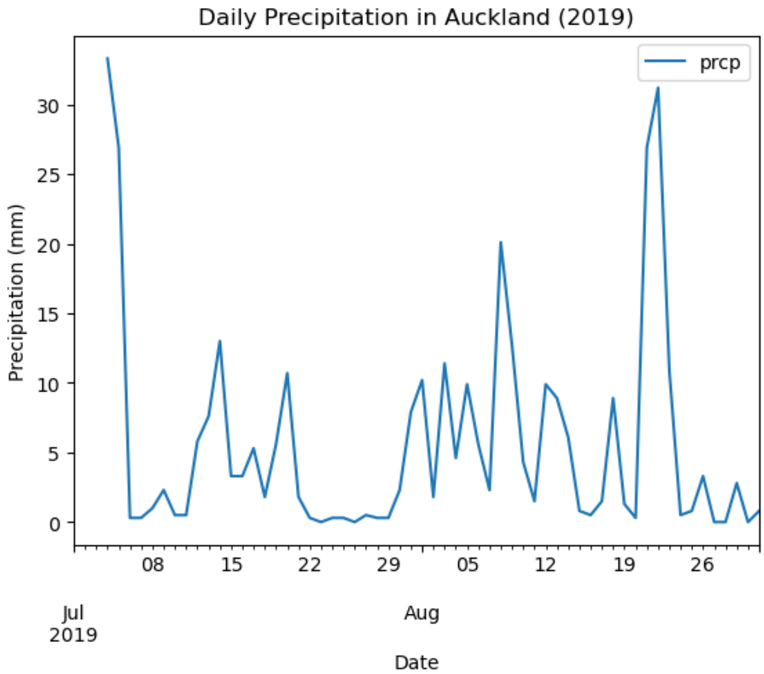
Source: Principal Economics analysis

4.3.1.5 Control variables

Weather conditions

Historical weather data (Stats NZ, 2023) is used for considering the impact of rainy days on accessibility measures. Figure 4.5 shows an example using MetService precipitation data.

Figure 4.5 Example of historical weather data



Source: Principal Economics based on Meteostat API

For this analysis, a rainy day is defined as a day where the total precipitation exceeds 0 millimetres (mm).

Seasonal conditions could affect accessibility

Seasonal variations could impact transportation patterns and accessibility. In conducting a transport accessibility analysis, it is important to incorporate at least four snapshots throughout the year to account for seasonal variations. It is also useful to consider the impact of vacations. In section 5.4.1, we test the usefulness of considering different seasons in the analysis of distance decay.

Generalised cost of different modes is added to the travel length and used as the variable of interest in our analysis of the deterrence function

We considered the financial cost of travel using a generalised cost function for each mode. The generalised cost (in minutes) is then added to travel duration and considered as the variable of interest in our analysis of the deterrence function in section 5.4.

The primary cost of travel for each mode is from the length of travel (time spent travelling in minutes). The additional cost for driving is vehicle operating cost, which is calculated consistent with NZTA's Monetised Benefits and Costs Manual (MBCM) (NZ Transport Agency Waka Kotahi, 2024b). The additional cost for public transport is the paid fare, which is converted to minutes after dividing by individual income.[17] For other modes (walking and cycling), we simply use the length of travel in our analysis.

Crowdedness could be considered in the future studies

Ticketing data is useful for analysing how crowded each public transport link is. By integrating ticketing data with the HTS, it will be possible to control for the impact of crowdedness on passenger experience and preferences. We have not included crowdedness in our current measurement of accessibility due to the tight timeframe of the project, but this could be added by practitioners in the future.

4.3.2 Deterrence function data

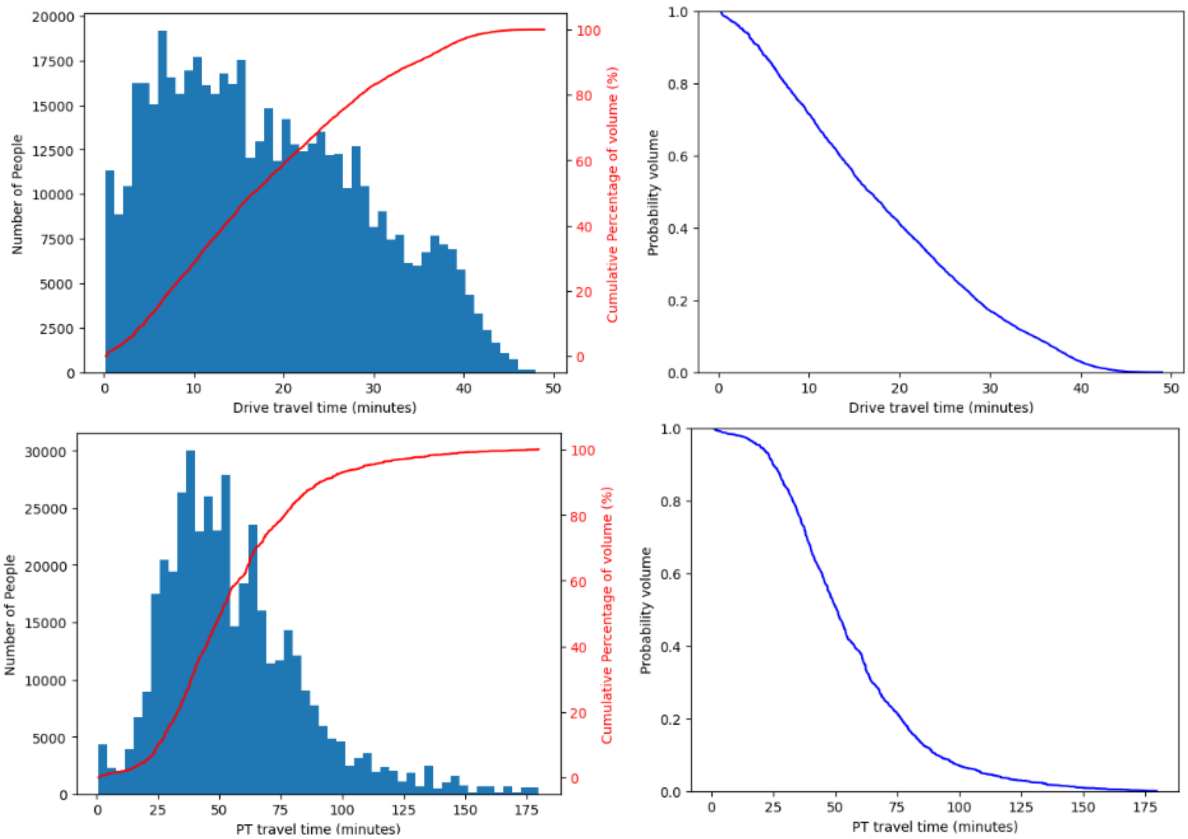
In this study, we assess perceived travel time using a spatial impedance function. The attractiveness of destinations tends to decrease as travel time increases, a phenomenon known as the distance decay effect. This effect results in fewer trips to destinations that are further away. Our approach, detailed in section 3.5.2, utilises a continuous distance decay function, which represents the range of traveller numbers across various travel times, offering a realistic portrayal of travel behaviours (Taylor, 1983).

To ensure accuracy, the deterrence function's parameters require calibration based on actual travel data. Key to this process is the HTS database, which provides comprehensive data on travel patterns. We will consider travel times for different modes of transportation to develop the reach curve for the deterrence function. Adjustments for spatial disparities in reach curves are made for each TLA.

As outlined in section 3.5.2, we plan to fit an S curve to the HTS data to formulate the decay function. Our goal is to generate 3,216 distinct curves, taking into account variables such as TLAs, transport modes, age groups and destination types. Figure 4.6 shows reach curves for access to jobs for private vehicle and public transport in Auckland. Graphs on the left show frequency and cumulative percentage of service volume on travel time to jobs, and graphs on the right show complementary reach curve probabilities of service volume on travel time to jobs. These graphs are based on the cumulative distribution method using Census 2018.

[17] If we used average income (as is commonly done), it would underestimate the value for the high-income group and underestimate for the low-income group, which will be a judgement about equity outcomes. For more discussion, see Torshizian et al (2022).

Figure 4.6 Reach curves for access to jobs for private vehicle and public transport in Auckland.



Souce: Principal Economics inspired by Wang et al. (2021)

4.3.3 Saturation function data

The accessibility measure offers an indication of the level of service for destinations. These measures conceptualise a region as a container of population and services. Accessibility can be used to calculate provider-to-population ratios that can be interpreted as the supply of a service (such as number of doctors or capacity of schools) divided by demand (such as number of people who can access the service).

The saturation function, integral to accessibility measures, accounts for competition among facilities. It posits that a facility's demand is affected by its proximity to others (Luo, 2014). In our analysis, we incorporate demand and service level adjustments in floating catchment area methods, as detailed in section 3.5.3. Among the various floating catchment area methods discussed, we adopt the balanced floating cost accessibility (BFCA) method, following the approach of Paez et al. (2019). While the saturation function and deterrence function employ a similar impedance function for calculating travel time, BFCA uses stepwise decay function, which is different from our deterrence function. In our model, unlike the stepwise function used in BFCA, the deterrence function for each destination remains constant. This approach simplifies the saturation function as it does not necessitate additional data.

Appendix H.5 provides a review of the available data for future network analysis.

4.4 Models and routing engines used

In this section, we provide a short description of the routing engines/tools used in our analysis of accessibility measures. Other available methods that might be helpful for future development of accessibility measures are presented in Appendix D.4.

4.4.1 UrbanAccess

UrbanAccess is an open-source Python library that provides a variety of tools for analysing urban accessibility. It can be used to calculate accessibility to a wide range of destinations, including jobs, schools, parks and public transportation. UrbanAccess also includes tools for visualising accessibility data and for identifying areas with poor accessibility.

UrbanAccess is a relatively new library released in 2020 but it has quickly become a popular tool for urban planners and researchers. It has been used in a variety of studies to assess the impact of transportation policies to identify areas in need of investment and to develop more equitable and sustainable cities (Blanchard & Waddell, 2017; Gazzé, 2018).

UrbanAccess utilises Pandana graphs, OSM and GTFS data to construct a multimodal network that supports routing. It leverages TAZs for evaluating accessibility to various destinations. Once the required data is compiled, UrbanAccess can compute accessibility scores for each origin point, typically TAZ centroids. These scores quantify the ease with which residents at an origin point can reach desired destinations. The tool is versatile, allowing for the creation of accessibility metrics for walking, cycling and combined walking and public transport. All three metrics are derivable through the UrbanAccess framework.

The advantages to using UrbanAccess are that it:

- is open source and freely available
- is easy to use and has a well-documented API
- provides a wide range of tools for analysing urban accessibility
- is constantly being updated and improved.

However, potential disadvantages to using UrbanAccess include:

- some of the more complex analysis tools can be computationally expensive
- it is still under development so there may be some bugs or limitations.

UrbanAccess is a powerful and versatile tool for analysing urban accessibility. It is well suited for a wide range of users. Although it is still under development, it is already having a significant impact on the field of urban planning.

4.4.2 R5 routing engine

R5 is the routing engine for Conveyal, with a web-based user interface that allows users to create transportation scenarios and evaluate them in terms of cumulative opportunities accessibility indicators. The engine has been extensively used in urban and regional planning projects. Its ability to analyse multimodal transport networks and accessibility makes it a valuable tool for assessing the impact of transport policies, infrastructure developments and service changes.

Comparative studies have shown that R5 offers several advantages over traditional routing engines such as faster processing times and more accurate multimodal routing. Its open-source nature also contrasts with proprietary software, offering a more collaborative and adaptable approach to transportation planning. Programming interfaces have been developed for commonly used language for R5 in Python (R5py) and in R (R5R).

4.4.2.1 Limitations

Performance indicators demonstrate that R5 outperforms both ArcGIS and UrbanAccess in speed. However, R5 is specialised for place-based accessibility analysis only. This research aims to integrate place-based and person-based accessibility. To fulfil this goal, it’s essential to individually assess and adjust the travel time for each link in the network. Overcoming the limitations of the R5 libraries involves modifying the walking and cycling networks separately before inputting them into the R5 engine. This additional step in the accessibility analysis might negate R5's speed advantage.

4.4.3 Web routing service APIs

There are many routing API services such as Mapbox, Openrouteservice, HERE Maps, Google Maps and GraphHopper. These APIs are widely used for their efficiency in providing routing information for all modes. However, they have certain limitations, especially in the context of transport accessibility analysis:

- **Data:** Every provider works on different spatial global datasets. While Google or HERE build on top of proprietary datasets, providers such as Mapbox or GraphHopper consume OSM data for their base network. These databases have very limited capabilities to integrate with local data.
- **Wayfinding algorithms:** Every provider uses a plethora of algorithms and offers a different amount of options to restrict the wayfinding.
- **Cost and usage restrictions:** The commercial nature of these APIs means they come with usage limits and cost implications, especially for high-volume users. This can be a barrier for extensive transport accessibility studies, particularly for non-profit and academic research.
- **Standardisation and comparability:** Different methodologies used by these APIs for calculating routes and traffic can lead to discrepancies in data, making it challenging to compare and standardise results across different platforms.
- **Accessibility features:** Both Google Maps and HERE Maps have incorporated some accessibility features, but these are often limited in scope and do not cover all aspects of transport accessibility. For example, HERE Maps do not provide isochrones for the public transport network.
- **Customisation and flexibility:** For specific transport accessibility analysis, the customisation options offered by these APIs may be insufficient. This research requires more flexible tools that can be tailored to specific conditions and criteria of place and human accessibilities.

In summary, while web routing APIs are valuable tools for basic routing and geographical information, their limitations in terms of data coverage, real-time data accuracy, cost, standardisation, comprehensive accessibility features, local data integration and customisation present significant challenges for transport accessibility analysis. These limitations mean that APIs could not be used for addressing the full scope of analysis required in this project and will be complemented with other tools.

4.5 Summary of findings of stage 1

We discuss the objectives of the project in section 1.4. Our conclusion for stage 1 based on chapters 2–4 is that the research project contributes significantly to both the technical and strategic inputs required for informed transport decision making. Our findings from the first stage are summarised below and identify the methods and data required for constructing measures of accessibility to meet the objectives of the second stage of the project in the following chapters.

In the first stage, we investigated four objectives of this research project and our findings are as follows:

A. Review national and international literature and experience of accessibility measures in transport.
   Addressing objective A: We explored the strategic context of transport accessibility in chapter 2. Subsequently, we discussed the paradigm shift in planning, transitioning from a focus on mobility to embracing accessibility. After that, we examined various transport accessibility measures and their methods and tools that can facilitate this paradigm shift and derive a useful accessibility measure.

B. Identify typical accessibility datasets used in urban areas worldwide that may not be readily available within New Zealand and suggest other approaches to measurement that may be adopted in the short and long term.
   Addressing objective B: We investigated the use of different datasets such as the Stats NZ IDI and AI-generated data, alongside existing datasets such as Census, GTFS, traffic data and network data. As discussed, AI-generated data can play a role in filling short-term data gaps, particularly in assessing service quality and desirability, as well as generating mock network data for testing future development scenarios. Additionally, leveraging GTFS Realtime data can help address data gaps related to service reliability and punctuality.
C. Identify how active-mode network analytics could consider levels of service and desirability of links given the datasets currently available in New Zealand.
   Addressing objective C: We investigated the potential of using AI with satellite imagery for generating data on traffic, safety and comfort for walking and cycling networks. Additionally, we explored the integration of other relevant databases such as Auckland Transport's asset management data, which includes information on bus stop shelters and other amenities. By combining these diverse variables, we can create an accessibility impedance function that takes into account the desirability and level of service offered by the active-mode network catering to pedestrians and cyclists.
D. Explain the various ways live and GTFS static files have been used overseas and in New Zealand to inform aspects of spatial accessibility (with more of a focus on connectivity rather than public transport performance-analytics).
   Addressing objective D: We explored the methodologies for measuring the impact of public transport travel time inaccuracy and variability on spatial accessibility using GTFS Realtime data.

The current project fits closely with our parallel work on identifying the most useful approach for transport appraisals. As highlighted in that project, the accessibility-based appraisal frameworks are aligned with an integrated approach to land use and transport planning, which is critical for achieving sustainable transport outcomes. The outputs of this project provide important information on the approach for measuring accessibility that will be used in the preferred accessibility-based appraisal methodology.

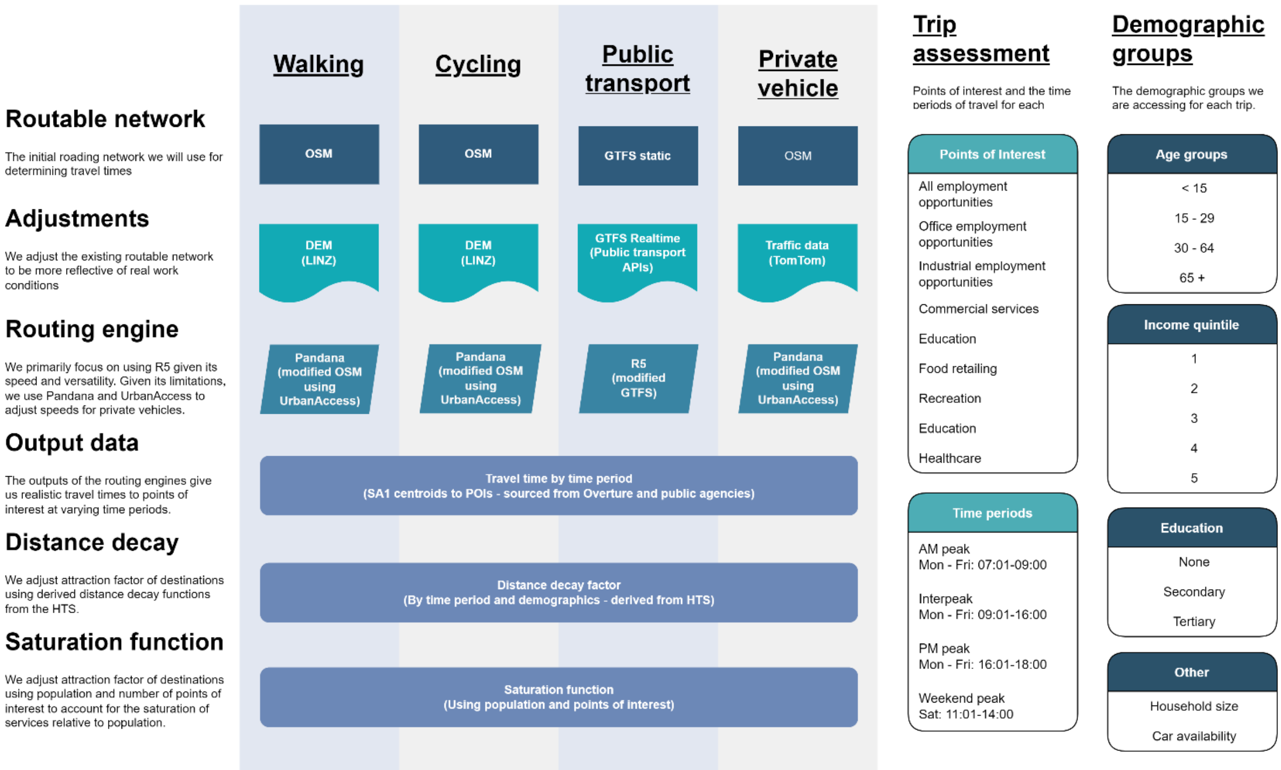
5 Constructed measures of accessibility

We have outlined a range of data, methodologies and algorithms for constructing measures of accessibility. In this chapter, we bring all the data and methods together to construct the measures across New Zealand. Given the wide range of data used for the construction of accessibility measures, we describe the data used for each task in the relevant section.

5.1 Our methodology uses a wide range of data to construct the multi-dimensional measures

The construction of a comprehensive database of various accessibility measures is an enormous task. The collection of data for one component of accessibility measurement such as GTFS Realtime for one region in itself is a large project. This is because of the number of destinations (nine types), origins (over 1,000 depending on the size of a region) and time of travel (three) for each mode and by a specific socio-economic group over time. This is only to show the size of the task at hand. To simplify this, we present the dimensions and methods used for each mode in Figure 5.1.

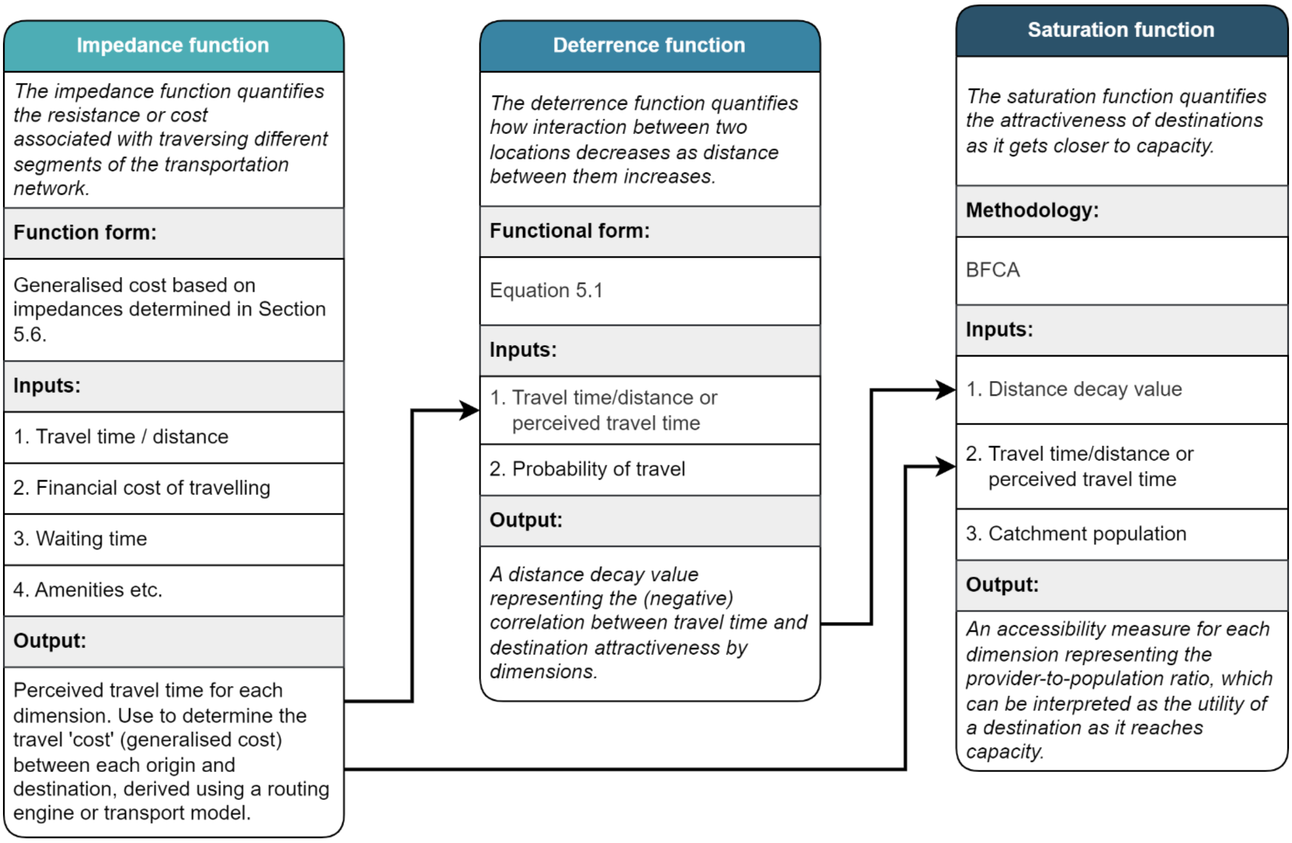
Figure 5.1 Constructing accessibility measures



Source: Principal Economics

Figure 5.2 shows the process of constructing accessibility measures. As presented, each function has a form as described in the corresponding sections of the report. The inputs and outputs of each function are also shown. The outputs of the impedance function are used to inform the deterrence function. The outputs of both impedance and deterrence functions are then used together with the saturation function's measure of serviceability as inputs to the BFCA methodology. The BFCA is described in the next section and is part of the toolkit used for accessibility measurement (as described in Appendix K).

Figure 5.2 Accessibility measurement process



Source: Principal Economics

5.2 Data description

BFCA is a method used in transport planning and project management to optimise accessibility by balancing the dynamic costs associated with accessibility features and user needs. It involves the strategic allocation of resources to ensure that transportation systems are both financially sustainable and accessible to all users.

The methodology brings different components of accessibility together.

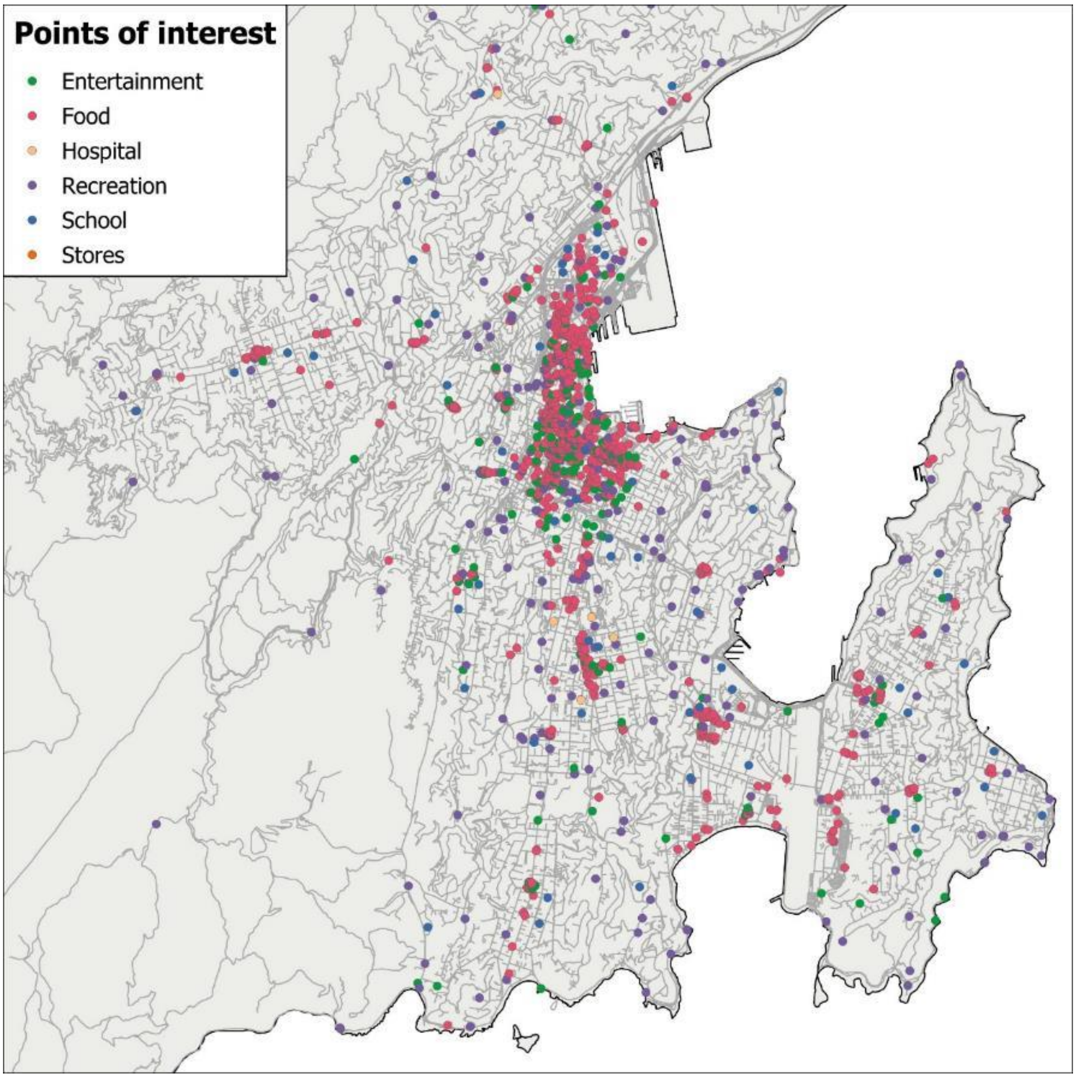
The first step is to allocate the population to be serviced by each (service) station. The population allocated to station j is the weighted sum of the population in the region. A spatial weight wij represents the friction that the population at i faces when reaching station j and is given by a distance decay function so that each station is assumed to service only a segment of the population within a limited geographical range. The level of service of station j per person is the supply at each station (the maximum level of service) divided by the population within the established catchment area.

In the second step, the accessibility of population unit i is calculated as the weighted sum of the level of service of all stations that can be reached from there according to the spatial weights. Using a proportional allocation procedure means that any proportion of the population allocated to a station is never allocated to other stations, and conversely any level of service allocated to a population is never reallocated elsewhere. This property is replicated for any level of aggregation.

5.2.1 Points of interest were collected for each destination type

We collected locations from Overture Maps and identified and categorised locations into entertainment, food, hospital, recreation, schools and stores.[18] The outcome of the analysis for the Wellington urban area is shown in Figure 5.3. For hospital and schools, we used the facilities list from LINZ. For all jobs, industrial and commercial, we used SA1 centroids. To capture the coordinate locations of points of interest, we determine the travel times from SA1 centroids to all points of interest. For each origin point SA1 area, we take the average travel time to all points of interest of each type within each SA1 to reduce the computational intensity in later accessibility analysis. We use the count of points of interest by type within each SA1 as a proxy for service level (employment counts in the case of job opportunities) ensuring that all points of interest are accounted for in measurement of accessibility.

Figure 5.3 Points of interest across Wellington urban area



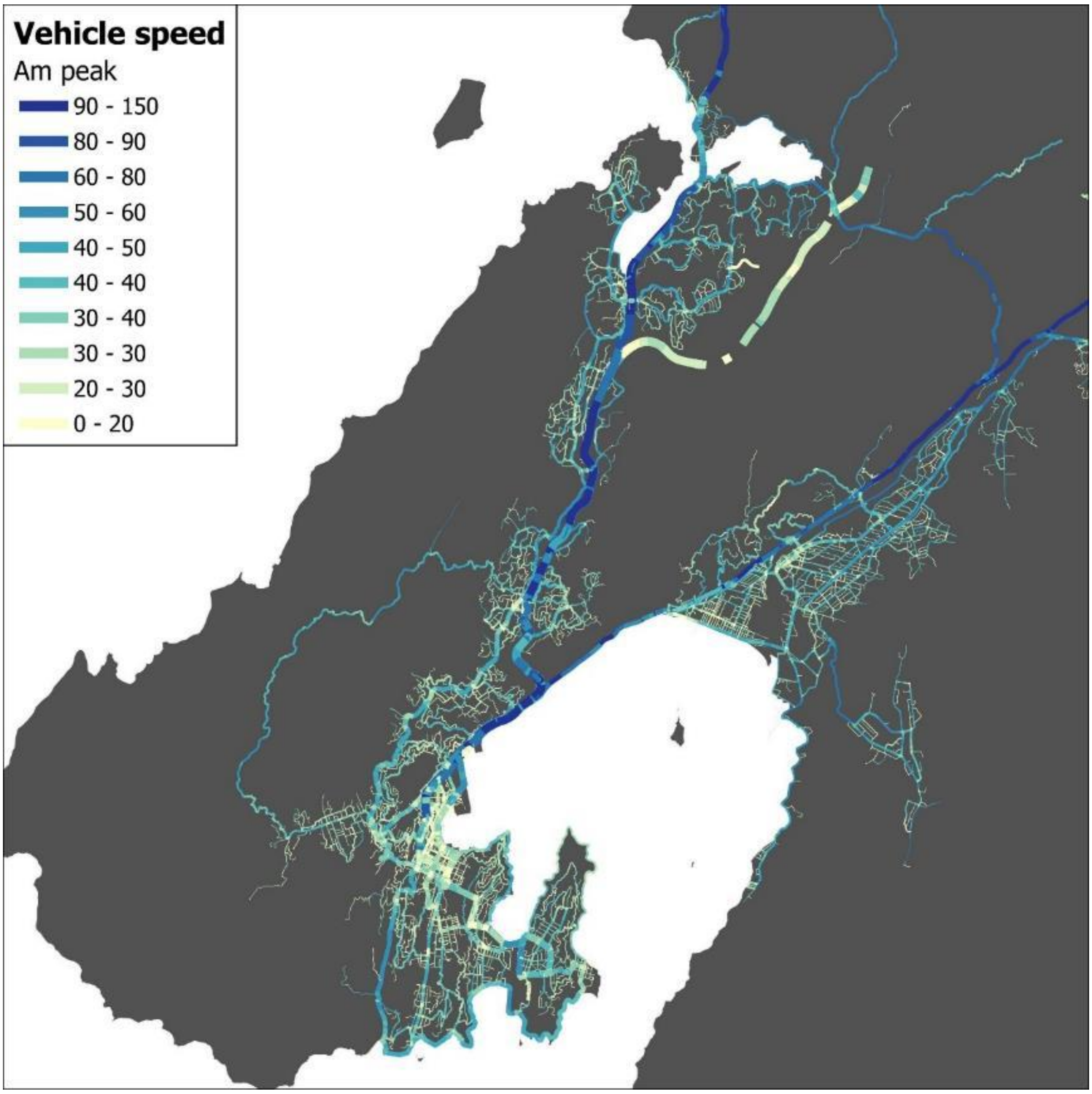
Source: Principal Economics

[18] We manually categorise points based on our best judgement as the Overture dataset lacks a defined set of points of interest categories owing to many of the points of interest being sourced from user-submitted data.

5.2.2 Historical private vehicle travel times collected using TomTom

Our initial plan was to use the TomTom Multinet routable network alongside its historical traffic data for this assessment, aiming to capture realistic travel times across different periods. As we were unable to source the TomTom Multinet routable network, we matched the historical road speeds for light vehicles sourced from TomTom's Traffic Stats API to a routable network created using OSM data.[19] To mitigate for query limits with the TomTom API, we split New Zealand into 26 areas. For each area, we submit the query to API for the average historical travel speeds at different time periods – AM peak, interpeak, PM peak and weekend peak. The historical travel speeds for the entire New Zealand road network, as recorded by TomTom, provided the basis for deriving the driving-based travel matrices used in our accessibility measures. Figure 5.4 illustrates a subset of the matched data we collected, specifically showing vehicle speeds during the AM peak period.

Figure 5.4 Average speed of light passenger vehicles during AM peak hours, Wellington region



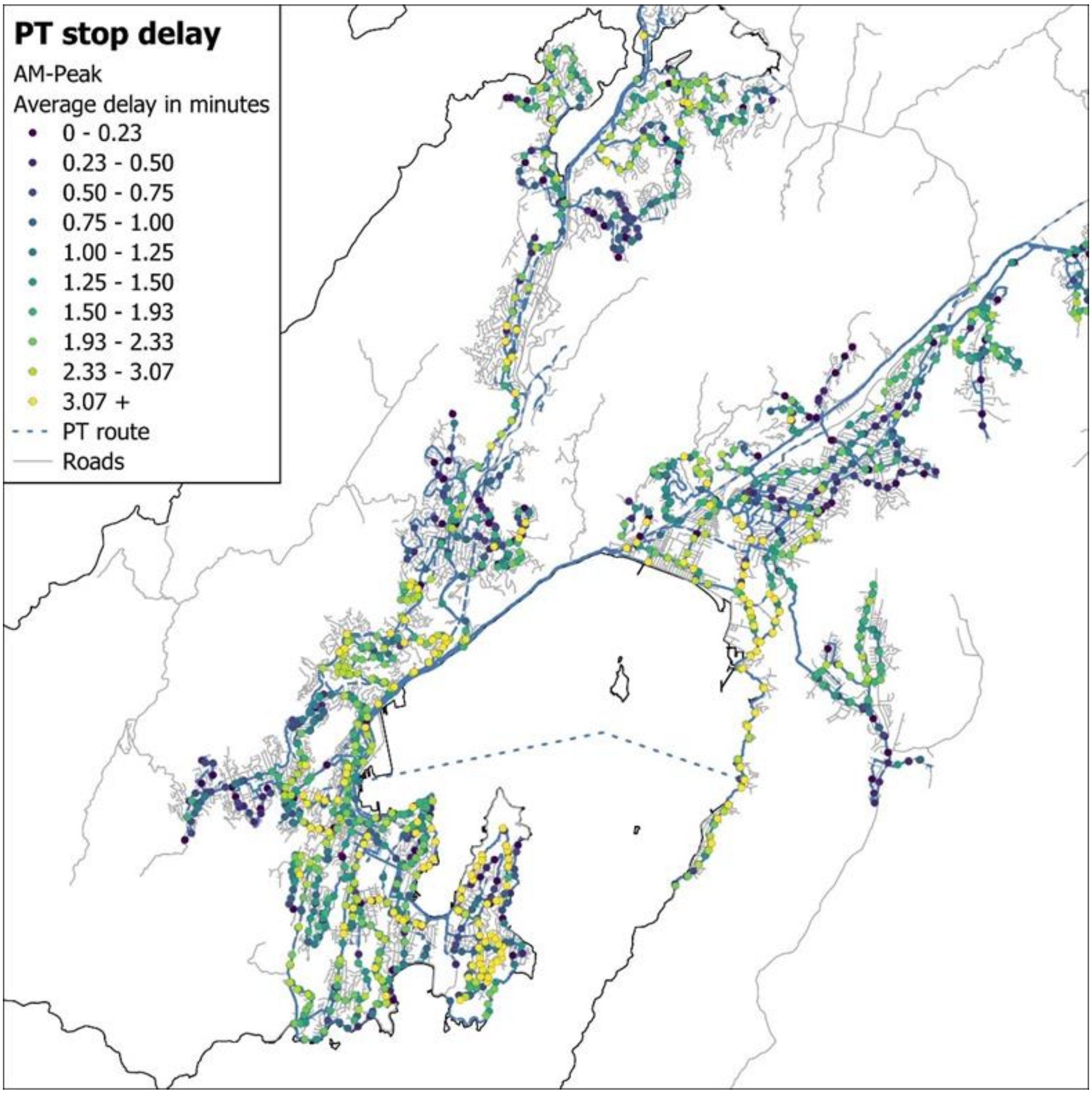
Source: TomTom Move

[19] We find that roading network varies between TomTom and OSM data sources. We use the buffer of the TomTom road centrelines by 5 m and use a spatial one-to-one intersection based on the largest road overlap to join the two datasets.

5.2.3 Historical public transport travel times sourced from GTFS

Following recent studies on the enhancement of scheduled GTFS timetables using collected real-time GPS data, we collect GTFS Realtime for the regions of Auckland, Wellington and Canterbury to account for the variability of scheduled timetables (Liu et al., 2023; Wessel et al., 2017; Wessel & Farber, 2019). We find riders of public transport can experience travel delays of over 3 minutes during a typical AM peak period. We show a subset of the GTFS Realtime data we collected in Figure 5.5. We use the average delays at each public transport stop for each route from collected GTFS Realtime data during a typical day to adjust the existing GTFS static schedules, creating credible schedules that reflect variability during peak hours for each assessment period – AM peak, PM peak, interpeak and weekend peak. The adjusted GTFS schedules are then used as an input for determining travel times on public transport using the R5 routing engine, forming the basis for our public transport accessibility measures.

Figure 5.5 Average stop delay for public transport during AM peak hours, Wellington region



Source: Principal Economics analysis

5.3 Impedance functions constructed using different functions for each mode

5.3.1 Private vehicle

We adapt the generalised cost function from the Auckland Transport Models Project (Sinclair Knight Merz, 2008) as our impedance function for private vehicle travel, including travel time, vehicle operating cost and travel distance in our measurement (Equation 5.1):

$$GC = TIME + \frac{(V * DIST)}{(VOT * 100/60)} \quad \text{(Equation 5.1)}$$

where:

TIME = travel time (minutes)

V = vehicle operating cost parameter (cents/km)

DIST = travel distance (km)

VOT = base value of time ($/hour).

To construct the impedance function for travel using private vehicles, we adjust the travel times derived from Pandana across each dimension by the value of time based on the income levels of households. We use vehicle operating cost factors from the MBCM and value of time based on the income levels of households to derive generalised cost for private vehicle travel across each time period, purpose and demographic dimension.[20]

5.3.2 Public transport

To construct the impedance function for travel using public transport, we derive travel times for each dimension using R5. To account for public transport fare prices, we collect fare prices across SA3 origin-destination for different demographic groups using journey planner APIs for each region. These are then converted to time using the value of time based on the income levels of households to derive generalised cost across each time period, purpose and demographic dimension (Figure 5.2):

$$GC = TIME + \frac{FARE}{(VOT * 100/60)} \quad \text{(Equation 5.2)}$$

5.3.3 Walking and cycling

To construct the impedance function for walking and cycling, we use the results of Liang et al. (2023) as shown in Table 4.2. We attempted collecting information using spatial analysis, which soon proved difficult given the national scope of our report. For example, for calculating sidewalks, we looked into the width of streets and the boundaries of properties but the setback regulation was different for different urban areas across each region. The variables we could derive included walking distance, presence of restaurants and stores, and slope. The lack of information about other attributes means a lower variation in our walking accessibility measures.

[20] We use the vehicle operating cost for an average speed of 60 km/h with a 0% gradient for passenger cars from the MBCM and update the values using the most recent MBCM update factors (NZ Transport Agency Waka Kotahi, 2024a, 2024b).

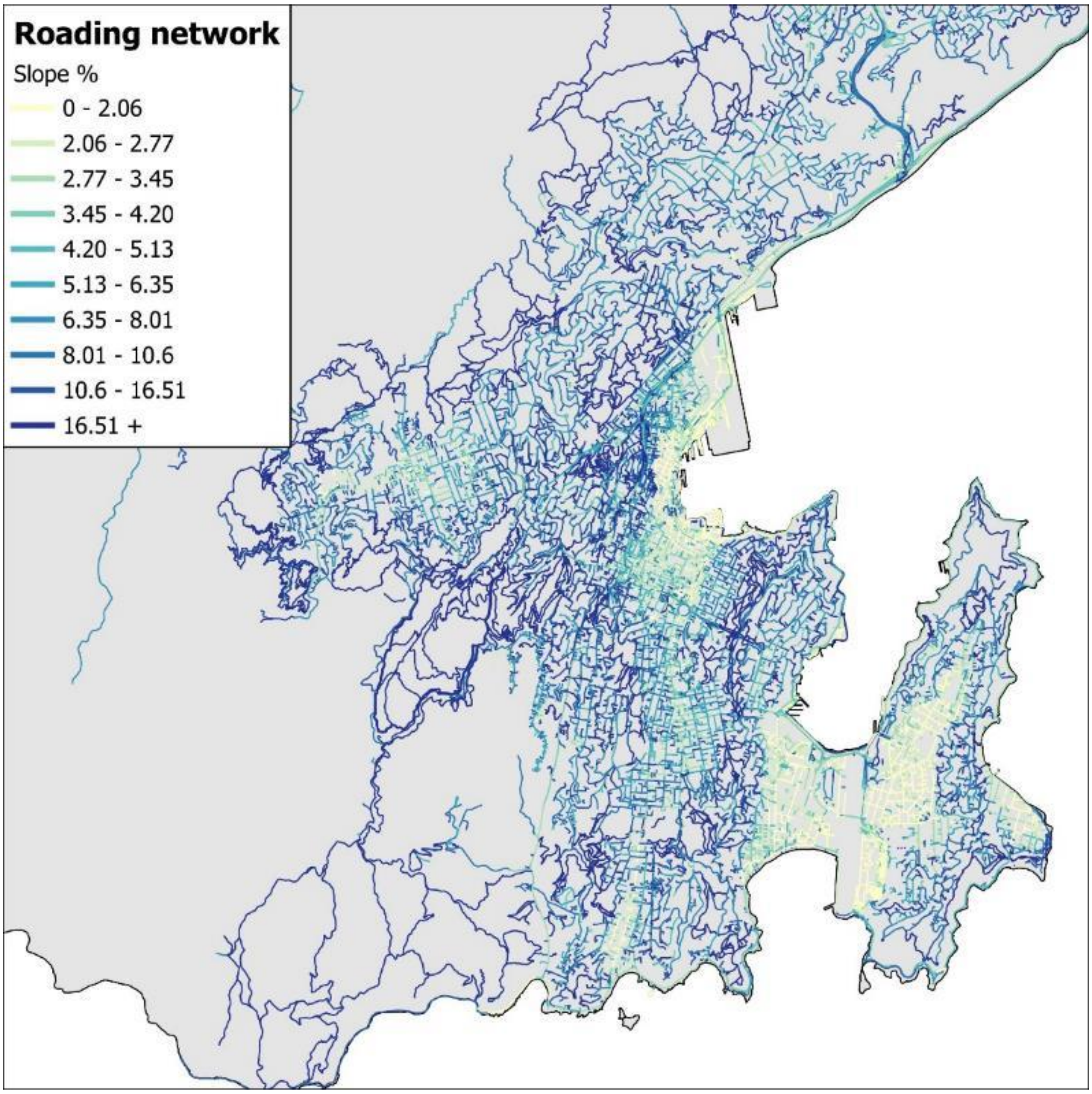
We show the impedance function we use for walking and cycling in Equation 5.3 and Equation 5.4 respectively:

$$Perceived\ distance = DISTANCE\ +\ -23.6 * RETAIL\ +\ 31.82 * SLOPE \qquad \text{(Equation 5.3)}$$

$$Perceived\ distance = DISTANCE\ +\ -6.67 * RETAIL \qquad \text{(Equation 5.4)}$$

For road slope attributes, we use DEM data sourced from LINZ and matched with the OSM routable network to identify paths with slopes <5%. We determine the average slope of roads across its entire length and determine the average. Figure 5.6 shows our results for Wellington City.

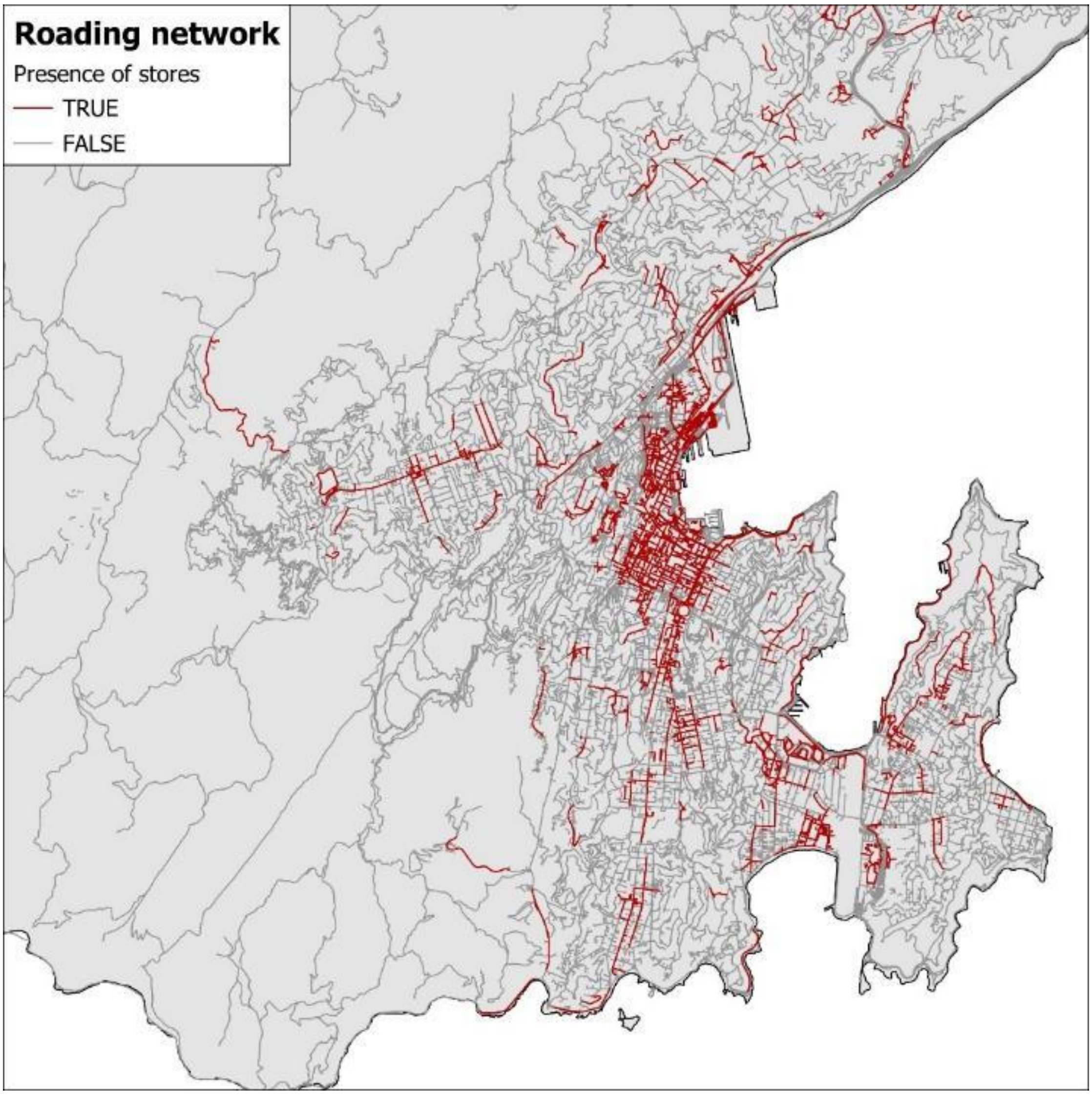
Figure 5.6 Average slope of roads in Wellington City



Source: Principal Economics analysis

Using the points of interest collected for retail activities, we identify path edges within 10 m of a restaurant or store. Figure 5.7 shows the path edges we identify as having retail stores present using the sidewalk distance equivalent values from Liang et al. (2023) to modify the edge distances to use as impedance values for determining travel cost for walking and cycling using the Pandana routing engine.

Figure 5.7 Presence of retail stores in Wellington City



Source: Principal Economics analysis

5.4 Deterrence function constructed using the HTS data

We used the HTS data to calibrate an S-shaped deterrence function to estimate the attractiveness of destinations for different socio-economic groups in various areas.

The HTS provides information on a total of 50,353 observations (obs) for 2019 and 2020 across all regions of New Zealand.[21] For the purpose of our analysis, we categorised the regions into Auckland, Wellington, Canterbury and the rest of New Zealand (RoNZ).

Table 5.1 shows the average travel duration by region.

[21] The number of observations reported after dropping 430 observations that were categorised as 'NA' and 'Other' for travel modes.

Table 5.1 Travel duration by region and mode

Region	Statistics	Mode				
		Cycle	Drive	Public transport	Walk	Total
Auckland	Duration (minutes)	44.53	30.05	70.80	27.76	31.30
	Number of obs	75	6,173	230	670	7,148
Wellington	Duration (minutes)	34.41	26.63	66.53	27.89	28.52
	Number of obs	120	4,303	214	1,055	5,692
Canterbury	Duration (minutes)	30.32	27.13	61.69	32.37	27.97
	Number of obs	164	6,232	66	587	7,049
RoNZ	Duration (minutes)	32.09	24.98	54.90	26.98	25.50
	Number of obs	465	27,143	247	2,579	30,434
Total	Duration (minutes)	33.20	26.16	63.61	27.93	27.01
	Number of obs	824	43,851	757	4,891	50,323

Source: HTS – Principal Economics analysis

For the methodology, we adopt the S-shaped functional form from the literature. For deriving the decay coefficient by mode, purpose and time of travel for different age and income groups across regions, we used regression analysis.

We estimated a log-linear equation (Equation 5.5):

$$\log\left(l_{d,m,p,t}\right) = \alpha_m + \beta.d_{d,m,p,t} + \rho.d_{d,m,p,t}^2 + \gamma.c_{d,m,p,t} + \theta.d_{d,m,p,t} \times c_{d,m,p,t} + \varepsilon_{d,m,p,t}, l_{d,m,p,t} = 1 - t_{d,m,p,t},$$

$$t_{d,m,p,t} = \sum_i t_{i,d,m,p,t} \qquad \text{(Equation 5.5)}$$

$$t_{i,d,m,p,t} = \begin{cases} 1 \; if \; individual \; i \; travelled \; after \; d \; minutes \; (duration) \; using \; mode \; m \\ 0 \; if \; individual \; i \; travelled \; after \; d \; minutes \; (duration) \; using \; other \; m \end{cases}$$

where:

$l_{d,m,p,t}$ = likelihood of travel using mode m for duration d and purpose p at travel time t

α_m = intercept for each mode

$d_{d,m,p,t}$ = the portion of travels continued after d minutes for mode m, purpose p and travel time t – the duration of travel includes both the length of travel and its generalised cost

$c_{d,m,p,t}$ = a vector of control variables, including average household income, average age of observed individuals, season and region

$d_{d,m,p,t} \times c_{d,m,p,t}$ = the interaction between the duration of travel and the control variables

$t_{d,m,p,t}$ = the likelihood of travel at duration d (for mode m, purpose p at time t)

$t_{i,d,m,p,t}$ = the observed travel decision of individual i at duration d (for mode m, purpose p at time t)

$\varepsilon_{d,m,p,t}$ = random error term.

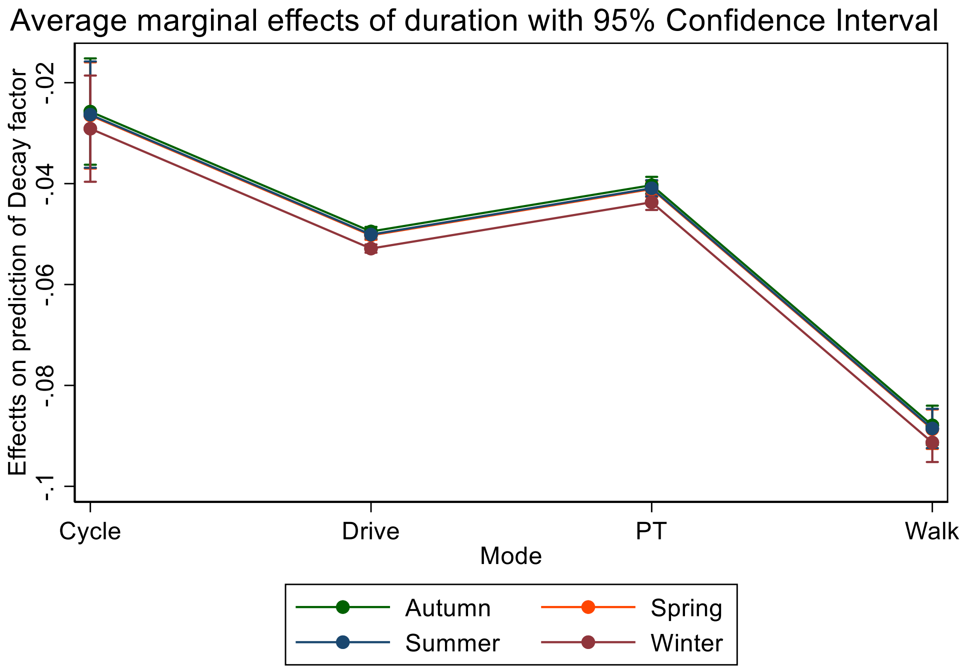
Given the negative exponential distribution of $l_{d,m,p,t}$, the log-linear function is estimated using ordinary least squares. We used the HTS survey weights in our estimations.

The estimated results for the distance decay function are shown in Appendix J.

5.4.1 The impact of season on decay factor was insignificant

We tested the impact of travel season on estimated distance decay. For this analysis, we add a categorical variable for seasons and its interaction with d to Equation 5.5. As shown in Figure 5.8, after controlling for other factors, the difference in distance decay across seasons is statistically insignificant. We lose precision with our estimates due to drop in the number of observations when we included the season variable. The goodness of fit reduced as well. Hence, we decided to exclude season from the analysis.

Figure 5.8 Impact of season on the estimated decay factor



Source: Principal Economics

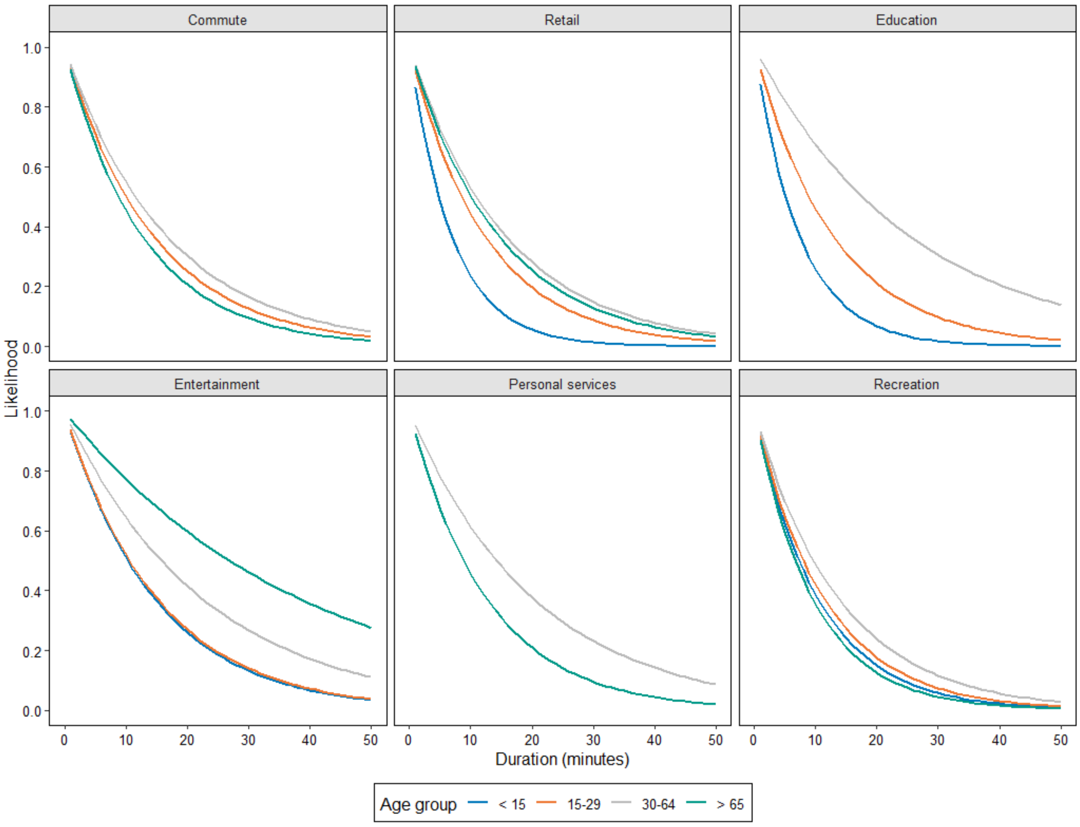
Weather information was used in the distance decay function to control for the impact on likelihood of travel.[22] Addition of rain did not change goodness of fit. We also did not observe any change in the likelihood of travel at different durations so we did not include rain as an additional variable in the final set of equations.

5.4.2 We obtained 800 distance decay curves for each travel purpose

Overall, we estimated 4,800 distance decay regressions to obtain the decay factor disaggregated by travel modes, travel time, income group, age group and destination types. The output by age group is shown in Figure 5.9. An example of decay by travel mode for AM peak for the 30–64 age group is shown in Figure 5.10. We also show an example of distance decay by travel time in Figure 5.11. We present distance decay by destination type and travel time in Appendix J.

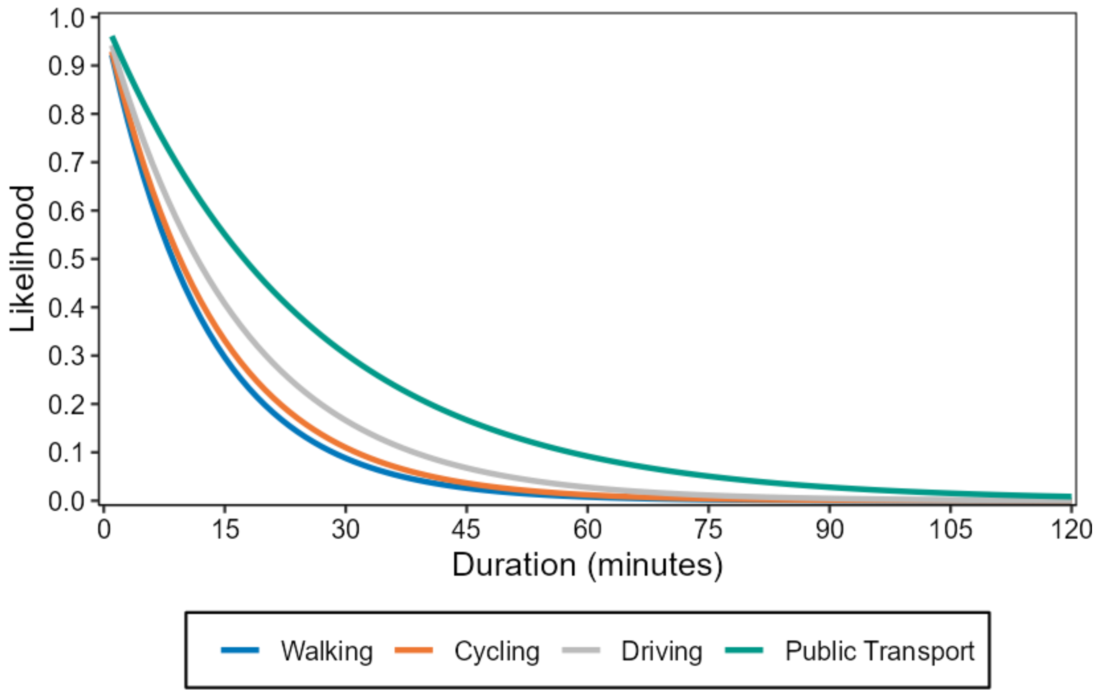
[22] Rain is a dummy variable equal to 1 if the day of travel was rainy. When we reduce the dimension of the analysis to the travel duration level, the considered rain variable is the average of the rain dummy variable, which is interpreted as the likelihood of rain. Similar to other variables, we included rain at the level and as an interaction with the duration of travel. For the definition of the rain variable, we also consider rainfall greater than 1 mm and rainfall as a continuous variable. The results of the dummy variable defined as 1 mm or greater rainfall led to a lower statistical significance compared to the first dummy variable (of 0 mm or greater rainfall considered as rainy). The results of analysis using a continuous rainfall variable led to improved statistical significance of the rain variable but goodness of fit was unchanged.

Figure 5.9 Deterrence function across destination types by age group



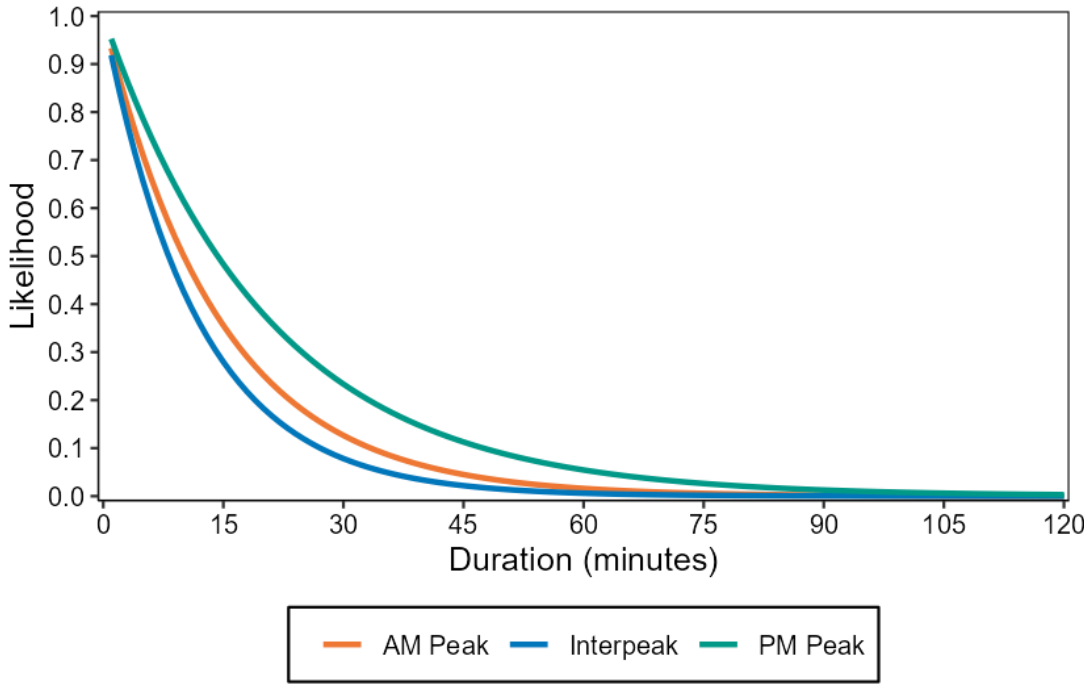
Source: Principal Economics

Figure 5.10 Distance decay by travel mode for the 30–64 age group driving during the AM peak



Source: Principal Economics

Figure 5.11 Distance decay by travel time for the 15–29 age group commuting to work



Source: Principal Economics

5.5 2,904 multi-dimensional measures of accessibility constructed

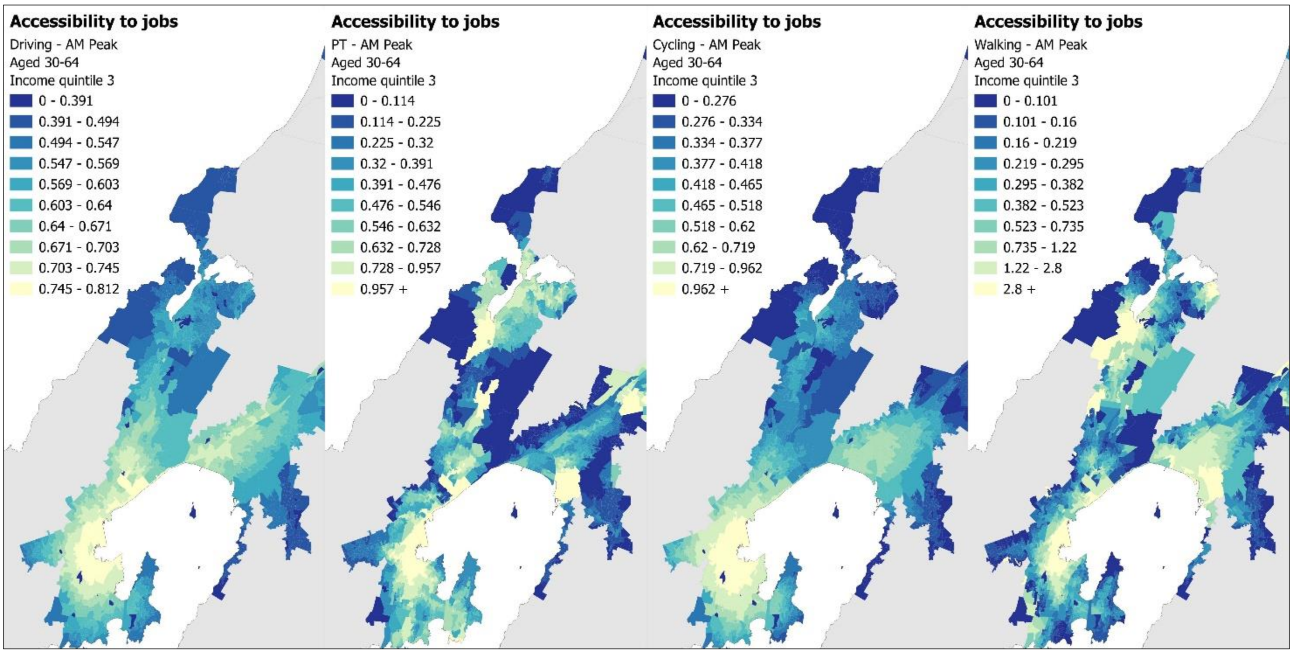
We used all the available dimensions, including nine travel destinations, four travel times, four travel modes, five age groups and five personal income quintiles to derive 2,880 accessibility measures for each region. We also considered 19 aggregated measures of access, including access by mode, by time, by age group and by income deciles. We constructed five combined measures of access using principal component analysis (PCA) for each mode and for all accessibility measures. This led us to a total of 2,904 measures for each region.

Figure 5.12 and Figure 5.13 show examples of the accessibility measures for access to jobs for different travel modes for the working-age group and the median (personal) income at AM peak and for driving accessibility across different purposes for the 15–64 age group and median income group at AM peak.

The current figures show static access levels – they do not measure a change in access as is usually done for evaluations. The measures presented in Figure 5.12 and Figure 5.13 are useful for understanding the relative access of suburbs for the specific mode. For example, based on Figure 5.12, the accessibility measures suggest a significantly worse public transport access for Lower Hutt compared to driving. In comparison with other suburbs of Wellington during AM peak time, central Porirua has a high public transport access but relatively less car access.

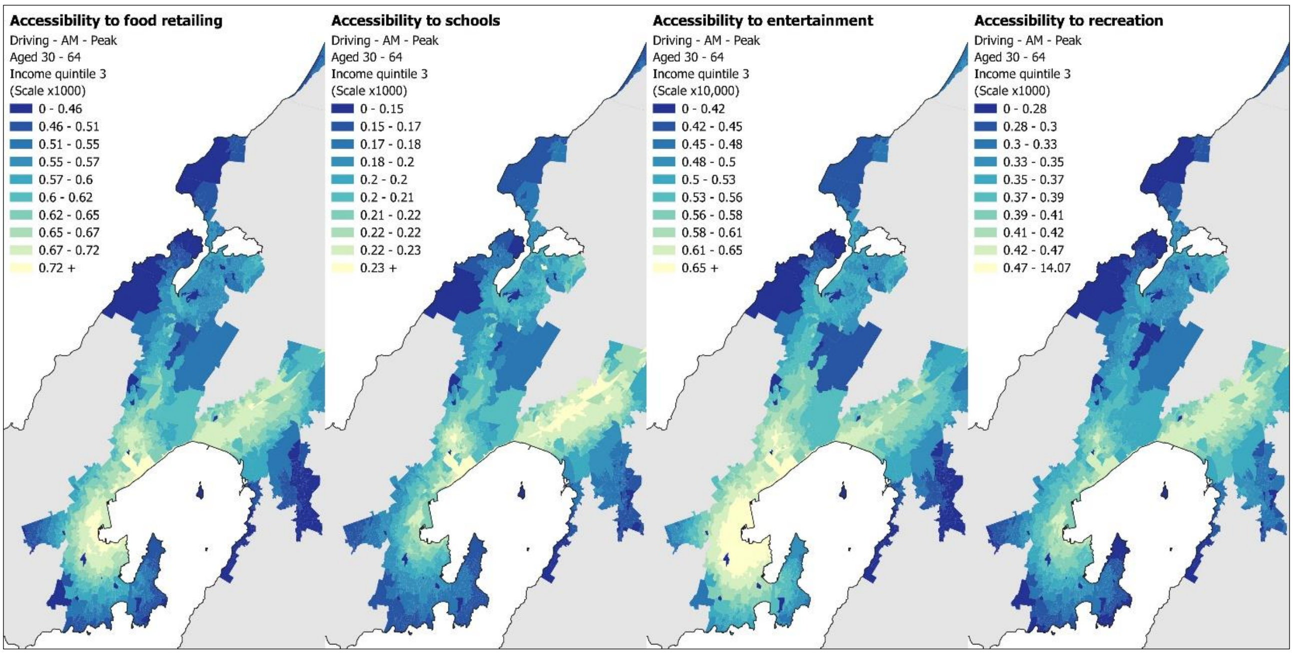
While certain areas seem to have an overall level of access advantage (or disadvantage), there are certainly variations in access for different modes, destination types and travel purposes. This highlights the need for disaggregation of accessibility measures for the dimensions of access identified in this report (and not only relying on aggregate accessibility measures).

Figure 5.12 Job accessibility by travel mode in Wellington



Source: Principal Economics

Figure 5.13 Driving accessibility by travel purposes in Wellington[23]



Source: Principal Economics

[23] As the numbers of entertainment services are low relative to the population, we increase the accessibility ratio by a factor of x1,000 for the purpose of illustration.

5.6 We developed an accessibility measurement toolkit

Measurement of accessibility requires bringing together various sources of data and tailoring them to construct the accessibility functions and, eventually, the measures of accessibility. As described in our report, we have over 2,500 measures of accessibility for each region. To apply these for various projects and appraisals/evaluations, users may require adjusting the factors of accessibility. Hence, we have appended a toolkit for accessibility measurement. Users will need to have proficiency in R language for using the toolkit. Appendix K provides a high-level description of the toolkit.

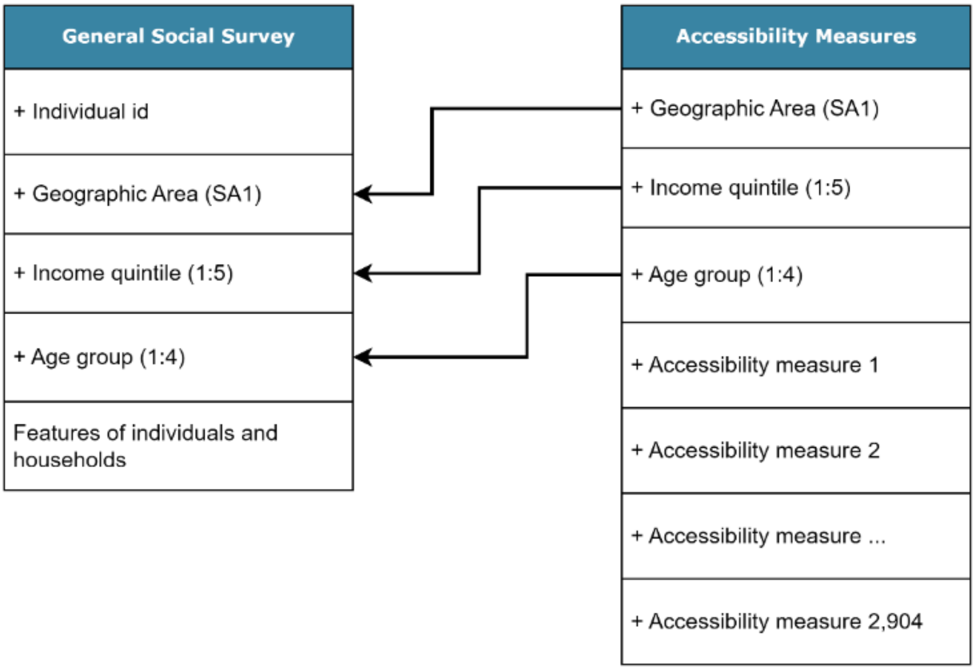
6 Selected measures of accessibility

An important objective of this report is to identify the best (or most suitable) measure (or measures) of accessibility. Given the multifaceted concept of access, the most useful accessibility measure needs to explain the welfare of New Zealanders above and beyond the impact of other features of households and their living environment. We used all the constructed accessibility measures in a regression analysis to explain the welfare of residents after controlling for other factors. This chapter presents our findings.

6.1 Methodology for estimating impacts and dollar values

As shown in Figure 6.1, the GSS was merged with the accessibility measures based on the SA1 codes, the respondents' age group and the household income quintiles. We allocated accessibility measures for the <15 age group to households with children. Using this data structure is critical for future replication of variables.

Figure 6.1 Merging the GSS with the accessibility dataset



To estimate the impact of accessibility measures, we use Equation 6.1:

$$u_i = \theta + \beta . a_i + \rho . h_i + \gamma . c_i + \varepsilon_i \quad \text{(Equation 6.1)}$$

where:

u_i = the utility of individual i (measured using life satisfaction)

θ = intercept

a_i = the normalised measure of access

h_i = household income brackets (dummy variables)

c_i = a vector of control variables (described in the text)

ε_i = the random error term.

The output is originally a categorical variable. However, the literature suggests that life satisfaction could be considered as a cardinal variable and the results will not change significantly compared to the case of using the categorical variable.[24] We used GSS 2016, 2018 and 2021 (pooled cross-section). We use an ordinary least squares regression together with the available jackknife weights for the estimation.[25] For a total observation of 16,380 individuals available across 2016–2021 GSS waves for Auckland and Wellington, the population size represented is 10,839,489.

The confounding factors controlled for include individual sex, age group, household composition, household tenure, a measure of belonging to their neighbourhood (share of their ethnicity in their suburb), their health status, the safety of their neighbourhood and the conditions of their dwelling (number of bedrooms, having issues with temperature, dampness and condition of their dwelling) and the location of individuals across the functional urban areas.

We used the goodness of fit measures (R squared) to identify the explanatory power of the accessibility measures for the output – in our case, life satisfaction.[26] For the choice of output, we suggest considering alternative choices in the future. At the time of this study, there were significant changes in the GSS over time, which did not provide us with a wider range of useful welfare measures. In the past waves, the GSS provided a useful measure of satisfaction with access to amenities and facilities, but this measure has changed across various recent waves of the GSS.

To identify the variation of impacts of accessibility measures by socio-economic features, we interact the accessibility measures with income, age and income variables and test the statistical significance of the difference between the impacts across those features. If the impacts vary across socio-economic groups, we report the variation. It is likely the impacts do not vary across the socio-economic groups due to the endogeneity of access concerning location choice factors. While this is an important factor, we do not further investigate this in the current research project and suggest that as a topic for future research.

There are two common methods for inferring the dollar value of access using the wellbeing equation. First is based on Clark and Oswald (2002) using the relative weight of the identified accessibility measure to the weight of the income variable in the estimated welfare equation. Accordingly, the dollar value of access is equal to:

$$\partial I_i / \partial a_i = \frac{\partial u_i / \partial a_i}{\partial u_i / \partial h_i} = \hat{\rho} / \hat{\alpha}$$

The alternative approach is based on Fujiwara (2013) to estimate the compensating surplus or equivalent surplus of each non-market outcome using compensating surplus for welfare gains and equivalent surplus for welfare losses as this yields the most conservative estimate for each outcome.

We first estimate the impact of the log-transformation of income (in function f(M)) and then add access to the same equation and estimate that (function g(M)). Using the marginal values, the compensating surplus is equal to:

$$f(M) = u_i = \theta + \gamma . \ln(\mathrm{h}_i) + \gamma . c_i + \varepsilon_i$$
$$g(Q) = u_i = \theta + \beta . a_i + \gamma . \ln(\mathrm{h}_i) + \gamma . c_i + \varepsilon_i$$

[24] Ferrer-i-Carbonell and Frijters (2004) test the impact of treating life satisfaction data as cardinal and as ordinal in regression analyses and find no important effects. This is commonly taken as evidence that life satisfaction data can be used as if it were cardinal.

[25] The GSS provides us with replicate weights produced by the delete-a-group jackknife method (Kott, 2001). In the dataset, 100 groups are derived by using primary sampling units that are randomly sorted into each stratum. This strategy results in 100 replicate samples, in each of which one of the groups is omitted and weights are adjusted accordingly. Using these weights leads to estimates that tend asymptotically to true values (Torshizian, 2017, p. 138).

[26] Life satisfaction is on a scale of 1–10, where 0 is completely dissatisfied and 10 is completely satisfied.

Following Fujiwara's third-stage transformation, we estimate the compensating surplus (CS) or equivalent (ES) surplus of the (positive) non-market outcome using compensating surplus for willingness to pay (WTP), which is the value users are willing to pay for the positive change, and equivalent surplus for willingness to accept (WTA), which is the value accepted to pay to forego the positive change. For welfare gains (losses), WTA is greater (smaller) than WTP.[27] The CS (WTP) and ES (WTA) are estimated using:

$$CS = M^0 - e^{\left[\ln(M^0) - \frac{\widehat{g_a}}{\widehat{f_M}}\right]}$$
$$ES = M^0 - e^{\left[\frac{\widehat{g_a}}{\widehat{f_M}} + \ln(M^0)\right]} \qquad \text{(Equation 6.2)}$$

where, $\ln(h_i)$ is the log transformation of the equivalised household income,[28] u_i is the utility of individual i, M^0 is the median income, $\widehat{f_M}$ is the marginal wellbeing value of income and $\widehat{g_a}$ is the marginal wellbeing value of the non-market (accessibility) outcome. The other variables are the same as explained in Equation 6.1.

This methodology provides us with the estimated dollar value of an accessibility measure. To understand the impact of combined access, we need a gauge of the total value of access. This measure is constructed using PCA and the first principal component score.[29] All accessibility measures contribute to the total value of access. Hence, we fit Equation 6.1, including the (normalised) overall principal component measure and (normalised) principal component measures for each travel purpose. We test the joint significance of all accessibility measures using a Wald test. The most comprehensive combination of accessibility measures will be chosen for our evaluation of the dollar value of access for each purpose. To derive each measure's access value, we drop that specific measure from the equation and measure the impact on the estimated value of total access (PCA_all). We convert that to a dollar value using Fujiwara's methodology described above.

It is important to note that our methodology, while robust, does not provide causal inferences about the impact of accessibility measures. Given the wide range of factors considered in accessibility measurement and the dynamic nature of the built environment, reaching causal inference requires substantial additional work (if possible at all). We suggest a useful approach is to test for the robustness of the estimated impacts after controlling for interrelated (third) factors. In any case, we suggest that the current approach to valuing access is significantly more evidence-based than a mobility-based measure or accessibility measures without linkage to welfare.

6.1.1 For choice of accessibility measures, we focus on Auckland and Wellington

Based on a forthcoming NZTA report investigating climate change interventions to reduce land transport greenhouse gas emissions, travel patterns and mode choice significantly differ between Auckland and Wellington. These distinct travel features will improve the usefulness (and appropriateness) of the selected accessibility measure(s). We used regression analysis to control for the confounding factors, including a variable to control for regional impacts.

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[27] The concept of loss aversion, which may explain the WTP-WTA disparity for a particular good, would be evident in this framework if the removal of a non-market good had a greater absolute effect on welfare than its addition.

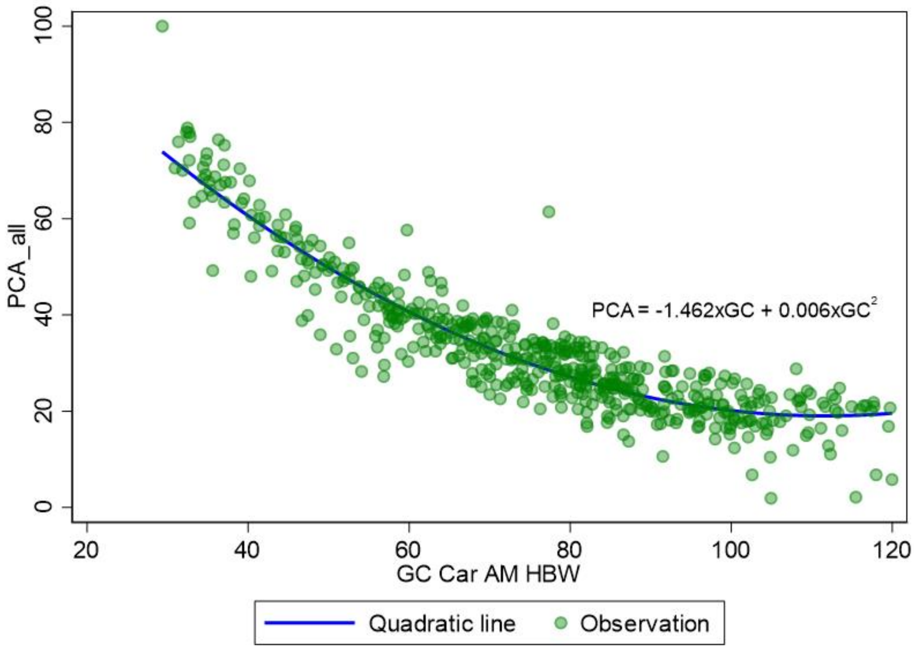
[28] We equivalise the unadjusted GSS measure of household income using the square root of household size to account for the impact of household economies in consumption as household size increases.

[29] Principal component analysis is commonly used to reduce the dimensions of data by projecting it onto lines drawn through the data, starting with the line that goes through the data in the direction of the greatest variance. Technically, this is calculated by looking at the eigenvectors of the covariance matrix. The first principal component is considered as the component with the highest signal-to-noise ratio – it captures most of the useful information for the common aspect of the considered variables, which in this case is access.

6.1.2 Accessibility and generalised cost

The conventional way of measuring travel burden is through cost and distance, which ultimately are used to construct generalised costs (by mode, destination and travel time). Any attempt to identify the correlation between the conventional single-dimensional measures and the multi-dimensional accessibility measures is inaccurate. To provide an example, we looked at the relationship between generalised cost of home base work (HBW) for those aged 30–65 years using light vehicle travel to the CBD and the aggregated accessibility measure (PCA_all) as shown in Figure 6.2. The observations are Auckland's Macro Strategic Model (MSM) zones. Accordingly, after considering the non-linearity of the relationship, PCA decreases by 0.49% with a 1-minute increase in generalised cost. After we test this relationship by adding more generalised cost variables, the considered measures will be statistically insignificant. Given the inaccuracy associated with this analysis, we do not pursue it further.

Figure 6.2 Relationship between PCA_all and generalised cost car AM peak HBW across MSM zones



Source: Principal Economics analysis

6.2 Regression results identified access to school as the most relevant single measure of access followed by public transport access to entertainment during PM

It is not feasible or useful to report the regression results for all estimations. The usefulness of measures is identified based on their goodness of fit, correct sign of their estimated impact in the welfare function and the statistical significance (at 90% or better confidence level). Accordingly, in terms of their alignment with welfare (of Auckland and Wellington residents), the best correlates of accessibility are listed in Table 6.1.

The accessibility measure with the highest explanatory power for life satisfaction was the combined modes and times measure for accessing school. The other measures that are not listed in the table are statistically insignificant. This is most likely due to the multi-dimensionality of access, which requires considering a range of accessibility measures. It is not feasible for our research project to identify all possible combinations of the wide range of accessibility measures constructed and test them in this welfare analysis. In the next section, we try to provide the most useful combination of accessibility measures for the purpose of appraisal.

Table 6.1 provides information about the WTP and WTA dollar value estimated for the best correlate. For the combined school measure, the WTP is $6,402 and the WTA is $9,290. These individual measure value estimates will likely change once we control for other dimensions of access in the next section.

Table 6.1 Preferred measures of access for different purposes

Destination type	Best correlate	2nd best	3rd rank	$ value of best correlate using GSS coefficients	
				WTP	WTA
School	Combined measure (PCA_School)	Public transport, PM	Public transport, AM	$6,402	$9,290
Entertainment	Public transport, PM	Public transport, AM		$10,041	$19,599

Source: Principal Economics analysis

6.3 Value of an improvement in overall accessibility is $14,266 per year per household

We then estimated the value of access for the identified combination of measures. For this purpose, we converted the categorical income variable to a continuous variable (using the average value of each income band) and then used the Reserve Bank CPI to derive the 2023 dollar value. For the methodology, we followed Fujiwara's (2013) approach. All the accessibility measures are normalised for this analysis. The output provides dollar value of access for the identified purposes as perceived by the communities of Auckland and Wellington. This led to the estimated dollar value of access as shown in Table 6.2. We provide estimates of WTA and WTP using our estimated coefficient of income using GSS as well as using the income coefficient from Fujiwara (2013).[30]

Table 6.2 Dollar value of 1% increase in normalised aggregated accessibility measures – 2023 real prices

Measure (mode, purpose, time)	GSS coefficient		Fujiwara coefficient	
	$ WTP	$ WTA	$ WTP	$ WTA
Education	$974	$8,944	$482	$761
Retail	$1,178	$8,076	$520	$771
School	$1,878	$9,075	$720	$995
Other	$283	$1,087	$99	$130
Industry	$128	$475	$44	$58
Food	$7,090	$15,637	$1,973	$2,322
Health	$1,033	$1,452	$289	$306
Recreation	$165	$272	-	$3
All industries	$1,430	$1,537	$302	$307
Total	$14,266	$46,448	$4,434	$5,648

Source: Principal Economics analysis

30 The larger magnitude of the GSS income coefficient was also observed in previous studies (Smith & Davies, 2020).

While this could be considered as a range estimate, we suggest that our estimate is more relevant to the latest available evidence on the value of access. For example, Mann and Levinson's (2024) results using a hedonic price approach suggest that land values per square metre increase by 0.205–0.223% per 1% increase in access to jobs. In Auckland, the 2020/21 price of land was around $1,300 per square metre, equal to $650,000 for a 500 square metre residential section. That implies a value of $1,332 and $1,449. Our most relevant measure for access to jobs is access to all industries, which is valued between $1,430 and $1,537 using the GSS income coefficient and between $302 and $307 using Fujiwara's income coefficient. Hence, we suggest our estimates using GSS provide sensible estimates of access value. It is also interesting to see the close estimates of the value of access to jobs in comparison to Mann and Levinson's estimates given the significant methodological difference – our methodology is based on unrevealed preference using life satisfaction as the output while Mann and Levinson use revealed preference methodology by considering land values as the output.

Accordingly, the dollar value column shows the 2023 dollar value for a unit change in the combined accessibility measure. Accordingly, the overall value of access is between $14,266 (WTP) and $46,448 (WTA) per household per annum. The WTP consists of the value of access to food retail ($15,637), school ($9,075), education ($8,944), retail ($8,076) and so on. It should be noted that a change in overall accessibility is practically a significant improvement in transport and land use. The values for improvement in other measures of access are illustrated in Table 6.2. The measures of access are included such that they are jointly significant at the 90% confidence level (and hence access to the office is not included as an additional variable).

We then tested the usefulness of common cumulative accessibility measures, particularly the number of jobs accessible within 30 minutes of driving and 45 minutes of travel using public transport during the AM peak. We first added each and both of these measures to the equations that we used above, excluding the other accessibility measures. The results indicated that the impact of these measures on welfare is equal to zero – – statistically insignificant. Then we added the PCA measures to test the mutual impact of our aggregated measures of multi-dimensional access and the cumulative accessibility measures. The results showed that the cumulative accessibility measures are still statistically insignificant and their addition did not change the sign and the joint statistical significance of the PCA measures.[31] Hence, we conclude that our PCA measures provide a robust estimate of the value of access (and the cumulative accessibility measures, while they might be a useful administrative tool, do not relate to social welfare).

6.4 Disaggregation of values by income quintiles

We then applied the same method for the estimation of WTP and WTA of different income quintiles. We first tested the variation in the estimated impact of PCA measures across (adjusted) income quintiles. The results showed that the parameters do not change.[32] This is likely due to the endogeneity of access concerning social norms that leads to a spatial welfare equilibrium. We recommend that a future study further explores this. Then we simply replaced the M^0 in Equation 6.2 with the median income of each (adjusted) income quintile.

[31] The cumulative measures might still be relevant if we added other cumulative measures and looked at their joint statistical significance. Hence, we suggest that using these two conventional measures to inform policy may still be useful, but we certainly know that it is not enough to explain welfare. This is particularly because access is multi-dimensional and planning for one dimension leads to biased outcomes.

[32] The parameters measure the impact of access on welfare. However, with the impact of access on welfare unchanged, the ability to pay still varies across income quintiles. For example, if we say that impact of access on welfare is 20%, the WTP for that 20% is higher for Q5 compared to Q1.

Table 6.3 Dollar value of 1% increase in normalised aggregated accessibility measures to different income quintiles – 2023 real prices using GSS income impact estimate

Measure (mode, purpose, time)	WTP					WTA				
	Q1	Q2	Q3	Q4	Q5	Q1	Q2	Q3	Q4	Q5
Education	$186	$369	$525	$871	$2,036	$1,711	$3,389	$4,821	$8,002	$18,700
Retail	$226	$447	$635	$1,010	$2,463	$1,545	$3,061	$4,353	$7,226	$16,886
School	$359	$712	$1,013	$1,726	$3,929	$1,736	$3,440	$4,893	$8,119	$18,977
Other	$54	$107	$152	$252	$590	$207	$411	$585	$972	$2,271
Industry	$25	$49	$69	$115	$268	$91	$180	$256	$425	$993
Food	$1,065	$2,111	$3,003	$4,983	$14,585	$1,065	$5,393	$7,671	$12,732	$29,754
Health	$291	$575	$828	$1,365	$274	$3,209	$534	$759	$1,259	$2,979
Recreation	$3	$7	-	$10	-	$4	$8	$12	$20	$11
All industries	$520	$1,030	$1,465	$2,432	$5,684	$599	$1,187	$1,688	$2,802	$6,548
Total	$2,729	$5,407	$7,690	$12,764	$29,829	$10,167	$17,603	$25,038	$41,557	$97,119

Source: Principal Economics analysis

Table 6.4 Dollar value of 1% increase in normalised aggregated accessibility measures to different income quintiles – 2023 real prices using Fujiwara's income impact estimate

Measure (mode, purpose, time)	WTP					WTA				
	Q1	Q2	Q3	Q4	Q5	Q1	Q2	Q3	Q4	Q5
Education	$92	$183	$260	$431	$1,000	$145	$288	$409	$680	$1,590
Retail	$100	$197	$280	$465	$1,362	$148	$292	$416	$690	$1,612
School	$138	$273	$388	$644	$1,506	$190	$377	$537	$891	$2,081
Other	$18	$37	$53	$89	$1,067	$25	$50	$70	$116	$273
Industry	$9	$17	$24	$39	$121	$11	$22	$31	$52	$121
Food	$319	$633	$901	$1,495	$2,825	$387	$767	$1,091	$1,811	$4,221
Health	$58	$115	$163	$271	$533	$57	$112	$160	$266	$632
Recreation	$1	$1	$2	$3	$108	$1	$2	$3	$4	-
All industries	$113	$224	$318	$528	$1,134	$116	$230	$327	$543	$1,279
Total	$848	$1,680	$2,389	$3,965	$9,656	$1,080	$2,140	$3,044	$5,053	$11,809

Source: Principal Economics analysis

7 How the outputs of this research can be accessed and used

As described in our report, we have over 2,900 measures of accessibility for each region. To apply these for various projects and appraisals/evaluations, users may require adjusting the factors of accessibility. Hence, we have appended a toolkit for accessibility measurement. Users will need to have proficiency in R language for using the toolkit. Appendix K provides a high-level description of the toolkit.

We recommend using the constructed measures to disaggregate impacts for different socio-economic groups. For calculating the dollar value, the socio-economic outputs should be summed up at the purpose, mode and time level and multiplied by the value of accessibility measures estimated in the previous chapter. It is critical to use the same normalised accessibility measures for the evaluations. For appraisal, as described in our parallel work on alternative appraisal methodology, it is critical to use the same data structure shown in Figure 6.1 to construct the aggregate measures by using the first principal component scores.

It is important to note that Torshizian et al. (in publication) suggest using the WTP values for the purpose of appraisal because the change in access caused by an investment shows the potential for improvement (and is usually not about a loss). The negative access impacts are indicative of the potential for improvement in serviceability levels. WTA is still useful for special circumstances such as climate catastrophes leading to road redundancies.

8 Further discussion and future research

Accessibility is at the core of urban economics. Technically, the access level is crucial to consider in any hedonic price model. The available literature uses a range of distance measures to control the access features of land to various locations, including town centres, employment hubs and a range of amenities and facilities. We suggest multi-dimensional accessibility measures offer a more nuanced approach for measuring the accessibility concept as (should be) considered by policy makers and communities, accounting for all aspects of access such as availability of services (and level of service), time of travel, travel duration (traffic) and other features that should be considered. Hence, we suggest a future research project investigates the relationship between the constructed accessibility measures and land values.

The role of accessibility in agglomeration economies – a concept central to economic theory – is not as clearly understood as needed. Agglomeration economies refer to the benefits firms and individuals obtain by locating near each other (in spatial and industrial clusters). The impact of digital accessibility on these economies is still evolving. The emerging 'science of cities' suggests that these economies scale with city growth, primarily due to increased social and physical network interactions. However, the explicit demonstration of these effects remains underdeveloped. We suggest the main reason for the lack of evidence in this space is the underdeveloped accessibility measurement, which is now addressed in this report.[33] Hence, we suggest using our identified accessibility measures and further investigating the relationship between access and land values in a future study. That study also needs to consider the impact of digital accessibility.

We suggest further research into the impact of reliance on cars on accessibility in New Zealand. While the literature mostly agrees that increased accessibility is associated with less car usage, a few recent articles discuss that reliance on the motor vehicle in US cities mostly leads to greater accessibility compared to European cities (The Economist, 2023).[34]

Public transport patronage and private vehicle driving were subject to significant changes during and after the COVID-19 pandemic. Since the data used for public transport and driving is live data, the vehicle kilometres travelled and public transport patronage may already have bounced back – as is evident from the national data. However, the results may still be affected by the aftermath of COVID-19 if we are not yet back to the equilibrium.

A significant range of outputs could be further produced from our welfare analysis:

- Further investigation of the interaction between accessibility measures. This will be particularly useful to inform policy intervention and appraisal for areas with high/low access level for specific purposes and identify the low-hanging fruit (with highest return on investment).
- Consideration of factors of location choice and other third-factor impacts on the relationship between accessibility measures and the output (life satisfaction).
- For the choice of the output, we suggest considering alternative choices in the future. At the time of this study, there were significant changes in the GSS over time, which did not provide us with a wider range of useful measures of welfare. In the past waves, GSS provided a useful measure of satisfaction with access to amenities and facilities but this has changed across various recent waves of the GSS.

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[33] The literature on the impact of accessibility on agglomeration benefits is mixed. There are studies showing that employment density is the main driver of agglomeration benefits and not access as measured in land transport (Melo et al., 2017). However, measures considered in these studies are usually only based on distance to employment centres.

[34] The article is titled "In praise of America's car addiction: How vehicle dependence makes the country fairer and more efficient".

To improve accessibility measurement and its usefulness, we suggest the following:

- With the increase in working from home and uptake of various technologies, there has been a change in the way that access has been considered by population groups. It is critical to investigate further the integration between virtual and physical accessibilities using STP in a future study.[35]
- Collect real-time GTFS for other regions. We used real-time GTFS for Auckland and Wellington. For Canterbury, the real-time GTFS was not used as information for arrival delays seemed unusual (with no delays identified).
- Develop a behavioural survey of walking and cycling to inform logsum analysis and impedance function. This could improve our analysis of cycling and further consider the increased role of ebikes – not only are they faster than conventional bikes but, more importantly, they flatten out a city so that hilliness is no longer an issue for ebike riders. This will likely have important implications for the distance decay function considered in our study, which considers slope as a negative factor for the likelihood of cycling.
- For walking, we used the available information from the OSM data and spatial data. Given the broad scope of our report (at the national level), it proved difficult to collect information on other attributes that contribute to walking access such as sidewalk width. While OSM has included fields for these attributes, there is no information included in those fields. We suggest that practitioners could calculate and update accessibility measures for smaller areas – particularly for urban areas.
- For cycling, we used the OSM data and other information available from spatial layers. While we could not fit within the time and budget of this project, we identified other data sources available from council data to complement this information and present that in a table in Appendix H.3. We suggest that practitioners use these data sources in the construction of their accessibility measures.
- In our analysis of distance decay, we have not controlled for chained trips. The HTS provides the required information. This could further be incorporated into distance decay analysis in a future study.
- Further disaggregation of points of interest according to demographics for better matching of destinations that are relevant to life stages. This needs to further investigate that points of interest for a child are different to points of interest for adults or pensioners.

[35] Virtual accessibility is particularly important for future network analysis since changes in virtual accessibility could have major implications for future demand for transport accessibility. As one example, doctor’s consultations are now often conducted via the internet, especially for people who have transport accessibility issues such as people who have mobility issues or who are contagious.

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Appendix A: Meaning of accessibility

Transport accessibility has different components such as individual, land use, transport modes and its temporal and spatial distribution, and liberal understanding emphasises different aspects of accessibility:

- **Utilitarianism:** Formulated by philosophers such as Jeremy Bentham (1988) and John Stuart Mill (1967), this consequentialist theory seeks to maximise society's overall happiness or wellbeing. Utilitarianism defines accessibility as the extent to which resources and opportunities are distributed to maximise overall welfare of the population. It emphasises the importance of removing barriers and ensuring as many people as possible can access and benefit from resources and opportunities.
- **Human capability approach:** Developed by Amartya Sen (2005) and Martha Nussbaum (2007), this centres on people's capabilities to lead the kind of lives they value. In this framework, accessibility means eliminating barriers that prevent individuals from developing their capabilities and pursuing their chosen life goals. It's about providing opportunities for people to achieve a decent standard of living and engage in activities that they value.
- **Libertarianism:** Influenced by thinkers like Robert Nozick (1974), this emphasises individual liberty, minimal government intervention and the protection of property rights. In the context of accessibility, it can be seen as a matter of individuals or private entities making their resources and services available on a voluntary basis without coercion. It ensures that people have the freedom to access or provide resources and services as they see fit within the framework of non-interference and voluntary exchange.
- **Intuitionism:** This is an ethical theory that relies on individual moral intuitions or judgements (Prichard, 1912). In this context, accessibility depends on the moral intuitions of individuals. Transport accessibility measures would be evaluated based on a subjective and intuitive understanding of how easy it is for individuals to reach their destinations using a particular mode of transportation. Intuitionism emphasises the role of human intuition and subjective experience.

In accordance with the normative positivist approach that underpins this study's conceptual framework for assessing accessibility, it is imperative to emphasise that a libertarian perspective cannot serve as a suitable foundation. This is primarily due to the libertarian philosophy, which posits that all forms of accessibility arise organically from the workings of a free market and the voluntary agreements of consenting adults. Consequently, within the libertarian paradigm, there exists no inherent need for the technical measurement of accessibility. The very essence of accessibility distribution is deemed unnecessary under this ideology.

In our scholarly perspective, accessibility should be construed as an endeavour to optimise the utility of opportunities available to an individual. From the vantage point of the human capability approach, it is essential to recognise that potential accessibility can only be realised when an individual possesses the capability to harness and fully utilise the opportunities offered. Therefore, the proposed methodology harmonises these two philosophical traditions to provide a more comprehensive and nuanced framework for evaluating accessibility. This approach acknowledges the intrinsic value of accessibility while also recognising the importance of a person's ability to actualise it.

Furthermore, it is essential to underscore that an intuitionist viewpoint, which places accessibility entirely within the subjective intuition of individual users, runs counter to the fundamental premise of this study. Our central tenet posits that accessibility can indeed be quantified and evaluated. Transport accessibility measures demand a basis in empirical data such as travel times, costs and connectivity to accurately assess and improve transport services. Intuitionism, however, provides useful information about unrevealed preference, which could be complemented by quantitative methods to derive estimates of accessibility and its value to community groups. Intuition, being non-empirical, cannot provide the concrete data needed to inform these measures. Therefore, the proposed methodology departs from both libertarianism and intuitionism, seeking instead to combine elements of utilitarianism and the human capability approach.

Appendix B: Transport accessibility and the space-time prism (STP)

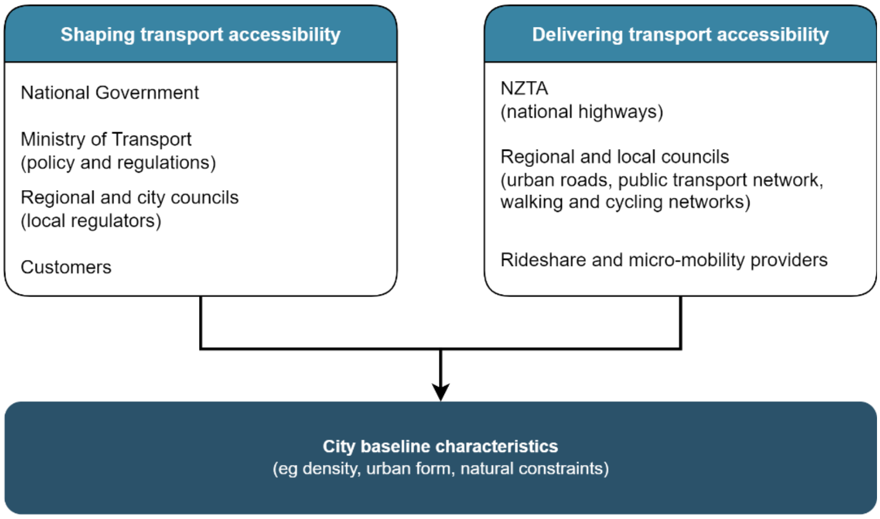
B.1 Why can't urban transport be managed like other public services?

Urban transport management presents unique challenges that set it apart from other public services. Its complexity arises from intricate interplay of multiple modes of transportation, wide array of stakeholders and bespoke nature of solutions tailored to individual city contexts. Urban transport systems often suffer from chronic congestion and underfunding. Managing these systems involves coordinating an array of transport modes, including road infrastructure and public transport networks. Stakeholders range from government and regional councils to city councils and service providers, each with differing objectives, budgets and funding sources. The complexity of transport systems and the variety of stakeholders make universal solutions unfeasible, necessitating city-specific, bespoke approaches that are difficult to replicate and scale.

In New Zealand, major cities such as Auckland are key contributors to the country's GDP, highlighting the vital importance of urban road networks for economic development and access to services. Urban productivity hinges on the efficiency of transport systems in providing accessibility. However, the increasing complexity of traffic systems makes effective orchestration a formidable task.

Traditional transportation funding, primarily public sector-driven and based on a mix of fares and taxes, struggles to address the extensive externalities generated by modern transport systems. Outdated financing frameworks and a focus on traditional mobility outcomes have led to inefficiencies in managing urban transport networks. The governance and delivery mechanisms in the transport sector are often fragmented, impacting both the financing and delivery of transport accessibility (Figure B.1).

Figure B.1 Stakeholders in urban accessibility



Source: Principal Economics

Decision making in transport occurs across multiple government levels (national, regional, local) and is distributed among various agencies, each responsible for different aspects (operation, maintenance, repair, construction) or modes (car, bus, rail, ferry), which results in lack of coordination and suboptimal efficiency.

The transition from a mobility-focused paradigm to one centred on accessibility is a significant change. The existing structure of the transport sector, characterised by multiple actors and interests, makes significant change challenging. Moreover, the sector's reliance on central and local government finance makes it susceptible to political change that threatens continuity, often leading to swings in transport priorities.

Managing urban transport differs from other public services due to its complex multimodal nature, diverse stakeholder landscape and the specificities required for each urban context. This complexity is compounded by funding and governance challenges, making it difficult to apply a one-size-fits-all approach. Effective management of urban transport thus requires innovative, context-specific solutions, robust funding mechanisms and coordinated governance structures to ensure efficient and equitable transport accessibility.

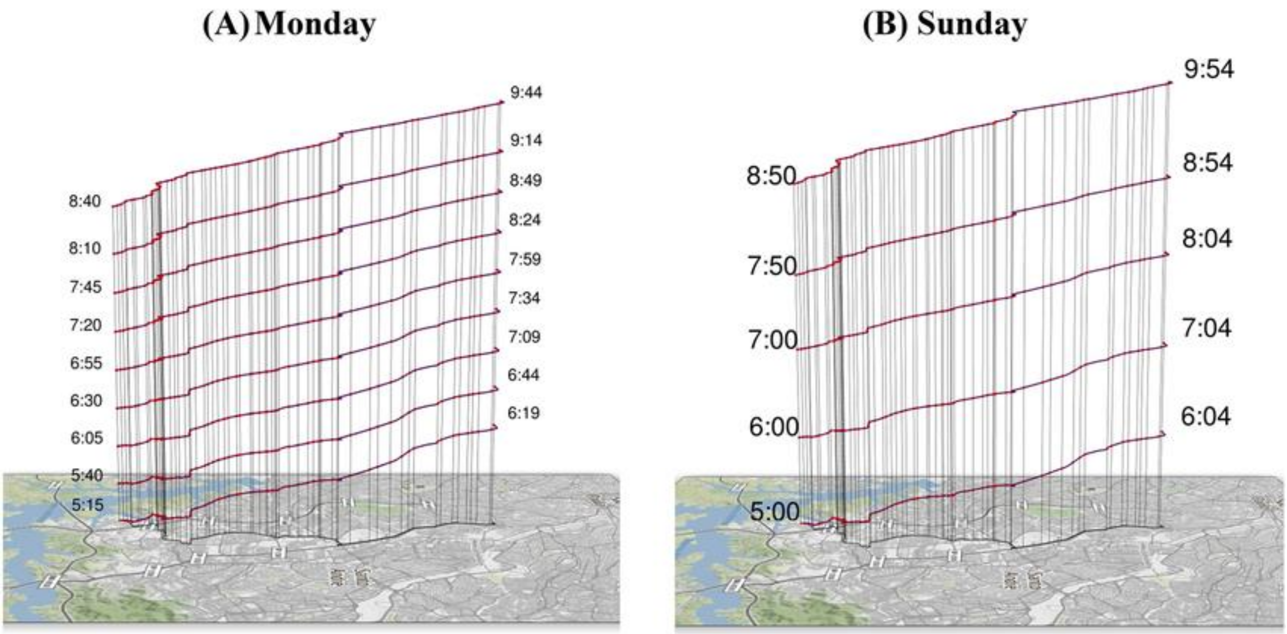
B.2 What are the complexities of assessing transport accessibility?

Assessing transport accessibility is not a straightforward task. It involves understanding and interpreting the dynamic interplay of spatial and temporal factors within urban and regional planning. This complexity stems from the nature of transportation itself combined with individual limitations in utilising the provided accessibility. A critical concept in this assessment is the space-time prism (STP), which encapsulates the spatio-temporal constraints on an individual's movement.

The STP is a conceptual tool acknowledging that accessibility varies throughout the day and week and even seasonally. It considers individual differences such as non-standard working hours and the resultant impacts on travel patterns and health outcomes. Understanding these dynamic aspects is essential in creating inclusive and effective transport policies (Fenwick & Tausig, 2001; Jamal, 2004; Minnen et al., 2016).

According to time geography (Hägerstrand, 1970), an individual's capacity to engage in discretionary activities is constrained by fixed activities at specific locations and times. The assumption is that discretionary activity engagement by an individual j at location q is constrained by a set of chronologically ordered successive fixed activities at anchor locations $\{p_i, p_{i+1}, p_{i+2}, \dots, p_n\}$. The STP, viewed as a three-dimensional construct, defines the limits of where and when an individual can travel within a given time budget. Figure B.2 shows paths of multiple trips of a public transport route under an STP.

Figure B.2 Presentation of public transport route trips under an STP (reprinted from Pereira et al., 2022, p. 11)



In an STP, space is represented in two dimensions while time serves as the third dimension. While a bus route's alignment is constant, its STP representation reveals Monday's services are more frequent. Furthermore, in public transport systems, mere intersecting bus routes at a stop don't necessarily enable transfers. For a transfer to be possible, the routes must coincide both spatially and temporally, as demonstrated in Figure B.3.

Figure B.3 The potential path between two bus routes under an STP (reprinted from Pereira et al., 2022, p. 12)

The projection of the STP, known as the potential path area (PPA), captures all locations accessible to an individual considering their time budget and travel constraints (Forer & Huisman, 2000; Kwan, 1998; Lenntorp, 1978; Miller, 1991; Yu & Shaw, 2008). The PPAs corresponding with successive pairs of fixed activities within a person's daily activity skeleton can be superimposed to create the daily PPA (DPPA) (Figure B.4). The feasible opportunity set (FOS) within this DPPA is given in Equation B.1 (Kwan, 1998):

$$STP = \{(q,t)|(t_i + t_{p_iq} \leq t + \overline{T} \leq t_{i+1} - t_{qp_{i+1}})\}, and\ (t_q^o \leq t + \overline{T} \leq t_q^c) \quad \text{(Equation B.1)}$$

where:

t = activity time

t_{p_iq} = travel time from the anchor location i to the discretionary activity location q

$t_{qp_{i+1}}$ = travel time from the discretionary activity location q to the next anchor location p_{i+1}

$\overline{T}$ = minimum activity duration

t_q° = time the facility at location q opens

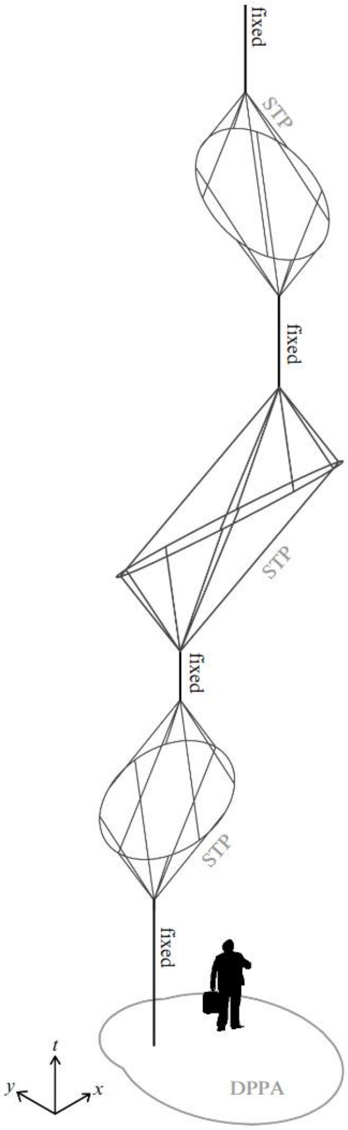
t_q^c = time the facility location q closes.

In other words, the STP gathers all locations q where individual j can perform a discretionary activity of a meaningful duration $\overline{T}$ that falls within the opening hours of the facility located at q.

The FOS within the DPPA is defined by a set of feasible locations and times where an individual can perform activities (Equation B.2). This concept helps in understanding the actual accessible opportunities available to an individual, considering their unique constraints and schedules.

$$FOS = \{q|(q,t) \in STP\} \quad \text{(Equation B.2)}$$

Figure B.4 Space-time prisms and daily potential path area (reprinted from Neutens et al., 2010)



An opportunity within the accessibility measure is characterised by its attractiveness, travel time and duration of the activity at the opportunity location. This is formalised as a function of all opportunities in the FOS, considering factors such as opportunity attractiveness, travel time and activity duration (Equation B.3):

$$AM = f(FOS) = \mathrm{G}\left[\sum_{i=1}^{n} z(a_i, t_i, T_i)\right] \quad \text{(Equation B.3)}$$

where n is the number of opportunities in the FOS, G is a continuous and increasing function satisfying $G(0) = 0$ and z is a standard distance substitution function with the properties:

- for fixed a and t, $z(a_i, t_i, T_i)$ does not decrease with increasing T_i
- for fixed a and T, $z(a_i, t_i, T_i)$ does not increase with increasing t
- for fixed t and T, $z(a_i, t_i, T_i)$ does not decrease with increasing a
- $\lim_{t\to\infty}(a, t, T) = 0$
- $z(a, t, 0) = 0$
- $z(0, t, T) = 0$
- $z(a, t, T)$ is independent of the presence of other opportunities.

B.2.1 Physical accessibility vs virtual accessibility under a STP

In recent years, rapid advancements in information and communication technologies (ICT) such as the increase in internet penetration rate, mobile phones and AI digital assistants have significantly altered our societal dynamics. This technological surge has not only changed how we perform daily activities but also revolutionised interpersonal interactions, impacting the spatial and temporal distribution of potential human activities.

Integration of ICT into daily life has led to the emergence of a virtual space alongside the traditional physical space. This virtual space, also known as cyberspace, is underpinned by physical ICT infrastructures and is pivotal in the flow of information. It connects people electronically, enabling them to share information across different physical locations – a concept known as telepresence, which extends a person's ability to sense and influence environments far beyond their immediate physical surroundings (Janelle & Hodge, 2000).

However, existing STP frameworks, which effectively depict potential activities in physical space, are inadequate for encompassing activities in both physical and virtual spaces. Thus, these frameworks require modifications to accurately represent and analyse activities where both spaces coexist.

Physical and virtual spaces have distinct characteristics. Activities in physical space, distributed across various locations, necessitate travel, requiring individuals to balance travel and activity time. In contrast, virtual space, accessible via telepresence, lessens the significance of physical location, saving time and adding flexibility to activity participation.

While telepresence diminishes the importance of physical distance (Batty & Miller, 2000), access to virtual space is still dependent on physical space as it is not universally available. Additionally, the flow of information in virtual space can influence activities in physical space (Salomon, 1986; Shen, 1998b).

Physical space functions both as a carrier for physical activities and a connector for virtual activities. It hosts the necessary ICT infrastructures and facilities for accessing virtual space. The omnipresent access to virtual space is limited,[36] and physical presence near access points (such as high-speed internet spots) is essential for engaging in virtual activities. Therefore, physical constraints still govern virtual activities.

To address this interplay between physical and virtual spaces, Yu and Shaw (2008) developed an adjusted STP concept for virtual activities. This concept considers the opportunities in physical space that enable connection to virtual space, accounting for the constraints of physical space and time. Identifying potential virtual activities involves locating access channels in physical space within these constraints.

B.2.2 STP adjusted for virtual activities

Based on Yu and Shaw (2008), an adjusted STP is derived by intersecting a conventional STP with the life paths of virtual space access channels in physical space. These life paths represent the existence of a virtual space access channel over time, contrasting with a space-time path that shows an individual's trajectory. A space-time life path shows a virtual space connection service at a specific extent in space and time, formed by extending a virtual space access channel along the time dimension based on its operational hours, indicating when and where individuals can access virtual space.

The life path allows DPPA to extend beyond its physical constraints, enabling it to engage with a wider FOS. To assess how the life path influences the FOS, it is crucial to examine the interaction between physical and virtual accessibilities.

[36] Some of limitations include higher cost of cell phone internet and its lower speed.

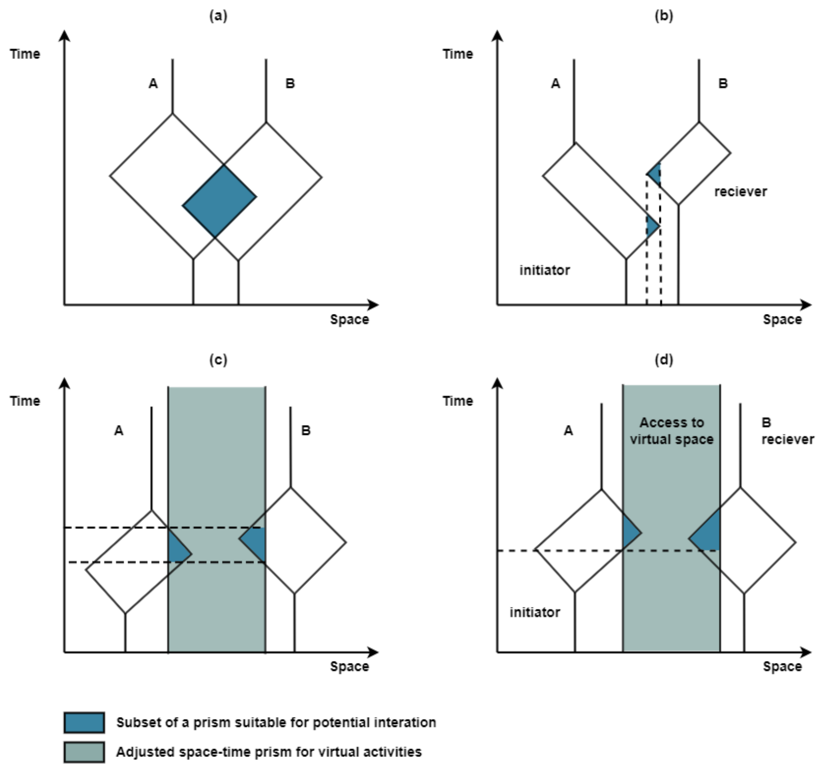
Harvey and Macnab (2000) and Janelle (1995) suggest four accessibilities based on their spatial and temporal characteristics:

- Synchronous presence requires the participant to be present in the destination location at the specific timeframe. For example, access to jobs requires physical presence at the workplace during AM peak.
- Asynchronous presence occurs when an individual visits the destination at any time such as a post office box.
- Synchronous telepresence enabled by ICT such as a videoconference requires simultaneous time but not location.
- Asynchronous telepresence such as movie streaming services is free from both space and time coincidence.

These modes help examine FOS, as different interactions require varying spatial-temporal accessibility. Synchronous presence and asynchronous presence interactions, occurring in physical space, can be studied using conventional STPs. In Figure B.5(a), overlapping prisms indicate potential synchronous presence interactions at the same location and time. In Figure B.5(b), overlapping in space but not time suggests asynchronous presence interaction opportunities.

Synchronous telepresence and asynchronous telepresence interactions, involving virtual space, require adjusted STPs. In Figure B.5(c) and Figure B.5(d), the grey areas represent access to virtual space. Overlapping in time, individual A in Figure B.5(c) has access to destination B over a virtual co-location in time relationship and will have opportunities to conduct synchronous telepresence interactions. Figure B.5(d) illustrates the pattern of prisms when individual A has access to destination B in asynchronous telepresence interactions (such as movie streaming services).

Figure B.5 Spatio-temporal relationships of prisms and potential interactions (reprinted from Yu & Shaw, 2008)



Note: A is DPPA of individual A and B is PPA of destination B. (a) = potential synchronous presence interactions; (b) = potential asynchronous presence interactions; (c) = potential synchronous telepresence interactions; (d) = potential asynchronous telepresence interactions.

For synchronous telepresence and asynchronous telepresence accessibilities, telepresence necessitates adjusted prisms in the analysis. Identifying potential synchronous telepresence accessibilities involves determining the overlap of vertical spatio-temporal lines on the time dimension. The overlapping time is found by comparing the start and end times of these lines. The subset within this overlapped period forms a new set of lines, indicating potential synchronous telepresence interaction opportunities.

B.2.3 Conclusions

The assessment of transport accessibility, particularly through the lens of the STP and its extensions, reveals a multi-dimensional and dynamic process. This approach acknowledges the complex interplay of spatial and temporal factors that shape an individual's access to transportation and activities. Key aspects such as the variability of accessibility across different times and the influence of individual circumstances on travel patterns are crucial in understanding and designing inclusive transport policies.

The application of STP in both physical and virtual contexts highlights the evolving nature of accessibility. The distinction between physical and virtual spaces and their respective accessibility challenges underscores the need for flexible and adaptive approaches in urban and regional planning. This includes accounting for the unique constraints and opportunities presented by both synchronous and asynchronous interactions in these spaces.

Ultimately, a comprehensive understanding of transport accessibility requires considering both the physical constraints of travel and the expanding role of virtual connectivity. This dual focus is essential for creating transport systems and policies that are responsive to the diverse needs and realities of individuals in a rapidly changing technological landscape. The continued development and refinement of conceptual tools like the STP and its adaptations are vital in navigating these complexities.

Appendix C: International perspectives on accessibility measurement

C.1 Statistics Canada

A recent application of transport accessibility measures is Spatial Access Measures developed by Statistics Canada, which primarily utilise location-based accessibility measures, focusing on the spatial aspects of accessibility to various services and amenities. These measures do not explicitly incorporate a human capability approach.

In these measures, accessibility is quantified based on the ease of reaching various destinations from a given origin point (dissemination block), with a significant emphasis on the geographical and infrastructural aspects. The seven categories of amenities include educational facilities, healthcare facilities, employment places, grocery stores, cultural and arts facilities, and sports and recreational facilities. The measures combine these amenities with four modes of transportation: public transit during peak and off-peak hours, cycling and walking.

The travel times for these measures are calculated using specific software[37] and methodologies, integrating data from sources like the GTFS and OSM. The gravity model used for analysis considers the interaction likelihood between locations based on the destination's attractiveness and the travel distance or duration.

While these measures are comprehensive in terms of location-based factors, they do not explicitly address individual capabilities, preferences or specific socio-economic factors that might affect accessibility for different population groups. The focus remains on the physical and infrastructural elements of accessibility such as the availability of transport modes and proximity to amenities.

In summary, the Spatial Access Measures provide a detailed framework for assessing accessibility based on location and infrastructure, but they do not incorporate a human capability approach that takes into account individual needs and abilities in accessing services and amenities.

C.2 TUM Accessibility Atlas (Munich)

The TUM Accessibility Atlas, created in 2009, aimed to facilitate common regional identity and effective planning by assessing land use and transport measures. The Atlas integrates various accessibility measures applied to land use and transport planning. It focuses on building trust and shared language among stakeholders, crucial for regional development. The tool functions as a GIS toolbox, combining multimodal transport networks and land-use data. It facilitates the visual representation of spatial and socio-economic disparities in accessibility, using data from sources such as OSM and VISUM transport models.

Future developments of the Atlas aim to enhance its flexibility and dynamic nature, including online availability and carbon dioxide emissions analysis. The tool's effectiveness in visualising accessibility disparities aids in formulating and guiding sustainable regional land-use and transport strategies.

The Atlas uses various measures of accessibility, primarily focusing on location-based metrics that consider both land use and transportation aspects. This approach is distinct from human capability as it not only involves the ability to travel but also encompasses the opportunities accessible through such travel. This encompasses the spatial separation between opportunities and the transportation system necessary to bridge this gap.

[37] The travel times via public transportation were calculated using r5rNote, an R package that accounts for the transit stops and schedules provided in the collected GTFS data.

In defining accessibility, four aspects are generally considered: the study area, transport network, economic activities and economic actors.

The Atlas specifically addresses the need to reduce car dependency and improve the integration of land use and transport and the vulnerability to gasoline price increases. It also highlights the importance of balancing accessibility across socio-economic groups, emphasising public transport and non-motorised modes as crucial for achieving equity. The Atlas identifies and addresses disparities in accessibility, particularly for females and lower-income households who are less likely to drive and more likely to use public transport. This focus helps in formulating policies to improve accessibility for various population groups and at different times of the day, ensuring a comprehensive approach to regional planning and development.

C.3 Spatial Network Analysis of Public Transport Accessibility (SNAPTA) (Edinburgh)

SNAPTA is a tool designed to evaluate the spatial accessibility and social equity of urban public transport systems, specifically applied to the Edinburgh transport network. It assesses the distribution of urban services and the impact of planned transport projects. The Scottish Government views good accessibility as crucial for economic growth, enhancing the competitiveness and attractiveness of cities.

SNAPTA employs three main measures of accessibility:

- Time access to the city centre by public transport during morning peak hours.
- A contour measure calculating the number of economic activities or destinations within a maximum travel time by public transport for different purposes.
- A potential accessibility measure, a gravity-based measure using peak hour travel time between zones, weighted by the quantity of activity opportunities per zone.

The tool uses UK Census data zones for contextual population and socio-economic data. It includes data on jobs, retail services, healthcare, education and leisure facilities. The digital multimodal transport network, modelled in GIS, covers bus services, tramways and railways.

SNAPTA considers walk access time, waiting time, in-vehicle time and interchange time for accessibility calculation.

SNAPTA’s planning relevance includes evaluating the impact of transport infrastructure changes, identifying zones poorly served by public transport and assessing the potential congestion hotspots. It also assists in evaluating the impact of service closures or relocations.

However, SNAPTA has limitations. It assumes uniform accessibility within each zone, potentially overlooking significant intra-zone variations and travel demands. The tool’s reliance on zonal centroids and the neglect of opportunities just outside the modelled area are notable drawbacks. Furthermore, inputting transport data into GIS is time-consuming.

SNAPTA’s approach primarily focuses on location-based accessibility and does not use a human capability approach. It assumes that social and economic activity needs are met at different destinations and that travel demand is determined by the attractiveness of these locations and the quality of the transport infrastructure linking them. However, it does not specifically incorporate individual characteristics or abilities as part of its analysis.

In summary, SNAPTA is a GIS-based tool providing crucial insights into public transport accessibility and equity, with a focus on morning peak hours and various types of urban services. Its innovative approach is valuable for strategic planning and operational decision making, despite some inherent limitations.

C.4 Accessibility Tool for Road and Public Transport Travel Time Analysis in Västra Götaland

The Accessibility Tool for Road and Public Transport Travel Time Analysis was initially developed by WSP for Region Skåne with the aim of understanding geographic accessibility within the region. The Department of Human and Economic Geography later adapted it for Västra Götaland, intending to provide more detailed data for road and public transport accessibility, especially for regional infrastructure planning.

The tool defines accessibility as the possibility of connecting origin and destination points for specific purposes. It currently employs a location-based accessibility measure (isochronic or cumulative opportunity measure). This measure uses travel times as distance functions, considering travel time as a cost. The tool integrates with socio-economic and land-use data for geographical analysis such as examining regional and local labour markets and commuting patterns.

Operational aspects of the tool include calculating travel times using public transport systems and private cars, identifying potential customers and workplaces within a catchment area and factoring in walking times to public transport stops and local facilities.

In practice, the tool provides information about travel time for both cars and public transport to selected destinations at a high geographical resolution. It is compatible with a vast amount of socio-economic data, making it a valuable resource for planning and visualisation. The tool has been used in projects to understand accessibility issues in remote areas, highlighting its potential in enhancing planning processes and addressing local data and tool deficiencies.

The tool's strengths include its high geographical resolution and ability to compare different travel modes. However, it requires significant resources and expertise to set up and maintain, which can be challenging for continuous use. Future developments aim to address these limitations by implementing more advanced measures and expanding the analysis to include various factors affecting connectivity such as traffic lights, congestion and one-way streets.

In summary, the Accessibility Tool for Västra Götaland is a significant development in measuring and analysing road and public transport travel times. Its use of location-based accessibility measures, combined with socio-economic data, offers valuable insights for regional planning. However, it does not explicitly use a human capability approach and focuses more on geographical and infrastructural aspects of accessibility.

C.5 Measuring Public Transport Accessibility Levels (Transport for London)

The Public Transport Accessibility Levels (PTAL) methodology provides a detailed measure of accessibility to the public transport network in Greater London, considering factors such as walk access time and service availability. This method primarily assesses the density of the public transport network at various locations. Components of the PTAL methodology include:

- defining the point of interest
- calculating walk access times from the point of interest to a service access point
- identifying valid routes at each service access point and calculating average wait times
- calculating the minimum total access time for each valid route at the service access point
- converting total access times to equivalent doorstep frequencies (EDFs) to compare benefits offered by routes at different distances
- summing all EDFs with a weighting factor favouring the most dominant route for each mode
- determining PTALs using six banded levels – level 6 = high accessibility and level 1 = low accessibility.

The PTALs reflect walk times to public transport access points, the reliability and number of services within the catchment and the level of service at the access points, including average waiting time. However, the methodology does not consider the speed or utility of accessible services, crowding and the ability to board services or ease of interchange.

The PTAL calculation involves converting access time to EDFs and summing these EDF values to give an accessibility index. Additional factors such as the parallel travel of routes and the need for travellers to change routes are considered in the calculation. The accessibility index is a summation of individual accessibility indices over all transport modes categorised into six levels of accessibility.

The PTAL methodology, developed for London's dense and integrated public transport network, is a location-based accessibility measure. It does not explicitly incorporate a human capability approach, focusing instead on the availability and frequency of public transport services and the walk access times to these services.

C.6 Maximum Recommendable Size of Shopping Centres (MaReSi SC) (Oslo)

The MaReSi SC method, developed by the planning authorities in Oslo, helps determine the maximum size for new or expanded shopping centres, ensuring they serve the population within walking and cycling distance. This method supports Oslo's strategy of maintaining numerous smaller retail centres in densely populated areas well served by public transport, enhancing accessibility and reducing car use.

Accessibility is measured by the real walking distance from dwellings to the shopping centre. The method calculates the centre's size based on the population living within specific distances and their expected spending, ensuring the centre does not attract customers from farther away, thereby supporting local markets without increasing car dependency.

The method's strengths include its simplicity, understandability and alignment with the overall urban plan. It is considered the best practice in Oslo for retail development planning, contributing to ease of understanding and transparency. This method is less labour-intensive and can be easily applied by planners, making it a practical tool in urban planning processes.

Appendix D: Technical notes on measurement of accessibility

D.1 Overview of transport accessibility measures

The evaluation of transport accessibility has been a focus of urban planners and transportation researchers for over three decades (Knox, 1978; McLafferty, 1982; Pacione, 1989; Talen & Anselin, 1998). This section provides an overview of the primary types of accessibility measures, highlighting their characteristics, applications and potential limitations.

Place-based measures assess accessibility based on the proximity of key locations in an individual's life such as their home or workplace to desired activity locations (Miller, 2007). They are primarily used to evaluate the accessibility of facilities and services from static points. While these measures are straightforward and have been widely used in empirical research, they have faced criticism for not adequately accounting for the interconnectivity between an individual's activities and the space-time constraints imposed by facility opening hours and personal schedules (Kwan, 1999; Weber & Kwan, 2003).

Recent advancements in computational power and the availability of individual-level activity-travel data have enabled more sophisticated person-based accessibility measures. These measures consider an individual's travel behaviour and space-time environment, offering a more dynamic and personalised view of accessibility. Examples include methodologies proposed by Kwan (1998) and Miller (1991), which focus on the individual's travel patterns rather than static locations.

The aim is to identify the most suitable accessibility measure for this study, taking into account the study's objectives and the context in which it is applied. An effective accessibility measurement framework should encompass a comprehensive evaluation of all constituent components and subelements, thus providing a holistic view of accessibility.

For this review, drawing on Neutens et al. (2010), four place-based and six person-based measures have been selected. These include operational accessibility measures for both offline and online service delivery following principles similar to the commonly used gravity-type measure for offline contexts. The classification of these measures is illustrated in Table D.1. The accompanying sections provide detailed definitions and distinctions between the considered measures.

Table D.1 Classification of the considered accessibility measures

Measure type	Short name	Measurement description
Place-based measures	DMIN	Reciprocal of minimum network distance
	TMIN	Reciprocal of minimum travel time
	CUM	Number of opportunities within cut-off distance
	GRAV	Attractiveness multiplied by proximity
Person-based measures	NUM	Number of opportunities in DPPA
	NUMD	Proximity of opportunities in DPPA
	DUR	Possible activity duration of in DPPA
	BMAX	Maximum utility of opportunities in DPPA
	BAGG	Aggregated utility of opportunities in DPPA
	BTRANS	Expected maximum utility of opportunities in DPPA based on logit decision process

Source: Adapted from Neutens et al. (2010)

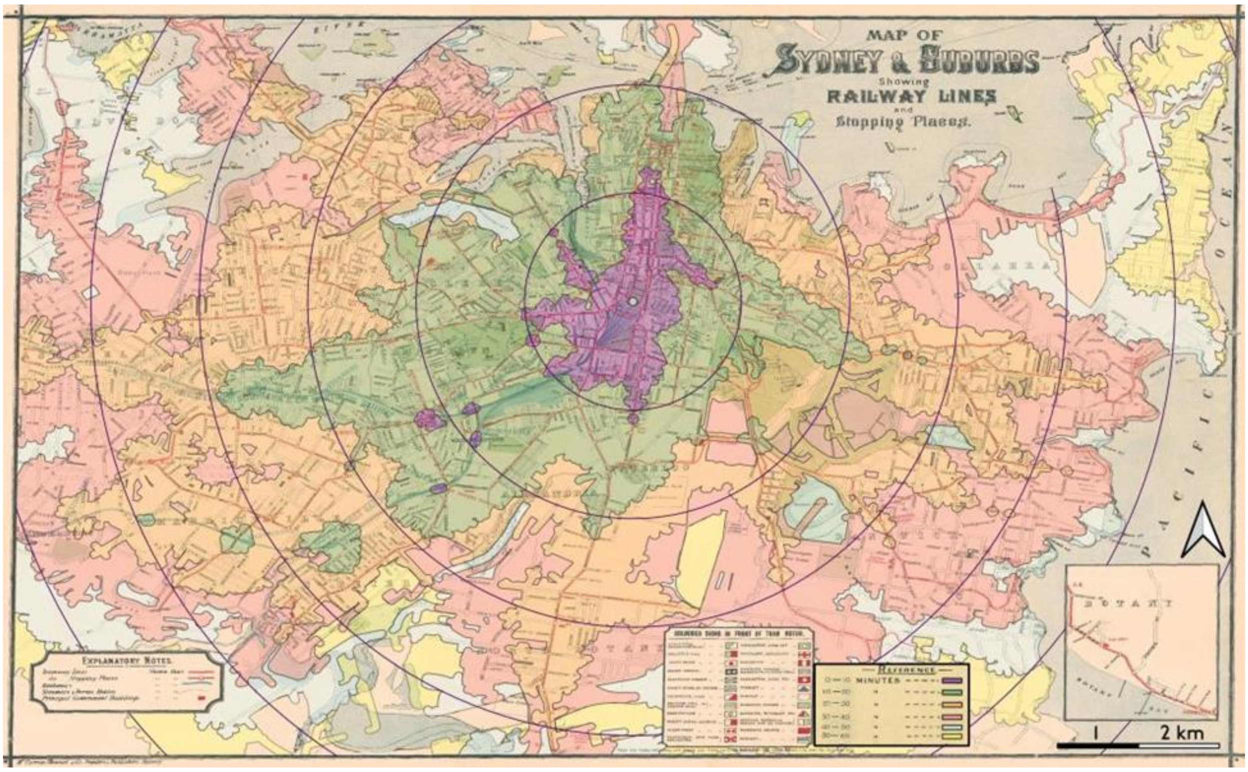
This section aims to provide a comprehensive understanding of different accessibility measures, their applicability and their limitations. The choice of the right measure is crucial in accurately capturing the multifaceted nature of accessibility and effectively informing urban and transport planning decisions. The goal is to ensure that the selected measures align well with the study's objectives and accurately reflect the complexities of transport accessibility in the given context.

D.1.1 Measuring place aspect of accessibility

Place-based accessibility measures, which are fundamental in understanding spatial dynamics, can be broadly categorised into three functional domains: impedance, deterrence and saturation. These functions are discussed in section 3.5. These categories reflect different ways of quantifying accessibility, shaping how urban spaces are analysed and planned.

The impedance function adopts a place-based view, assessing accessibility based on spatial relationships. Early methodologies such as those of Ingram (1971) primarily used direct distance as a determinant of accessibility, reflecting a basic but essential dimension of spatial interaction (Figure D.1).

Figure D.1 Map of Sydney and suburbs showing railway lines including trams in 1925 (reprinted from Levinson, 2022)



The deterrence function, evolving from the impedance approach, incorporates more complex metrics of network distance and traffic variables such as congestion levels and average travel speeds. This perspective, prominent in civil and transport engineering, refines the understanding of accessibility by considering the actual conditions of transport networks and the desirability of destinations.

Saturation functions are used in transport accessibility measures to account for the diminishing marginal utility of additional opportunities. In other words, the more opportunities that are available, the less valuable each additional opportunity becomes. Saturation functions help to ensure that accessibility measures are not biased towards areas with a high concentration of opportunities.

Place-based accessibility measures tend to use contour measures (or isochrones) to evaluate the abundance of accessible opportunities (Walker, 2012) from a given location within a set time, distance or cost parameter. These measures were adopted early by researchers (Wickstrom, 1971; Wachs & Kumagai, 1973; Gutiérrez & Urbano, 1996; Bruinsma & Rietveld, 1998).

The cumulative accessibility measure (CUM) quantifies the absolute number of opportunities within a specified travel impedance. It is straightforward to calculate and interpret but has limitations in reflecting the combined effect of land use and transport, considering competition and capacity constraints and accounting for individual preferences (Ben-Akiva & Lerman, 1979; Vickerman, 1974).

Despite these limitations, location-based measures remain widely used in urban planning (Hull et al., 2012). They serve as vital tools for understanding the potential access from or to specific locations such as residences or commercial centres. The operational aspect is as shown in the following functional form of the CUM (Equation D.1), integrating travel time parameters to express accessibility quantitatively:

$$A_i = \sum_{i=1}^{n} D_j f\left(C_{ij}\right) \quad \text{(Equation D.1)}$$

where A_i is the accessibility at location i, D_j is the number of destinations at location j and C_{ij} is the travel cost or impedance from location i to j. The cost is based on network distance (DMIN) or travel time between i and j (TMIN). $f\left(C_{ij}\right)$ is the weighting function where $f\left(C_{ij}\right) = 1$ if $C_{ij} \leq DMIN\ or\ TMIN$ and $f\left(C_{ij}\right) = 0$ if $C_{ij} > DMIN\ or\ TMIN$.

NZTA's use of the cumulative approach exemplifies the practical implementation of these measures in policy and planning contexts. It underscores the relevance of not just the nearest opportunity (no saturation function) but all reachable ones within a specific travel timeframe.

The cumulative measure's outcomes depend on land-use and travel-time data. Land use changes less frequently, making the measure highly responsive to travel time alterations. Geurs and Ritsema van Eck (2001) noted that this sensitivity limits its effectiveness in tracking accessibility changes over time. Therefore, it is a less dependable metric for assessing social and economic impacts of land use and transport modifications.

The GRAV estimates the accessibility of opportunities in a given zone to all other zones. It considers the diminishing influence of opportunities that are smaller or more distant using distance decay functions for a more comprehensive accessibility analysis (Geurs, 2018). The negative exponential form appears to be the most popular distance decay function, given also their theoretical roots in the entropy maximising approach (Reggiani et al., 2011).

To address these challenges, a more complex version of cumulative approach using distance decay overcomes some of the theoretical shortcomings of the cumulative measure based on isochrones. These potential accessibility measures are called gravity-based measures and have been widely used in urban and geographical studies since the late 1940s (Hansen, 1959; Ingram, 1971; Stewart, 1947; Vickerman, 1974). The measure is expressed in Equation D.2, assuming a negative exponential cost function:

$$A_i = \sum_{i=1}^{n} D_j e^{-\beta c_{ij}} \quad \text{(Equation D.2)}$$

where A_i is the accessibility in zone i and β is the cost sensitivity parameter. The cost sensitivity function used has a significant influence on the results of the accessibility measure. The cost sensitivity function significantly influences GRAV results. For plausible outcomes, the function's form should be carefully chosen based on recent empirical data of spatial travel behaviour in the study area.

This is the most commonly used deterrence function in accessibility literature due to its close tie to travel behaviour theory (Neutens et al., 2010). Gravity-based measures are better suited to be used as an indicator for social and economic evaluation of transportation projects (Fürst et al., 2000).

The potential drawbacks of these measures stem from their complex nature, making interpretation and communication challenging. Additionally, the approach has theoretical limitations, including the omission of competitive dynamics and time-related constraints. To include competition effects, scholars have suggested three possible solutions:

- Dividing the opportunities within reach from an origin zone by a demand potential from the same zone. This approach is useful for analysing short-distance travel such as to primary schools (Knox, 1978; van Wee et al., 2001; Weibull, 1976).
- Using the quotient of opportunities within reach from an origin and potential demand of those opportunities from each destination. This is applicable for destinations where competition occurs at the location such as nature areas or facilities with capacity limits (Breheny, 1978; Joseph & Bantock, 1982; Shen, 1998a).
- Applying Wilson's double constrained spatial interaction model balancing factors (Wilson, 1970, 1971), which account for competition effects at both the origin and destination locations. This model is particularly useful for scenarios such as job accessibility.

Equation D.3 and Equation D.4 demonstrates these balancing factors:

$$a_i = \sum_{i=1}^{n} \frac{1}{b_j} D_j e^{-\beta c_{ij}} \qquad \text{(Equation D.3)}$$

$$b_j = \sum_{i=1}^{n} \frac{1}{a_i} O_i e^{-\beta c_{ij}} \qquad \text{(Equation D.4)}$$

The balancing factors a_i and b_j in Wilson's model are estimated iteratively and reflect the competition on supplied opportunities and demand. While GRAV and its variations offer practical advantages such as ease of computation with existing data, they also face challenges in interpretability and complexity, especially in iterative models. These complexities may limit their frequent use as accessibility measures.

D.1.2 Measuring human aspect of accessibility

The human aspect of accessibility in transport planning is multifaceted, focusing on the individual's economic preferences and capacity to utilise transportation systems. This section delves into various person-based measures that emphasise these aspects.

Utility-based measures assess the welfare benefits derived from access to spatially distributed activities. The decision to undertake a trip is based on the principle that the benefits outweigh the costs. Various models have been developed (Burns & Golob, 1976; de Jong et al., 2007; Geurs et al., 2010b), which differ in their approach to modelling the utility of accessible opportunities. The focus is on analysing the welfare benefits that people derive from levels of access to the spatially distributed activities.

These measures evaluate accessibility at an individual level, considering personal activity schedules and both spatial and temporal dimensions of activities. Person-based measures use the volume of the STP or the number of opportunities within the PPA to indicate personal accessibility. Developed by Miller (1999) and others, these measures integrate transportation system configuration, urban opportunities and individual constraints. Combining utility-based and person-based accessibility, these measures represent an individual's benefit to perform an activity in space and time. For instance, Miller (1991) and Dong et al. (2006) developed approaches estimating maximum utility within a space-time framework.

The NUM measure calculates the number of opportunities in the FOS, treating each alternative as equally accessible (Equation D.5):

$$NUM = \sum_{i=1}^{n} f(C_{ij}) \quad \text{(Equation D.5)}$$

where $f(C_{ij}) = 1$ if $C_{ij} \in FOS$ and $f(C_{ij}) = 0$ if $C_{ij} \notin FOS$.

To address the lack of spatial factor in NUM, the hybrid measure (Equation D.6) accounts for spatial proximity by incorporating a mode-specific, negative exponential deterrence function:

$$NUMD = \sum_{i=1}^{n} e^{-\lambda_m f(C_{ij})} \quad \text{(Equation D.6)}$$

where λ_m denotes the distance decay parameter for transport mode m of an individual. Despite similar formulation, GRAV and NUMD are different in how they interpret the distance decay and $f(C_{ij})$. For NUMD, the distance decay and $f(C_{ij})$ are based on FOS, whereas in GRAV, they are based on DMIN or TMIN.

Another limitation of the NUM measure is its failure to account for the temporal flexibility of visiting opportunities. This drawback is addressed by the DUR measure. This measure evaluates the maximum duration an individual can spend at an opportunity, addressing the temporal flexibility aspect (Equation D.7):

$$DUR = \max_{\{j\}}\left[(t_j^e - t_j^s) f(C_{ij})\right] \quad \text{(Equation D.7)}$$

where t_j^e and t_j^s represent the earliest start time and the latest end time, respectively, for discretionary activities at destination j. DUR uses the benefit obtained from the most advantageous opportunity within the FOS instead of sum benefits. Miller (1999) introduced measures considering both proximity and temporal freedom as well as the attractiveness of activity locations. These measures aggregate the benefits of accessible opportunities Equation D.8:

$$BAGG = \sum_{i=1}^{n} a_j (t_j^e - t_j^s) e^{-\lambda_m f(C_{ij})} \quad \text{(Equation D.8)}$$

where a_j is the attractiveness of destination j. This measure gauges an individual's advantage derived from the array of options available for engaging in an activity across space and time. BAGG, denoting an aggregated benefit measure, will be more significant when the location-choice set within the DPPA encompasses a greater number of alternatives. A variant of BAGG is BMAX, which, instead of amalgamating benefits, concentrates solely on the primary benefit, emphasising that only the most advantageous opportunity holds significance (Equation D.9):

$$BMAX = \max_{\{j\}}\left[a_j (t_j^e - t_j^s) e^{-\lambda_m f(C_{ij})}\right] \quad \text{(Equation D.9)}$$

Rooted in random utility theory, the logsum measure assumes that individuals choose the alternative that maximises their utility. This measure, derived from the MNL model, is a well-known approach to estimate consumer surplus – the difference between the market value and user value of a service (Equation D.10). Logsum accessibility can be expressed in monetary terms, defining the utility that a person receives in a choice situation, including the disutility of travel time and costs (Geurs et al., 2012; Zondag et al., 2015):

$$A_i = ln\left(\sum_{i=1}^{n} e^{u_j}\right) \quad \text{(Equation D.10)}$$

where A_i signifies the anticipated highest utility within a decision scenario, determined through a logit decision-making process. When faced with a choice situation, individual i opts for the alternative offering the highest utility. Assuming linearity in income-related utility, the accessibility benefit can be computed in monetary terms by multiplying the logsum by the reciprocal of the marginal utility of income. The expression of the accessibility measure within an STP involves converting the logsum into monetary units by dividing it by the coefficient of travel costs. BTRANS, denoting a measure of accessibility that incorporates transformative elements, represents the anticipated peak utility derived from the opportunities within the FOS (Equation D.11):

$$BTRANS = \frac{1}{\lambda_m} ln \sum_{i=1}^{n} e^{a_j\left(t_j^e - t_j^s\right)e^{-\lambda_m f\left(c_{ij}\right)}} \quad \text{(Equation D.11)}$$

Despite its theoretical robustness, the logsum measure is not frequently used in practical applications, though it has been applied in studies by Niemeier (1997) and Geurs et al. (2010a, 2012). Martínez and Araya (2000) developed transport-user benefit measures derived from the doubly constrained spatial interaction model, offering an alternative approach to measuring utility-based accessibility (Equation D.12):

$$A_i = -\frac{1}{\lambda_m} ln(a_i), A_j = -\frac{1}{\lambda_m} ln\left(b_j\right), A_{ij} = -\frac{1}{\lambda_m} ln\left(a_i b_j\right) \quad \text{(Equation D.12)}$$

where A_i is trip generated and A_j is trip attracted and A_{ij} is trip between zone i and j for a given transport situation and subject to trips complying with total trip origins and destinations from the entropy model. These measures should result in similar measurements of economic benefits as the logsum benefit measure since MNL and spatial interaction models are equivalent formally (Anas, 1983). We discuss their equivalency in more detail in section 3.5.

Measuring the human aspect of accessibility involves a complex interplay of economic preferences, individual capacity and the spatio-temporal constraints of the urban environment. By incorporating these diverse elements into various measurement models, transportation planning can more accurately assess and address the individualised needs and preferences of users, leading to more effective and inclusive transportation systems.

D.2 Technical measurement issues

In accessibility analysis, various methodological issues arise from the ways in which transport and land-use data are organised and interpreted. This section outlines some known biases and issues in spatial statistical analysis relevant to access computations along with considerations and trade-offs between common methods of computing access (**Error! Reference source not found.**).

Table D.2 Accessibility measurement issues

Issue type	Spatial dimension	Temporal dimension
Boundary	Edge effects	-
Aggregation	Modifiable areal unit problem	Modifiable temporal unit problem
Starting	Starting point effects	Starting time effects Real-time effects

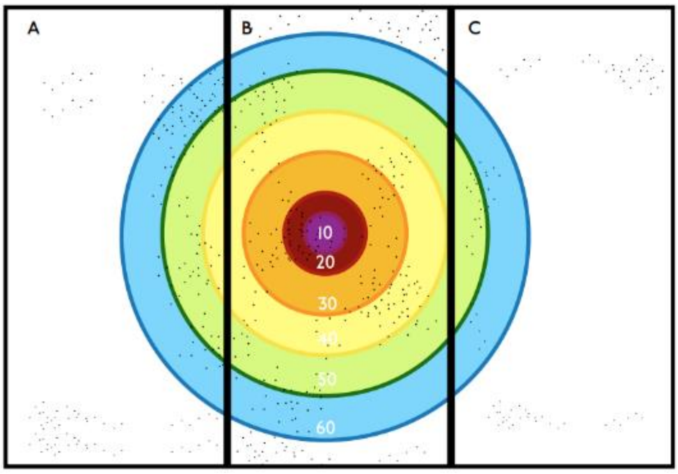
Source: Levinson and King (2020, p. 77)

D.2.1 Edge effects

Boundary or edge effects occur when discrete boundaries are imposed on unbounded spatial phenomena. In accessibility studies, if destinations or network data outside the study area is not included, the access measured at the edges may be artificially low.

An individual in one jurisdiction may have access to opportunities in adjacent jurisdictions (Figure D.2). Not accounting for this can lead to underestimation of accessibility. To mitigate this, we include a wider area in the study or use methods that account for cross-boundary traffic.

Figure D.1 Edge effects occur when the study area does not include all relevant destinations (reprinted from Levinson & King, 2020, p. 78)



Note: The diagram shows three jurisdictions (A, B, C) and 10 to 60-minute travel sheds for someone located in the centre of jurisdiction B, with opportunities denoted by dots. In the diagram, someone located in the central ring (the 10-minute isochrone) can reach some areas in the 50 and 60-minute isochrone that are outside jurisdiction B (in A or C).

D.2.2 Modifiable areal unit problem (MAUP)

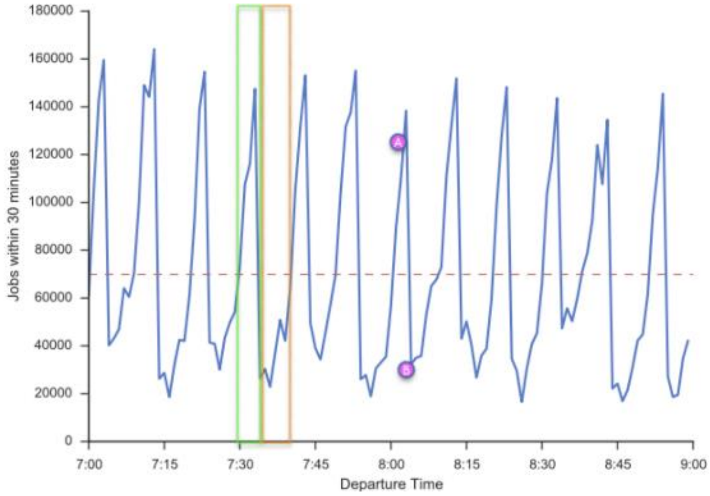
MAUP arises from aggregating spatial data at different scales or zoning schemes, leading to varying results. Scale effect pertains to differences arising from using larger or smaller geographical units, while zone effect refers to differences based on the shape of the zoning areas used. Using smaller TAZs can minimise MAUP, reducing sampling bias. Sensitivity analysis with various spatial resolutions can also help find an optimal balance.

D.2.3 Modifiable temporal unit problem (MTUP)

Similar to MAUP but for temporal data, MTUP reflects how organising data in different temporal windows affects analysis results. These effects result from varying the temporal length of data or aggregating data points in different time windows. Sampling multiple departure times and using tools to average wait times can help. Analysing accessibility over a day and sensitivity analysis with multiple travel times can also mitigate MTUP. The dashed horizontal line in Figure D.3 indicates the average accessibility value over the entire time period. The new accessibility tools such as Python's UrbanAccess library allow for average wait time to address the fluctuation of public transport accessibility. Another way to mitigate these fluctuations is to analyse the accessibility over the course of the day. Finally, a sensitivity analysis with multiple travel times, departure times and zone sizes can validate the accessibility results and address both MTUP and MAUP.[38]

[38] For further details, see Stępniak et al. (2019) and Murphy and Owen (2019).

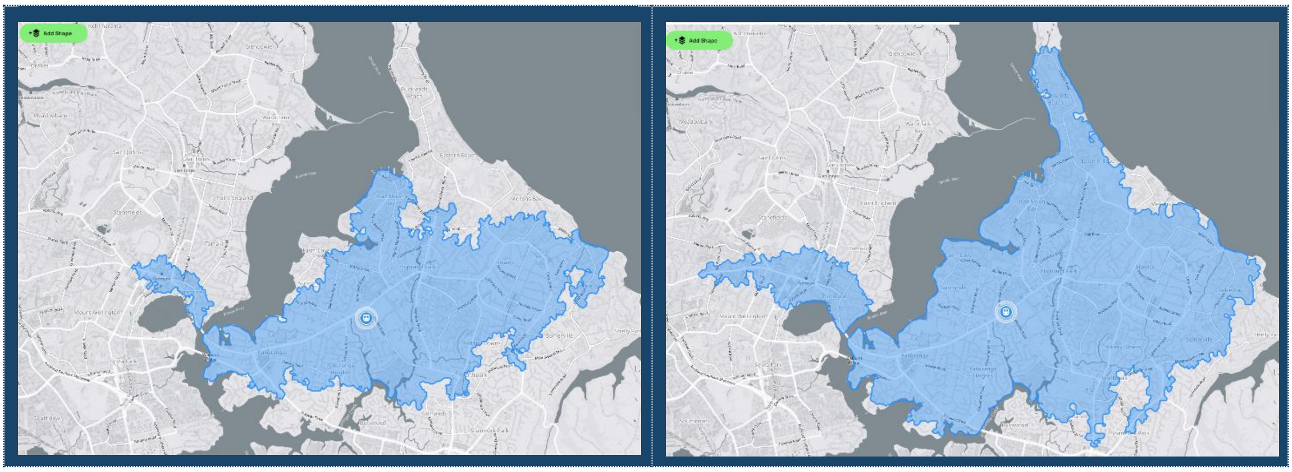
Figure D.2 Accessibility plot for a single Census block (reprinted from Levinson & King, 2020, p. 80)



D.2.4 Starting point effects

Small changes in starting locations can lead to significant differences in accessibility, especially in areas with non-uniform network connectivity like cul-de-sacs (Figure D.4). Using representative start points, sampling multiple locations or using population-weighted centroids for larger TAZs can reduce these effects.

Figure D.3 Impact of starting point on transport catchment



Source: Principal Economics adapted from app.traveltime.com
Note: A minor alteration in the start point (150 metres) yields a significant effect on the isochrone of public transport catchment. The graphs illustrate a 30-minute travel time during the morning peak in Pakuranga, Auckland. The left starting point is situated at the cul-de-sac's terminus, while the right starting point is positioned on the main street.

Cui et al. (2019) show the model fit to predict mode share is better when accessibility is generated using detailed spatial and temporal data, though the improvement is minimal. A sensitivity analysis can be used to find a balance between the cost of detailed analysis and the benefits of marginal improvement of the results.

D.2.5 Starting time effects

Similar to starting point effects but in a temporal context, the chosen departure time significantly influences accessibility, particularly for modes with variable service levels such as public transit. Using multiple start times or determining representative conditions such as averaging transit access over a peak hour can mitigate this bias (Murphy & Owen, 2019).

D.2.6 Real-time effects

Accessibility has until recent years most commonly been analysed as a static phenomenon that does not include stochasticity issues. A common practice in urban accessibility studies is that they rely on transit scheduled timetables to calculate accessibility estimates. By doing so, they overlook inherent uncertainties in public transport travel times and the ways in which scheduled levels of service might differ from what is delivered to the population (inaccuracy) and delivered levels of service might vary across different days (variability) (Wessel & Farber, 2019). These two issues might generate unrealistic or biased results when analysing accessibility socio-spatial inequalities or assessing transport projects. The problem of inaccuracy and variability emerges for various reasons, including reliability of the public transport system and the methodology each city uses to build its own scheduled timetables. Dedicated infrastructure to public transport may be important in mitigating the impact of variability. Recent studies have developed methodologies to correct scheduled GTFS timetables with GPS data and improve accessibility accuracy (Liu et al., 2023; Wessel et al., 2017; Wessel & Farber, 2019). A mitigation for inaccuracy and variability of the transit data is employing real-time information to correct the scheduled timetables.

D.3 STP concept and measuring accessibility

Improvements in computer technologies and location data have also allowed greater refinement and wider application of the STP. Abundant data helps refine STP models and enhance the reliability of STP measures. Malekzadeh and Chung (2020) suggest there are two major trends for transit accessibility studies: better capturing travellers' behaviours and developing more disaggregated transit accessibility measurements. Both trends exemplify how larger, more detailed and more accessible datasets impact the formulation of transit accessibility models.

A recent trend in transit accessibility analysis is more disaggregated transit accessibility measurements. Studies can assess trip-level or even person-level accessibility based on fine-grained standard data like GTFS and smartcard data (Arbex & Cunha, 2020; Batty, 2013; Lee & Miller, 2018). Detailed spatio-temporal data on transportation and destinations along with detailed spatial-social data on population has allowed creation of well-structured STP models. Therefore, many recent studies develop STP at a larger scale without compromising the fine details of transport systems (Lee & Miller, 2018; Tasic et al., 2014). Researchers utilise big spatio-temporal databases, including opening/closing hours as well as locations of various resources to model and simulate urban accessibility (Fosset et al., 2016; Legrain et al., 2015).

In the preceding sections, we delved into the accessibility function $f(C_{ij})$, which determines the feasibility of reaching two locations (i and j) within a designated timeframe under STP. While STP encompasses all accessible areas for an individual, it is crucial to dissect it into classes and categories for a more nuanced assessment of accessibility. This section explores these categories, the methods of costing accessibility and their potential issues.

D.3.1 Breaking down the STP

Breaking down the STP into distinct categories such as population groups, destination types, time of day and travel modes is crucial for several reasons, primarily stemming from the complexity and continuous nature of the STP concept. The STP in its raw, continuous form represents a highly complex and dynamic model of individual mobility potential. It encompasses all possible locations an individual can reach within a given timeframe, factoring in the constraints of time and space. Calculating the STP in its entirety can be computationally intensive, if not impractical. The continuous nature of the STP, with its infinite possible points, poses significant challenges in terms of data processing and analysis. Breaking down the STP into homogeneous categories simplifies the model without significantly compromising its accuracy. This categorisation transforms a complex, continuous model into more manageable, discrete segments. By categorising the STP, planners can strike a balance between computational feasibility and the accuracy of outcomes. This approach allows for more practical and timely analyses without losing critical insights.

Different demographic groups, destinations and travel modes have unique accessibility needs and constraints. Disaggregating the STP allows for more tailored and relevant transportation planning that addresses these specific requirements. By understanding the accessibility dynamics of various population groups, planners can formulate more effective policies. Different destinations have varied accessibility patterns and different travel modes offer varying levels of accessibility. Understanding these differences is crucial for promoting multimodal transportation and improving overall network efficiency. Breaking down the STP into specific categories is vital for making this complex concept computationally manageable and practically applicable. It enables transportation planners to develop more nuanced, accurate and relevant accessibility analyses.

Population groups: Accessibility analyses can be disaggregated for different population groups such as people with disabilities, various income levels, age groups, ethnicities and genders. Analysing the additional costs borne by these groups compared to drivers can indicate the extent of transport options available. While disaggregation provides detailed insights, over-disaggregation may lead to losing sight of broader trends. The level of detail should match the intended audience and goals of the accessibility measurement.

Destination type: Common destination types include workplaces, supermarkets, schools, medical offices and parks. Access to workplaces is frequently studied due to its significance in daily travel. However, accessibility to other activities like shopping, healthcare and recreation is equally important. Breaking down jobs by categories such as ANZSIC allows for understanding specific accessibility needs for different job types, including variations in earning potential. Accessibility measures can include point-based representations of locations or assessing the size and quality of amenities often aggregated at the TAZ level.

Time of day: Accessibility varies throughout the day as travel times and the availability of opportunities change. Literature suggests categorising time into segments such as AM peak, interpeak, PM peak, evening and overnight. The time of analysis should align with the destination type, recognising that different destinations have different peak times. Transportation networks must be designed to serve not just the weekday commute but also the weekend visit to a park, the after-school trip to the library or the routine visit to a neighbourhood clinic. This reorientation necessitates a holistic perspective on accessibility that transcends traditional boundaries.

Travel mode: Traditionally, urban accessibility has been understood in terms of physical transportation modes – walking, biking, public transport and driving – each requiring distinct analysis, particularly when considering how they combine in daily commutes and access to urban amenities. The HTS offers valuable insights into these combinations, highlighting diverse needs and capabilities of urban residents. However, not every individual has equitable access to all physical modes of transportation. The introduction of virtual accessibilities such as telework significantly changes the traditional understanding of urban accessibility. Unlike conventional modes, virtual accessibility eliminates the need for physical travel, thereby redefining the idea of access to employment and other socio-economic opportunities within a city. Treating virtual accessibility as a separate mode is essential for a comprehensive understanding of urban accessibility. This approach acknowledges the growing role of digital infrastructure as a determinant of socio-economic participation. The STP adjusted for virtual accessibility, as discussed in sections B.2.1 and B.2.2, provides a conceptual framework to include virtual accessibility as a mode.

D.3.2 Combining accessibility measures under STP

Combining multiple accessibility measures into a single measure depends on how the weightings of each measure are defined. The literature suggests various methodologies to define these weightings.

Share of total trips: One of the simple ways to define the weightings is based on the share of trips in each accessibility measure from the total trips. For example, Knap et al. (2023) measure accessibility to 11 destinations and use percentage of trips to each destination type to combine into a single measure.

Diversity of opportunities: In this method, the importance of each accessibility measure is measured using a grading system. Silva and Pinho (2010) presented a structural accessibility layer, evaluating access based on the diversity of opportunities for a specific travel mode. They assessed 18 types of activities in Greater Oporto, Portugal, categorising each destination's importance and reporting the population and area coverage for each category.

User preferences: Revealed preference and stated preference data can also be used to define the relative weighting for accessibility measures. The number of visits to each destination has been used in multiple studies to define the weights of the accessibility measures. Cui and Levinson (2020) combined travel diary information and travel times with business information reports in Minneapolis for seven destination categories. Their weighting system was based on the frequency of destination visits recorded in travel diaries. McNeil (2011) used cycling-focused travel survey data to identify and weigh a range of destinations. This study derived weights from literature reviews and trip frequency data, assigning points based on occurrence frequency.

Statistical analysis: Some studies have proposed different statistical methods to measure importance of each accessibility measure. Klumpenhouwer and Huang (2021) proposed measuring correlation coefficient between percentile values of each destination from total accessibility of each zone (Figure D.5). They determined values over 0.75 as the threshold to define high correlation to bundle destinations. Each category is assigned a weight by subject matter experts or additional data sources such as travel surveys.

Figure D.4 Correlation matrix of percentile of level of access to points of interest for OSM points of interest (reprinted from Klumpenhouwer & Huang, 2021)

	Population	Jobs	Supermarkets (OSM)	Restaurants (OSM)	Pubs (OSM)	Playgrounds (OSM)	Schools (OSM)	Childcare (OSM)	Parks (OSM)	Pitches (OSM)	Theatres (OSM)	Cinemas (OSM)	Pharmacy (OSM)	Clinics (OSM)	Dentists (OSM)
Population	1.00	0.77	0.90	0.79	0.69	0.91	0.93	0.18	0.87	0.86	0.69	0.64	0.88	0.53	0.31
Jobs		1.00	0.79	0.97	0.91	0.54	0.74	0.11	0.52	0.72	0.93	0.80	0.81	0.60	0.33
Supermarkets (OSM)			1.00	0.84	0.74	0.83	0.91	0.28	0.81	0.80	0.66	0.70	0.91	0.61	0.41
Restaurants (OSM)				1.00	0.92	0.59	0.77	0.17	0.59	0.71	0.90	0.80	0.86	0.60	0.37
Pubs (OSM)					1.00	0.50	0.72	0.30	0.50	0.74	0.86	0.80	0.81	0.76	0.56
Playgrounds (OSM)						1.00	0.89	0.30	0.93	0.82	0.43	0.49	0.77	0.47	0.31
Schools (OSM)							1.00	0.27	0.85	0.91	0.62	0.64	0.88	0.66	0.45
Childcare (OSM)								1.00	0.31	0.31	0.03	0.32	0.38	0.53	0.65
Parks (OSM)									1.00	0.75	0.41	0.51	0.78	0.44	0.31
Pitches (OSM)										1.00	0.65	0.64	0.83	0.73	0.50
Theatres (OSM)											1.00	0.73	0.71	0.50	0.25
Cinemas (OSM)												1.00	0.75	0.65	0.48
Pharmacy (OSM)													1.00	0.72	0.54
Clinics (OSM)														1.00	0.88

These methods for combining accessibility measures have drawbacks. First, Zheng et al. (2019) assert that relying solely on trip frequency to gauge a destination's importance is unreliable as it can be influenced by external factors. Moreover, stated preference and revealed preference data have limitations in scenario evaluation. These approaches also restrict the addition of new destination types. Finally, with the trend towards virtual accessibility, the current relative importance of destinations is likely to change.

We recommend basing the weighting of accessibility measures on their impact on wellbeing. This method aligns with existing national policies and offers an objective means to assess the relative significance of various accessibilities.

D.3.3 The cost of accessibility

This section elaborates on how travel costs, C_{ij}, vary based on different factors and the methodologies to compute these costs. Travel costs are often represented by travel times from one centroid in a TAZ to another using network analysis procedures such as shortest path algorithms. TAZs linked to transport networks with centroid connectors typically represent places in accessibility measures.

More advanced accessibility measures incorporate a range of relevant costs into a full generalised cost model (Conway & Stewart, 2019; El-Geneidy et al., 2016). These might include fares, number of transfers for public transport or risks associated with auto travel. Reflecting multiple constraints simultaneously such as exposure to pollution and collision risks offers a more comprehensive view of accessibility costs.

Travel costs can vary significantly across different population groups, times of the day and modes of transport. Incorporating network restrictions such as limitations on bicycles in certain areas is crucial in calculating accurate travel costs.

A routable network is used to generate an origin-destination matrix between each pair of TAZs, considering the travel cost for each link in different networks. To measure access to opportunities, destinations are associated with travel times from an origin, and opportunities reachable within a travel time budget are tallied using measures such as BMAX or BTRANS.

This measure considers the ratio of opportunities at a destination to the number of people able to reach it within a time threshold. It effectively reflects the level of available opportunities by considering competition. The two-step floating catchment area method used in GIS applications is an example of this approach (Equation D.13):

$$A_i^g = \sum_{j=1}^{n} \left(O_j f(C_{ij}) / \sum_{i=1}^{n} D_i f(C_{ij}) \right) \qquad \text{(Equation D.13)}$$

where A_i^g is access to opportunities for zone i, $f(C_{ij})$ is accessibility of zone i and j, O_j is the opportunity at zone i and D_i is demand at zone i. Some studies have a more complicated method that applies on impedance functions or considers the competition from different modes of transport (Cervigni et al., 2008; Joseph & Bantock, 1982; Kawabata & Shen, 2007; Luo & Wang, 2003; Mao & Nekorchuk, 2013; Neutens, 2015; van Wee et al., 2001).

The concept of accessibility costs varies in urban planning and economics. In job search theory, for instance, agglomeration benefits are a key consideration. Establishing a link between agglomeration benefits and accessibility measures can provide deeper insights into the economic implications of transportation planning.

Studies employ various methods to apply impedance functions and consider competition from different modes of transport. These methodologies can significantly impact how accessibility costs are understood and quantified.

The cost of accessibility is a multi-dimensional concept that encompasses more than just financial expenses. It includes time, effort, risk and other factors that vary by demographic group, destination type, time of day and travel mode. Accurately assessing these costs is crucial for creating effective and equitable transportation systems that cater to the diverse needs of all community members. By understanding and incorporating these various costs, planners and policy makers can enhance the overall accessibility of urban environments.

D.4 STP concept and measuring accessibility

The transport accessibility presented in this report highlights the need for tools that offer both flexibility and efficiency. **Error! Reference source not found.** shows a summary of available tools. As described, we used a range of these tools such as R5 and web APIs. This section provides more information about the other tools that may be useful for future developments of accessibility measures.

Table D.3 Summary of available tools

Tools	Network	Data	Level of service	Stochastic routing	Speed
ArcGIS	Drive	TomTom network	Historical traffic data	N/A	High
OTP	Public transport, walk, cycle	OSM, AI, GTFS,	Slope, AI	No	Low
Valhalla	Public transport, walk, cycle	OSM, AI, GTFS	Slope, AI	No	Low
UrbanAccess	Public transport, walk, cycle	OSM, AI, GTFS, GTFS Realtime	Slope, AI, delays for all networks	Yes	High
R5	Public transport, walk, cycle	OSM, AI, GTFS	Slope, AI	No	High
Web APIs	Drive, public transport, walk, cycle	N/A	Historical traffic data, slope	No	Low

Source: Principal Economics

D.4.1 ArcGIS Network Analyst

A routable network in ArcGIS is a digital representation of a transportation system that can be used to perform network analysis. To create a routable network, a feature class that represents the transportation network such as roads, railroads or airways is needed. The feature class must have fields that contain the following information:

- Junctions – the points where network elements connect.
- Edges – the lines or segments that connect junctions.
- Network costs – the cost of travelling along each edge such as distance, time or fuel consumption.

In addition to the required fields, you may also want to include other fields in the feature class:

- Network restrictions – rules that govern how network elements can be used such as one-way streets or turn restrictions.
- Network descriptors – attributes that describe the network elements such as road type or speed limit.
- Network travel modes – the different ways that people can travel on the network such as by car, bicycle or on foot.

Once a feature class with the required and optional fields is created, the Create Network Dataset tool can be used to create a routable network.

Routable networks in ArcGIS offer a few advantages, including:

- it does not need coding but it can accept codes in Python and VBA
- once the network is created, the accessibility analysis can be automated in Python and R
- it is fast
- the platform is widely accepted in the industry, including New Zealand's local councils and NZTA
- it can integrate with open data sources such as OSM or paid historical data sources such as TomTom
- it can include GTFS for the public transport network.

However, there are also a few potential disadvantages to using routable networks in ArcGIS:

- The public transport network is not accurate. It cannot differentiate between walking and in-vehicle time.
- It cannot measure average wait time for public transport.
- Snapping to network is simply finding nearest edge, which in many cases is not suitable.

Overall, it is a useful tool for a fast and ready-to-use answer such as driving networks. It does not perform for more complex networks such as public transport networks.

D.4.2 OpenTripPlanner (OTP)

OpenTripPlanner (OTP), an open-source platform, integrates various transport modes such as buses, trains and walking for multimodal trip planning. OTP has significantly contributed to the popularity of cumulative opportunities accessibility metrics. For instance, the University of Minnesota Accessibility Observatory employed OTP in its Access Across America project.[39]

However, OTP1, an early version of the platform, has limitations despite its popularity. It is slower and more memory-intensive compared to more advanced systems such as Conveyal's R5. OTP1's analysis capabilities are outdated and not maintained, primarily due to its inability to efficiently handle variations in travel times and wait times for scheduled transit over different departure times. Moreover, OTP1 doesn't support modifications in travel time for walking and cycling networks such as accounting for demand, which restricts its applicability for the scope of this research.

In contrast, OTP2 offers improvements in transit routing and doesn't share OTP1's inefficiencies. Despite this, there has been a decision not to incorporate OTP1's analysis features into OTP2 to maintain focus on passenger information and support existing projects such as R5 and Conveyal Analysis.

D.4.3 Valhalla

Valhalla is an open-source routing engine and accompanying libraries for use with OSM data. Valhalla also includes tools such as time+distance matrix computation, isochrones and elevation sampling. Available libraries such as routingpy can provide access to Valhalla. Valhalla is very similar to OTP and they have similar limitations. Valhalla is designed for place-based accessibility analysis and doesn't provide a detailed access to modify travel time at each link to include person-based accessibility.

[39] https://www.access.umn.edu/research/america/

Appendix E: Shortest path algorithms

Finding the shortest path between two points on a network is a fundamental problem in graph theory. When we want to show how someone would choose a path in a network, there are two options: deterministic models and stochastic models (Gendreau et al., 2015). Deterministic algorithms such as Dijkstra's algorithm are like the disciplined scholars of the optimisation world. They guarantee finding the shortest path with certainty, assuming the input data is accurate and the environment is static. On the other hand, stochastic models are the rebels of the optimisation world. They embrace uncertainty and randomness. In the context of shortest path problems, stochastic models consider the unpredictable nature of real-world scenarios such as traffic fluctuations or weather conditions. Monte Carlo simulations and evolutionary algorithms fall into this category, exploring multiple possible paths and providing probabilistic solutions.

The deterministic models shine in well-defined environments with reliable data such as driving and public transport networks. They are efficient and often faster than their stochastic counterparts. However, when faced with dynamic and unpredictable situations such as walking and cycling networks, deterministic models may struggle to adapt.

In this section, we delve into two primary algorithms – Dijkstra's algorithm for the deterministic model and multinomial logit (MNL) for the stochastic model – and explore their strengths and weaknesses.

E.1 Dijkstra's algorithm

This deterministic method is a widely used tool for determining the shortest path in a network. It operates as a single-source shortest path algorithm, systematically updating paths from the source to all other nodes in the network. Dijkstra's algorithm (see Appendix F) can adapt to dynamic cost scenarios, crucial for time-dependent routing problems. Dijkstra's algorithm is a classic and efficient algorithm to solve the shortest path routing problem (Golden, 1976). It uses a greedy strategy to find the shortest path from the origin node to every other node (Xie et al., 2012), which significantly reduces the size of the subproblems and is very useful and efficient to calculate the STPs.

However, the algorithm's accuracy relies on the non-negative and static nature of cost inputs, which can be a limitation in time-varying transit networks. To address this, many studies implement a first-in-first-out rule, ensuring the algorithm's applicability to time-dependent contexts (Ahn & Shin, 1991; Ichoua et al., 2003). For example, in transit systems, the first-in-first-out rule is tested to ensure that earlier departing vehicles don't arrive later than those departing subsequently (Gendreau et al., 2015).

E.2 Multinomial logit (MNL)

MNL is a statistical model that can be used to predict the probability of choosing one alternative from a set of alternatives. The MNL model is often used in transportation planning to model route choice behaviour.

The MNL model can also be used to find the shortest path between two points on a network (Liang et al., 2023). To do this, we can define the utility of each path as a function of its length, travel time, pavement, slope, safety, environmental, aesthetics and other factors. The probability of choosing a path is then given by the MNL model.

To find the shortest path using the MNL model, we can use the following steps:

- Identify all of the possible paths between the origin and destination.
- Calculate the utility of each path.
- Use the MNL model to calculate the probability of choosing each path.
- Select the path with the highest probability.

The utility function for maximum likelihood estimation is defined in Equation E.1:

$$V_i = \sum_{k=1}^{K} \beta_k^i x_k^i \qquad \text{(Equation E.1)}$$

where V_i is the utility of path i, which is the sum of all its segments weighted by distance or time equivalent, x_k^i is the type k attribute on path i and β_k^i is the coefficient of type k attribute on path i. Each attribute can add or subtract from perceived distance.

The accessibility measure to find the preferred route can be calculated based on the Equation E.2:

$$A_{ij} = E\left[\max_{i\epsilon C_{ij}} U_i\right] = E\left[\max_{i\epsilon C_{ij}} (V_i + \varepsilon_i)\right] = log \sum_{i\in C_m} e^{v_i} \qquad \text{(Equation E.2)}$$

where A_{ij} is the best route between i and j and C_{ij} is a set of paths between i and j. In this method, first k paths with maximum utilities for each origin-destination pair are set under C_{ij}. Unlike the deterministic shortest path algorithms, a set of various walking attributes are considered to find the distance equivalent for each path between i and j.

The MNL model has several advantages over deterministic methods for finding the shortest path. The MNL model can be used to model a wide range of factors that influence route choice behaviour, the MNL model is relatively easy to implement and use and the MNL model is computationally efficient even for large networks.

However, the MNL model also has some disadvantages. The MNL model assumes that the decision maker is rational and that they have perfect information about the alternatives, and the MNL model does not account for correlation between alternatives. Despite its disadvantages, the MNL model is a useful tool for finding the shortest path between two points on a network.

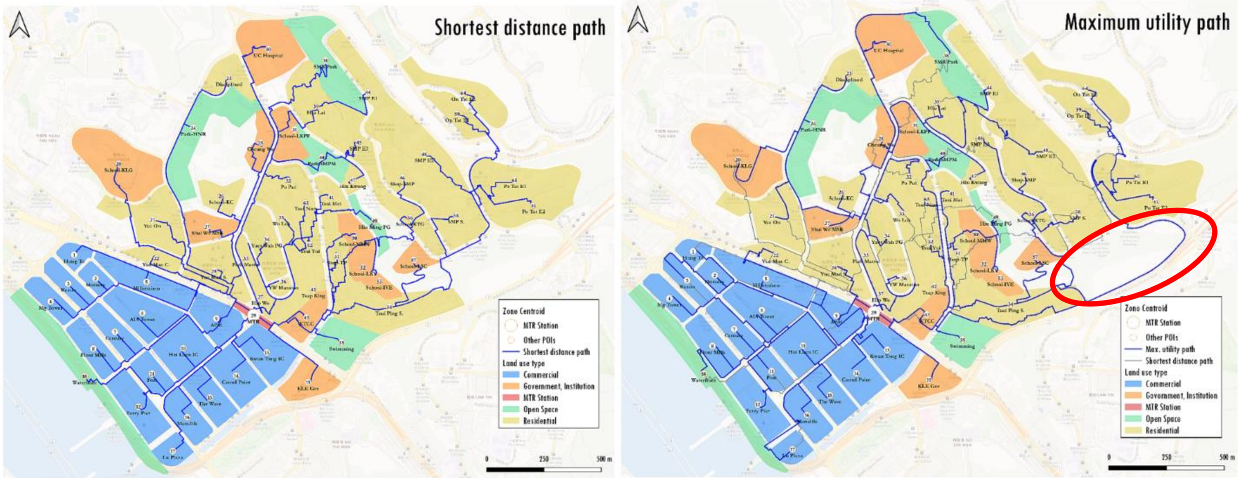
E.3 Deterministic algorithm vs probabilistic algorithm

Probabilistic algorithms are particularly effective in complex networks such as walking and cycling where traditional deterministic methods may not be able to factor in behavioural aspects. However, probabilistic algorithms are based on stated preference, which can be biased to some extent. Revealed preference and stated preference are discussed in Appendix G.

Deterministic algorithms are generally preferred for their predictability and guaranteed optimal solutions in well-defined environments. In public transport networks, for example, because actual arrival times are based on public transport schedules at all the stops, a deterministic approach can address the time-dependent routing problem more efficiently. However, in real-world applications, time-dependent networks such as public transport networks are subject to uncertainties. Li et al. (2017) found that the walking condition in the first/last mile of a public transport trip was a critical component that should be duly addressed to enhance the accessibility performance. The trade-off between the certainty of deterministic algorithms and the flexibility of probabilistic approaches is a critical consideration in accessibility measures.

Recent research such as Liang et al. (2023) has focused on hybrid algorithms that combine the predictability of deterministic methods with the adaptability of probabilistic approaches. They have measured perceived distance equivalency of each link in the network to 1 metre of walking on flat sidewalk and then used the shortest path algorithm to find the path with highest utility between two points. For example, Figure E.1 shows access to the Kwun Tong Mass Transit Railway station (Zone 29, in red) in Hong Kong. The path circled in red (right) is not chosen by the shortest path algorithm (left) but it provides higher utility.

Figure E.1 Shortest distance path vs maximum utility path (reprinted from Liang et al., 2023)



Appendix F: Dijkstra's algorithm

The algorithm begins at the source node, expanding outwards, updating tentative distances to neighbouring nodes and choosing paths based on minimal distance criteria. This process repeats until all nodes are visited (Figure F.1).

Figure F.1 Dijkstra's algorithm

```
function Dijkstra(Graph, source):
    dist[source] ← 0                           // Initialization

    create vertex priority queue Q

    for each vertex v in Graph.Vertices:
        if v ≠ source
            dist[v] ← INFINITY                 // Unknown distance from source to v
            prev[v] ← UNDEFINED                // Predecessor of v

        Q.add_with_priority(v, dist[v])


    while Q is not empty:                      // The main loop
        u ← Q.extract_min()                    // Remove and return best vertex
        for each neighbor v of u:              // Go through all v neighbors of u
            alt ← dist[u] + Graph.Edges(u, v)
            if alt < dist[v]:
                dist[v] ← alt
                prev[v] ← u
                Q.decrease_priority(v, alt)

    return dist, prev
```

Appendix G: Stated preference (SP) and revealed preference (RP)

There is a logical connection between the concept of accessibility and travel demand. People reveal their preferences for different activity locations and modes of travel through their travel destination and mode choices. Person-based accessibility not only measures the physical aspects of transport networks but also captures how commuters perceive factors such as network desirability and destination appeal. This includes understanding their preferences for various routes, destinations and transportation modes. Such an approach can reveal the changes in a user's experience following modifications in the transport system, thereby aligning the accessibility measures more closely with actual user benefits.

To develop these user-centric measures, it is necessary to gather information on user preferences through RP and SP surveys. RP data, derived from actual choices in specific contexts, helps understand existing market preferences but is less effective for new alternatives. SP data, on the other hand, involves hypothetical scenarios to gauge preferences in new or potential market conditions (Louviere et al., 1999).

The collection of RP data often involves comprehensive mobility surveys, which can be costly due to the high precision required. Therefore, transport agencies tend to collect RP data under household travel surveys, which can be used for multiple purposes. The SP data collection is usually more economical, although it often lacks the rigorous design needed to ensure reliability (Ortúzar & Willumsen, 2011). Emerging technologies, including smartphones, tracking tools and sensors, offer new, efficient ways to collect transportation data, providing real-time insights into (revealed) user behaviour (Willumsen, 2021).

Passive data sources such as smartcard validations and mobile tracking can significantly enhance accessibility measures by reflecting current user behaviour. Active online surveys, meanwhile, can gather both RP and SP data, offering insights into mobility patterns and preferences. This data, when effectively integrated, can significantly refine accessibility measures (Bonnel & Munizaga, 2018; Harrison et al., 2020).

However, both RP and SP data has limitations. RP data may not provide enough variability for robust model development and its focus on dominant factors can obscure secondary attributes. SP data, while more flexible, can suffer from unrealistic scenarios or design flaws (Bates, 1988; Louviere et al., 1999). Combining RP and SP data, as suggested by several studies (Ben-Akiva et al., 1994; Cherchi & Ortúzar, 2006; Guzman et al., 2023; Louviere et al., 1999), can offer a more comprehensive understanding of user preferences and the impact of new transport policies or alternatives. This approach can better inform accessibility measures, ensuring they reflect a wider range of user experiences and preferences.

G.1 Including desirability and level of service

This section examines how levels of service and desirability influence accessibility measures, focusing on integrating these elements into mode choice models using SP and RP data. Specifically, we address transportation desirability, encompassing factors such as aesthetics and convenience. Integrating desirability enhances our understanding of travel choices. Research by Onderwater et al. (2019) and Vos et al. (2021) underscores the impact of personal preferences on travel behaviour.

Person-based accessibility measures consider accessibility as an outcome of human capability. These measures assess accessibility at the individual level, factoring in commuters' characteristics and modal attributes (Banister & Berechman, 2001). They can estimate benefits of transport and land-use projects, as discussed in Appendix D.3.3. In an MNL model, the logsum component serves as an accessibility measure, representing the natural logarithm of the MNL probability denominator (Ben-Akiva & Lerman, 1985).

The utility function U_{ij} captures the desirability of mode m for individual i to reach destination j, measuring its utility (Equation G.1):

$$U_{ijm} = U\left(f_m\left(C_{ij}\right), F\left(C_{ij}\right), Z_i, y_i\right) \quad \text{(Equation G.1)}$$

where $f_m\left(C_{ij}\right)$ is the existing accessibility for destination j by mode m for individual i, $F\left(C_{ij}\right)$ represents all alternative accessibilities for individual i, Z_i is a vector of demographic characteristics of individual i and y_i is the income of individual i.

By surveying a large population for RP and SP data, we can measure the expected consumer surplus (CS) for existing and proposed transport systems based on individual perceptions of accessibility (Equation G.2):

$$E(CS_i) = \frac{1}{\alpha_i} E\left(max_j\left(U_{ij}\right)\right) \quad \text{(Equation G.2)}$$

where α_i is the marginal utility of income.

G.2 Including all social opportunity destinations in accessibility analysis

Assessing accessibility involves categorising destinations within a STP as outlined in Appendix D.3. However, merely selecting these destinations in an ad hoc, subjective manner does not fully represent actual travel patterns. It is also essential to evaluate the attractiveness of these destinations. This assessment can be effectively conducted using both RP and SP data. Destinations with higher popularity tend to attract commuters for more extended and frequent trips.

Zhang et al. (2021) propose considering three key factors to determine a destination's attractiveness: travel time, travel frequency and the duration spent at the destination. They present Equation G.3 to calculate destination attractiveness at any given time interval *t*:

$$Attr_{i,t} = \sum_{j=1}^{N_{i,t}} \left(\frac{T_j}{T_{ave}} + \frac{Dur_{ave}}{Dur_j}\right) \quad \text{(Equation G.3)}$$

where:

$Attr_{i,t}$ = attractiveness of a destination i at time interval t

$N_{i,t}$ = number of trips that end at i

T_j = travel time of jth trip that arrives at i

T_{ave} = average travel time of all trips that finish during t

Dur_j = time of duration at i for the jth trip

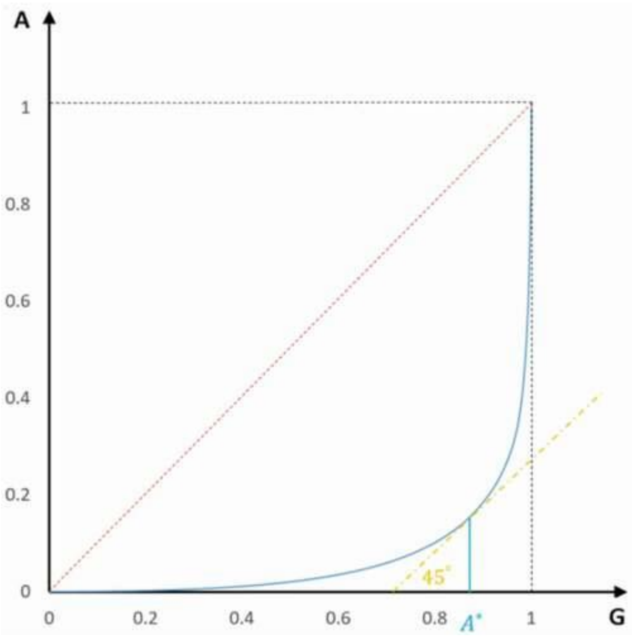
Dur_{ave} = average duration time during t for all trips in the study area

T_j = time difference between boarding and final alighting of the jth trip

Dur_j = time between alighting and next boarding for the same passenger.

To identify popular destinations, the selection criterion method (Louail et al., 2014) is used after computing attractiveness for all destinations. This method involves arranging the attractiveness values in ascending order ($Attr_{1,t} < Attr_{2,t} < Attr_{3,t} < \cdots < Attr_{i,t}$) and plotting them on a Lorenz curve. This curve, with its horizontal axis G representing the cumulative number of destinations and its vertical axis A representing the cumulative percent of attractiveness values, helps identify disparities in destination popularity (Figure G.1).

Figure G.1 Discovering popular destinations based on the Lorenz curve (reprinted from Zhang et al., 2021, p. 728)



As the Lorenz curve reflects data distribution inequality, we can pinpoint a criterion point where the slope is steep enough to reveal major attractive destinations. This involves finding a point A* on the horizontal axis, where its corresponding point G(A*) on the Lorenz curve lies on a 45° tangent line (i.e. slope = 1). The attractiveness of destination A* then represents the central rank of destinations.

Appendix H: Available data

H.1 Socio-economic data details

H.1.1 GSS information on welfare and household features

The GSS has been conducted every 2 years from 2008–2024 and provides extensive information about New Zealanders' life satisfaction and residential satisfaction. Each wave consists of around 12,000 observations and is a rich source for evaluating the relevance of accessibility to the utility of New Zealanders.

H.1.2 HTS information about travel behaviour of households and individuals

The survey has been conducted for the years of 1989/90, 1997/98 and then annually since 2003. For the last survey wave of 2019/2020, a total of 2,194 households were surveyed – each household has many entries for each travel. The survey provides population weights to represent the population of New Zealand and their travel on an average annual basis. The survey itself is conducted over the course of 2 days of travel. The HTS provides data on household vehicle travel with household demographics (Ministry of Transport, 2022). The survey collects data on household travel attributes, including:

- kilometres travelled – distance travelled by individual trips, transport mode, purpose, vehicle occupancy and demographic attributes
- travel mode – walking, cycling, passenger in a vehicle, driving, public transport and motorcycling
- trip purpose – shopping, personal appointments, entertainment, work trips and recreation
- trip duration – length of time spent travelling
- vehicle occupancy – whether the traveller was a driver or a passenger
- demographic attributes– individual attributes such as age and gender.

H.1.3 Census data

New Zealand's Census data provides a comprehensive view of the country's demographic and socio-economic landscape, encompassing a wide range of variables and statistical zones. Key demographic variables include age and household composition, offering insights into population dynamics. We derived information about age groups (and population) from the Census.

H.1.4 Safety data

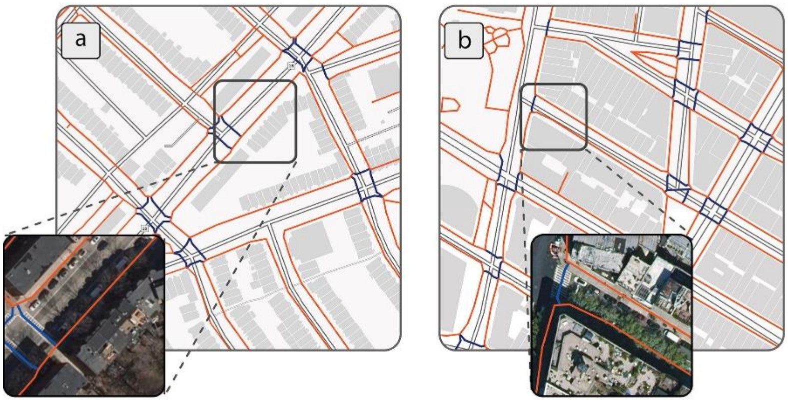
The New Zealand Crime and Victims Survey, a collaborative effort between the Ministry of Justice and New Zealand Police since 2021, provides comprehensive data on New Zealand adults' experiences of crime. Police regularly releases detailed crime statistics, which are made available to the public. This data could be further used for understanding the spatial distribution of victimisation in New Zealand, providing a basis to enrich network data (walking, cycling and public transport) and inform the route choice model.

H.2 Improving walking data using tile2net

Tile2net[40] is a trained semantic segmentation model used to automate mapping of pedestrian infrastructure from aerial imagery. The outputs of tile2net processing are sidewalk, crosswalk and footpath polygons and the generation of pedestrian networks (Figure H.1). This has the potential to provide further refinement to walking impedance function, particularly in the consideration of sidewalk widths for perceived distances.

[40] https://github.com/VIDA-NYU/tile2net

Figure H.1 Mapping pedestrian facilities in Cambridge, MA, and Manhattan by tile2net (reprinted from Hosseini et al., 2023, p. 17)



Since the tile2net library has only been trained in some US cities, there is a chance that the quality of the AI-generated data is not up to the standards for an accessibility measure. Furthermore, as the model requires high-definition aerial imagery (several terabytes for all of New Zealand), processing the images would take an extensive compute time with uncertain accuracy.

H.3 Improving cycling data using complementary data sources

To address the gaps in data, local council data could be used to complement the OSM data. Table H.1 shows some cycling infrastructure data around New Zealand.

Table H.1 Cycling infrastructure data available via open data portal

Layer	Area	Author	Description	Latest update
Cycle Facility Network	Auckland Region	Auckland Transport	The Auckland Cycle Network provides a plan for the development of and investment in a comprehensive cycle network for the region.	2022
PNCC Cycle Network	Palmerston North TLA	Palmerston North City Council	On-road cycle lanes within Palmerston North TLA.	2023
Walking and Cycling Tracks	Marlborough District	-	Walking and cycling tracks and paths. Includes information about dog access, mobility access, walking and cycling information.	2019
City Cycle and Walkways	Gisborne District	Gisborne District Council	Council-maintained walkways, mountain-biking and fitness trails and other popular walking tracks and cycling trails through Gisborne district. References the LINZ walkways dataset.	2019
DP Rangatahi Walkway Cycle	Waikato	Waikato District Council	Datasets associated with the council district plan.	2019
Hawke's Bay Walking, Biking Tracks	Hawke's Bay	Hawke's Bay Regional Council	Indicative of cycleways in Hawke's Bay. Data also includes name, location, status, maintenance and type.	2023
Wellington Region Tracks	Wellington	Greater Wellington Regional Council	Walking and cycling tracks in the Greater Wellington Region, 2016. Created by merging data from various sources.	2020

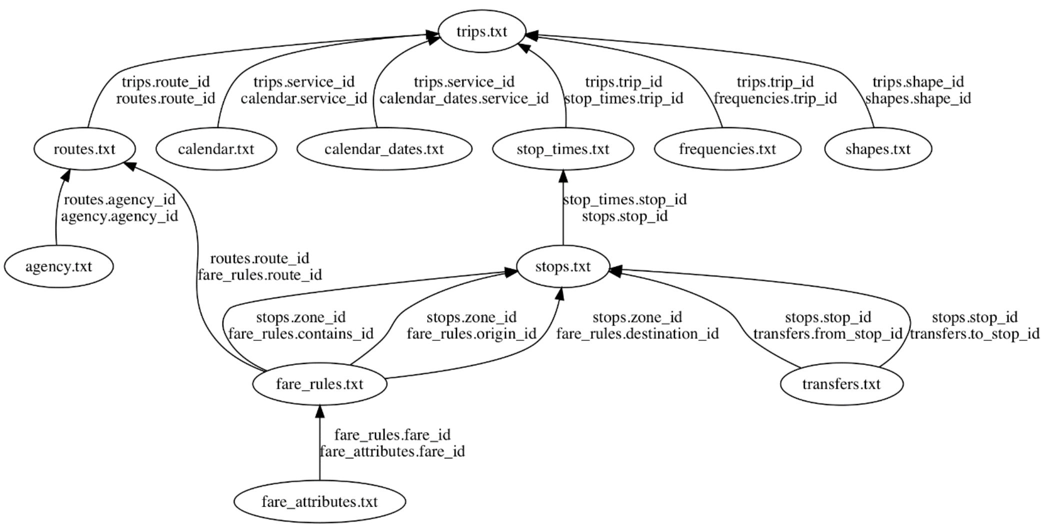
Source: Principal Economics based on data available on open portal (data.govt.nz)

H.4 GTFS data structure depending on data availability

Data collection, manipulation and analysis required for constructing measures of accessibility is extensive – accessibility data is possibly one of the most complex in big data analysis. The accessibility measure is constructed based on the deterrence and saturation functions, with impedance as an input to both. At a high level, these components are combined to derive the single measure of accessibility.

Figure H.2 shows GTFS static files and how they can be related to each other using the key fields.

Figure H.2 GTFS relational data



Source: Principal Economics inspired by Google for Developers (2022b)

Data structure

GTFS Realtime data includes three parts (Google for Developers, 2022a) – trip update (expected arrival/departure time of each trip at each stop in the transit system), vehicle position (similar to automatic vehicle location data and shows the location of active vehicle in the system) and service alerts (information on changes in stops, unforeseen events affecting a station, route or the entire network). Transit authorities broadcast GTFS Realtime data at regular time intervals from 10 to 90 seconds to support navigation apps (Liu & Miller, 2020).

GTFS Realtime data is accessible through the official APIs of Auckland Transport and Metro Christchurch. Greater Wellington has developed GTFS Realtime, but its API remains private. **Error! Reference source not found.** lists all components of Auckland's GTFS Realtime data. (It is important to recognise that GTFS Realtime information varies across cities.) Each column represents a table in a GTFS Realtime dataset.

Table H.2 Available tables and fields in Auckland's GTFS Realtime

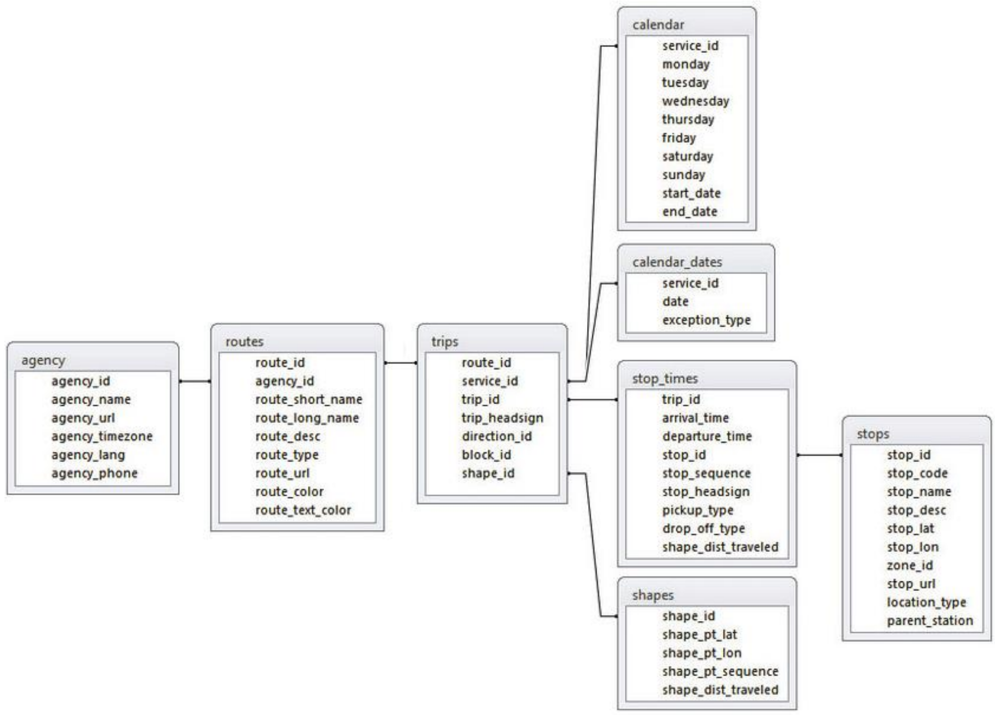
Vehicle	Trip update	Alert
id	id	id
trip.trip_id	trip.trip_id	cause
trip.start_time	trip.start_time	effect
trip.start_date	trip.start_date	header_text.translation
trip.schedule_relationship	trip.schedule_relationship	description_text.translation

Vehicle	Trip update	Alert
trip.route_id	trip.route_id	url.translation
position.latitude	trip.direction_id	informed_entity.0
position.longitude	stop_time_update.stop_sequence	informed_entity.stop_id
position.bearing	stop_time_update.departure.delay	informed_entity.route_id
position.speed	stop_time_update.departure.time	informed_entity.trip
timestamp	stop_time_update.departure.uncertainty	active_period.0
id	stop_time_update.stop_id	active_period.start
label	stop_time_update.schedule_relationship	active_period.end
license_plate	vehicle.id	
trip.direction_id	vehicle.label	
occupancy_status	timestamp	
position.odometer	delay	
	stop_time_update.arrival.delay	
	stop_time_update.arrival.time	
	trip_update.stop_time_update.arrival.uncertainty	
	trip_update.vehicle.license_plate	

Source: Principal Economics based on Auckland Transport's GTFS Realtime API

The arrival and departure dates in the trip update section, essential for updating GTFS static schedules, appear consistent across all cities. The main fields required for the accessibility measurement are trip_id, stop_id, departure_time and arrival_time (see Figure H.3).

Figure H.3 Available tables and fields in GTFS static



Source: Principal Economics

H.5 Data for future network analysis

By utilising AI-powered tools, we can efficiently create indicative street networks for future developments, considering future zoning and transport model outcomes. In section 3.1.1, we highlight that those current approaches to accessibility measures in New Zealand have predominantly been centred on assessing the existing network system. Furthermore, as elucidated in section 1.5, the policy context underscores the criticality of utilising accessibility measures for appraising future scenarios and guiding investment decisions. Achieving this necessitates the generation of network, land-use, socio-economic and socio-demographic data for future scenarios. While socio-economic and socio-demographic data can be extrapolated from projections and land-use data obtained from councils' future zoning plans, a significant challenge has been the absence of network data and the difficulty in its production. This data gap has largely been bridged through the development of new tools and methodologies for creating simulated networks.

Among various tools available, two stand out for their utility: ESRI's ArcGIS generate street networks tool for walking, cycling and driving networks and Conveyal's GTFS Editor tool, which is specialised for public transport. These tools are recommended for generating prospective transport scenarios, facilitating data utilisation to evaluate the impact of different transport investment options. Such evaluations can inform NZTA's business cases and the spatial plans.

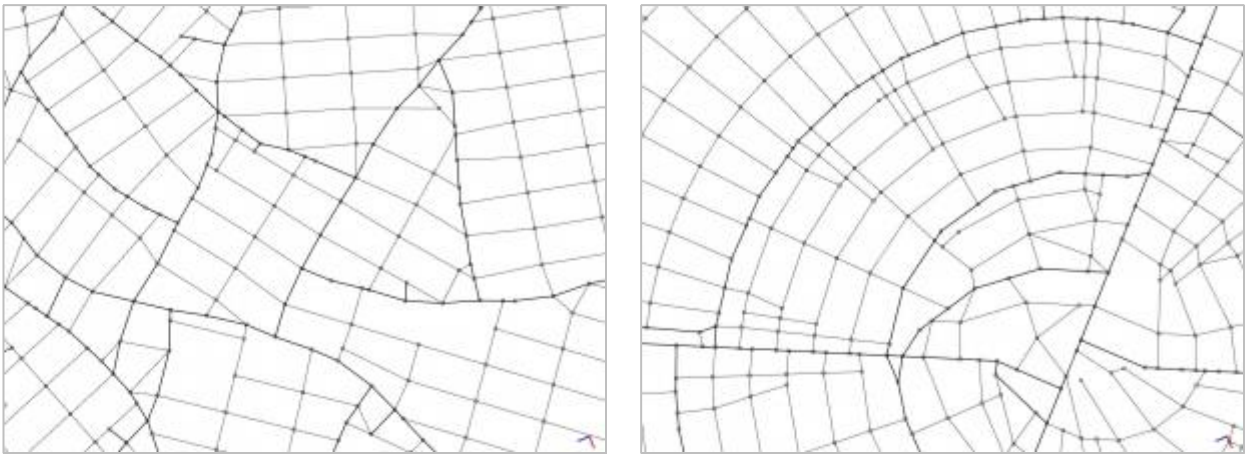
H.5.1 Walk, cycle and drive networks

This section reviews a few tools that could be used to generate walking networks for future developments.

H.5.1.1 ArcGIS generate street networks

The Grow Streets tool can be used to generate typical street networks. Three street patterns (organic, raster and radial) can be arbitrarily combined (Figure H.4).

Figure H.4 Sample street network generated by ArcGIS Grow Streets tool – organic major street pattern and raster minor street pattern (left) and radial pattern for both major and minor streets (right)



Source: https://doc.arcgis.com/en/cityengine/latest/help/help-grow-a-street.htm

A dialog box with a number of settings allows the user to generate street networks according to their needs. The tool can be used to:

- create a street network (deselect all and start the generator)
- extend an existing street network by selecting an existing street layer before growing
- extend part of an existing street network (select streets of an existing street network and apply the tool).

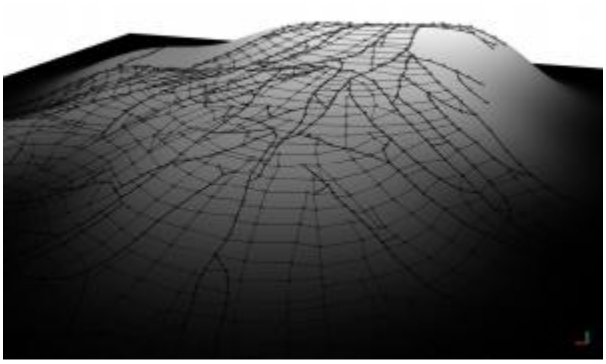
The algorithm distinguishes between major and minor streets. Basically, major streets are created until they enclose an area called a quarter and then the quarter is subdivided by minor streets. The algorithm continues creating major streets and so on.

The wizard creates a user-chosen number of streets. Each new street is added locally to the existing street network depending on a number of settings (where the street pattern is probably the most important):

- Basic settings – consist of the number of streets to generate and the street patterns.
- Pattern-specific settings – define the street patterns more precisely.
- Advanced settings – specify the algorithm behaviour and the algorithm constraints.
- Environment settings – include obstacle maps to restrict the growth area and terrains to adapt the created streets to the elevation.
- Street settings – define the street settings of the created streets.

The basic settings consist of the number of streets, the street patterns and the street lengths. Street patterns need two street lengths – long and short. The organic pattern needs just one length (the short length is used). Using environment maps, you can define boundary conditions such as terrains or obstacles. Moreover, the adaptation of new streets to elevation is active if a terrain is selected and the adaptation is enabled. If the proposed street's length is close to long length, the proposed street is adapted to go along an elevation contour line – in other words, the goal is to create a street with slope 0. If its length is close to short length, the proposed street is adapted in order to go maximally elevation up or downward (Figure H.5).

Figure H.5 Proposed street network adapted to elevation



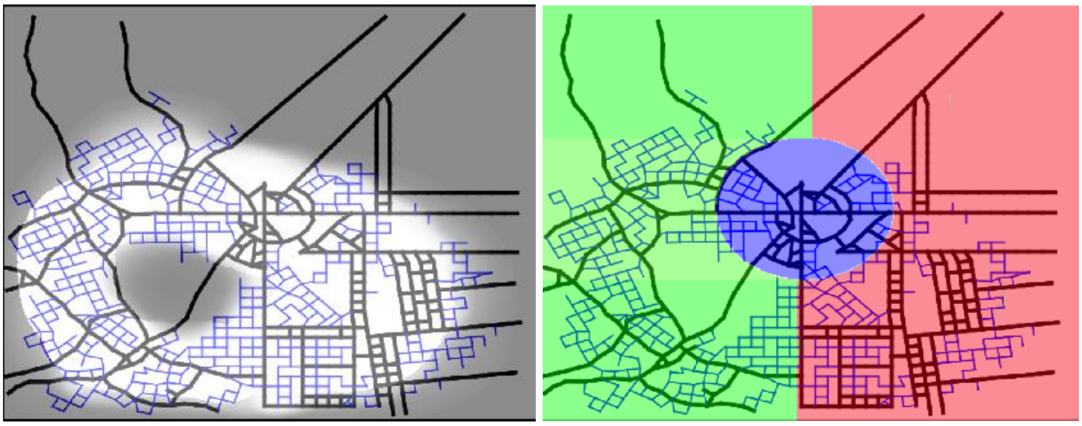
Source: https://doc.arcgis.com/en/cityengine/latest/help/help-grow-a-street.htm

The Grow Streets tool can be used independently and the results can be exported to OSM format. It is recommended the OSM file for the new development area is downloaded first into ArcGIS. Then the Grow Streets tool is used to expand the OSM file into new developments based on design features and assumptions (land use, density etc.) for the proposed development. The final results can be exported back to OSM, which can be used as an input for the accessibility analysis.

H.5.1.2 Procedural City Generation

Another tool that can be used to generate street networks is Procedural City Generation. This project, initiated at Technische Universität Berlin, focuses on creating city roadmaps (using Python). It involves defining rules for vertex addition and connection to form edges. One of the advantages of this tool over the ArcGIS Grow Streets tool is its ability to use inputs such as growth-rule and population-density images to guide roadmap development (Figure H.6). A council's proposed zoning, Stats NZ's projects or Auckland Forecasting Centre's traffic model can be used to generate a population density image for future developments.

Figure H.6 A network generated by the Procedural City Generation library



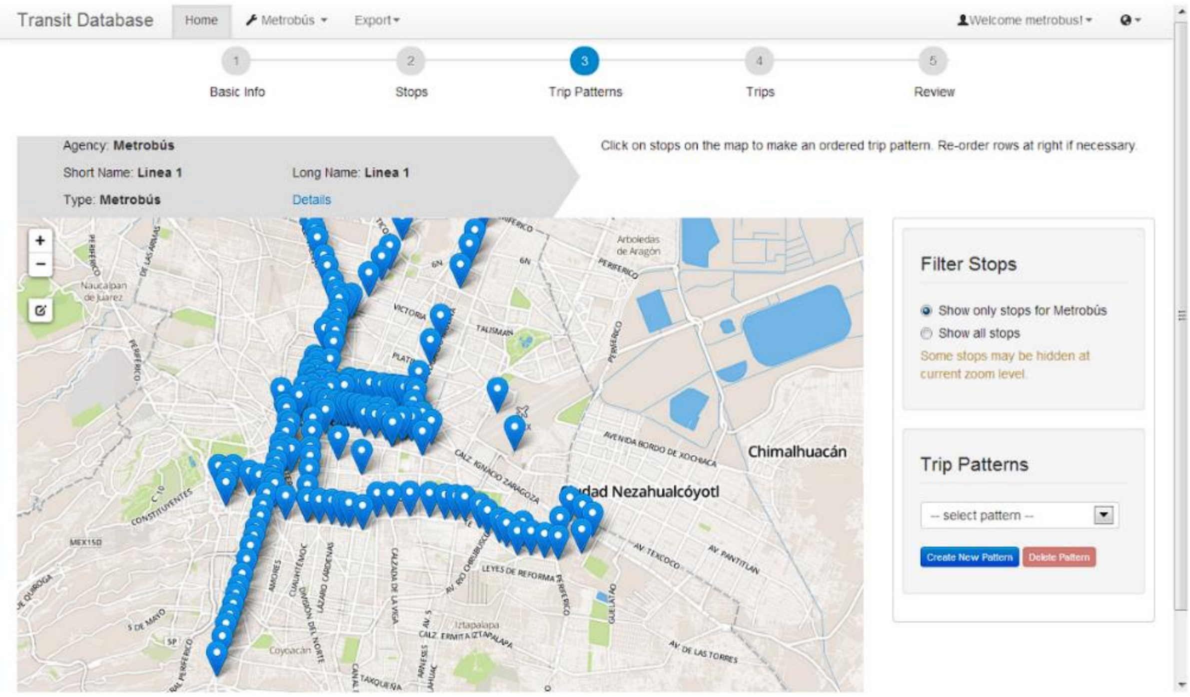
Source: https://josauder.github.io/procedural_city_generation/#getting-it-to-work

In Figure H.6, the background image on the left shows the probabilities that vertices will be connected at all. The lighter it is, the more probable it is that an edge will be built. On the right, the background image describes which growth rule will be used in which area. Blue means the radial rule will be used, red means the grid rule will be used and green means the organic rule will be used. The street network can be merged with OSM data, allowing for automatic vertex connections. The tool's code is open source and under development. However, the last update was in 2016 and it has not been actively maintained since.

H.5.2 Public transport data

The GTFS Editor by Conveyal is a comprehensive tool designed for the creation and editing of GTFS data. The web-based user-friendly interface provides an easy way to interact with this tool and generate new transit services or modify the existing ones to match any proposed scenarios (Figure H.7).

Figure H.7 A snapshot of the GTFS Editor tool



Source: https://github.com/conveyal/gtfs-editor/blob/master/public/docs/user_guide.pdf

After uploading and exiting the GTFS file, this tool allows viewing and exploring public transport services before starting to modify it in five easy steps:

- **Basic Info:** Essential for creating new routes or editing existing ones, including details such as route name and type.
- **Stops/Stations:** Facilitates adding and editing stops or stations on the map, with features such as merging duplicate stops.
- **Trip Patterns:** Enables the creation and modification of trip patterns within a route, including travel time between two stops and dwell times.
- **Trips:** Assists in assigning trips, defining service frequencies or timetable-based schedules.
- **Review:** Offers a final check to ensure complete and accurate route entry.

Overall, this open-source tool allows the user to create and edit GTFS files for any develop scenarios. There are other tools such as Remix Transit that provide similar capabilities. These tools, however, are not free. To the author's knowledge, Auckland Transport has access to Remix Transit.

H.5.3 Land use

Once a proposed street network is generated, it can be complemented by proposed land-use data. Generating the land-use data tends to be simpler because it follows the zoning data and planning regulations. All nine categories of destination type can be created based on the zoning data. However, this process requires some manual work.

H.5.4 Traffic history data

Many traffic models can be used to model traffic flow for a new development area. Traffic models rely on a variety of tools such as Aimsun or Visum. The choice of model and tool depends on the specific requirements of the traffic study but generally these models are considered standard practice. The model's road network data can be obtained from network generator tools and the historical traffic data can be sourced from surrounding neighbourhoods.

H.5.5 Socio-economic data

Socio-economic data can be partly created by future land-use scenarios such as number of jobs and households in an area. Other variables can also be generated by benchmarking against real data. If possible, use real socio-economic data from similar development areas as a reference. This helps in creating realistic data. Finally, statistical methods (using Monte Carlo simulation) can be used for predicting different outcomes based on varied inputs.

Appendix I: Data and methods for accessibility measurement

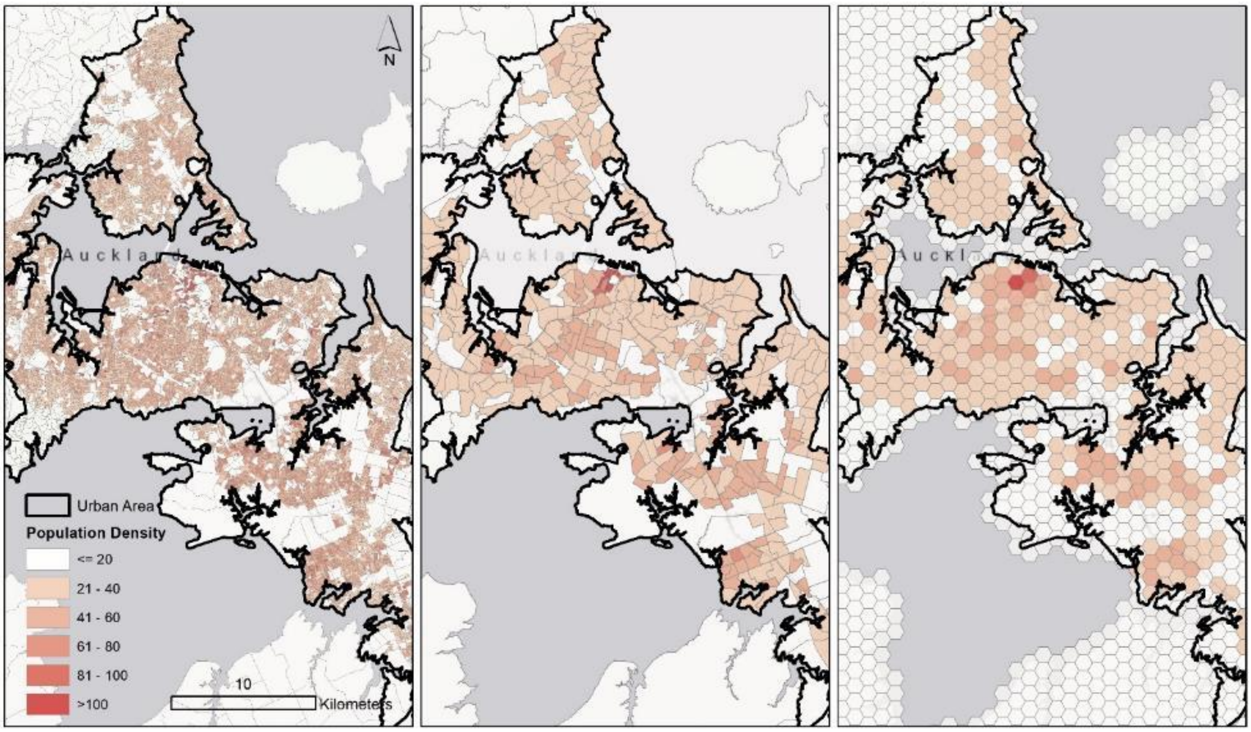
In this appendix, we examine the data and tools commonly used to assess transport accessibility, encompassing a wide range of open data sources and emerging technologies. These variables from datasets and formulas that need to be applied into the tools are informed from chapter 3. The outcomes of this appendix were used to inform our data source and methodology in chapter 4 to:

- identify typical accessibility datasets used in urban areas
- identify how network analytics could consider levels of service and desirability of links
- explain the various ways live and static GTFS files have been used overseas and in New Zealand to inform aspects of spatial accessibility.

I.1 Geographic definition – traffic analysis zone (TAZ)

Census tracts are fundamental building blocks in the realm of transport accessibility analysis. These geographic divisions serve a dual purpose, offering insights into the socio-economic make-up of a region while simultaneously acting as TAZs. Statistical areas provide researchers with detailed socio-economic data. This information is typically sourced from the Census but can also be derived from other sources such as IDI. By breaking down regions into smaller statistical areas, accessibility analysts provide the spatial perspective to transportation analysis. This data helps to identify spatial disparities in access to transportation and opportunities as well as socio-economic disparities. In essence, TAZs act as the canvases upon which accessibility analysts paint the intricate portrait of urban transport. For illustration, we present Auckland's population density map across different TAZ levels in Figure I.1.

Figure I.1 Population density map of Auckland at different TAZ levels – SA1s, SA2s and hexagons of 1 km²



Source: Principal Economics based on Census 2018 data

Stats NZ employs various statistical zones to disseminate data (Stats NZ, 2022). The smallest unit in the hierarchy, a meshblock, typically contains around 80–120 dwellings. This represents the most granular level of data collection and is often used for analysing local demographics, housing types and socio-economic disparities. However, meshblock boundaries can be sensitive to population changes and may not always reflect community boundaries, leading to challenges in analysing local dynamics. While the inferences from these maps are similar at a high level, small differences at more granular geographic levels lead to significant differences in their usefulness for informing decisions (and explaining population welfare).

An SA1 – an aggregation of meshblocks – typically contains around 400–1,000 people. It offers a broader view of population demographics and is often used for analysing housing affordability, educational attainment and employment patterns. The larger size of an SA1 compared to a meshblock may mask underlying inequalities within the area, requiring careful interpretation of data.

An SA2 – an aggregation of SA1s – generally contains around 2,000–20,000 people. It provides a regional view of population trends and is often used for analysing migration patterns, economic activity and infrastructure needs. As the largest unit, an SA2 may not capture the nuances of smaller communities within the area, and researchers may need to disaggregate data further for in-depth analysis.

H3 is a geospatial indexing system that partitions the world into hexagonal cells. H3 is open source under the Apache 2 licence. H3 cells are topological hexagons in the sense that they have six neighbours in the H3 grid. The size of H3 cells can vary depending on the objectives of a project.

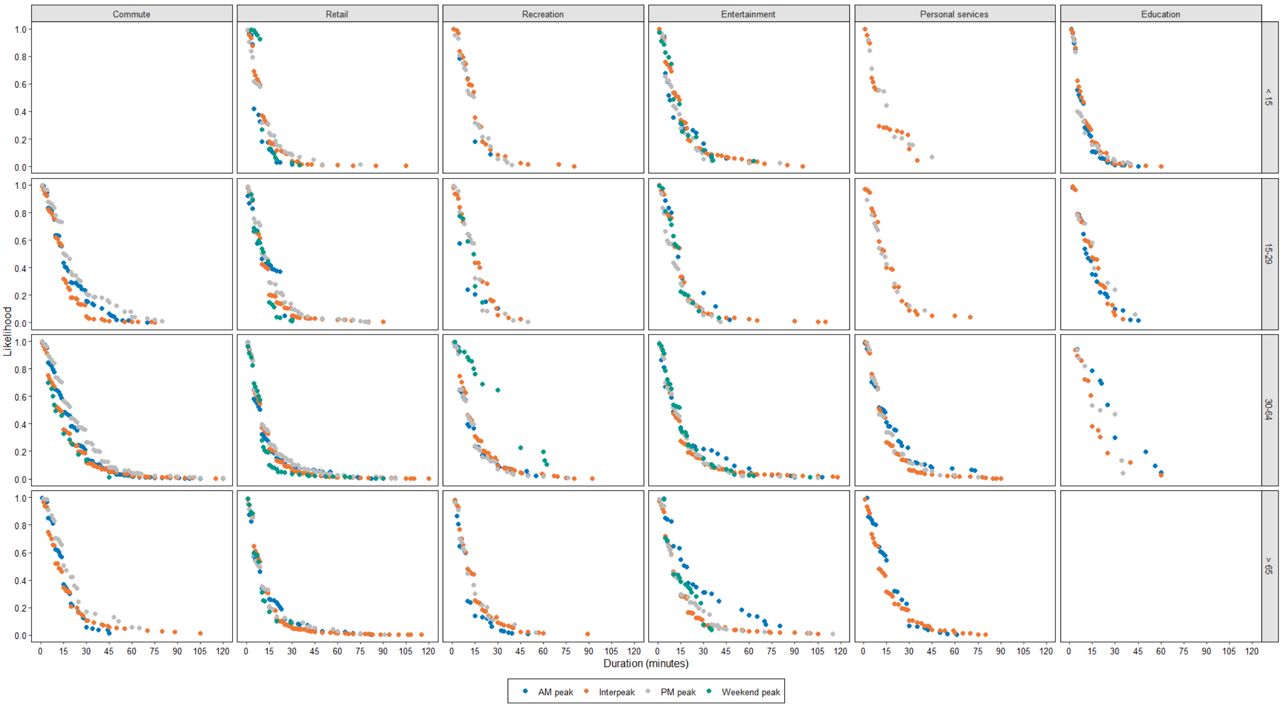
Torshizian and Grimes (2014) investigated the most appropriate definition of neighbourhood boundaries by comparing the explanatory power of various crowding and density measures defined at different geographic levels for residential satisfaction, which accounts for perceived understanding of the factors of space. They used three waves of GSS between 2006 and 2010, which provides information on socio-economic features and housing and neighbourhood characteristics. That study controlled for the impact of other factors and used goodness of fit measures to identify the most useful measures of crowding across space. They also considered both administrative and dynamic definitions of geographic boundaries. Their results suggested that a 5-minute walking distance provides the best definition for neighbourhood boundaries. Across the administrative definitions, their results suggested that area unit (suburb) boundaries are consistent with individuals' understanding of the boundaries of their neighbourhood. This study provides a useful approach for this report's consideration of the most suitable measure of accessibility.

In conclusion, statistical areas are integral to transport accessibility analysis. They provide a structured approach to data aggregation and interpretation, balancing detail with manageability. We recommend using SA1 for the accessibility measure. This choice offers a practical balance between detailed socio-economic data and the computational resources needed for accessibility analysis. Additionally, SA1 codes facilitate linking accessibility analysis results with other datasets.

Appendix J: Distance decay results

Figure J.1 shows distance decay by travel time.

Figure J.1 Distance decay for each travel destination by travel time



Source: Principal Economics

Table J.1 shows the estimation results for the distance decay function. GC is the generalised cost or the combined distance variables, measuring duration and the cost of travel for each mode. The second column shows our estimated coefficients and the standard errors (SDs) are shown in brackets. The third column shows the statistical significance (*** p<.01, ** p<.05, * p<.1).

Table J.1 Estimated results – distance decay function

Variables	Estimate and SD	Significance
GC	-0.063 (0.003)	***
GC squared	0.000 (0.000)	***
Purpose		
Education	-0.403 (0.029)	***
Entertainment	-0.337 (0.020)	***
Errands	-0.258 (0.034)	***
Home	-0.505 (0.075)	***
NA	-0.562 (0.730)	
Other	-0.538 (0.061)	***
Personal services	-0.286 (0.026)	***
Recreation	-0.183 (0.026)	***

Variables	Estimate and SD	Significance
Retail	-0.412 (0.019)	***
Transport	-0.319 (0.021)	***
Travel	0.182 (0.068)	**
Work	-0.335 (0.025)	***
Purpose x GC		
Education	0.005 (0.001)	***
Entertainment	0.002 (0.001)	***
Errands	-0.012 (0.001)	***
Home	0.004 (0.003)	***
NA	0.030 (0.044)	
Other	0.004 (0.002)	***
Personal services	-0.004 (0.001)	
Recreation	-0.008 (0.001)	
Retail	-0.009 (0.001)	*
Transport	-0.007 (0.001)	***
Travel	0.007 (0.001)	***
Work	0.001 (0.001)	***
Time		
interpeak	-0.033 (0.017)	***
other	-0.006 (0.018)	***
pm_peak	0.091 (0.021)	
wkd_peak	0.193 (0.038)	
Time x GC		
interpeak	0.001 (0.001)	***
other	0.005 (0.001)	***
pm_peak	-0.000 (0.001)	***
wkd_peak	-0.019 (0.001)	***
Income		
1	-0.124 (0.016)	***
2	0.019 (0.016)	
3	0.085 (0.024)	***
4	-0.016 (0.021)	
5	-0.006 (0.021)	
Income x GC		
1	0.039 (0.000)	***
2	0.012 (0.001)	***
3	0.010 (0.001)	***
4	0.008 (0.001)	***
5	0.006 (0.001)	***

Variables	Estimate and SD	Significance
Region		
Wellington	-0.120 (0.012)	***
Region x GC		
09 WELLINGTON	-0.001 (0.000)	***
Age		
30–64	-0.079 (0.015)	***
<15	-0.111 (0.024)	***
>65	-0.021 (0.020)	
NA	-0.270 (0.048)	
Age x GC		
30–64	0.007 (0.000)	***
<15	0.006 (0.001)	***
>65	0.002 (0.001)	***
NA	0.011 (0.002)	***
Mode		
Drive	0.127 (0.072)	***
Public transport	0.630 (0.081)	***
Walk	0.117 (0.073)	***
Mode x GC		
Drive	-0.002 (0.003)	***
Public transport	-0.000 (0.003)	***
Walk	-0.036 (0.003)	***
Intercept	0.130 (0.075)	
Number of observations	41060	
Adjusted R-squared	0.57	

Source: Principal Economics

Table J.2 shows the estimated decay for Auckland across different purposes by travel time, income decile (I), age (A) (1 = 15–29, 2 = 29–64, 3 = 65 and over) and mode (M) (PT = public transport).

Table J.2 Estimated decay for each travel purposes by time, income (I), age (A), and mode (M) for Auckland

Time	I	A	M	Commute	Education	Entertainment	Personal services	Recreation	Retail	Work
AM	1	1	Cycle	-0.006	-0.002	-0.001	-0.005	-0.007	-0.007	-0.001
AM	1	1	Drive	-0.025	-0.021	-0.02	-0.024	-0.025	-0.025	-0.019
AM	1	1	PT	-0.017	-0.013	-0.012	-0.016	-0.017	-0.017	-0.011
AM	1	1	Walk	-0.067	-0.063	-0.062	-0.066	-0.067	-0.067	-0.061
AM	1	2	Cycle	-0.001	0.003	0.004	-0.001	-0.002	-0.002	0.004
AM	1	2	Drive	-0.02	-0.016	-0.015	-0.019	-0.021	-0.021	-0.015
AM	1	2	PT	-0.012	-0.008	-0.007	-0.011	-0.013	-0.013	-0.007

Time	I	A	M	Commute	Education	Entertainment	Personal services	Recreation	Retail	Work
AM	1	2	Walk	-0.062	-0.058	-0.057	-0.061	-0.063	-0.063	-0.057
AM	1	3	Cycle	-0.007	-0.003	-0.002	-0.006	-0.008	-0.008	-0.002
AM	1	3	Drive	-0.026	-0.022	-0.021	-0.025	-0.027	-0.027	-0.021
AM	1	3	PT	-0.018	-0.014	-0.013	-0.017	-0.018	-0.019	-0.013
AM	1	3	Walk	-0.068	-0.064	-0.063	-0.067	-0.069	-0.069	-0.063
AM	2	1	Cycle	-0.038	-0.034	-0.033	-0.037	-0.039	-0.039	-0.033
AM	2	1	Drive	-0.057	-0.053	-0.052	-0.056	-0.058	-0.058	-0.052
AM	2	1	PT	-0.049	-0.045	-0.044	-0.048	-0.049	-0.049	-0.044
AM	2	1	Walk	-0.099	-0.095	-0.094	-0.098	-0.099	-0.099	-0.094
AM	2	2	Cycle	-0.034	-0.03	-0.029	-0.033	-0.034	-0.034	-0.028
AM	2	2	Drive	-0.052	-0.048	-0.047	-0.051	-0.053	-0.053	-0.047
AM	2	2	PT	-0.044	-0.04	-0.039	-0.043	-0.045	-0.045	-0.039
AM	2	2	Walk	-0.094	-0.09	-0.089	-0.093	-0.095	-0.095	-0.089
AM	2	3	Cycle	-0.04	-0.035	-0.035	-0.039	-0.04	-0.04	-0.034
AM	2	3	Drive	-0.058	-0.054	-0.053	-0.057	-0.059	-0.059	-0.053
AM	2	3	PT	-0.05	-0.046	-0.045	-0.049	-0.051	-0.051	-0.045
AM	2	3	Walk	-0.1	-0.096	-0.095	-0.099	-0.101	-0.101	-0.095
AM	3	1	Cycle	-0.037	-0.033	-0.032	-0.036	-0.038	-0.038	-0.032
AM	3	1	Drive	-0.056	-0.052	-0.051	-0.055	-0.056	-0.056	-0.05
AM	3	1	PT	-0.048	-0.044	-0.043	-0.047	-0.048	-0.048	-0.042
AM	3	1	Walk	-0.098	-0.094	-0.093	-0.097	-0.098	-0.098	-0.092
AM	3	2	Cycle	-0.032	-0.028	-0.027	-0.032	-0.033	-0.033	-0.027
AM	3	2	Drive	-0.051	-0.047	-0.046	-0.05	-0.052	-0.052	-0.046
AM	3	2	PT	-0.043	-0.039	-0.038	-0.042	-0.044	-0.044	-0.038
AM	3	2	Walk	-0.093	-0.089	-0.088	-0.092	-0.094	-0.094	-0.088
AM	3	3	Cycle	-0.038	-0.034	-0.033	-0.037	-0.039	-0.039	-0.033
AM	3	3	Drive	-0.057	-0.053	-0.052	-0.056	-0.058	-0.058	-0.052
AM	3	3	PT	-0.049	-0.045	-0.044	-0.048	-0.049	-0.05	-0.044
AM	3	3	Walk	-0.099	-0.095	-0.094	-0.098	-0.1	-0.1	-0.094
AM	4	1	Cycle	-0.04	-0.036	-0.035	-0.039	-0.041	-0.041	-0.035
AM	4	1	Drive	-0.059	-0.055	-0.054	-0.058	-0.06	-0.06	-0.054
AM	4	1	PT	-0.051	-0.047	-0.046	-0.05	-0.051	-0.051	-0.046
AM	4	1	Walk	-0.101	-0.097	-0.096	-0.1	-0.102	-0.102	-0.096
AM	4	2	Cycle	-0.036	-0.032	-0.031	-0.035	-0.036	-0.036	-0.03
AM	4	2	Drive	-0.054	-0.05	-0.049	-0.054	-0.055	-0.055	-0.049
AM	4	2	PT	-0.046	-0.042	-0.041	-0.045	-0.047	-0.047	-0.041
AM	4	2	Walk	-0.096	-0.092	-0.091	-0.095	-0.097	-0.097	-0.091
AM	4	3	Cycle	-0.042	-0.038	-0.037	-0.041	-0.042	-0.042	-0.036
AM	4	3	Drive	-0.06	-0.056	-0.055	-0.059	-0.061	-0.061	-0.055

Time	I	A	M	Commute	Education	Entertainment	Personal services	Recreation	Retail	Work
AM	4	3	PT	-0.052	-0.048	-0.047	-0.051	-0.053	-0.053	-0.047
AM	4	3	Walk	-0.102	-0.098	-0.097	-0.101	-0.103	-0.103	-0.097
AM	5	1	Cycle	-0.04	-0.036	-0.035	-0.039	-0.041	-0.041	-0.035
AM	5	1	Drive	-0.059	-0.055	-0.054	-0.058	-0.06	-0.06	-0.054
AM	5	1	PT	-0.051	-0.047	-0.046	-0.05	-0.052	-0.052	-0.046
AM	5	1	Walk	-0.101	-0.097	-0.096	-0.1	-0.102	-0.102	-0.096
AM	5	2	Cycle	-0.036	-0.032	-0.031	-0.035	-0.036	-0.036	-0.03
AM	5	2	Drive	-0.055	-0.05	-0.05	-0.054	-0.055	-0.055	-0.049
AM	5	2	PT	-0.046	-0.042	-0.041	-0.045	-0.047	-0.047	-0.041
AM	5	2	Walk	-0.096	-0.092	-0.091	-0.096	-0.097	-0.097	-0.091
AM	5	3	Cycle	-0.042	-0.038	-0.037	-0.041	-0.042	-0.042	-0.036
AM	5	3	Drive	-0.06	-0.056	-0.055	-0.06	-0.061	-0.061	-0.055
AM	5	3	PT	-0.052	-0.048	-0.047	-0.051	-0.053	-0.053	-0.047
AM	5	3	Walk	-0.102	-0.098	-0.097	-0.101	-0.103	-0.103	-0.097
Inter	1	1	Cycle	-0.005	-0.001	0	-0.005	-0.006	-0.006	0
Inter	1	1	Drive	-0.024	-0.02	-0.019	-0.023	-0.025	-0.025	-0.019
Inter	1	1	PT	-0.016	-0.012	-0.011	-0.015	-0.017	-0.017	-0.011
Inter	1	1	Walk	-0.066	-0.062	-0.061	-0.065	-0.067	-0.067	-0.061
Inter	1	2	Cycle	-0.001	0.003	0.004	0	-0.001	-0.001	0.005
Inter	1	2	Drive	-0.02	-0.015	-0.015	-0.019	-0.02	-0.02	-0.014
Inter	1	2	PT	-0.011	-0.007	-0.006	-0.01	-0.012	-0.012	-0.006
Inter	1	2	Walk	-0.061	-0.057	-0.056	-0.061	-0.062	-0.062	-0.056
Inter	1	3	Cycle	-0.007	-0.003	-0.002	-0.006	-0.007	-0.007	-0.001
Inter	1	3	Drive	-0.026	-0.021	-0.02	-0.025	-0.026	-0.026	-0.02
Inter	1	3	PT	-0.017	-0.013	-0.012	-0.016	-0.018	-0.018	-0.012
Inter	1	3	Walk	-0.067	-0.063	-0.062	-0.066	-0.068	-0.068	-0.062
Inter	2	1	Cycle	-0.038	-0.034	-0.033	-0.037	-0.038	-0.038	-0.032
Inter	2	1	Drive	-0.056	-0.052	-0.051	-0.055	-0.057	-0.057	-0.051
Inter	2	1	PT	-0.048	-0.044	-0.043	-0.047	-0.049	-0.049	-0.043
Inter	2	1	Walk	-0.098	-0.094	-0.093	-0.097	-0.099	-0.099	-0.093
Inter	2	2	Cycle	-0.033	-0.029	-0.028	-0.032	-0.034	-0.034	-0.028
Inter	2	2	Drive	-0.052	-0.048	-0.047	-0.051	-0.052	-0.052	-0.046
Inter	2	2	PT	-0.044	-0.039	-0.039	-0.043	-0.044	-0.044	-0.038
Inter	2	2	Walk	-0.094	-0.09	-0.089	-0.093	-0.094	-0.094	-0.088
Inter	2	3	Cycle	-0.039	-0.035	-0.034	-0.038	-0.039	-0.039	-0.034
Inter	2	3	Drive	-0.058	-0.054	-0.053	-0.057	-0.058	-0.058	-0.052
Inter	2	3	PT	-0.05	-0.045	-0.045	-0.049	-0.05	-0.05	-0.044
Inter	2	3	Walk	-0.1	-0.095	-0.095	-0.099	-0.1	-0.1	-0.094
Inter	3	1	Cycle	-0.036	-0.032	-0.031	-0.036	-0.037	-0.037	-0.031

Time	I	A	M	Commute	Education	Entertainment	Personal services	Recreation	Retail	Work
Inter	3	1	Drive	-0.055	-0.051	-0.05	-0.054	-0.056	-0.056	-0.05
Inter	3	1	PT	-0.047	-0.043	-0.042	-0.046	-0.048	-0.048	-0.042
Inter	3	1	Walk	-0.097	-0.093	-0.092	-0.096	-0.098	-0.098	-0.092
Inter	3	2	Cycle	-0.032	-0.028	-0.027	-0.031	-0.032	-0.032	-0.026
Inter	3	2	Drive	-0.051	-0.046	-0.046	-0.05	-0.051	-0.051	-0.045
Inter	3	2	PT	-0.042	-0.038	-0.037	-0.041	-0.043	-0.043	-0.037
Inter	3	2	Walk	-0.092	-0.088	-0.087	-0.092	-0.093	-0.093	-0.087
Inter	3	3	Cycle	-0.038	-0.034	-0.033	-0.037	-0.038	-0.038	-0.032
Inter	3	3	Drive	-0.057	-0.052	-0.051	-0.056	-0.057	-0.057	-0.051
Inter	3	3	PT	-0.048	-0.044	-0.043	-0.047	-0.049	-0.049	-0.043
Inter	3	3	Walk	-0.098	-0.094	-0.093	-0.097	-0.099	-0.099	-0.093
Inter	4	1	Cycle	-0.04	-0.036	-0.035	-0.039	-0.04	-0.04	-0.034
Inter	4	1	Drive	-0.058	-0.054	-0.053	-0.058	-0.059	-0.059	-0.053
Inter	4	1	PT	-0.05	-0.046	-0.045	-0.049	-0.051	-0.051	-0.045
Inter	4	1	Walk	-0.1	-0.096	-0.095	-0.099	-0.101	-0.101	-0.095
Inter	4	2	Cycle	-0.035	-0.031	-0.03	-0.034	-0.036	-0.036	-0.03
Inter	4	2	Drive	-0.054	-0.05	-0.049	-0.053	-0.054	-0.054	-0.048
Inter	4	2	PT	-0.046	-0.042	-0.041	-0.045	-0.046	-0.046	-0.04
Inter	4	2	Walk	-0.096	-0.092	-0.091	-0.095	-0.096	-0.096	-0.09
Inter	4	3	Cycle	-0.041	-0.037	-0.036	-0.04	-0.042	-0.042	-0.036
Inter	4	3	Drive	-0.06	-0.056	-0.055	-0.059	-0.06	-0.06	-0.054
Inter	4	3	PT	-0.052	-0.047	-0.047	-0.051	-0.052	-0.052	-0.046
Inter	4	3	Walk	-0.102	-0.098	-0.097	-0.101	-0.102	-0.102	-0.096
Inter	5	1	Cycle	-0.04	-0.036	-0.035	-0.039	-0.04	-0.04	-0.034
Inter	5	1	Drive	-0.059	-0.054	-0.054	-0.058	-0.059	-0.059	-0.053
Inter	5	1	PT	-0.05	-0.046	-0.045	-0.049	-0.051	-0.051	-0.045
Inter	5	1	Walk	-0.1	-0.096	-0.095	-0.1	-0.101	-0.101	-0.095
Inter	5	2	Cycle	-0.035	-0.031	-0.03	-0.034	-0.036	-0.036	-0.03
Inter	5	2	Drive	-0.054	-0.05	-0.049	-0.053	-0.054	-0.054	-0.049
Inter	5	2	PT	-0.046	-0.042	-0.041	-0.045	-0.046	-0.046	-0.04
Inter	5	2	Walk	-0.096	-0.092	-0.091	-0.095	-0.096	-0.096	-0.09
Inter	5	3	Cycle	-0.041	-0.037	-0.036	-0.04	-0.042	-0.042	-0.036
Inter	5	3	Drive	-0.06	-0.056	-0.055	-0.059	-0.06	-0.06	-0.054
Inter	5	3	PT	-0.052	-0.048	-0.047	-0.051	-0.052	-0.052	-0.046
Inter	5	3	Walk	-0.102	-0.098	-0.097	-0.101	-0.102	-0.102	-0.096
Other	1	1	Cycle	-0.005	-0.001	0	-0.004	-0.006	-0.006	0
Other	1	1	Drive	-0.024	-0.02	-0.019	-0.023	-0.025	-0.025	-0.019
Other	1	1	PT	-0.016	-0.012	-0.011	-0.015	-0.016	-0.016	-0.01
Other	1	1	Walk	-0.066	-0.062	-0.061	-0.065	-0.066	-0.066	-0.061

Time	I	A	M	Commute	Education	Entertainment	Personal services	Recreation	Retail	Work
Other	1	2	Cycle	-0.001	0.003	0.004	0	-0.001	-0.001	0.005
Other	1	2	Drive	-0.019	-0.015	-0.014	-0.018	-0.02	-0.02	-0.014
Other	1	2	PT	-0.011	-0.007	-0.006	-0.01	-0.012	-0.012	-0.006
Other	1	2	Walk	-0.061	-0.057	-0.056	-0.06	-0.062	-0.062	-0.056
Other	1	3	Cycle	-0.007	-0.002	-0.002	-0.006	-0.007	-0.007	-0.001
Other	1	3	Drive	-0.025	-0.021	-0.02	-0.024	-0.026	-0.026	-0.02
Other	1	3	PT	-0.017	-0.013	-0.012	-0.016	-0.018	-0.018	-0.012
Other	1	3	Walk	-0.067	-0.063	-0.062	-0.066	-0.068	-0.068	-0.062
Other	2	1	Cycle	-0.037	-0.033	-0.032	-0.037	-0.038	-0.038	-0.032
Other	2	1	Drive	-0.056	-0.052	-0.051	-0.055	-0.057	-0.057	-0.051
Other	2	1	PT	-0.048	-0.044	-0.043	-0.047	-0.049	-0.049	-0.043
Other	2	1	Walk	-0.098	-0.094	-0.093	-0.097	-0.099	-0.099	-0.093
Other	2	2	Cycle	-0.033	-0.029	-0.028	-0.032	-0.033	-0.033	-0.027
Other	2	2	Drive	-0.052	-0.047	-0.047	-0.051	-0.052	-0.052	-0.046
Other	2	2	PT	-0.043	-0.039	-0.038	-0.042	-0.044	-0.044	-0.038
Other	2	2	Walk	-0.094	-0.089	-0.089	-0.093	-0.094	-0.094	-0.088
Other	2	3	Cycle	-0.039	-0.035	-0.034	-0.038	-0.039	-0.039	-0.033
Other	2	3	Drive	-0.058	-0.053	-0.053	-0.057	-0.058	-0.058	-0.052
Other	2	3	PT	-0.049	-0.045	-0.044	-0.048	-0.05	-0.05	-0.044
Other	2	3	Walk	-0.099	-0.095	-0.094	-0.098	-0.1	-0.1	-0.094
Other	3	1	Cycle	-0.036	-0.032	-0.031	-0.035	-0.037	-0.037	-0.031
Other	3	1	Drive	-0.055	-0.051	-0.05	-0.054	-0.056	-0.056	-0.05
Other	3	1	PT	-0.047	-0.043	-0.042	-0.046	-0.047	-0.047	-0.042
Other	3	1	Walk	-0.097	-0.093	-0.092	-0.096	-0.097	-0.097	-0.092
Other	3	2	Cycle	-0.032	-0.028	-0.027	-0.031	-0.032	-0.032	-0.026
Other	3	2	Drive	-0.05	-0.046	-0.045	-0.049	-0.051	-0.051	-0.045
Other	3	2	PT	-0.042	-0.038	-0.037	-0.041	-0.043	-0.043	-0.037
Other	3	2	Walk	-0.092	-0.088	-0.087	-0.091	-0.093	-0.093	-0.087
Other	3	3	Cycle	-0.038	-0.033	-0.033	-0.037	-0.038	-0.038	-0.032
Other	3	3	Drive	-0.056	-0.052	-0.051	-0.055	-0.057	-0.057	-0.051
Other	3	3	PT	-0.048	-0.044	-0.043	-0.047	-0.049	-0.049	-0.043
Other	3	3	Walk	-0.098	-0.094	-0.093	-0.097	-0.099	-0.099	-0.093
Other	4	1	Cycle	-0.04	-0.035	-0.035	-0.039	-0.04	-0.04	-0.034
Other	4	1	Drive	-0.058	-0.054	-0.053	-0.057	-0.059	-0.059	-0.053
Other	4	1	PT	-0.05	-0.046	-0.045	-0.049	-0.051	-0.051	-0.045
Other	4	1	Walk	-0.1	-0.096	-0.095	-0.099	-0.101	-0.101	-0.095
Other	4	2	Cycle	-0.035	-0.031	-0.03	-0.034	-0.035	-0.035	-0.03
Other	4	2	Drive	-0.054	-0.05	-0.049	-0.053	-0.054	-0.054	-0.048
Other	4	2	PT	-0.046	-0.041	-0.04	-0.045	-0.046	-0.046	-0.04

Time	I	A	M	Commute	Education	Entertainment	Personal services	Recreation	Retail	Work
Other	4	2	Walk	-0.096	-0.091	-0.091	-0.095	-0.096	-0.096	-0.09
Other	4	3	Cycle	-0.041	-0.037	-0.036	-0.04	-0.041	-0.041	-0.035
Other	4	3	Drive	-0.06	-0.055	-0.055	-0.059	-0.06	-0.06	-0.054
Other	4	3	PT	-0.051	-0.047	-0.046	-0.05	-0.052	-0.052	-0.046
Other	4	3	Walk	-0.102	-0.097	-0.096	-0.101	-0.102	-0.102	-0.096
Other	5	1	Cycle	-0.04	-0.035	-0.035	-0.039	-0.04	-0.04	-0.034
Other	5	1	Drive	-0.058	-0.054	-0.053	-0.057	-0.059	-0.059	-0.053
Other	5	1	PT	-0.05	-0.046	-0.045	-0.049	-0.051	-0.051	-0.045
Other	5	1	Walk	-0.1	-0.096	-0.095	-0.099	-0.101	-0.101	-0.095
Other	5	2	Cycle	-0.035	-0.031	-0.03	-0.034	-0.035	-0.036	-0.03
Other	5	2	Drive	-0.054	-0.05	-0.049	-0.053	-0.054	-0.054	-0.048
Other	5	2	PT	-0.046	-0.041	-0.041	-0.045	-0.046	-0.046	-0.04
Other	5	2	Walk	-0.096	-0.092	-0.091	-0.095	-0.096	-0.096	-0.09
Other	5	3	Cycle	-0.041	-0.037	-0.036	-0.04	-0.041	-0.041	-0.036
Other	5	3	Drive	-0.06	-0.056	-0.055	-0.059	-0.06	-0.06	-0.054
Other	5	3	PT	-0.052	-0.047	-0.046	-0.051	-0.052	-0.052	-0.046
Other	5	3	Walk	-0.102	-0.097	-0.097	-0.101	-0.102	-0.102	-0.096
PM	1	1	Cycle	-0.005	-0.001	0	-0.004	-0.006	-0.006	0
PM	1	1	Drive	-0.024	-0.02	-0.019	-0.023	-0.025	-0.025	-0.019
PM	1	1	PT	-0.016	-0.012	-0.011	-0.015	-0.016	-0.016	-0.011
PM	1	1	Walk	-0.066	-0.062	-0.061	-0.065	-0.067	-0.067	-0.061
PM	1	2	Cycle	-0.001	0.003	0.004	0	-0.001	-0.001	0.005
PM	1	2	Drive	-0.02	-0.015	-0.014	-0.019	-0.02	-0.02	-0.014
PM	1	2	PT	-0.011	-0.007	-0.006	-0.01	-0.012	-0.012	-0.006
PM	1	2	Walk	-0.061	-0.057	-0.056	-0.06	-0.062	-0.062	-0.056
PM	1	3	Cycle	-0.007	-0.003	-0.002	-0.006	-0.007	-0.007	-0.001
PM	1	3	Drive	-0.025	-0.021	-0.02	-0.024	-0.026	-0.026	-0.02
PM	1	3	PT	-0.017	-0.013	-0.012	-0.016	-0.018	-0.018	-0.012
PM	1	3	Walk	-0.067	-0.063	-0.062	-0.066	-0.068	-0.068	-0.062
PM	2	1	Cycle	-0.038	-0.033	-0.033	-0.037	-0.038	-0.038	-0.032
PM	2	1	Drive	-0.056	-0.052	-0.051	-0.055	-0.057	-0.057	-0.051
PM	2	1	PT	-0.048	-0.044	-0.043	-0.047	-0.049	-0.049	-0.043
PM	2	1	Walk	-0.098	-0.094	-0.093	-0.097	-0.099	-0.099	-0.093
PM	2	2	Cycle	-0.033	-0.029	-0.028	-0.032	-0.033	-0.033	-0.028
PM	2	2	Drive	-0.052	-0.048	-0.047	-0.051	-0.052	-0.052	-0.046
PM	2	2	PT	-0.044	-0.039	-0.039	-0.043	-0.044	-0.044	-0.038
PM	2	2	Walk	-0.094	-0.089	-0.089	-0.093	-0.094	-0.094	-0.088
PM	2	3	Cycle	-0.039	-0.035	-0.034	-0.038	-0.039	-0.039	-0.034
PM	2	3	Drive	-0.058	-0.054	-0.053	-0.057	-0.058	-0.058	-0.052

Time	I	A	M	Commute	Education	Entertainment	Personal services	Recreation	Retail	Work
PM	2	3	PT	-0.049	-0.045	-0.044	-0.049	-0.05	-0.05	-0.044
PM	2	3	Walk	-0.1	-0.095	-0.095	-0.099	-0.1	-0.1	-0.094
PM	3	1	Cycle	-0.036	-0.032	-0.031	-0.035	-0.037	-0.037	-0.031
PM	3	1	Drive	-0.055	-0.051	-0.05	-0.054	-0.056	-0.056	-0.05
PM	3	1	PT	-0.047	-0.043	-0.042	-0.046	-0.047	-0.047	-0.042
PM	3	1	Walk	-0.097	-0.093	-0.092	-0.096	-0.098	-0.098	-0.092
PM	3	2	Cycle	-0.032	-0.028	-0.027	-0.031	-0.032	-0.032	-0.026
PM	3	2	Drive	-0.051	-0.046	-0.045	-0.05	-0.051	-0.051	-0.045
PM	3	2	PT	-0.042	-0.038	-0.037	-0.041	-0.043	-0.043	-0.037
PM	3	2	Walk	-0.092	-0.088	-0.087	-0.091	-0.093	-0.093	-0.087
PM	3	3	Cycle	-0.038	-0.034	-0.033	-0.037	-0.038	-0.038	-0.032
PM	3	3	Drive	-0.056	-0.052	-0.051	-0.055	-0.057	-0.057	-0.051
PM	3	3	PT	-0.048	-0.044	-0.043	-0.047	-0.049	-0.049	-0.043
PM	3	3	Walk	-0.098	-0.094	-0.093	-0.097	-0.099	-0.099	-0.093
PM	4	1	Cycle	-0.04	-0.036	-0.035	-0.039	-0.04	-0.04	-0.034
PM	4	1	Drive	-0.058	-0.054	-0.053	-0.057	-0.059	-0.059	-0.053
PM	4	1	PT	-0.05	-0.046	-0.045	-0.049	-0.051	-0.051	-0.045
PM	4	1	Walk	-0.1	-0.096	-0.095	-0.099	-0.101	-0.101	-0.095
PM	4	2	Cycle	-0.035	-0.031	-0.03	-0.034	-0.036	-0.036	-0.03
PM	4	2	Drive	-0.054	-0.05	-0.049	-0.053	-0.054	-0.054	-0.048
PM	4	2	PT	-0.046	-0.041	-0.041	-0.045	-0.046	-0.046	-0.04
PM	4	2	Walk	-0.096	-0.092	-0.091	-0.095	-0.096	-0.096	-0.09
PM	4	3	Cycle	-0.041	-0.037	-0.036	-0.04	-0.041	-0.041	-0.036
PM	4	3	Drive	-0.06	-0.056	-0.055	-0.059	-0.06	-0.06	-0.054
PM	4	3	PT	-0.052	-0.047	-0.047	-0.051	-0.052	-0.052	-0.046
PM	4	3	Walk	-0.102	-0.097	-0.097	-0.101	-0.102	-0.102	-0.096
PM	5	1	Cycle	-0.04	-0.036	-0.035	-0.039	-0.04	-0.04	-0.034
PM	5	1	Drive	-0.058	-0.054	-0.053	-0.058	-0.059	-0.059	-0.053
PM	5	1	PT	-0.05	-0.046	-0.045	-0.049	-0.051	-0.051	-0.045
PM	5	1	Walk	-0.1	-0.096	-0.095	-0.099	-0.101	-0.101	-0.095
PM	5	2	Cycle	-0.035	-0.031	-0.03	-0.034	-0.036	-0.036	-0.03
PM	5	2	Drive	-0.054	-0.05	-0.049	-0.053	-0.054	-0.054	-0.048
PM	5	2	PT	-0.046	-0.042	-0.041	-0.045	-0.046	-0.046	-0.04
PM	5	2	Walk	-0.096	-0.092	-0.091	-0.095	-0.096	-0.096	-0.09
PM	5	3	Cycle	-0.041	-0.037	-0.036	-0.04	-0.042	-0.042	-0.036
PM	5	3	Drive	-0.06	-0.056	-0.055	-0.059	-0.06	-0.06	-0.054
PM	5	3	PT	-0.052	-0.047	-0.047	-0.051	-0.052	-0.052	-0.046
PM	5	3	Walk	-0.102	-0.098	-0.097	-0.101	-0.102	-0.102	-0.096
Weekend	1	1	Cycle	-0.017	-0.013	-0.012	-0.016	-0.018	-0.018	-0.012

Time	I	A	M	Commute	Education	Entertainment	Personal services	Recreation	Retail	Work
Weekend	1	1	Drive	-0.036	-0.032	-0.031	-0.035	-0.037	-0.037	-0.031
Weekend	1	1	PT	-0.028	-0.024	-0.023	-0.027	-0.028	-0.028	-0.023
Weekend	1	1	Walk	-0.078	-0.074	-0.073	-0.077	-0.078	-0.078	-0.073
Weekend	1	2	Cycle	-0.013	-0.009	-0.008	-0.012	-0.013	-0.013	-0.007
Weekend	1	2	Drive	-0.031	-0.027	-0.026	-0.03	-0.032	-0.032	-0.026
Weekend	1	2	PT	-0.023	-0.019	-0.018	-0.022	-0.024	-0.024	-0.018
Weekend	1	2	Walk	-0.073	-0.069	-0.068	-0.072	-0.074	-0.074	-0.068
Weekend	1	3	Cycle	-0.019	-0.014	-0.014	-0.018	-0.019	-0.019	-0.013
Weekend	1	3	Drive	-0.037	-0.033	-0.032	-0.036	-0.038	-0.038	-0.032
Weekend	1	3	PT	-0.029	-0.025	-0.024	-0.028	-0.03	-0.03	-0.024
Weekend	1	3	Walk	-0.079	-0.075	-0.074	-0.078	-0.08	-0.08	-0.074
Weekend	2	1	Cycle	-0.05	-0.045	-0.044	-0.049	-0.05	-0.05	-0.044
Weekend	2	1	Drive	-0.068	-0.064	-0.063	-0.067	-0.069	-0.069	-0.063
Weekend	2	1	PT	-0.06	-0.056	-0.055	-0.059	-0.061	-0.061	-0.055
Weekend	2	1	Walk	-0.11	-0.106	-0.105	-0.109	-0.111	-0.111	-0.105
Weekend	2	2	Cycle	-0.045	-0.041	-0.04	-0.044	-0.045	-0.045	-0.04
Weekend	2	2	Drive	-0.064	-0.06	-0.059	-0.063	-0.064	-0.064	-0.058
Weekend	2	2	PT	-0.055	-0.051	-0.05	-0.055	-0.056	-0.056	-0.05
Weekend	2	2	Walk	-0.106	-0.101	-0.101	-0.105	-0.106	-0.106	-0.1
Weekend	2	3	Cycle	-0.051	-0.047	-0.046	-0.05	-0.051	-0.051	-0.045
Weekend	2	3	Drive	-0.07	-0.065	-0.065	-0.069	-0.07	-0.07	-0.064
Weekend	2	3	PT	-0.061	-0.057	-0.056	-0.06	-0.062	-0.062	-0.056
Weekend	2	3	Walk	-0.111	-0.107	-0.106	-0.111	-0.112	-0.112	-0.106
Weekend	3	1	Cycle	-0.048	-0.044	-0.043	-0.047	-0.049	-0.049	-0.043
Weekend	3	1	Drive	-0.067	-0.063	-0.062	-0.066	-0.068	-0.068	-0.062
Weekend	3	1	PT	-0.059	-0.055	-0.054	-0.058	-0.059	-0.059	-0.054
Weekend	3	1	Walk	-0.109	-0.105	-0.104	-0.108	-0.109	-0.109	-0.104
Weekend	3	2	Cycle	-0.044	-0.04	-0.039	-0.043	-0.044	-0.044	-0.038
Weekend	3	2	Drive	-0.062	-0.058	-0.057	-0.061	-0.063	-0.063	-0.057
Weekend	3	2	PT	-0.054	-0.05	-0.049	-0.053	-0.055	-0.055	-0.049
Weekend	3	2	Walk	-0.104	-0.1	-0.099	-0.103	-0.105	-0.105	-0.099
Weekend	3	3	Cycle	-0.05	-0.045	-0.045	-0.049	-0.05	-0.05	-0.044
Weekend	3	3	Drive	-0.068	-0.064	-0.063	-0.067	-0.069	-0.069	-0.063
Weekend	3	3	PT	-0.06	-0.056	-0.055	-0.059	-0.061	-0.061	-0.055
Weekend	3	3	Walk	-0.11	-0.106	-0.105	-0.109	-0.111	-0.111	-0.105
Weekend	4	1	Cycle	-0.052	-0.047	-0.047	-0.051	-0.052	-0.052	-0.046
Weekend	4	1	Drive	-0.07	-0.066	-0.065	-0.069	-0.071	-0.071	-0.065
Weekend	4	1	PT	-0.062	-0.058	-0.057	-0.061	-0.063	-0.063	-0.057
Weekend	4	1	Walk	-0.112	-0.108	-0.107	-0.111	-0.113	-0.113	-0.107

Time	I	A	M	Commute	Education	Entertainment	Personal services	Recreation	Retail	Work
Weekend	4	2	Cycle	-0.047	-0.043	-0.042	-0.046	-0.047	-0.047	-0.042
Weekend	4	2	Drive	-0.066	-0.062	-0.061	-0.065	-0.066	-0.066	-0.06
Weekend	4	2	PT	-0.058	-0.053	-0.053	-0.057	-0.058	-0.058	-0.052
Weekend	4	2	Walk	-0.108	-0.103	-0.103	-0.107	-0.108	-0.108	-0.102
Weekend	4	3	Cycle	-0.053	-0.049	-0.048	-0.052	-0.053	-0.053	-0.047
Weekend	4	3	Drive	-0.072	-0.067	-0.067	-0.071	-0.072	-0.072	-0.066
Weekend	4	3	PT	-0.063	-0.059	-0.058	-0.063	-0.064	-0.064	-0.058
Weekend	4	3	Walk	-0.114	-0.109	-0.109	-0.113	-0.114	-0.114	-0.108
Weekend	5	1	Cycle	-0.052	-0.048	-0.047	-0.051	-0.052	-0.052	-0.046
Weekend	5	1	Drive	-0.07	-0.066	-0.065	-0.069	-0.071	-0.071	-0.065
Weekend	5	1	PT	-0.062	-0.058	-0.057	-0.061	-0.063	-0.063	-0.057
Weekend	5	1	Walk	-0.112	-0.108	-0.107	-0.111	-0.113	-0.113	-0.107
Weekend	5	2	Cycle	-0.047	-0.043	-0.042	-0.046	-0.048	-0.048	-0.042
Weekend	5	2	Drive	-0.066	-0.062	-0.061	-0.065	-0.066	-0.066	-0.06
Weekend	5	2	PT	-0.058	-0.053	-0.053	-0.057	-0.058	-0.058	-0.052
Weekend	5	2	Walk	-0.108	-0.104	-0.103	-0.107	-0.108	-0.108	-0.102
Weekend	5	3	Cycle	-0.053	-0.049	-0.048	-0.052	-0.053	-0.053	-0.048
Weekend	5	3	Drive	-0.072	-0.068	-0.067	-0.071	-0.072	-0.072	-0.066
Weekend	5	3	PT	-0.064	-0.059	-0.059	-0.063	-0.064	-0.064	-0.058
Weekend	5	3	Walk	-0.114	-0.109	-0.109	-0.113	-0.114	-0.114	-0.108

Appendix K: Accessibility toolkit description

We adapt the R accessibility package of part of the Access to Opportunities Project[41] by the Instituto de Pesquisa Econômica Aplicada. The accessibility package allows for the determination of accessibility measures using the BFCA methodology, which we have used extensively in this report. Additionally, the package also allows for the use of various distance decay functions, including negative exponential values, which we have derived from across various demographic groups using the HTS.

Our toolkit comes with the derived distance decay values from the HTS as a dataset that can be used in conjunction with the accessibility package. For ease of use, we have created a function that simultaneously derives measures across all dimensions (age, income, travel purpose and time period) and merges the information into a single file.

Data requirements to derive these measures include a geographic file outlining the extent of transport zones (for output of geographic files), a population dataset of the same zones and travel matrix from zone to zone.

As noted in the documentation on accessibility, the functions calculate accessibility using travel cost rather than travel time. This means that the function accepts any travel impedance origin-destination matrix allowing for a more flexible analysis of accessibility, which can be adapted depending on the level of data available to users. For example, in this assessment, we adopt an income-weighted generalised cost of travel, giving the ability to use differing travel matrices to account for the difference in financial burdens that fare prices impose on people with different incomes.

Population and land use are also natively supported by the accessibility package as part of the inputs for determining accessibility using the BFCA methodology.

K.1 Components of the toolkit

The toolkit provided generalises the process we used to derive accessibility measures in this report. It encompasses various components used for obtaining inputs, including processes for data gathering and part of the spatial analysis required. Users will require proficiency primarily in R for its use. Additional languages, including Python, GDAL and Bash, alongside GIS software have also been used for some components.

The toolkit is designed to be modular with each component organised into separate R projects in individual folders. In some instances, users will need to adjust code and file paths and provide their own datasets. The example code provided is specific to our analysis and may require modification to fit other contexts.

K.1.1 Points of interest

Points of interest are retrieved from Overture Maps by running the script `01 Collection.qmd`. This script creates an in-memory database using DuckDB, queries the Overture database to fetch all points of interest within New Zealand and inserts them into the in-memory database. It then generates a local spatial file named `nz-places.gpkg`, which will be used for subsequent classification processes.

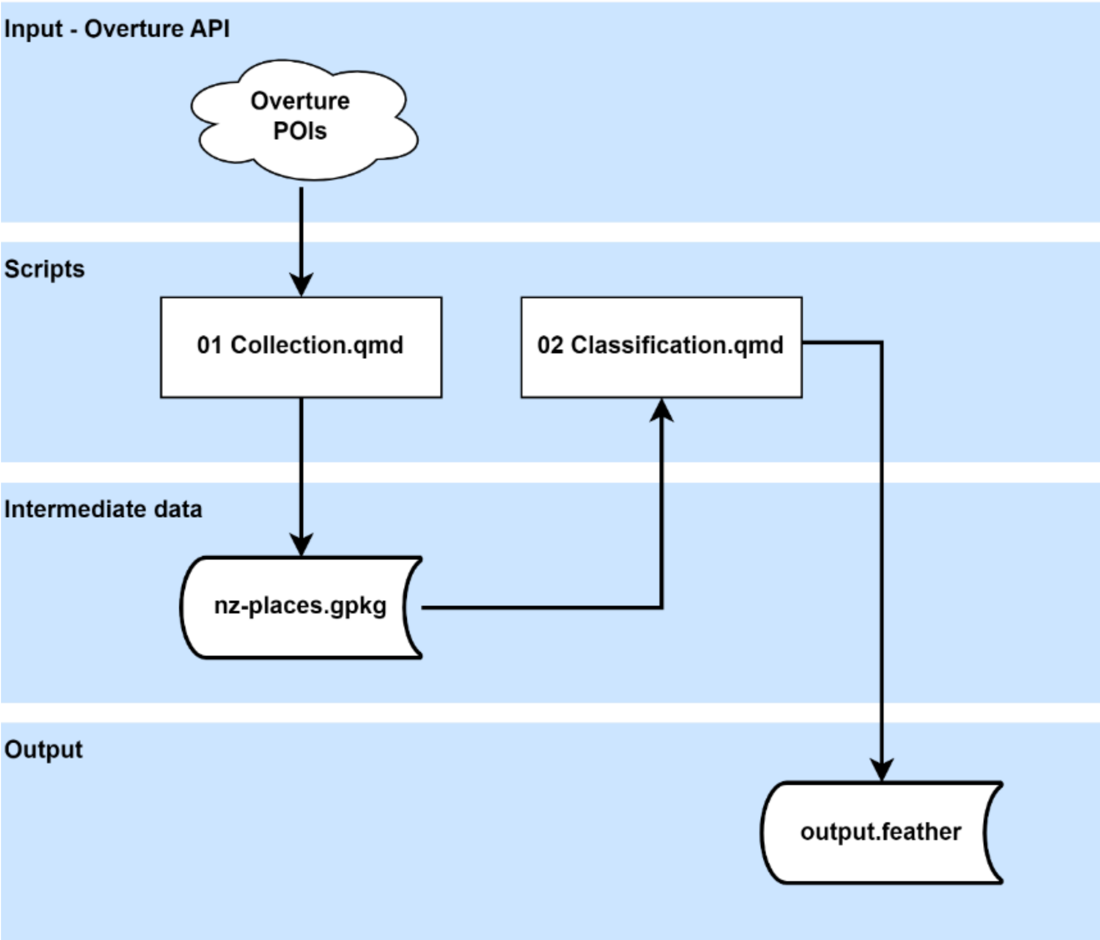
The script `02 Classification.qmd` reads the `nz-places.gpkg` file and classifies each point of interest into relevant categories based on predefined rules. Users can specify the output directory in

[41] https://www.ipea.gov.br/acessooportunidades/en/sobre/

`02 Classification.qmd`, which will save the classified points of interest, including location and category, into a portable `.feather` file.

Figure K.1 illustrates the workflow of the points of interest toolkit, showing the sequence of steps from querying Overture data and classifying these into broad categories.

Figure K.1 Workflow of the points of interest toolkit



Source: Principal Economics

K.1.2 TomTom

As noted in section 5.2.2 we collect TomTom Traffic Stats to adjust road speeds based on historical travel times. The scripts for this process are contained in the folder TomTom. We also provide a set of queries we used to query the API for all of New Zealand in `queries`. The `r` folder contains the scripts for sending the premade queries to TomTom, which the user must download from their web user interface. We also provide scripts for aggregating the collected dataset and our method for matching with OSM network data. The outputs of this component provide adjusted road speeds for use with private vehicle routing networks.

We describe the steps to using the TomTom toolkit below.

1. **Post queries to TomTom Traffic Stats**

   Script file: `01 post_queries.r`

Description: This script automates the process of sending 40 queries to TomTom Traffic Stats using the NZTA API. It is designed to gather traffic data for various time periods and conditions, covering the entirety of New Zealand while adhering to the spatial limits of the API.

Instructions: Run this script to send the 40 premade queries to TomTom Traffic Stats using the NZTA API. After execution, download the resulting shapefiles from the TomTom Traffic Stats web portal.

2. **Combine shapefiles and update local database**

Script: `02 Combine_queries.r`

Description: This script combines the shapefiles collected from the previous step into a single dataset. It calculates the proportional speed ratios for different times (AM, interpeak, PM, weekend peak) relative to free-flow speeds.

Instructions: Run this script to match TomTom data with OSM road network data and join speed information. Results are saved to a local database as a spatial dataset.

3. **Match OSM network with TomTom data**

Script: `03 osm_matching.r`

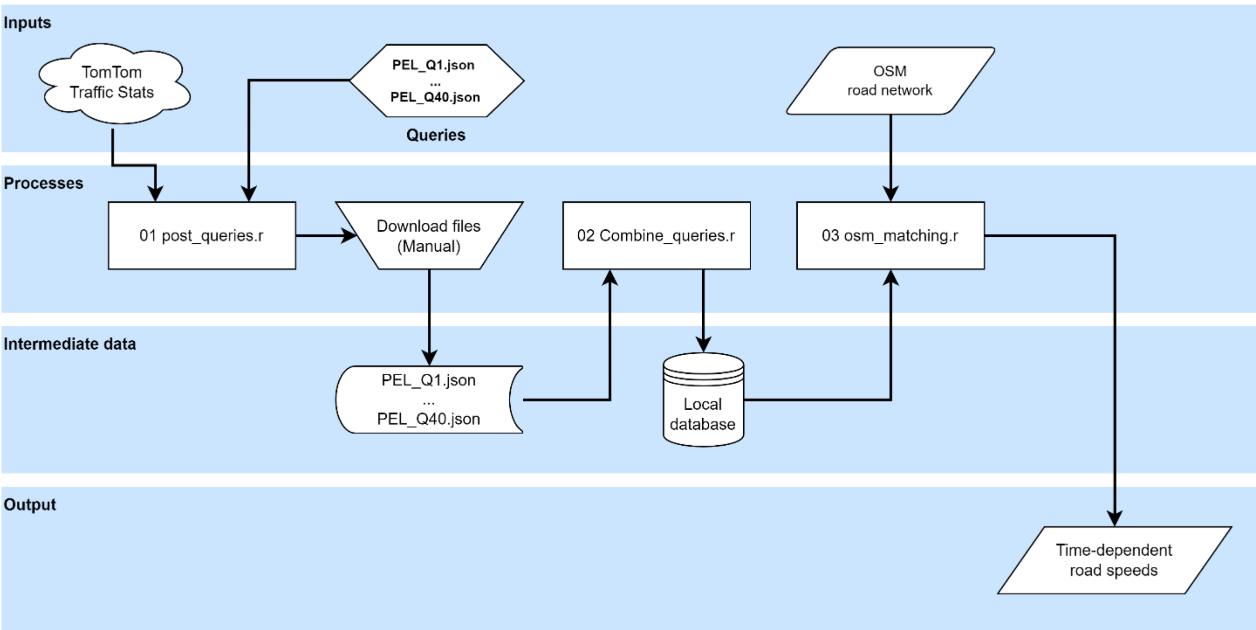
Description: This script matches the TomTom traffic data with an existing road network spatial file (such as OSM lines) based on spatial overlap. It joins time-dependent road speeds with the matched network.

Instructions: Prepare the existing road network file (such as OSM lines) and ensure the combined dataset is available. Open and execute the `03 osm_matching.r` script in R. The script will align TomTom data with the road network, integrating time-dependent speed information.

Outcome: Results are saved to a local spatial database and as CSV files (split by North Island and South Island).

Figure K.2 illustrates the workflow of the TomTom toolkit, showing the sequence of steps from querying traffic data to integrating it with road network information.

Figure K.2 Toolkit – TomTom Traffic Stats



Source: Principal Economics

K.1.3 Walking and cycling

As inputs to the impedance cost of walking and cycling, we use the average slope of roads, and the presence of retail stores to estimate perceived distances based on the literature (Liang et al., 2023).

To derive the slope of roads for the routable network, users will need to source LiDAR 1m DEM files from LINZ to perform this analysis. We provide details on the GDAL command that combines .tif files to .vrt for more convenient use with GIS software. Deriving the slope of roads can be undertaken by deriving the slope from DEM layers and taking the mean slope zonal statistic of buffered road lines.

Presence of retail stores can be determined using GIS software by buffering retail points of interest and checking their intersection with road lines.

We give examples of how we match these datasets and adjust for perceived distances with the routable network we adopted. The outputs of this component provides perceived road lengths for walking and cycling.

We describe steps to using the walking and cycling toolkit below.

K.1.3.1 Deriving average road gradients

1. Collect LiDAR DEM files

Obtain LiDAR 1m DEM files for the desired areas from LINZ. Ensure that all files are correctly downloaded and stored in a single directory. Create a text file name `tif_list.txt` listing all the DEM files that will be combined into the .vrt. Each file path should be listed on a new line.

2. Combine LiDAR DEM files

GDAL installed, open command prompt and navigate to the location of the folder containing both the .tif files and the `tif_list.txt` and execute the following command: `gdalbuildvrt -input_file_list tif_list.txt mega.vrt`

The output is a file named `mega.vrt` that combines the DEM data for use with GIS software.

3. Matching land gradients to roads

Load the road network file and the `mega.vrt` into GIS software. Buffer the road lines by their width to account for road dimensions. Then perform a zonal analysis to determine the average gradient within each buffered road zone using the `mega.vrt` as the source of land gradient data. Save the output for use in determining the walking impedance.

We provide the script `01 slope.r` that can be used to combine multiple regional outputs and converts road gradients from degrees to percentage values.

K.1.3.2 Deriving retail presence on roads

To determine the presence of retail stores, using GIS software, undertake the following spatial analysis:

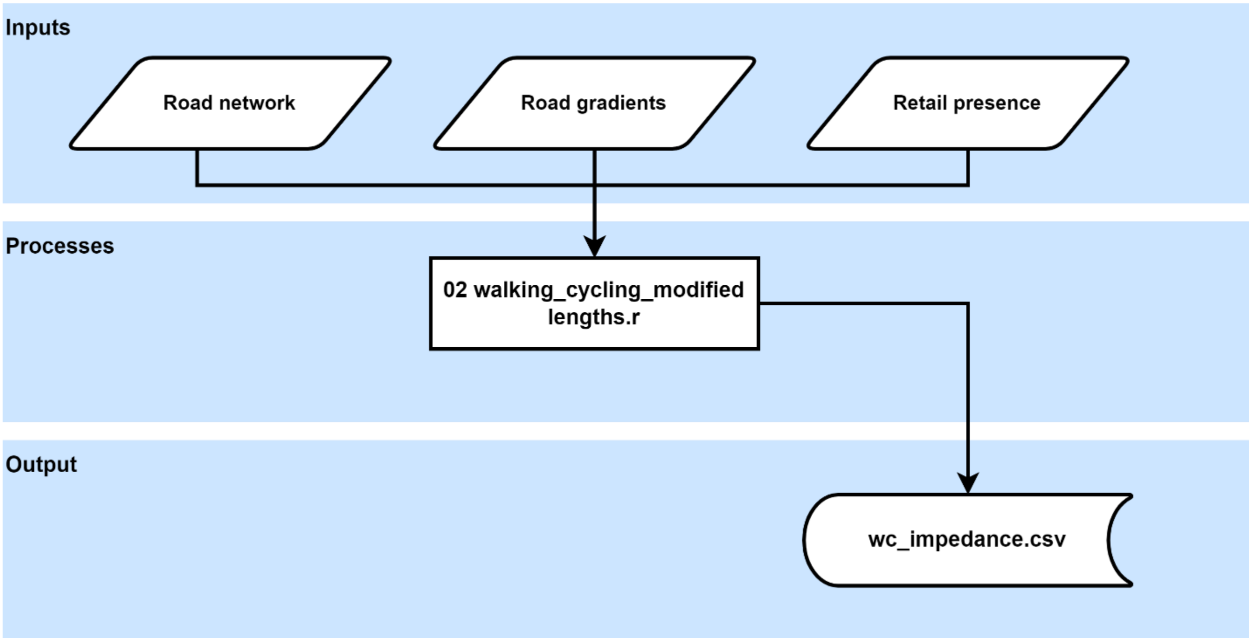
1. **Create buffers:** Generate buffer zones around each retail point of interest. These can be sourced from the categorised points of interest sourced from Overture data. The buffer distance should reflect the distance from the store centroid to the footpath. We have assumed a 10-metre radius.
2. **Spatial intersection:** Analyse the spatial overlap between these buffer zones and the road network to identify areas where they intersect.
3. **Save results:** Create a .csv concordance file of roads with retail presence for use in determining impedance values for walking and cycling.

K.1.3.3 Deriving walking and cycling impedance values

The script `02 walking_cycling_modified_lengths.r` processes road and retail data to assess walking impedances. It begins by loading the derived road slope data (in percentages), the road network dataset and the dataset of roads with a retail presence. The script then combines these datasets to integrate road characteristics with retail locations. Using the merged data and coefficients from relevant literature, it calculates walking impedances. The output is a .csv file with road ids and their modified road lengths/impedance values for walking and cycling respectively.

Figure K.3 illustrates the workflow of the `02 walking_cycling_modified_lengths.r` script showing the data inputs and output. The methods for deriving road gradients and retail presence are detailed above.

Figure K.3 Walking and cycling impedance – script logic



Source: Principal Economics

K.1.4 GTFS Realtime

K.1.4.1 Collection

We use Python package GTFSrDB[42] – GTFS Realtime to Database for the collection of GTFS Realtime data. The package allows users to collect GTFS Realtime data, trip updates, service alerts and vehicle locations and directly upload these to a database for analysis. We provide examples of our implementation of this package using Auckland Transport, Wellington Metlink and Metro Christchurch GTFS Realtime APIs.

K.1.4.2 Modification

We provide examples for Auckland and Wellington on how to modify GTFS static files from collected GTFS Realtime data using GTFSrDB. In our analysis, we find that adherence to the GTFS standard can vary significantly between sources. We suggest additional analysis is undertaken to understand how providers have structured their files.

[42] https://github.com/mattwigway/gtfsrdb

We provide two main functions for modifying static files – delay_summary, which aggregates collected GTFS Realtime data to determine arrival delays by stop_id and trip_id, and stop_mod, which modifies arrival delays based on collected information.

The outputs of this component are modified GTFS files that can be used with routing tools such as R5 to determine public transport travel times and subsequently the derivation of accessibility measures.

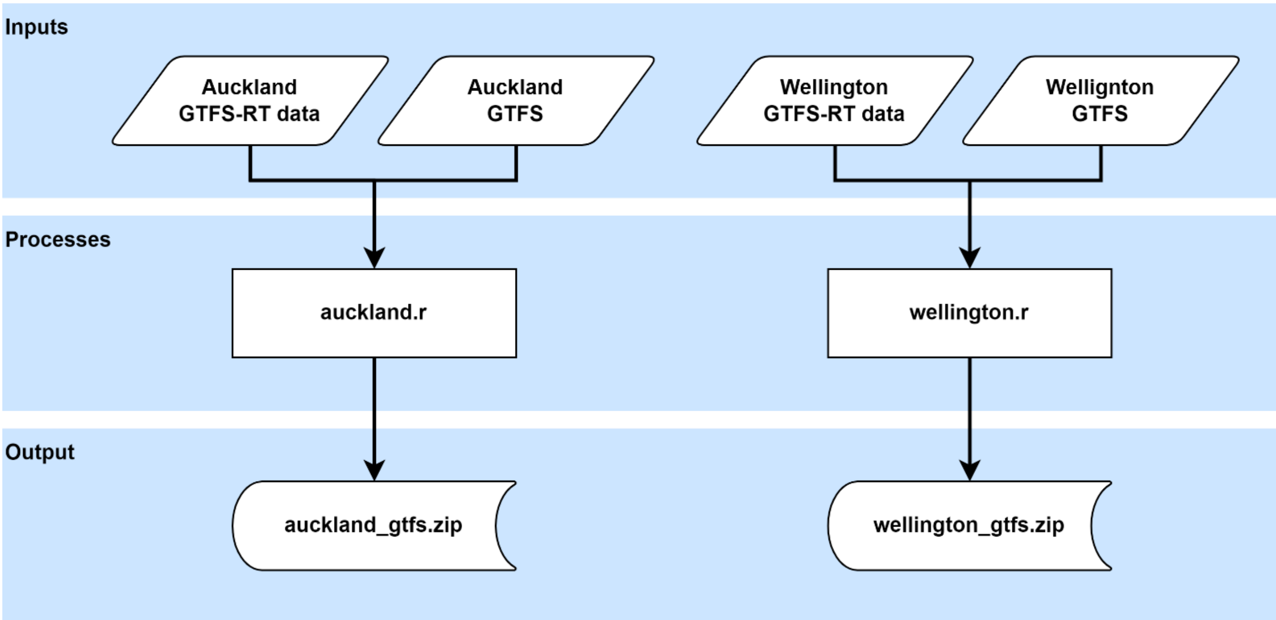
To modify GTFS static files, save the `output.feather` file from the collection phase into the raw_data folder within Modification. Place the matching GTFS static ZIP file in the same folder. Since there were no differences between static and real-time data for Christchurch, no processing file is provided for this region.

Run `auckland.r` and `wellington.r` to generate the modified GTFS ZIP files. These modifications involve replacing GTFS static schedule times with average arrival times from real-time data.

The final outputs are standard GTFS ZIP files, suitable for use with public transport routing engines.

Figure K.4 shows the workflow for modifying GTFS static files using collected GTFS Realtime data.

Figure K.4 GTFS static file modification using GTFS Realtime sampling



Source: Principal Economics

K.1.5 Network analysis

K.1.5.1 Pandana

We provide our code for adapting our network-matched TomTom data and derived impedances for walking and cycling to existing travel network (OSM). This includes the process for generating travel matrices for origin-destination combinations for each travel mode and time period.

Additional code is provided for exporting output in chunks to mitigate for processing time.

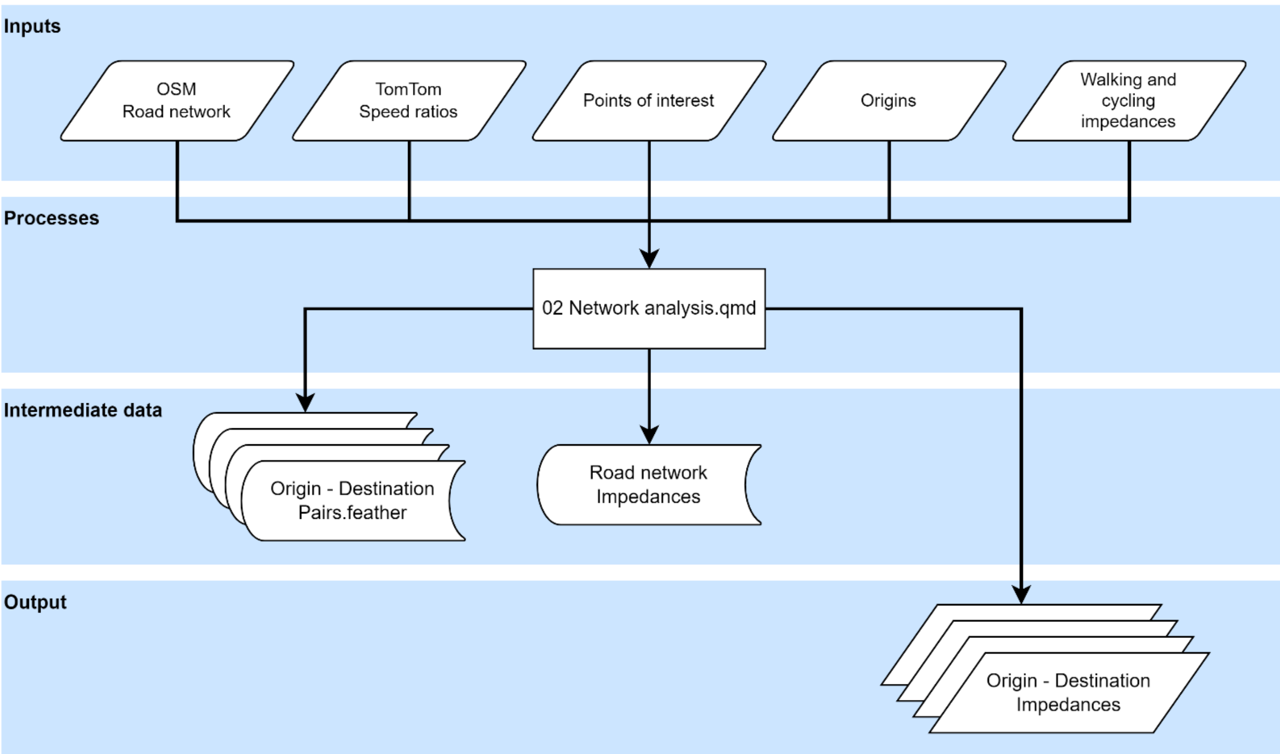
The outputs for this component are the travel cost matrices using modified impedance values for driving, walking and cycling travel modes for different time periods.

The `02 Network analysis.qmd` script follows the following logic:

1. **Import data:** Import origin and destination points.
2. **Calculate potential area:** Calculate the maximum travel area coverage based on a 3-hour travel time at 100 km/h Euclidean distance. This is undertaken to reduce the processing time required for the analysis. This later trimmed to maximum impedance values after travel time/impedance is determined for each origin-destination pair.
3. **Generate origin-destination pairs:** Create potential origin-destination pairs for each origin and destination that overlaps its potential travel area.
4. **Import adjustment factors:** Import TomTom and walking and cycling datasets that will be used to adjust travel times and impedance.
5. **Adjust network:** Merge TomTom travel speeds and walking and cycling factors that will be used to adjust impedance values in the OSM roading network. Replace travel times/calculate impedance values to those used in the analysis.
6. **Compute paths:** Derive the shortest paths from each origin to destination pair. Each origin has its own impedance matrix to destinations for each mode and time period. We split the analysis by origin to manage the high memory usage required. Impedance matrices for each origin is computed in sequentially (in sets of 10 in parallel).
7. **Save impedance matrices:** Each individual origin to destination impedance matrix is saved for later use.

Additional code processes the output matrices by merging and then chunks the merged data into larger files to facilitate easier transfer.

Figure K.5 Workflow for generating origin-destination impedance matrices – driving, walking and cycling



Source: Principal Economics

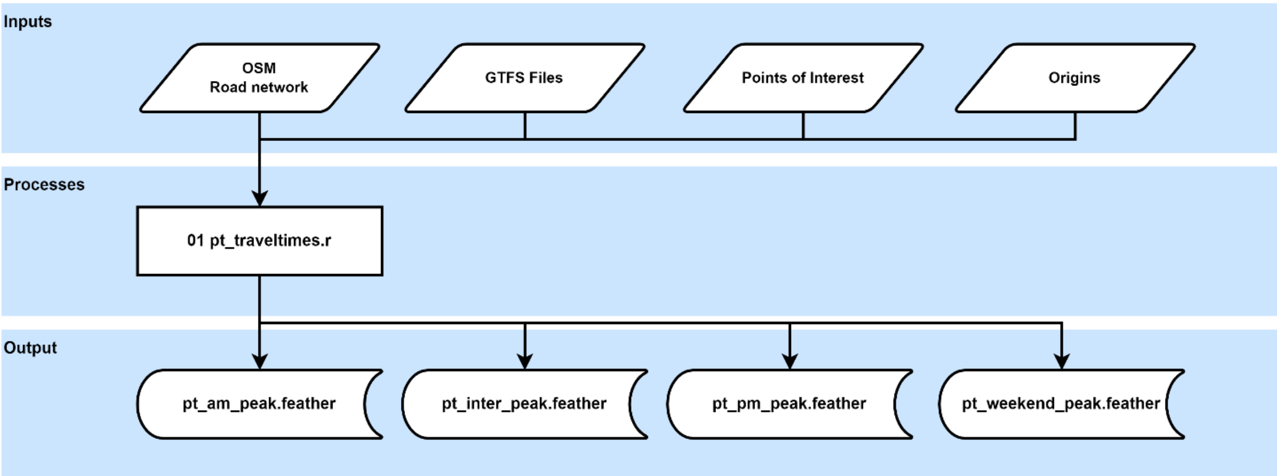
K.1.5.2 R5

For public transport, we use R5 to efficiently generate travel matrices. Inputs for this component include OSM .pbf files and GTFS static ZIP files. Modified public transport schedules such as those derived from modified GTFS static files incorporating GTFS Realtime arrival delays can be substituted to provide more realistic trip times. We also show how to create travel cost matrices for various travel time periods. The output of this component is public transport travel cost matrices for different time periods.

To generate the travel time matrix for public transport, we use the R5R package in R as the R5 application interface. This process integrates the OSM road network, GTFS ZIP files for public transport schedules and points of interest and destinations as origins and destinations. The script `01 pt_traveltimes.r` processes these inputs to produce four origin-destination matrices in .feather format, covering the travel periods of AM peak, interpeak, PM peak and weekend peak.

Figure K.6 shows the inputs and outputs used by `01 pt_traveltimes.r` to derive travel matrices from origin (points of interest) and destinations for different time periods.

Figure K.6 Deriving public transport travel matrices



Source: Principal Economics

K.1.6 Saturation function

This component of the toolkit derives balanced floating cost area accessibility measures across a range of demographic groups, points of interest and travel modes. It uses distance decay values derived from the HTS (provided), travel cost matrices (provided by the user) and land use (provided by the user) and outputs area-based accessibility for each demographic/point of interest/mode/time period combination.

Additionally, as we use income-adjusted travel cost matrices for our analysis, public transport fare prices and vehicle operating costs will need to be updated accordingly.

The main function provided in this component is `bfca_regfun`. This takes a dataset of inputs, including time period, use (point of interest), mode, demand (population for retailing, working age for employment, school age for schools) and income quintile. `bfca_regfun` is constructed to take inputs from this dataset and loop through each row of inputs providing a combined output dataset of accessibility measures for each dimension.

To determine accessibility measures using the toolkit, users must provide the following inputs:

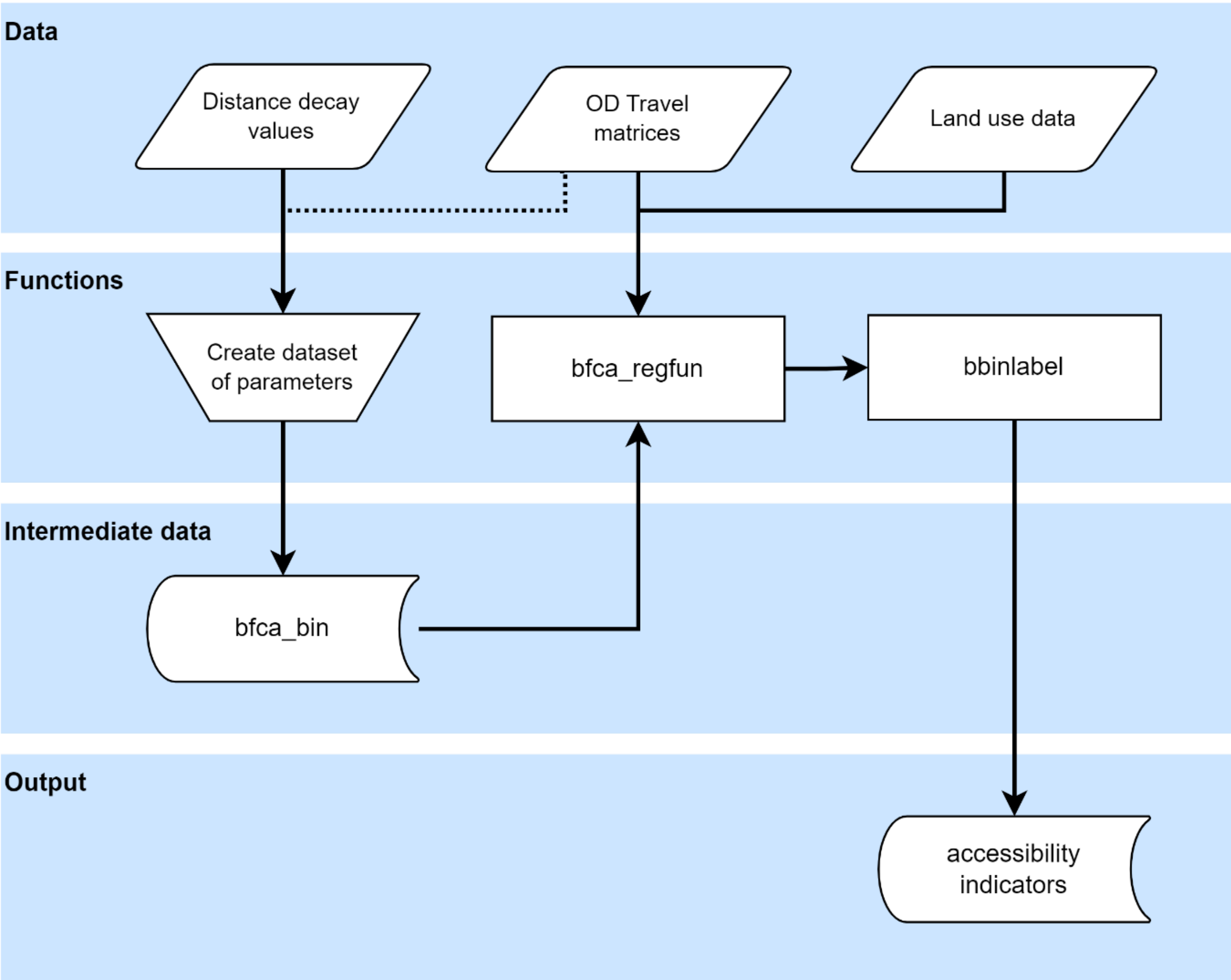
1. **Distance decay values:** We have provided these in the .csv file `ddcays.csv`, disaggregated by income, mode, travel time and purpose.
2. **Impedance/travel time matrices:** Impedance matrices between origin destination in long format. TAZs for origin and destinations must be identical. In our analysis, we take the average impedance value to all points of interest within SA1 units for each SA1 origin (by mode, time period and purpose).
3. **Land-use data:** This dataset includes the number of activity opportunities in each area (retail shops, jobs) and the relevant population. This is needed as the accessibility measure calculated represents the ratio of population to services adjusted for impedance.

Initial data preparation is necessary to define the parameters that will be used by `bfca_regfun`. This involves appending the distance decay table with labelling variables that match the column names for population variables in the land-use dataset.

Our example script shows how the function can be used to calculate accessibility measures for many combinations of period, purpose, mode, age groups, income quintiles, populations and time periods in bulk. The helper function `bbinlabel` is provided to assist with consolidating the results.

We show the workflow logic of the example script in Figure K.7.

Figure K.7 Saturation function workflow logic



Source: Principal Economics