PRIORITISING OBSTRUCTION REMOVAL ON ACTIVE TRAVEL NETWORKS

Chris Larkin

b8008458/180084588

Submitted in partial fulfilment of the requirements for the degree of Master in Research in Geospatial Data Science as part of the EPSRC Centre for Doctoral Training in Geospatial Systems in the Faculty of Science Agriculture and Engineering

School of Engineering

Newcastle University

Newcastle Upon Tyne

United Kingdom

25.09.2022

DECLARATION

"I hereby certify that this work is my own, except where otherwise acknowledge, and that it has not been submitted previously for a degree at this, or any other university".

Chris Larkin

ACKNOWLEDGEMENTS

I would like to thank the following people and organisations who have all supported this project:

Dr Craig Robson, primary supervisor of this project, for his support, advice and all the time he has given up to help me throughout this project.

Ralph Hughes, industry supervisor of this project, who this project could not have happened without. Many thanks for the opportunities, ideas, advice and time given to support me. A particularly large thank you for the data provided to me and the openness to engage in this MRes project.

Dr Alistair Ford, co-supervisor of this project, for his guidance, help and motivation during this project.

All of the members of Sustrans which I had the pleasure of meeting and working with. Your time, resource and knowledge given were invaluable for this MRes project.

Colleagues at the Geospatial Systems CDT, who were always happy to lead a hand with any issue.

The Engineering and Physical Sciences Research Council (EPSRC) Centre for Doctoral Training (CDT) in Geospatial Systems for providing the studentship and financial support during this Geospatial Data Science MRes under grant number EP/S023577/1.

ABSTRACT

This thesis presents the development of an automated methodology to determine the removal priority of physical obstructions on active travel networks. Obstructions reduce accessibility on active travel networks, particularly for those with additional mobility requirements such as wheelchairs or adapted cycles. To provide decision makers with a tool to identify where the best short-term gains are located, a novel methodology for scoring obstructions is developed.

The developed scoring index uses a combination of five metrics and six sub-metrics to provide an overall score per obstruction. Metrics were process, analysed and visualised using a combination of Python and QGIS. Metrics were weighted through an analytical hierarchy process in consultation with stakeholders from Sustrans. The methodology was applied the National Cycle Network within the United Kingdom. Results are found using two test sites namely York and Pembrokeshire.

Barrier critical width and potential accessibility gain were determined to be the most important metrics, constituting 77.1% of the overall weighting. The resulting scored obstructions displayed the locations of high removal priority barriers across both study areas. Clusters of high removal priority were identified at 95% confidence through use of spatial statistics. These were present in areas connecting suburbs to the city centre in York. In Pembrokeshire clusters were identified predominantly within urban areas.

The open-source and reproducible nature of this project allows decision makers to implement this methodology as a decision support tool on any area of the UK. The multi-factor nature of the index provides a holistic approach to determining the worst obstructions.

Key words:
Barrier removal, active travel, accessibility, decision support, spatial analysis, network analysis, national cycle network

CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

LIST OF ACRONYMS

AHP – Analytic Hierarchy Process

GIS – Geographic Information System

LSOA – Lower Super Output Area

MCDM – Multi-Criteria Decision Making

OD – Origin-Destination

OMS – OpenStreetMap

PWC – Population weighted centroid

UK – United Kingdom

INTRODUCTION

1.1 Background and rationale

1.1.1 Background

Active travel provides a low-carbon, health beneficial and low-cost mode of transport. It has proved to be a viable supplement to motorised transport (public or private), particularly within northern Europe. Notably, the Netherlands, Germany and Denmark have demonstrated that with the correct nurturing and investments, significant proportions of the population can switch from private vehicle use to non-motorised forms of transport (Pucher & Buehler, 2008). Since 2004, Dutch people cycle 9% and walk 13% more regularly, largely down to infrastructure improvements (Schapp *et al.,* 2016). Compared to these countries, the UK has low usage of active travel (Pucher & Buehler, 2008). The active travel infrastructure within the UK is also significantly further behind in terms of development compared to nations which have successfully implemented a large scale change to active travel (Powell *et al.,* 2010).

A switch to active travel from motorised transport within the UK provides widespread economic and social benefits. Estimates show that congestion from vehicles within cities costs the UK economy £11 billion per year (Cabinet Office, 2009), whilst causing further issues such as community severance (Clark, 1991), health issues derived from air pollution (Halonen *et al.*, 2016) and noise pollution (Khan *et al.,* 2018). It is suggested that active travel could cut as much as 1% of the annual budget for health in England and Wales, with estimates of a reduction of almost £1 billion spent on diabetes treatment (Jarrett *et al.*, 2012).

In the UK, investment into active travel has increased to develop and improve active travel during the past five years (Department for Transport, 2017). Despite the growing financial and physical improvements to networks, many potential user groups are unable to access the potential of active travel fully. Contrary to modern design principles (Department for Transport, 2020) much of the UK's existing active travel network contains obstructions. These obstructions or barriers are discriminatory against wheelchairs, people with buggies and mobility scooters, amongst several other modes of walking or wheeling. Active travel advocacy groups have called for removal of these obstructions, however limited finical budgets have not allowed for mass change (Sustrans, 2020; Wheels for Wellbeing, 2022).

Historically, barriers have been implemented on active travel corridors due to planning stipulations at the time of construction (BikeBiz, 2016). These were due to the perceived issues of crime, such as trespass of motorcycles. Barriers were also introduced to prevent cyclists from approaching intersections or tight passages on the network at a high speed. These barriers have led to the unintended consequence of rendering the routes inaccessible for users who cannot pass through the barrier. This affects many user groups, including people with mobility issues that require wheelchairs, mobility scooters, adapted cycles amongst other methods of movement. People with pushchairs, cargo-bikes, or even typical bicycles are also potentially hampered (Figure 1 and Figure 2). Even for those who can pass through the barrier with no issue, the interruption to movement speed (particularly for cyclists) makes these routes less preferable to alternatives with fewer interruptions.

Figure 2 - Cyclists struggle to pass through a barrier on the National Cycle network (Sustrans, 2021)

Figure 1 - Pushchair unable to access footpath due to barrier obstructions (Sustrans, 2020)

The National Cycle Network (NCN) provides over 8500 kilometres of path separated from road infrastructure across the UK. Currently, over 7000 barriers have been identified on the network, roughly equating to an obstruction every 1.2 kilometres. These barriers have been identified as part of a volunteered geographic information (VGI) initiative curated by Sustrans. It has been estimated that removal of all these barriers across the NCN could equate to usership doubling, generating £7.8bn in economic and local benefits every year (Sustrans, 2018). Sustrans aims to removal all barriers from the network by 2040, however these local and economic benefits can be accessed earlier if higher priority obstructions are removed first.

1.1.2 Rationale

Whilst the benefits of improving accessibility to active travel at both a national scale for the economy and at a personal scale for social value are evident, progress remains slow. Particularly with regard to barriers, no methods of determining which of these obstructions are the highest priority have been developed yet. This has led to sporadic and often uncoordinated work on network improvements. These do not obtain the highest potential short-term gains.

A decision support tool to assist the obstruction identification and removal process will likely enable a more robust, holistic, and coordinated approach to improving active travel networks. Current studies on accessibility and active travel have primarily focused on either the propensity to use active travel or the current accessibility of an area for active travel (Lovelace *et al.,* 2017; Anciaes, 2013). Obstruction removal will likely enhance both of these factors, however studies on where best to remove these obstructions are yet to be produced to the authors best knowledge.

Geospatial decision support tools have been long established as a valid method for identifying potential changes across a given area (Lovelace *et al.,* 2017; Ribeiro *et al.,* 2002; Rahman *et al.,* 2012). A geographic information system (GIS) enables the manipulation and analysis of spatial data to produce decision support outputs. Through use of spatial analysis and modelling, this project aims to develop a decision support tool which evaluates priority of removal for any given obstruction on an active travel network, thus finding the best short-term gains in accessibility for all.

1.2 Research goals

1.2.1 Research question, aims and objectives

Considering the lack of knowledge regarding the prioritisation of barrier removal, the overarching research question can therefore be considered as:

How can obstructions be evaluated for removal priority within the context of accessibility for all?

The aim of this project is to provide a methodology to answer this research question. More specifically, the aim will be:

To produce a decision support tool to enable the prioritisation of obstruction removal

To fulfil this aim, research objects must be met. The research objectives will be informed by a review of the current literature on accessibility, active travel, and spatial analysis. Objectives of the project are as follows:

- Determine the factors which influence removal priority
- Source and process data relating to each factor
- Weight the factors accordingly and apply the developed index to an obstruction dataset
- Identify spatial patterns and trends within each factor and the scored obstructions
- Automate methodology to provide a decision support tool for stakeholders

1.2.2 Proposed research impact and contribution

The tool developed as a result of this project is expected to have significant research impact. The open science/source approach taken through the project will allow stakeholder groups such as Sustrans to utilise the tool themselves. This will enable enhanced decisions to be made regarding the removal of barriers across the National Cycle Network (NCN), or more generally across active travel routes.

Research regarding physical barriers on active travel networks within the UK is currently limited. Further, removal of barriers from active travel networks is yet to be tackled in almost any literature. Therefore, this project will provide a novel approach to ranking obstructions in order of removal priority using a geospatial approach.

LITERATURE REVIEW

2.1 Active travel and accessibility

Transportation has been shown to be one of the largest contributing sectors to emissions of greenhouse gasses (Lamb *et al.,* 2021). As nations aim to mitigate the impacts of climate change, reductions in private vehicle usage will occur (Dulal *et al.,* 2011). Active transport provides a low carbon alternative to transportation by car. Active travel is characterised by various non-motorised means of transport based on human activity. Walking and cycling are commonly understood to be the most common modes of active transport, however modes such as scooters and other wheeled methods are increasingly also encompassed within the term (Aldred, 2019). Beyond greenhouse emissions, active travel also provides health benefits and minimises noise pollution, particularly in cities (Brand *et al.,* 2021). With regards to walking specifically, it has been shown to improve road safety and increase social interactions (Hermann-Lunecke *et al.,* 2020; Hillnhütter, 2016).

However, in a UK context, the infrastructure surrounding active travel is prohibitive to many user groups, such as: people with movement disabilities, pushchair users or adapted cycle users. Studies focused on motivations to cycle or walk have indicated there is significant unmet demand for active travel (Heinen *et al.,* 2010, Fernandez-Heredia *et al.,* 2014). Burns *et al.* (2019) states that 31% of disabled people would like to start cycling. However, potential users are faced with limitations to access to active travel infrastructure such as lack segregated bike lanes and obstructions on route. Transport for London (2012) asked whether respondents could ride a bike: 70% of disabled people responded yes in 2012. This highlights issue lies not with ability to move (cycling or otherwise), but the opportunity to access cycling (or other active methods) as a movement method.

For groups of active travel users with specialist equipment to facilitate travel (such as wheelchairs or cargo bikes), access issues commonly relate to the prevalence of obstructions which do not allow a user to continue onto the designated foot/cycle path. Roadblocks, barriers and gates are frequently too narrow for use by many users (Orving *et al.,* 2019; Clayton and Parkin, 2016). Department for Transport design standards mandate that corrections must be made where effective widths are below 1.5m, however audit data from Sustrans (Figure 3) indicates that over 5000 obstructions still exist across the UK with a critical width lower than this (Department for Transport, 2020).

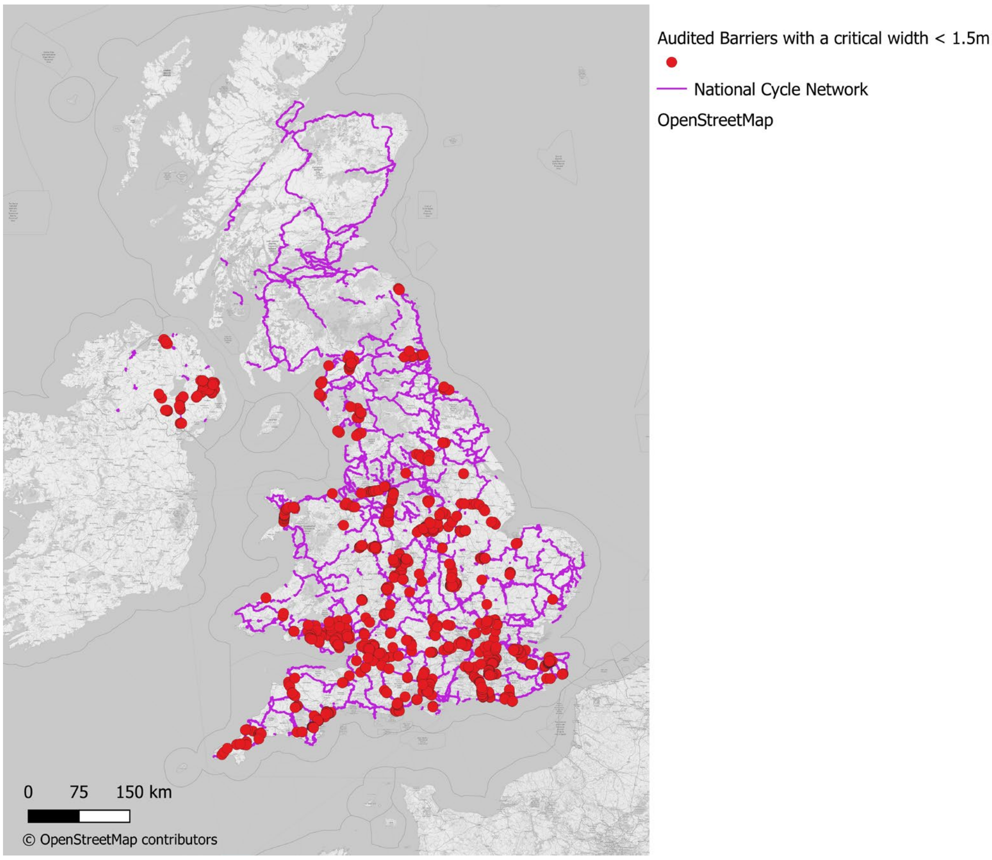


Figure 3 - Audited barriers with critical widths less than 1.5 meters across the UK's National Cycle Network

Within the UK, transport inequalities are not limited to personal mobility factors such as use of adapted bikes or wheelchairs. The overall affluence of an area is an indicator of how importance active travel is. In more deprived areas, reliance on active travel is greater than in areas of lower deprivation. Olsen *et al.,* (2017) found that the Scottish Index of Multiple Deprivation linked to the number of reported walking and cycling trips from the Scottish Household Survey. Similarly, this has been observed across the whole UK by Rind *et al*. (2015). The prevalence of obstructions on active travel networks therefore has greater effect on the more deprived population. Areas of lower car ownership are also found to have a higher level of active travel and are therefore again impacted disproportionality by obstructions (Norwood *et al.,* 2014). Car ownership does not necessarily follow the same spatial patterns as poverty. Within the UK, the phenomena of "Forced car ownership" often means people in lower income areas are more reliant on private vehicles for a number of social-economic reasons (Mattioli, 2017; Curl *et al.*, 2018). Lower ownership of private vehicles shows reliance on other methods of travel, such as public transport or active travel.

2.2 Measuring barrier impacts

Direct barrier effects have been defined as the impacts created by transport infrastructure on physical access to activities for people, and opportunities for business (van Eldijk *et al.*, 2020). The effects of a barrier on a given area have been quantified by many methods. Early attempts to assess the impact of a barrier was create by Trafikverket, the Swedish Transport Administration (van Eldijk et al., 2020;Reyier, 1987; Jarlebring *et al.*, 2002). This method achieved a value for impact based on flow of traffic, speed of traffic and number of trucks. It considered roads to be barriers in the context of pedestrian movement. Clark *et al.*, (1991) measured the impact of barriers on communities by quantifying the number of people affected by an obstruction, using the catchment area from a given point of interest to identify the population who would be able to access the facility without the presence of a barrier. The authors then estimated the number of people who can no longer access the facility, and are therefore affected. Anciaes (2013) provided a similar method of measuring community severance due to the barrier effect of major roads, however this method considered the underlying pedestrian network to measure the walking distance between a given origin and a given point of interest. The number of points of interests accessible from a given location indicated the level of accessibility. This was calculated using a GIS. The resulting score was then compared to the same network without the barrier present in order to determine the loss in accessibility between locations. Whilst this method provided a pure count for the accessibility change, it does not capture the relative accessibility change that may occur. Locations with low accessibility in the first instance will have a low count of points of interests. Even if the number of points of interest halves, the change in points of interest for a location with a high baseline accessibility will likely be far greater, despite the relative accessibility change remaining low. In order to negate this issue, considering the percentage change in amenities could pose an alternative method which better captures the potential change of an area.

2.3 Accessibility measures and modelling

2.3.1 Measuring accessibility

Varying methods of measuring accessibility to locations or areas through active transport have been proposed since the late 1960s and early 1970s (Pirie, 1978). Vale, Saraiva & Pereira (2016) categorised active accessibility measurement methods into four main categories: distance-based, gravity-based, topological, and walk-score type measurements.

Distance-based measures rely on Tobler's First Law of Geography and spatial analysis, specifically that: "everything is related to everything else, but near things are more related than distant things" (Tobler, 1970). Distance can relate to many measures of distance, such as Euclidean distance, network distance and network cost. Each measure produces differing results; network cost (for example travel time) and network distance may be similar for pedestrians but significantly different for a cyclist. Both network distance and network cost have be used frequently in walking and cycling accessibility studies, such as those by Pàez *et al*. (2012), Hull *et al.* (2012), Mavoa *et al*. (2012) and Yigitcanlar *et al*. (2007). The distance calculated in distance-based measures is commonly from a centre point (such as a population weighted centroid) to a point of interest, or many points of interest. The number of points reachable within a certain cut-off in either time or distance is considered the accessibility of a region (Calafiore *et al.,* 2022).

Gravity based measures consider the cost of traveling from a place to an opportunity via the spatial separation between the start and end point. Gravity-based accessibility studies commonly following the basic model outlined by Hansen (1959):

$$A_i = \sum_j O_j f(C_{ij})$$

where: A_i is the accessibility score for location i, O_j are opportunities within the given travel time located at j, and $f(C_{ij})$ is the impedance function between locations i and j.

Equation 1- Hansen's gravity-based accessibility studies

The attractiveness of a given opportunity is commonly measured via travel time (impedance), however the method to determine what the attractiveness is can vary from study to study (Manaugh & El-Geneidy, 2012; Sun, Lin, & Li, 2012; Apparicio *et al*., 2008). Attractiveness proves difficult to define, as attractiveness can vary from person to person. Thus this method of accessibility can prove to be a strong generalisation in regards to the population.

The topological methods do not consider the opportunities or the cost of traveling between points, rather using the overall connectivity or characteristics of an overall area (Zielstra & Hochmair, 2011; Emery & Crump 2003). These methods allow for the integration of factors such as traffic and the infrastructure of an area (City of Portland, 1998).

The final commonly employed accessibility measure for active transport are ‘walk-score’ type methods. Similar to distance-based and gravity-based measures, the travel cost between two points is considered. However walk-type scores are supplemented with data about the journey, such as the noise pollution or quality of pavement to model the external variables involved with (Frank *et al.,* 2010; Duncan *et al.,* 2011; Manuagh & El-Geneidy, 2011)

Active travel is limited by the velocity which can be achieved using this mode of mobility. Thus the region to be considered regarding the accessibility of a given location is highly time sensitive. Schapp *et al.* (2016) found the average walking speed for healthy, able-bodied adults to be 5km/h. An exact figure for people with mobility issues is not given, however it can be expected that this figure would be lower. To find an acceptable travel time, the preferred duration of trip must be known in order to estimate the radius that a person is willing to travel by foot (or other means). The duration that adults walk however is found to be much harder to measure, as route attractiveness, reason for trip and value of destination all influence the acceptable distance to travel. However, Schapp’s study does show that acceptable walking distances can range from 2.2km (to access rail travel) to 0.2km (for access to groceries). It estimates that adults overall find a 1km walk to be acceptable. In regard to cycling, a higher speed of movement and higher acceptable time spent moving is found. Pritchard *et al.* (2019) found a 6.0km trip as an acceptable distance when travelling by bike. The study uses a free flow speed of 13.0km/h to gives an acceptable travel time of 27 minutes. However, this figure is with regard to healthy, commuting adults. Again, a drop-off in both speed and distance is to be expected for people with additional needs with respect to cycling. Research into the trends of people with mobility issues is largely lacking, so assumptions must be made (Clayton *et al.,* 2017).

2.3.2 Modelling accessibility

Modelling of accessibility commonly employs network analysis. Graph networks have been utilised in geographic analysis for many years (Foda, & Osman , 2010; Wei *et al.,* 2019; Pritchard *et al.,* 2019; Alattar *et al.,* 2021). Conceptually, a graph is a collection nodes and edges. Nodes are discrete objects, whilst edges describe the pairwise interaction between edges, i.e., $E \subseteq V \times V$. Nodes and edges can be used to represent transport links (as edges) and transport junctions or blockages (as nodes). Graph structures are computationally effective data model for analysis, thus allowing for large datasets to be processed (Arfat *et al.,* 2020).

Graph networks have commonly been employed in transportation studies investigating accessibility (Saghapour *et al.,* 2017; Higgs *et al.,* 2012). These studies define accessibility as the ability to reach opportunities, such as places of work, medical care and other amenities. Saghapour *et al.*'s study used an Origin-Destination (OD) matrix between population centroids of a city to points of interest to investigate cycling accessibility. An impedance function of travel distance between origins and destinations was used to determine journey cost, using a graph network as the underlying topology. This allows service area analysis to be performed to calculate which points of interest could be reached.

Network cost can be used to define which destinations are accessible from any given origin through the generation of isochrones. Isochrones define the catchment area from a given point, using network travel time as the impedance cost (O'Sullivan *et al.,* 2000). Isochrones can therefore define the accessibility of a given location by the number of opportunities located within the given travel time or distance from an origin (Dong *et al.,* 2006). Kesarovski & Hernández-Palacio (2022) used this method to determine the 10-minute accessibility of the region of Stavanger, Norway between citizens and grocery shops using active travel. The authors generated separate isochrones for both walking and cycling as the vector of transport, using travel time across a path network dataset as the impedance. The number of grocery shops within each resulting isochrone was calculated to obtain an accessibility score.

Graph metrics can be employed to model the movement of users on active travel networks. The most common metric to model movements is betweenness centrality. Betweenness centrality is the measure of the importance of a given node to a network, calculated as the sum of the fraction of all-pairs shortest paths that pass through v where V is the set of nodes, $\sigma(s,t)$ is the number of shortest (s,t)-paths, and $\sigma(s,t|v)$ is the number of those paths passing through some v node other than s,t. Edge betweenness centrality replaces the set of nodes with a set of edges. Vybornova *et al.* (2022) used the edge betweenness centrality of Copenhagen's bikeable network as a proxy for the usage of each road or path by cyclists. By indicating how "central" a link is for the flow of cyclists, measures of usership can be achieved without empirical flow data or complex gravity-based models. Use of edge betweenness centrality to model active travel movements has been validated against crowdsourced data in Alattar *et al.*'s 2021 study. The authors find that flow of cyclists as recorded by Strava matches with the least-cost paths derived from betweenness centrality. However, using betweenness centrally as a proxy for the movement of users has been critiqued, as users may not always take the least-cost path due to external variables such as the quality of road surface (Nordström and Manum, 2015).

Recent developments of graph metrics for estimating route choice and travel flows through use of betweenness measures have brought about several methods with similar naming styles and applications. Nordström and Manum (2015) proposed OD betweenness, an adaptation of space syntax to capture bicycling flow between a set of start and end locations. McDaniel *et al.* (2014) on the other hand extended the graph metric stress centrality to estimate the usage of routes and travel patterns with a new metric called O-D centrality. Stress centrality measures the absolute number of least cost paths that pass through a node, whereas betweenness centrality measures the fraction of the least cost paths which pass through a node (Shimbel, 1953). The O-D centrality metric provides a score for every edge in the network, based on the number of times a least cost path has traversed each edge. The method differs from edge betweenness centrality as paths are only calculated between the given set of origins and destinations in the network. The authors state that whilst successful, further data on the impedance of every edge in the network would likely produce improved results. Both OD centrality and OD betweenness aim to capture the journeys which happen across a location based on known start and end locations. Standard betweenness centrality is best suited to estimating journey flows where the start and end locations of trips is unknown.

In order to produce more accurate impedances, weightings can be applied to network edges to encourage routing algorithms to mimic human route choice. Whilst some literature suggests that shortest path analysis works effectively as a proxy for route choice (Aultman-Hall *et al.,* 1997; Stinson & Bhat, 2003), other studies have found there to be statistically significant differences between usership of the shortest route and the dominant or most popular route (Lu *et al.,* 2018). External factors such as route characteristics (attractiveness, perceived danger, traffic volumes) alter the choice of users' routes (Callister *et al*., 2013). Models to find dominate or most popular routes between two locations have been employed successfully, including Bicycle Compatibility Index, Level of Traffic Stress and HCM6 (Harkey *et al*., 1998; Furth *et al*., 2018; Dowling *et al*., 2008). However, these models are reliant on data related to the external factors within route choice, such as traffic count or path quality. Grond's (2016) study showed that by reducing impedance of favourable highway types, the route choice of real cyclists could be effectively modelled. A hierarchy of highway types was implemented, with bike lanes and dedicated cycle paths assigned low impedances compared to major arterial roads. This method provides a simplistic method to estimating the route choice of active travel users. Only the length of each path segment and the path type is required to gain valuable insights into dominate routes.

2.4 Geospatial Decision Support

Geographic information systems have been prominent in decision support for many years (Crossland *et al.,* 1995; Nyerges & Jankowski, 2009). GISs allow for the capture, storage, analysis, and visualisation of data with a geospatial component (Longley *et al.,* 2015). Elements of the real world can be represented within a GIS through a variety of data models. Vector data models, which include points, lines and polygons, can be used to represent physical objects such as barriers and paths. Non-physical shapes can also be modelled with vector data such as administrative boundaries. Vector data models are the most common dataset used to represent reality within complex environments such as cities. The raster data model is also commonly implemented. Raster data uses a grid of values to represent phenomena within each cell. This form of data is suited to modelling continuous surfaces such as elevations or forest canopies (Longley *et al.,* 2015), and thus is not considered further in this study.

Within the topics of planning and management strategies, GIS is commonly used to collate, process, and visualise various metrics across a given location (Kong *et al.,* 2007). This allows a score to be determined at a given location which can inform decision makers in regard to the suitability of a site or location for the action the decision maker plans to make. Suitability studies have commonly employed raster layers to form a stack of values over each grid square. The stack of values can then be aggregated to form an overall suitability layer (Figure 4).

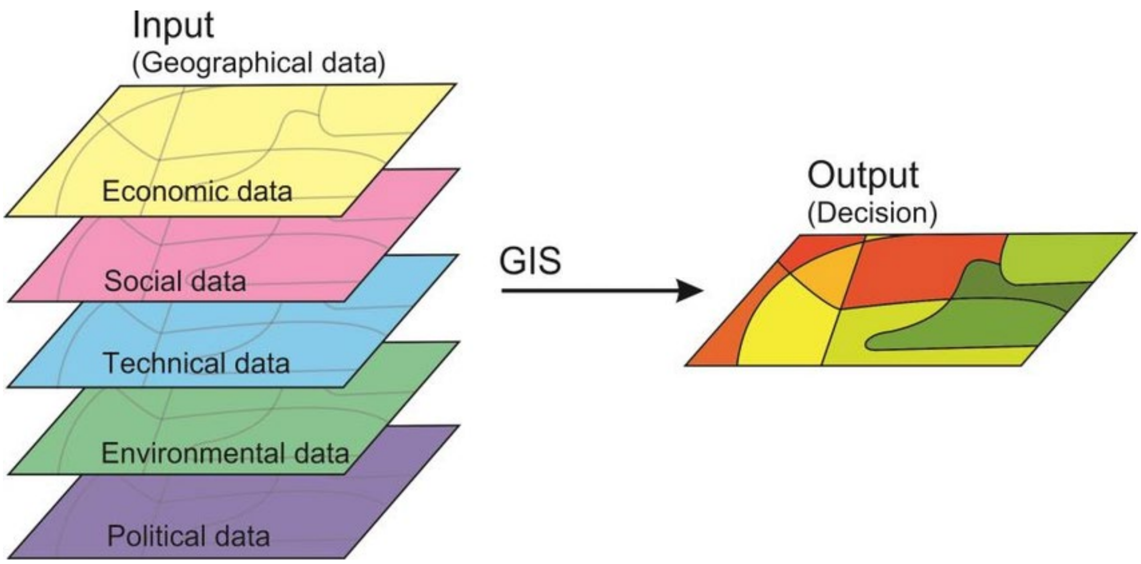


Figure 4 - A typical stack of layers to produce a suitability layer. Adapted from Rikalović et al. (2013)

This multi-factor analysis is not exclusive to raster-based studies. Combination of metrics to score individual vector points have been performed to rank assets such as hospitals (Ohta *et al*., 2007) and schools (Panahi *et al*., 2013). Hoenke *et al*. (2014) used this GIS approach to create a prioritisation tool for the removal of dams. Based on metrics obtained for each dam within the study area, an overall score is generated to highlight the 'worst' dams within their study area.

Within prioritisation studies where multiple factors must be considered, the relative importance of each factor is unlikely to be equal. The process of determining the importance of each factor originates from the non-geospatial research area of Multi-Criteria Decision Making (MCDM). MCDM evaluates the relative importance of each factor in a pairwise matrix in order to provide a weighting for each factor to be multiplied by (Stojčić *et al.,* 2019). Many MCDM approaches are prevalent in studies relating to geospatial problems. Most commonly, analytical hierarchy process (AHP) is used, particularly in studies of suitability analysis (Ohta *et al.,* 2007; Panahi *et al.,* 2013). Technique for Order Preference by Similarity to Ideal Solution (TOPIS), Best-Worst Method (BWM) and Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) can all be conceivably used to determine the ranking of factors. However, AHP is preferred for this study due to its prominence in geospatial decision making (Sałabun *et al.,* 2020). Conceived by Saaty (1980), AHP is a commonly implemented tool to reduce multi-factor metrics to a set of pairwise comparisons. In this pairwise comparison, metrics are traded off against each other and their relative importance is judged using a numerical scale which indicates how much more important a factor is over another with respect to the criterion which they are being compared. The AHP method combines effectively with GIS studies, as shown in the aforementioned research from Ohta *et al*. and Panahi *et al*.

2.5 Summary

Little research has provided a bridge between the "physical" accessibility relating to ability to move through a space, and the "transport" accessibility relating to ability to reach opportunities. This could be due to lack of research more broadly on barriers in active travel. This research aims to fill this literature gap by using both types of accessibility to score physical barriers impacts on ability to reach a given opportunity.

Further, whilst studies have shown the impact of barriers (van Eldijk *et al.,* 2020), to the author's knowledge no study has attempted to rank barriers in terms of removal priority. Given the potential benefits of unlocking key sections of active travel infrastructure for all, it is surprising that little research has attempted to quantify where barriers are least favourable for accessibility.

METHODS AND DATA

This chapter contains three sections: Study area and software selection, methods, and datasets. Study area highlights the regions selected as test sites for the methodology and highlights the tools used to perform processing and analysis in this study. The methods section involves identification of metrics to be used in the index, the processing workflow for each metric, and the development of the final index used to score barriers. The Datasets section highlights the data sources accessed for this study.

The overall aim of this methodology is to create an index which can be applied to any set of obstructions on active travel networks within the UK, in order to determine the priority of removal.

3.1 Study area and software selection

3.1.1 Study area

Research has been conducted in city region of York, and county region of Pembrokeshire. Both sites are within the UK. York and Pembrokeshire were chosen for the high prevalence of barriers within their respective areas, and for their distinct spatial characteristics (Table 1).

Table 1 - Study area characteristics

Study area	York	Pembrokeshire
Location	Northern England	South-West Wales
Region type	City	Rural
Population density	775 citizens per km^2	78 citizens per km^2
Propensity to use active travel	High	Low
Number of audited barriers	37	78
Area size	271.94 km^2	1,590 km^2

The regions covered by both study areas can be seen in Figure 5 and Figure 7. The audited barriers within these areas are also shown for context.

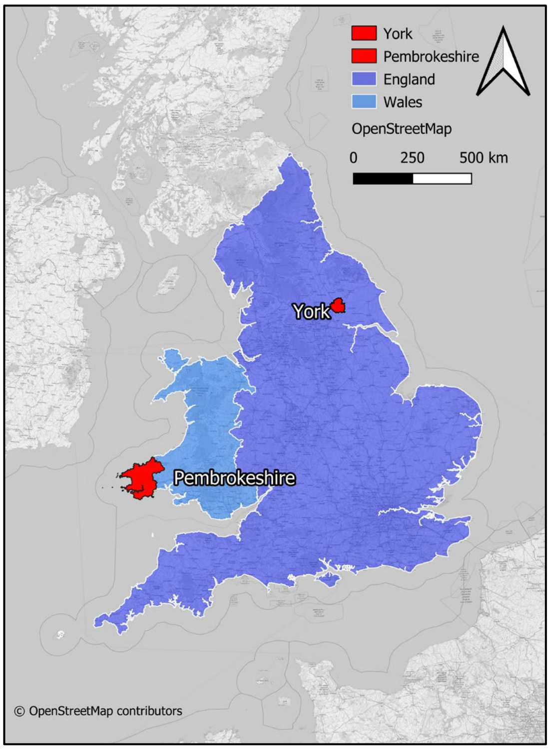


Figure 6 – Location of the study areas

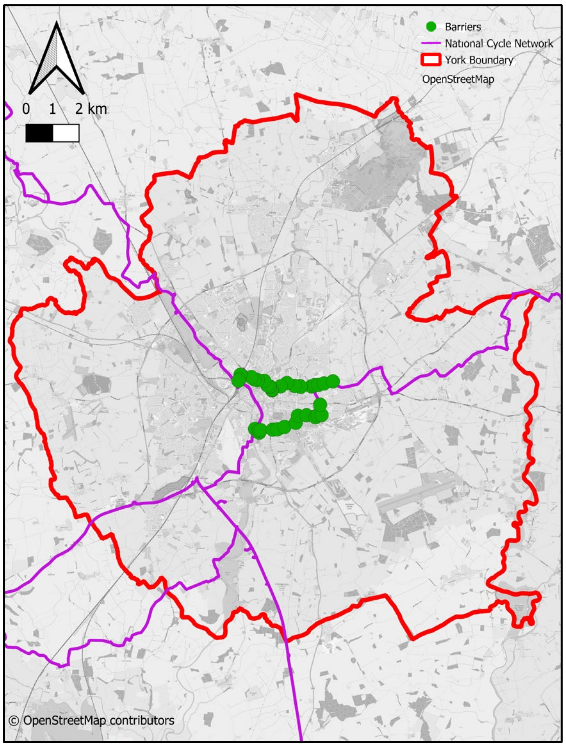


Figure 5 – Barriers in York

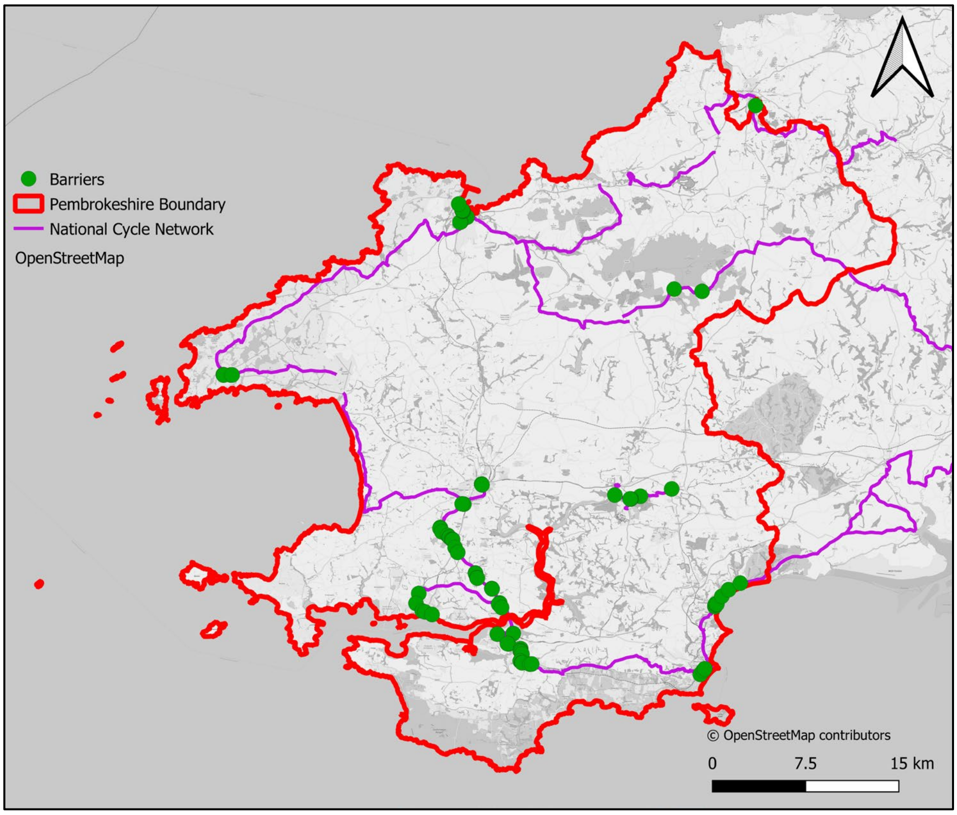


Figure 7 – Barriers in Pembrokeshire

Study sites were selected rather than a UK wide approach to ensure manageable processing times. However, the methods produced could be applied at a national scale in theory.

3.1.2 Software Selection

Processing and analysis of data uses an open-source stack of tools, namely QGIS (QGIS.org, 2022) and Python (Van Rossum & Drake, 1995). QGIS is a GIS program which allows for processing and visualisation of geographic data. It is chosen for this project due to its network analysis capabilities and extensive documentation. Python provides more configurable tools to process, manage and process geographic data. The NetworkX (Hagberg *et al.,* 2008) library provides complex network analysis on graph data structures. The OSMnx library extends this capability to work with graph data derived from OpenStreetMap (Boeing, 2017). Geopandas (Jordahl *et al.,* 2020) is used to manipulate geographic data within Python. All code and processing methods are available on a publicly available GitHub repository to ensure reproducibility. A link to the repository can be found in appendix 8.1.

3.2 Methods

The methodology aims to consolidate the factors discussed within the literature review into a simple overall score. The proposed score is formed of five overall metrics, namely: barrier width, route importance, potential accessibility gain, potential distance gained and relative transport poverty. These metrics are chosen based on the literature and through consultation with subject area experts. Some metrics are comprised of further sub-metrics. The overall hierarchy of metrics can be found in Figure 8. Once processed, metrics are weighted and normalised to provide an overall score.

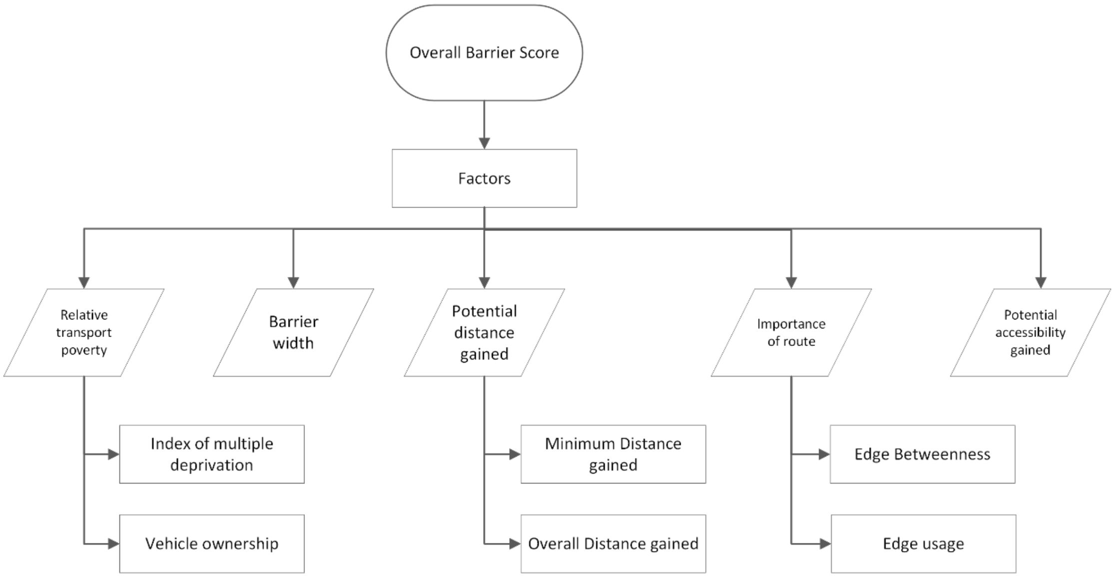


Figure 8 - Overall hierarchy of metrics

3.2.1 Critical widths

Critical width relates to the minimum width of obstructions. This data is derived from the VGI NCN Barrier Audit dataset described in Section 3.3 Table 5. The critical width used for analysis is accessed from the attribute table stored with the location of the barrier. Using a smartphone-based audit tool, users recorded the GPS location, critical width and barrier type (such as chicane, bollard, gate). The critical width provides a measurement for the maximum width a user can be to pass through a given obstruction. As highlighted by Clayton & Parkin (2016) in the literature, the ability to move through a space without hindrance or interruption is lower with marginalised groups. Obstructions with higher critical widths are lower in removal priority as higher proportions of users can pass through. Critical widths are processed in Python using Geopandas.

3.2.2 Route importance

The route importance metrics indicates how much use a section of path could have. Route importance is split into two measures: Edge usage and edge betweenness centrality. Edge usage is used to indicate current route usage based on real-world data from set origins and destinations. Edge betweenness centrality is used to indicate route usage from any location without the need for empirical data.

3.2.2.1 Centrality measures

Both measures of route importance are based around the concept of betweenness. As highlighted in the literature review, this indicates the flow of users over any given point in a network (Vybornova *et al.,* 2022). In this application, edge betweenness is used as a proxy for determining the flow over an edge for users starting and finishing a journey at any network location. Edge useage is defined as the betweenness of a given edge, with predefined start and end points sourced from an OD matrix. This follows the OD betweenness centrality metrics proposed by McDaniel *et al*., (2014) and Nordström & Manum (2015). The edge usage indicates the current flow of users across the network from point to point. In this study, origins and destinations are sourced from census travel to work data, with all modes of transport other than walking and cycling filtered out. Thus, this measures journeys which are known to have happened between two locations. The flow of users on the edge that a barrier is located on indicates how many users pass through the barrier, and therefore provides a tangible number for the amount of people who would benefit from the removal of said barrier.

The origins and destinations of journeys are measured at the Lower Super Output Area (LSOA) level. The population weighted centroid of each LSOA provides the start/end point, in order to best model where populations move to and from. An example of the population weighted centroids which act as origins are shown in Figure 9.

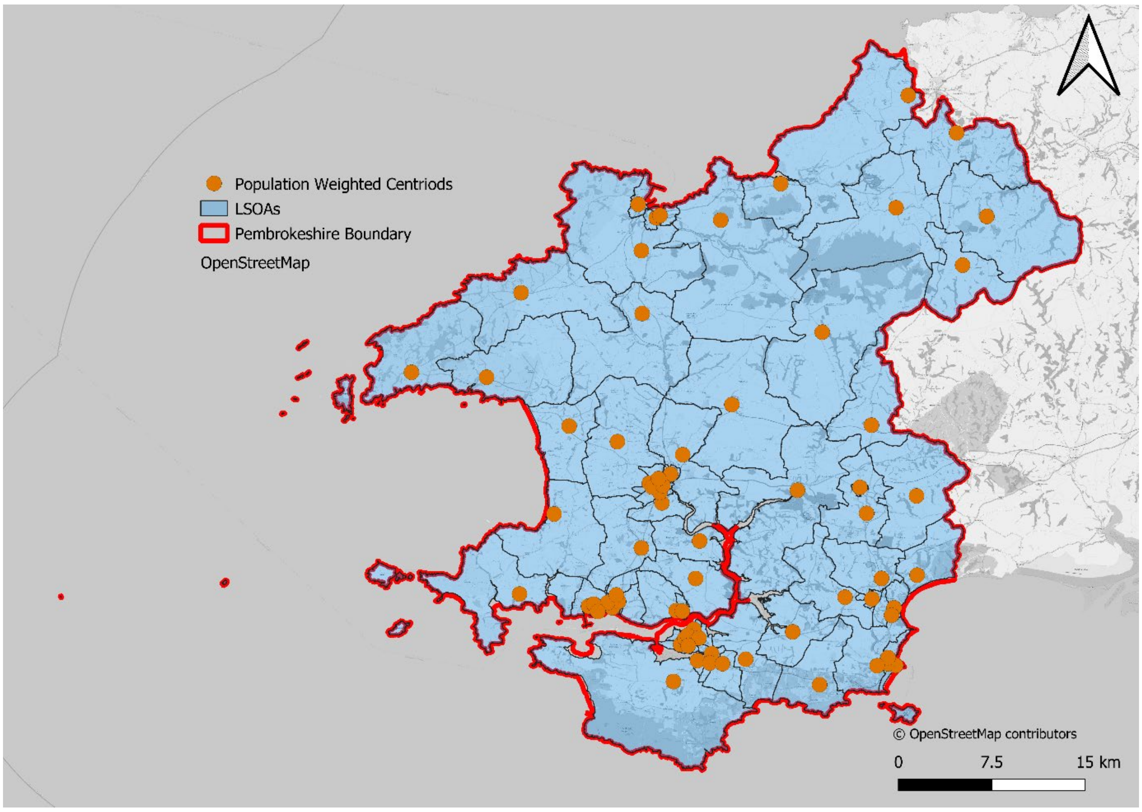


Figure 9 - Population weighted centroids within Pembrokeshire

Whilst edge usage relies on real-world data captured by the census, it is limited by the sample size provided by travel to work data. Further, only journeys to and from work by adults in employment are captured by the data. For this reason, edge usage cannot be relied on alone as a metric for the importance of a route. Edge betweenness centrality is an agnostic measure of flow across the network and considers the least-cost path at between every possible location on the network. For this reason, edge betweenness centrality is applied in this study to measure the flow from journeys that could happen, as a best estimate.

For both methods, graphs representing the street network for the respective study area are created using the OSMnx module (Boeing, 2017). Edge betweenness centrality then is calculated using the NetworkX python package for graph analysis (Hagberg *et al*., 2008). Edge usage is calculated using the Pandana python (Foti *et al.,* 2012) package to calculate route taken from LSOA centroid to LSOA centroid. Metrics are appended to each network edge to store for further analysis and visualisation. Metric values stored on edges are passed to their closest barrier via a spatial join using Geopandas. The workflow for these methods can be found in appendix 8.2.

3.2.2.2 Network weighting

In order to best model the flow of active travel users, the network of traversable routes is pre-processed in order to. Following the work of Grond (2016), edge costs are assigned based on the hierarchy of road type. The length of each edge is multiplied by a weighting factor, shown in Table 2.

Table 2 – Edge cost weighting multipliers

Path type	Weighting Multiplier
Cycleway	0.4
Bridleway	0.4
Path	0.4
Living street	0.6
Track	0.4
Trunk road	10
Service road	1
Primary road	1
Secondary road	1
Tertiary road	0.8
Motorways	100

Weighting of edges provides a simple model for route choice and prevents unrealistic paths such as use of central motorways. The network is accessed using the OSMnx package, and therefore the certain caveats relating to data sourced from OpenStreetMap are applied (Kouandi, 2009).

The resulting graph is simplified using OSMnx's strict mode to remove nodes that are present on non-junctions (Figure 10). This process reduces the fragmentation of the streets, and therefore produce more representative results (Boeing, 2017).

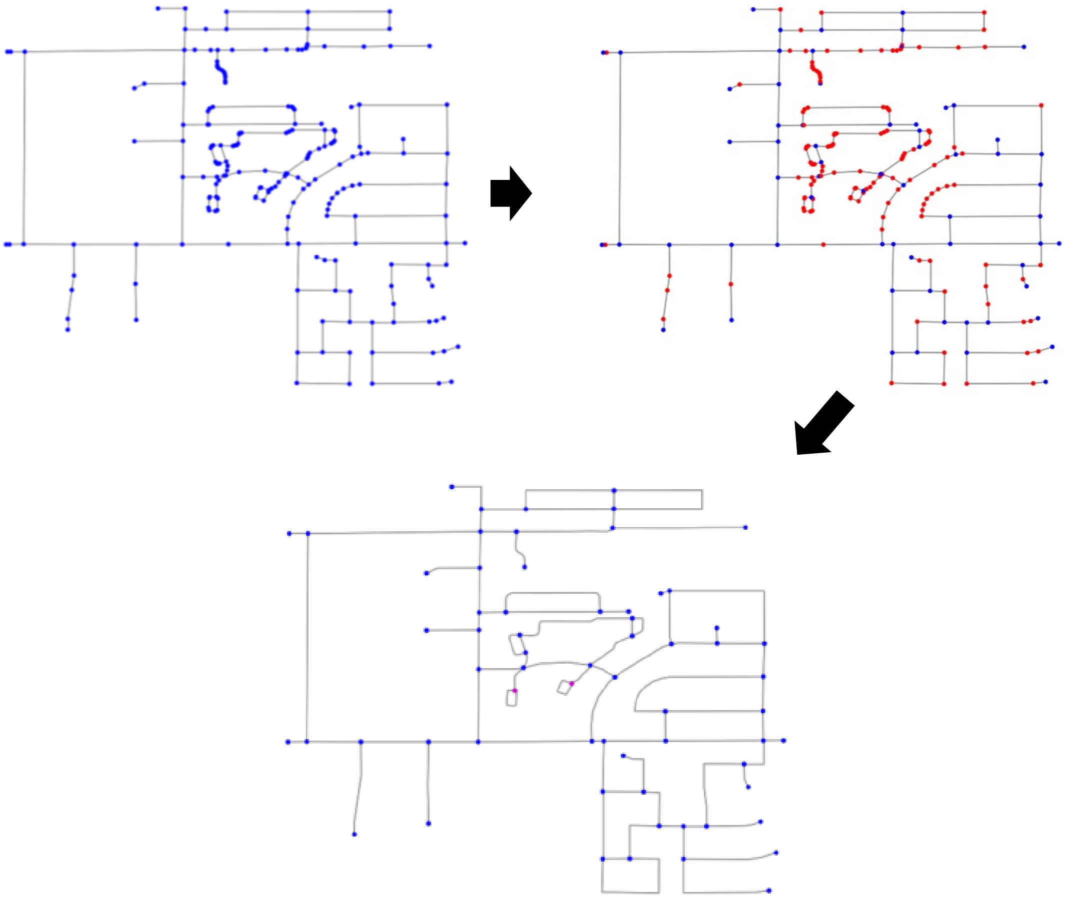


Figure 10 – OSMnx strict simplification mode
Non-junction nodes are removed to reduce street fragmentation. Further details can be found at: https://geoffboeing.com/2016/11/osmnx-python-street-networks/

3.2.3 Distance gained

Distance gained is the measure of how much more uninterrupted travel can be achieved if a given barrier is removed from the network. This measure considers only NCN routes, rather than the full street network. This is because most barriers which are not on the NCN have not been identified and audited yet. It is formed of two parts: minimum distance gained and overall distance gained. This is calculated via an O-D matrix between all barriers along a network, with edge length as the impedance cost. This is performed using QNEAT3 QGIS plugin. The O-D Matrix is then filtered to obtain only relevant points. Distances are then summed per Origin and minimum/overall distance is obtained.

Minimum distances are calculated on the basis that the removal of a barrier is only effective if it opens up a significant distance. Removal of a barrier only for another to be encountered within the next five meters would not be beneficial compared to a barrier which opens a minimum of one kilometre, for example.

Neighbouring barriers are determined using NetworkX. In order to calculate the neighbours, the NCN network is reduced from a full representation of the network to a simplified network where barriers act as nodes. The workflow for this method is found in appendix 8.4. A visualisation of this approach can be seen in Figure 11.

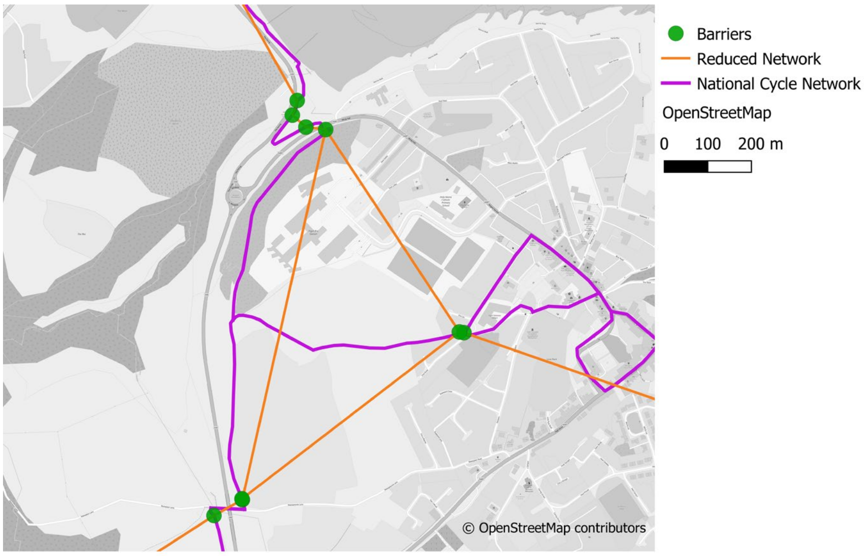


Figure 11 – Network reduced to the connectivity between barriers, based on NCN connectivity

3.2.4 Potential accessibility gain

To assess the accessibility improvement once a barrier is removed, an accessibility score for both pre- and post-removal is determined. Following the work of Calafiore *et al*., (2022), Kesarovski & Hernández-Palacio (2022), and van Eldiijk *et al.* (2020), accessibility is measured as the number of amenities available within a given catchment region or isochrone.

Amenities are sourced from OpenStreetMap using the “amenities” tag. The amenities used are shown in Table 3.

Table 3 – OpenStreetMap amenities used in accessibility analysis

OSM Amenity tags	Amenity type
College, Kindergarten, Library, School, University	Education
Bicycle repair station, Bicycle rental, Bus station, Ferry terminal, Taxi	Transport
ATM, Bank, Bureau de change	Finance
Clinic, Dentist, Doctors, Hospital, Pharmacy	Medical
Social facility, Veterinary, Community centre, Social centre, Place of Worship, Police, Fire station, Post box, Post depot, Post office, Parcel Locker, Telephone, Recycling	Social
Arts centre, Cinema, Public bookcase, Theatre, Marketplace, Townhall, Bar, Café, Pub, Restaurant	Cultural
Drinking water, Toilets, Water point, Shower, Kitchen, Childcare	Basic amenities

Using the distance of 1.2km at for walking accessibility and 6km for bicycle accessibility, the number of amenities available from every population weighted centroid within the study area is found. The distance is measured as the network distance from centroid to amenity. This is performed without the barriers acting as an impedance on movement. This is achieved through use of the OSMnx and pandana python packages.

This process is then repeated, however on this iteration the barrier acts as an impassable point on the network. In areas with barriers, this may reduce the walkable area from a population weighted centroid (Figure 12).

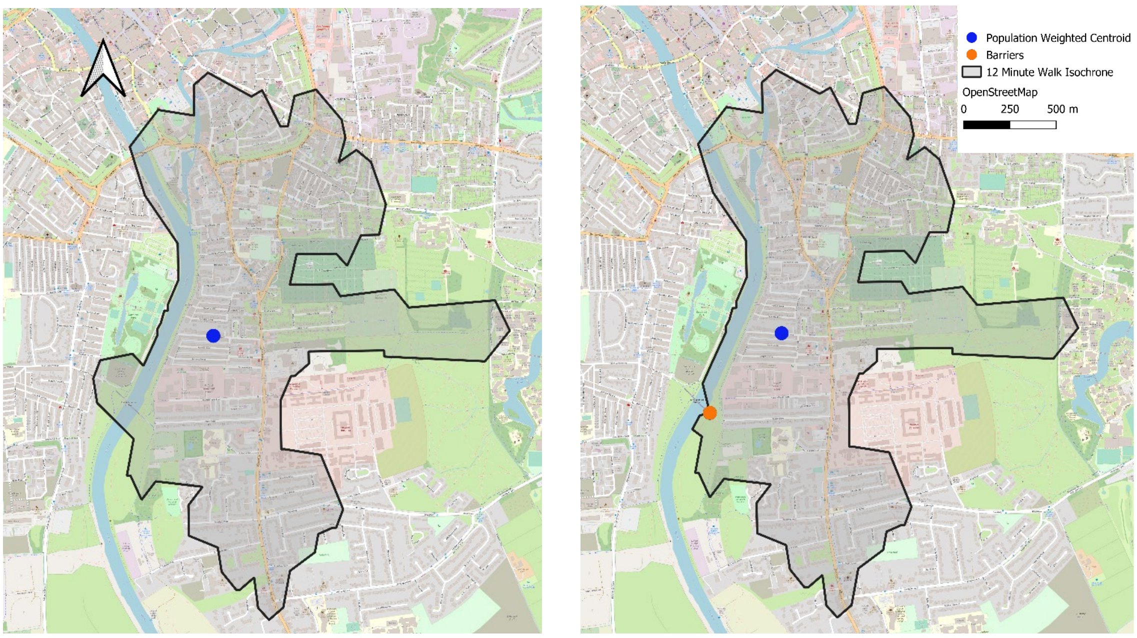


Figure 12 – Change in walkable areas within 12 minutes due to the presence of barriers

The amenity count from this iteration represents the current accessibility level. The difference in amenities between the current constricted network and an unrestricted network is calculated to provide a value for potentially amenity improvement per population weighted centroid. The difference count is converted to a percentage to provide potential percentage change in accessibility.

To determine a score per barriers, isochrones are calculated around each barrier with distances of 1.2km and 6km for walking and cycling respectively. These isochrones are calculated based on network travel time. Population weighted Centroids which fall within an isochrone are joined to the barrier and the total difference in amenities accessible per barrier is summed to give an overall accessibility change score. The full processing workflow is shown in appendix 8.3.

3.2.5 Relative transport poverty

As shown by Rind *et al*., (2015), Olsen *et al*., (2017) and Norwood *et al*., (2014), areas of higher deprivation and transport poverty have a greater reliance on active travel as a mode of transport. Therefore, it is important to consider the location of the barrier in relation the spatial social-economic characteristics present. The Index of Multiple Deprivation (Office for National Statistics, 2015) provides a rank for every LSOA within England (the Welsh Index of Multiple Deprivation, Northern Ireland Multiple Deprivation Measure and Scottish Index of Multiple Deprivation provide similar measures for their respective study areas).

Barriers are less prevalent in the areas of lowest deprivation (Figure 13). However, it is these barriers which carry the greatest impact to the local community. For this reason, the IMD score of the LSOA which a barrier is located in is applied to the overall score per barrier. Similarly, areas with lower vehicle ownership benefit more from the removal of a barrier than those from those with high.

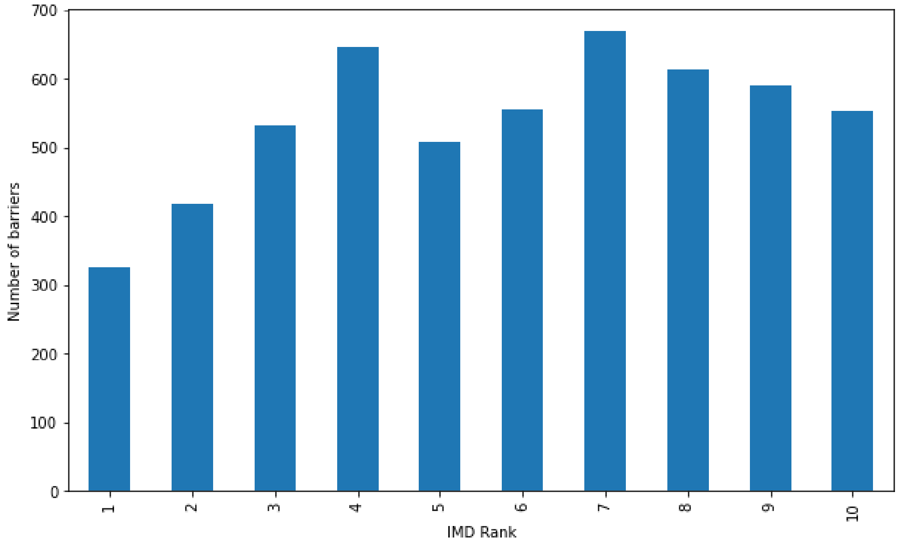


Figure 13 – Distribution of NCN barrier counts across IMD decile ranks in England

Vehicle ownership is taken from the 2011 census estimates, again at the LSOA level. Ownership per person is calculated using the adult population estimates per LSOA divided by the vehicle ownership of the area. The LSOA level metrics are then spatially joined to the barriers. The data was accessed through the Ministry of Housing, Communities and Local Government's ArcGIS Online web portal, and the Nomis census data web portal. The full workflow for these metrics can be found in appendix 8.5.

3.2.6 Index application

With all metrics computed and assigned to each barrier via spatial joins, the metrics are rescaled using a unity-based normalisation function prior to weighting (Equation 1) to bring all values with the range [0,1]. Rescaling ensures the relative metric score is considered, rather than absolute.

$$x_{new} = \frac{x - x_{min}}{x_{max} - x_{min}}$$

Equation 2 – Normalisation Function

3.2.7 Metrics weighting

In order to weight the metrics accordingly, subject experts and stakeholders were consulted. These consisted of domain specialists from within Sustrans, many of whom are involved in current barrier removal schemes and initiatives. Weightings of factors are determined using the multi-criteria decision-making approach of AHP, following the work of Saaty (1980), Ohta *et al.*, (2007) and Panahi *et al*., (2013). AHP follow a four-step method, which when applied to the problem of barrier removal scoring, take the following shape:

1. Define the goal of the process, with the goal in this instance being scoring of obstructions.
2. Create a hierarchy of factors. The hierarchy will start with the goal at the top, followed by critical metrics and then sub-metrics forming the lower layer.
3. Construction of pairwise comparison matrices for the critical metrics and sub-metrics.
4. Use the results of the pairwise comparison to assign weights.

The metrics used formed two hierarchical layer: the overall metrics and the sub-metrics. This can be found in Figure 14.

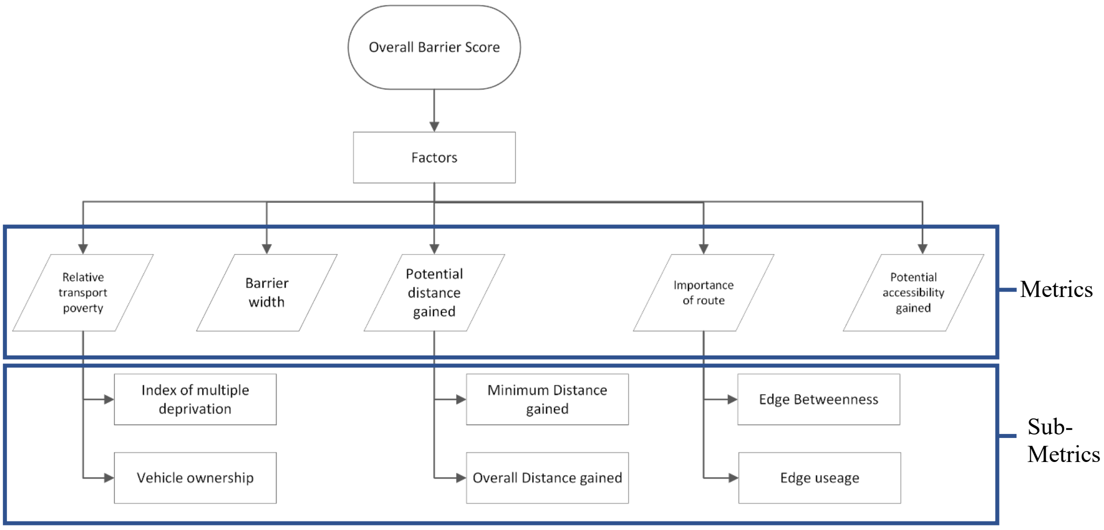


Figure 14 – Metric hierarchy

All metrics in the critical metrics layer are ranked against each other via pairwise comparison. Sub-metrics are also ranked via a pairwise comparison, however only ever against other sub-metrics belonging to the same critical metric. The pairwise comparison was performed through consultation with stakeholders involved in barrier removal projects from Sustrans. Priorities were obtained through a questionnaire, which utilised the following format:

a. If you were considering the removal of a barrier, what would you consider more important: factor x or factor y?

	x
	y

b. How much more important is your choice relative to the alternative?

	Equally important
	Slightly more important

	Strongly more important
	Very strongly more important
	Extremely more important

Prior to the completion of the questionnaire, a presentation and open discussion were held between the stakeholders and the authors. Within the presentation, metrics were explained in non-technical language in order to ensure that the questionnaire could be completed to the best possible standard. Discussion allowed for confirmation that the proposed methodology was sound, and any alterations could be made prior to weightings being assigned.

After collation of questionnaire feedback, linguistic responses were converted to numerical scores using Table 4.

Linguistic Scale	**Numerical Scale**	**Reciprocal Scale**
A is as equally important as B (exactly equal)	1	1
A is slightly more important than B (slightly strong)	3	1/3
A is strongly more important than B (fairly strong)	5	1/5
A is very strongly more important than B (very strong)	7	1/7
A is extremely more important than B (extremely strong)	9	1/9

Table 4 – Response comparison scale

The quality of judgements is assessed using a consistency ratio check. The consistency ratio determines how consistent weights were in comparison to allocating weights randomly. If stakeholders returned an answer to any question which exceeds the maximum threshold for acceptable randomness (set at a consistency radio of 0.1 (Saaty, 1987)), the responses cannot be used. Once consistency is confirmed, the normalised metric values are multiplied by the determined weights. Metrics are then summed per barrier to provide an overall score. This score indicates removal priority, with larger values signalling higher priority.

3.2.8 Validation

Whilst no empirical data on barrier removal can be obtained for this study, spatial trends identified within each metric/sub-metric can be confirmed through use of spatial statistics. To identify clusters of a given variable, local Moran's I is employed (Anselin, 2019). Local Moran's I indicates whether neighbouring features have statistically significant similarity, and the direction of the similarity (clusters of high values or clusters of low values). Significant outliers within clusters are also highlighted from this method. The formula for Local Moran's I are as follows:

$$I_i = \frac{x_i - \bar{X}}{S_i^2} \sum_{j=1, j \neq i}^{n} w_{i,j}(x_j - \bar{X})$$

where x_i is an attribute for feature $i, \bar{X}$ is the mean of the corresponding attribute, $w_{i,j}$ is the spatial weight between feature i and j, and:

$$S_i^2 = \frac{\sum_{j=1, j \neq i}^{n} (x_j - \bar{X})^2}{n - 1}$$

with n equating to the total number of features.

The z-score is computed as:

$$z_{I_i} = \frac{I_i - E[I_i]}{\sqrt{V[I_i]}}$$

where:

$$E[I_i] = -\frac{\sum_{j=1, j \neq i}^{n} w_{i,j}}{n - 1}$$

$$V[I_i] = E\left[I_i^2\right] - E[I_i]^2$$

Equation 3 – Local Moran's I

This statistic can be applied to any metric which exhibits some form of clustering.

To indefinity statically significant areas of high and low values, Getis-Ord Gi* statistic is applied (Ord & Getis, 1995). The Getis-Ord Gi* statistic indicates the location of 'hotspots' (or indeed 'coldspots') with relation to a given variable. The Gi* value is calculated as following:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \bar{X} \sum_{j=1}^{n} w_{i,j}}{S \sqrt{\frac{\left[n \sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2\right]}{n - 1}}}$$

where x_j is the attribute value for feature $j, w_{i,j}$ is the spatial weight between feature i and j, n is equal to the total number of features and:

$$\bar{X} = \frac{\sum_{j=1}^{n} x_j}{n}$$

$$S = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - (\bar{X})^2}$$

*Equation 4 – Getis-Ord Gi**

Both a z-score and p value are produced. Z-scores indicate the strength and direction (high or low value) of hotspots. The p values indicate whether a results is statistically significant or not. For the conceptualisation of spatial relationships, the contiguity edges method is used with polygon data and inverse distance is used with point data.

To test for an overall spatial pattern, the global variant of the Moran's I statistic is employed. Global Moran's I is a statistical measure of spatial autocorrelation. It is calculated using the following formula:

$$I = \frac{n}{S_0} \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{i,j} z_i z_j}{\sum_{i=1}^{n} z_i^2}$$

where z_i is the deviation of an attribute for feature i from its mean $(x_i - \bar{X})$, $w_{i,j}$ is the spatial weight between feature i and j, n is equal to the total number of features, and S_0 is the aggregate of all the spatial weights:

$$S_0 = \sum_{i=1}^{n} \sum_{j=1}^{n} w_{i,j}$$

The z-score is computed as:

$$z_I = \frac{I - E[I]}{\sqrt{V[I]}}$$

where:

$$E[I] = \frac{-1}{n-1}$$
$$V[I] = E[I^2] - E[I]^2$$

Equation 5 – Global Moran's I

To test for significant relationships between two variables, Spearman's rank is employed. Spearman's rank measures the monotonicity of a relationship between two variables. This allows for the strength and direction of correlation to be determined. The formula is shown below:

$$p = 1 - \frac{6 \sum d_j^2}{n(n^2-1)}$$

where $d_j = R(X_i) - R(Y_i)$ is the difference between the two ranks (R) for each observation, and n is the number of observations.

Equation 6 – Spearman's rank

The resulting correlation value ranges between -1 and 1, with -1 indicating a negative correlation, 0 indicating no correlation and 1 displaying a positive correlation. The p-value indicates the significance of a relationship, with $p < 0.05$ displaying significance at the 95% confidence interval.

3.3 Datasets

This research is dependent on seven key datasets, as shown in Table 5.

Table 5 - Datasets

Dataset Name	Data Type	Dataset description
National Cycle Network	Vector Geopackage (.gpkg)	A geospatial representation of all sections of the National Cycle Network. Data is accessed from Sustrans' public data hub.
NCN Barrier Audit	Vector Geopackage (.gpkg)	An audit of all potential obstructions and limitations of the NCN, recorded in the form of spatial points. Attributes relate to the issue of each barrier, such as a given barrier's critical width. Data is provided directly from Sustrans.
2011 Census Method of Travel to Work Matrix	Tabular dataset (.csv)	A record of the location of a workers place of residence and employment in the form of an Origin-Destination matrix at the Lower Super Output Area level. Accessed through the Nomis web portal
OpenStreetMap Network	Vector OSM data (.osm)	Topologically correct street network data accessed through the OSMnx Python package. Edge attributes such as street type are stored.
Indices of Multiple Deprivation (IMD)	Vector Shapefile (.shp)	A geospatial measure of relative deprivation at LSOA level. Accessed from the Ministry of Housing, Communities and Local Government ArcGIS Online web portal
OpenStreetMap Amenities	Vector OSM data (.osm)	Volunteered geographic data representing various amenities as geographic points. Attributes such as type of amenities are stored.
2011 UK Census Car or Van Availability	Tabular dataset (.csv)	An estimate dataset to classify households with access to motorised private vehicles. Measured at the LSOA level. Accessed through the Nomis web portal

Most datasets are publicly available and provided with an Open Government Licence, which will allow for reproducibility of the methods. Datasets which are not currently publicly available, such as the NCN Barrier Audit data from Sustrans, are planned to be accessible publicly in the near future at the time of writing.

Data from both OpenStreetMap and Sustrans are largely created as VGI. VGI has inherent limitations in regard to completeness and accuracy (Kouandi, 2009). However, for the purposes of this study the data quality is deemed appropriate. Census data is provided by the Office for National Statistics and is accessed at the lowest publicly available geography: Lower Super Output Areas. The data is deemed to be robust, and for the purpose of this study is available at an appropriate spatial resolution.

RESULTS

Presented in this chapter is the outputs and analysis of each metric when applied to the study areas, along with the weights derived from the AHP, and the final index scores as outlined in the methods chapter. The results are quantitatively and qualitatively examined to identify spatial patterns and understand how and why the results have occurred.

4.1 Metrics

To understand overall scores obtained, the results of each metric is analysed in turn. The statistical methods to analyse the outputs are shown in the section 3.2.8.

4.1.1 Critical width

The spatial distribution of barrier critical widths is shown in Figure 15 for York and Figure 16 for Pembrokeshire.

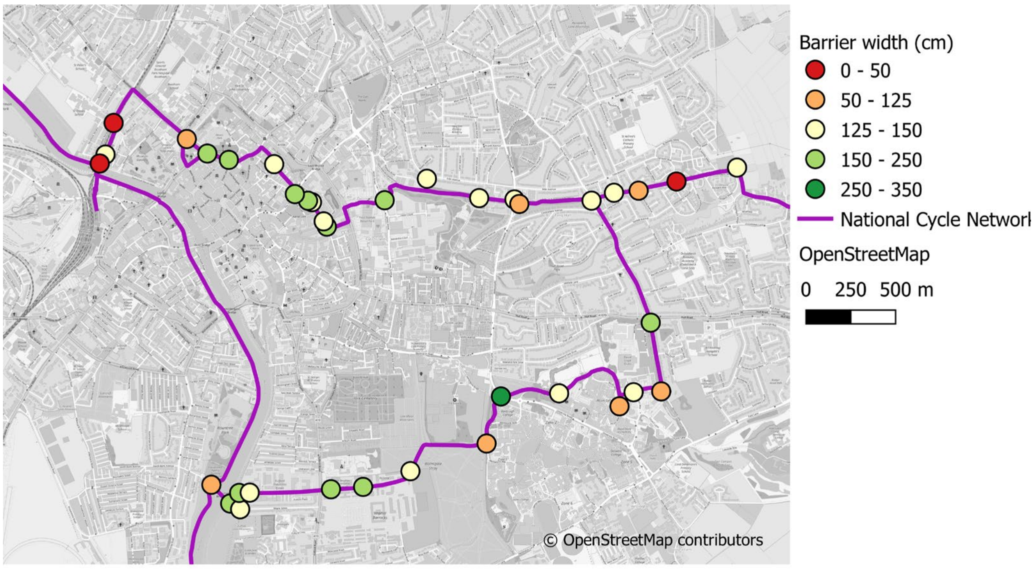


Figure 15 – Spatial distribution of critical widths in York

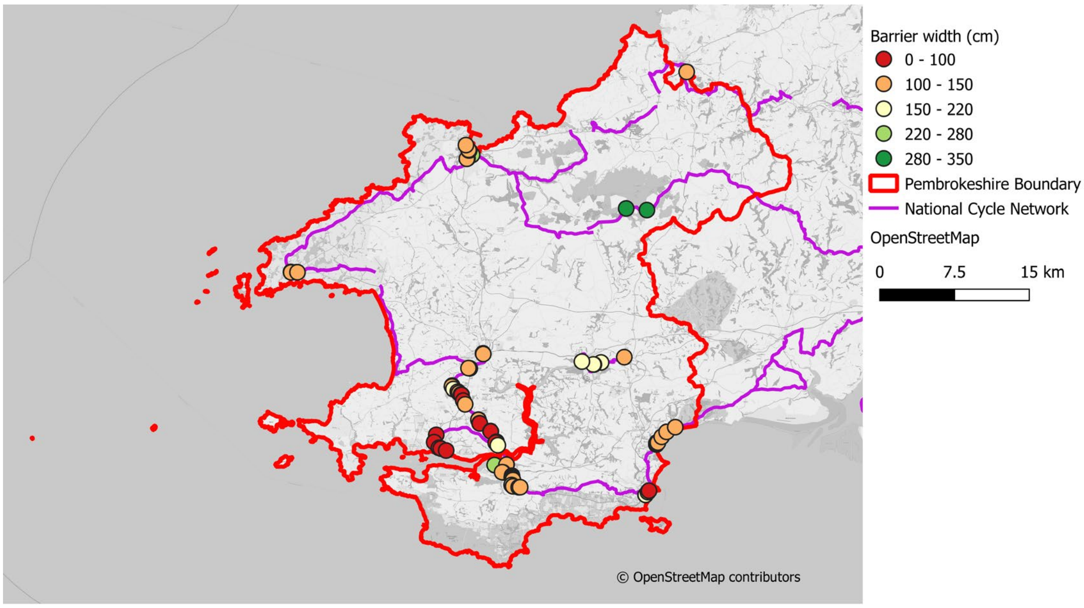


Figure 16 – Spatial Distribution of critical widths in Pembrokeshire

Global Moran's I statistic is applied to identify if there is a relationship between barrier width and location on the network. The resulting Moran's I value, expected I value, z-score and p-value are shown in Table 6. The z-score indicates the direction of a relationship. Negative z-values < -1.65 indicate dispersion, whilst values >1.65 indicate clustering and values between indicating no spatial correlation.

Table 6 – Global Moran's I values for the relationship of critical widths

STUDY AREA	MORAN'S I	EXPECTED I	P-VALUE	Z-SCORE
YORK	0.105	-0.028	0.373	0.891393
PEMBROKESHIRE	0.398	-0.013	0.000	4.771120

Critical widths of barriers within York demonstrate no significant spatial pattern, as the p-value is > 0.05 (null hypothesis is accepted, there is no spatial pattern). Pembrokeshire however exhibits high spatial correlation, with barrier widths being spatially clustered (z-score > 1.65, p-value < 0.05). This is likely due to how the NCN was constructed within this area, implementing the same barrier type when constructing a given segment.

4.1.2 Relative Transport Poverty

To assess how the IMD and vehicle ownership metrics impact the scoring of barriers, the spatial pattern of poverty across the study areas is considered. Barrier locations are first inspected visually, before the Getis-Ord Gi* statistic is employed to check for statistically significant hot or cold spots within the area. The relationship between barrier location and hot-spots is then analysed.

4.1.2.1 Index of Multiple Deprivation

The relative poverty of York is shown in Figure 17, using the IMD score. Within York, the more deprived areas are found towards the centre of the region. Poverty levels vary spatially across the region, with six LSOAs ranked within the lowest two deciles. Barriers are spread across all deprivation levels. IMD scores at barriers range from 34.209 at the most deprived to 2.062 in the least deprived area. The Gi* statistic indicates 21% of barriers reside within a hotspot at the 95% confidence interval. 16% of barriers are located in a coldspot (at the 90% confidence interval). These are all within the same LSOA area (Figure 18).

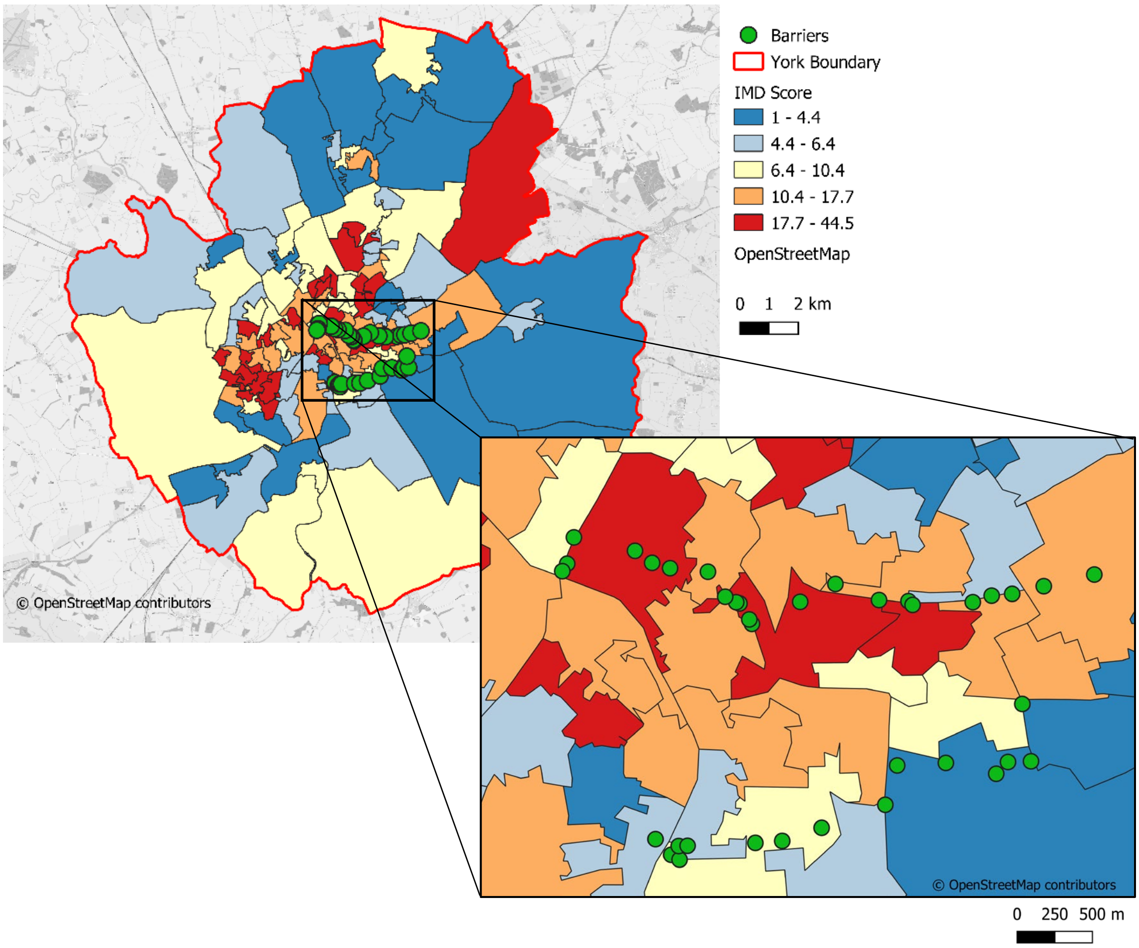
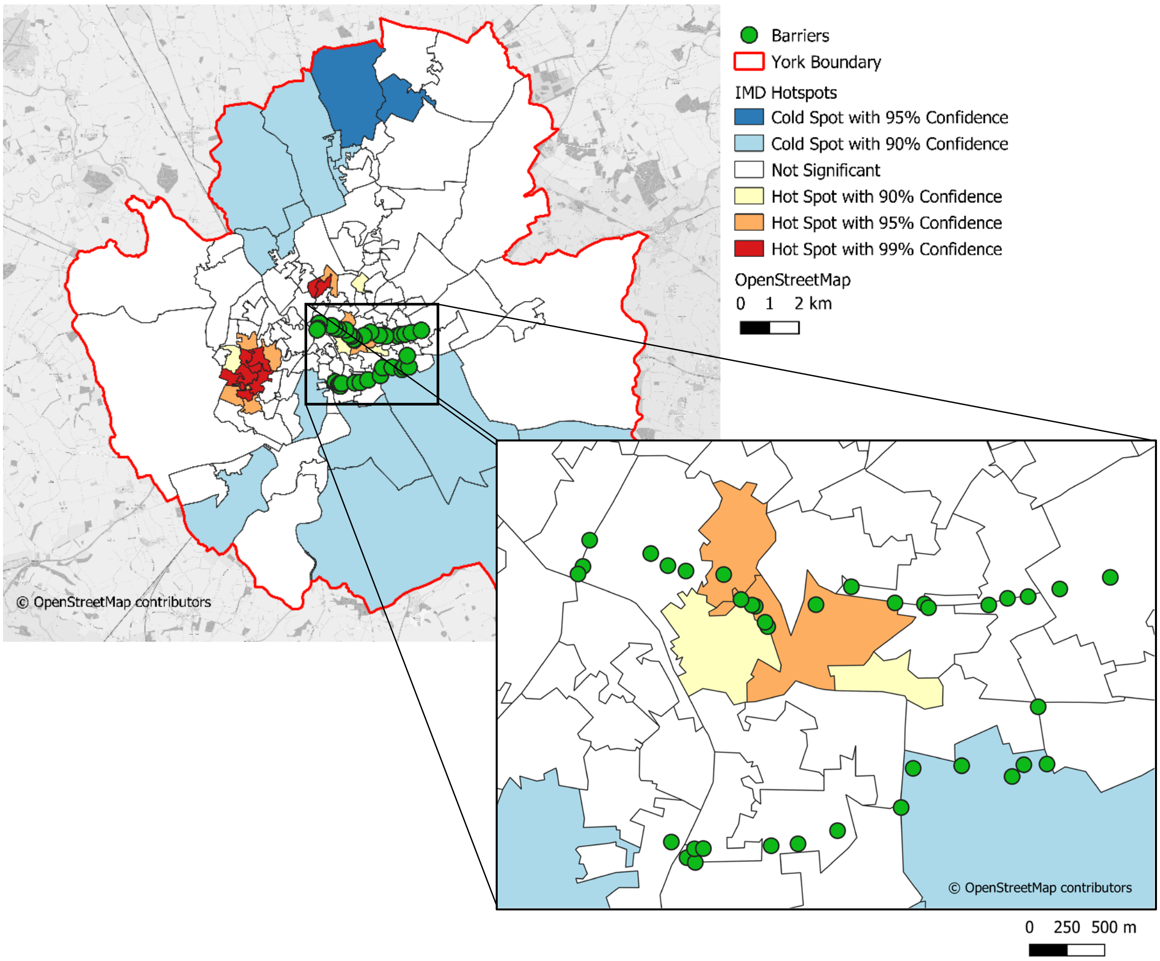


Figure 17 – IMD Scores in York



The IMD decile for Pembrokeshire is shown in Figure 19. A lower rank indicates higher levels of deprivation. Five LSOAs are within the first decile, indicating high poverty within the region. A central belt of affluence is found going West to East. Relative deprivation is at its highest within the South of Pembrokeshire, concentrated around the largest towns in the region (Pembroke and Milford Haven, Figure 19). The Gi* statics confirms these regions to be hotspots for deprivation (Figure 20). 15% of barriers are found within a hotspot at the 95% confidence level. No barriers are found within coldspots of low deprivation.

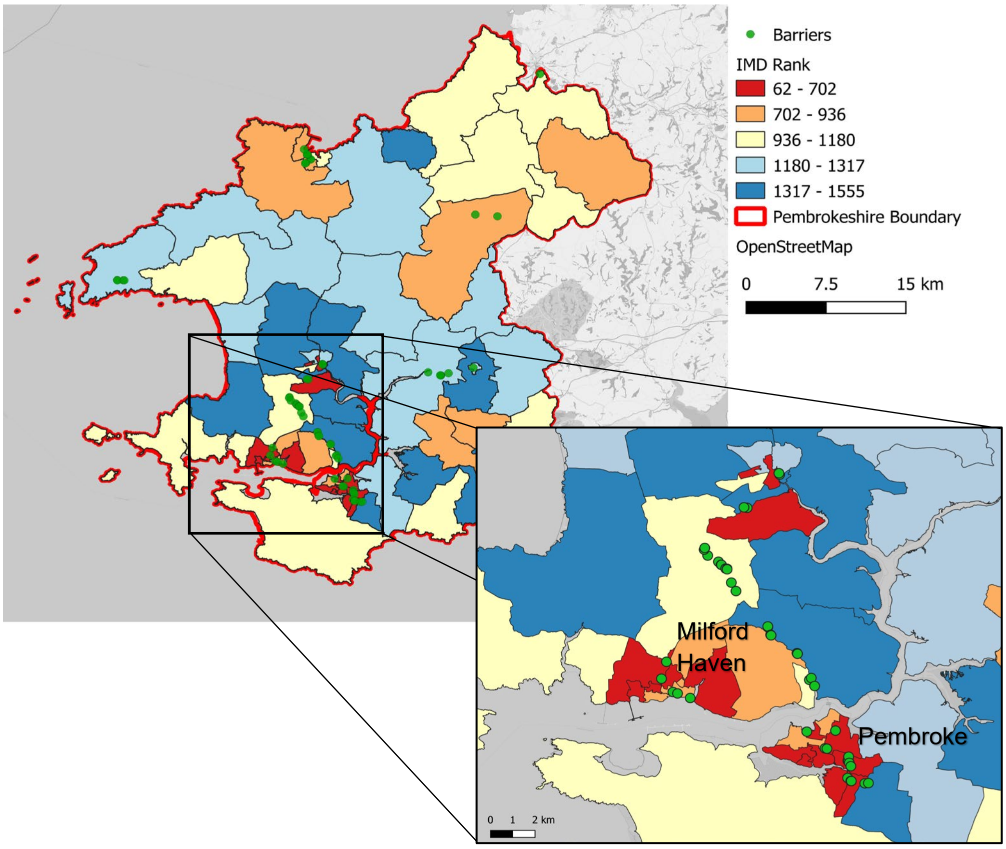


Figure 19 – IMD Ranks in Pembrokeshire

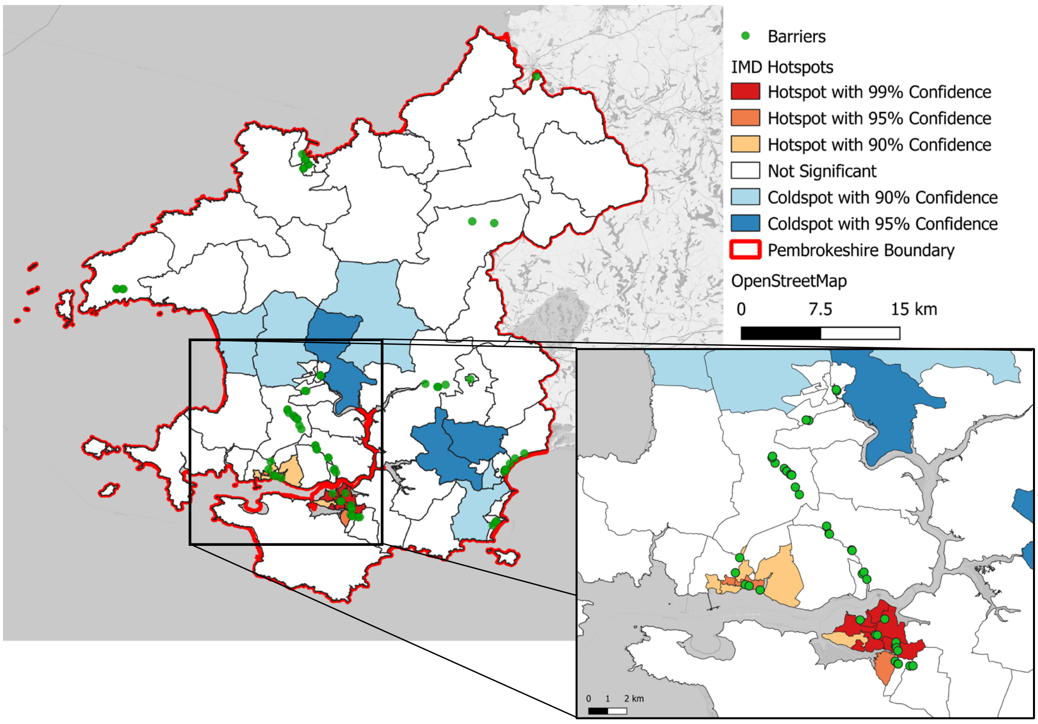


Figure 20 – IMD Hotspots in Pembrokeshire

Vehicle ownership per person appears highly varied across York (Figure 21). Barriers are located within both the lowest region of vehicle ownership and the area with the sixth highest level of vehicle ownership. From the Gi* hotspot analysis, 32% of barriers are located in coldspots. No barriers are located within hotspot clusters (Figure 22).

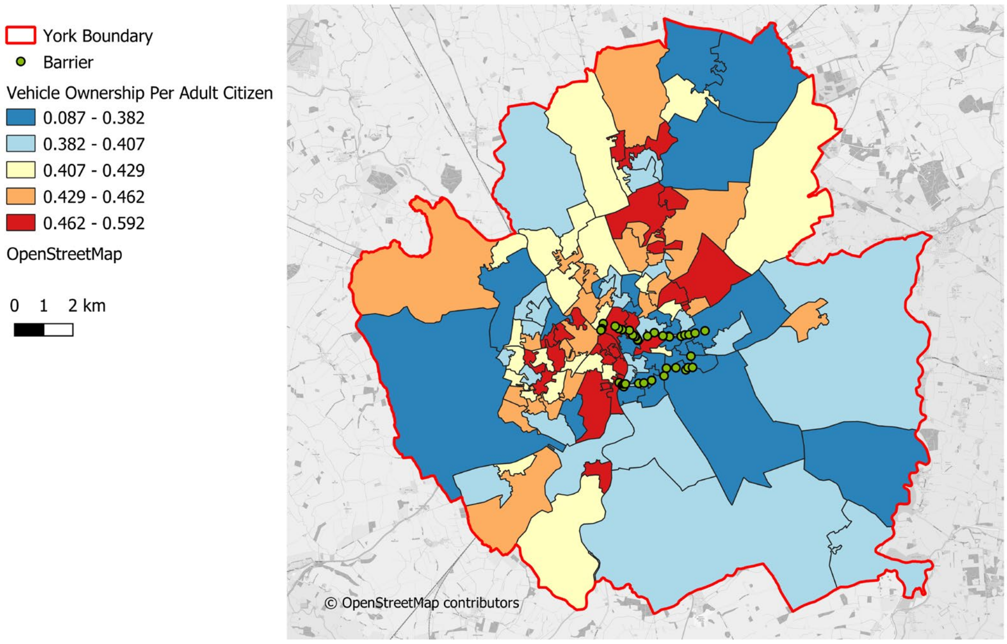


Figure 21 - Vehicle Ownership rates in York

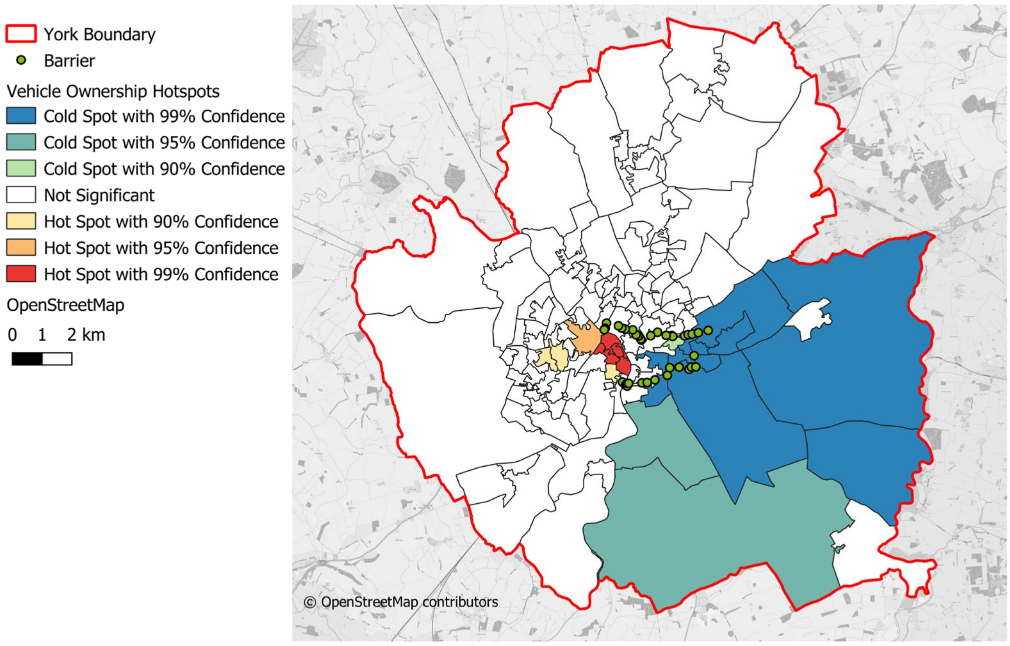


Figure 22 – Vehicle Ownership hotspots in York

In Figure 23, the Vehicle ownership is displayed for Pembrokeshire. Areas of high vehicle ownership are found within LSOAs which contain the major towns for the region such as St Davids and Tenby. There are few statistical hotspots within the area, with hotspots around Tenby to the South East and Milford Haven in the South West. Six barriers are found within these locations (8% of all barriers within the region). By comparison, 22% of barriers are located within coldspots where ownership is low (Figure 24).

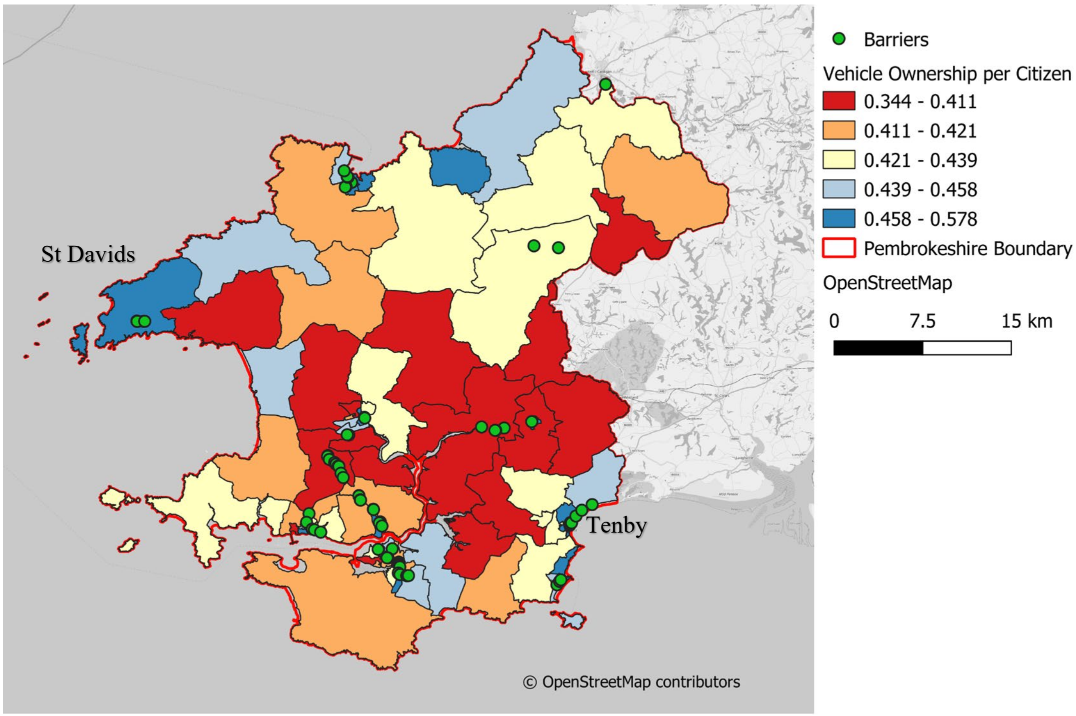


Figure 23 – Vehicle Ownership rates in Pembrokeshire,

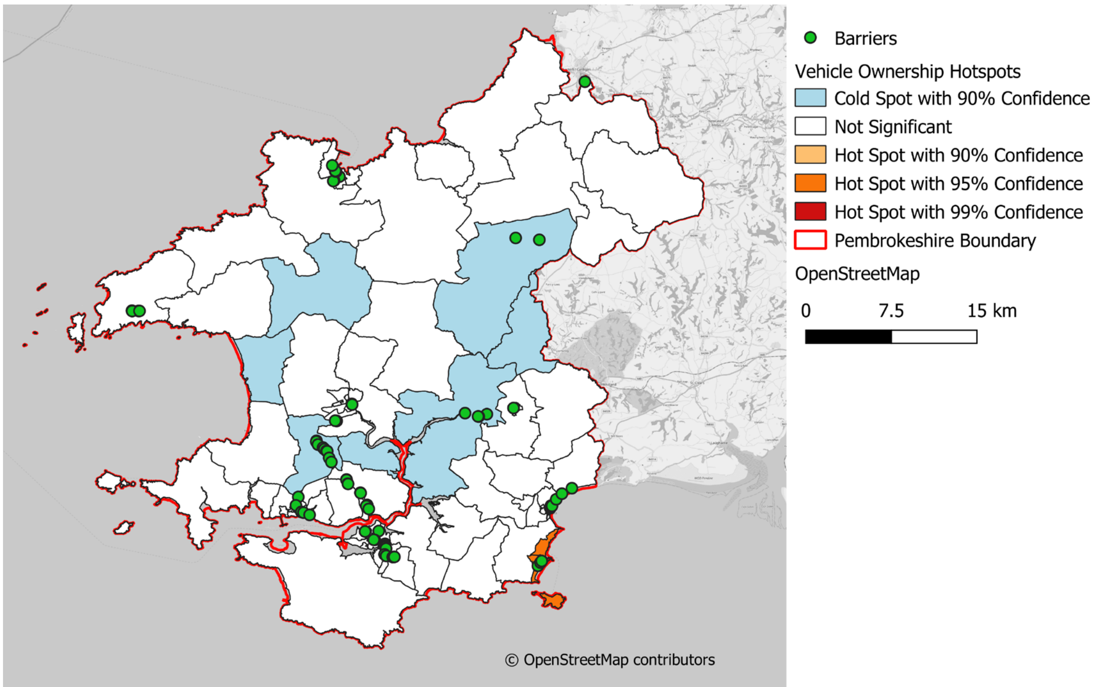


Figure 24 - Vehicle Ownership hotspots in Pembrokeshire

4.1.3 Potential distance gain

4.1.3.1 Minimum distance gain

Table 7 displays statistics in regard to the potential minimum distance gained within both study areas. Pembrokeshire exhibits larger differences between the lowest and highest figures than York. However this is to be expected as York is significantly more built up, thus the construction of barriers is more prevalent. York also contains fewer overall kilometres of NCN path available so any gain made is expected to be shorter. The minimum gained per barrier is shown in Figure 25 for York and Figure 26 for Pembrokeshire.

Table 7 – Potential minimum distance gained statistics

Study area	Lowest minimum gain	Highest minimum gain	Range	Mean	Median
York	33.2m	397.5m	364.3m	169.2m	150.6m
Pembrokeshire	2.3m	18862.3m	18860m	596.2m	107.3m

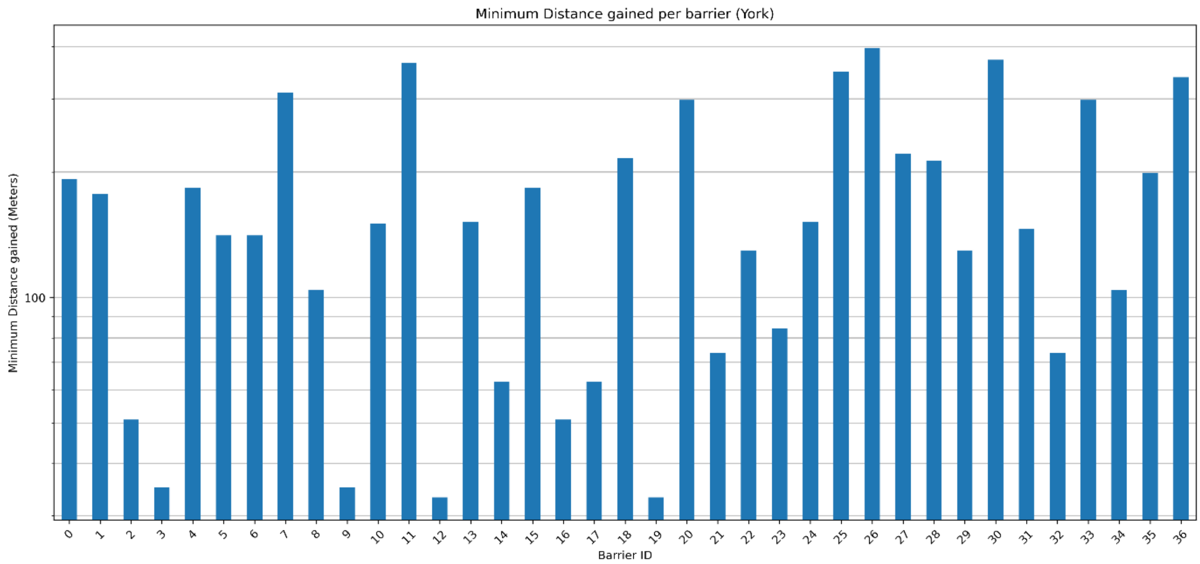


Figure 25 – Minimum distance gained per barrier in York

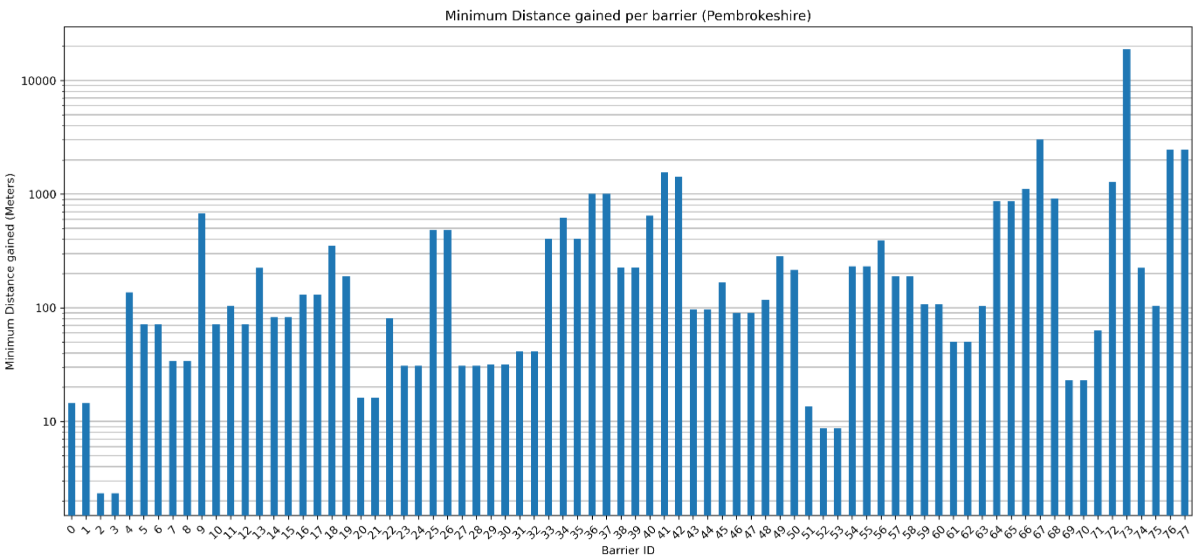


Figure 26 – Minimum distance gained per barrier in Pembrokeshire

4.1.3.2 Overall Distance gained

Table 8 displays statistics for the overall potential uninterrupted distance gain per barrier removal. Similar to the minimum distance gained results, Pembrokeshire exhibits values with greater magnitude, likely due to the sparsity of the area. The overall potential gain per barrier is shown in Figure 27 for York and Figure 28 for Pembrokeshire.

Table 8 - Potential overall distance gained statistics

Study area	Lowest Overall gain	Highest Overall gain	Range	Mean	Median
York	50.9m	12899.6m	12866.4m	1957.1m	807.2m
Pembrokeshire	22.1m	33591.4m	33569.3	4937.6m	1260.1m

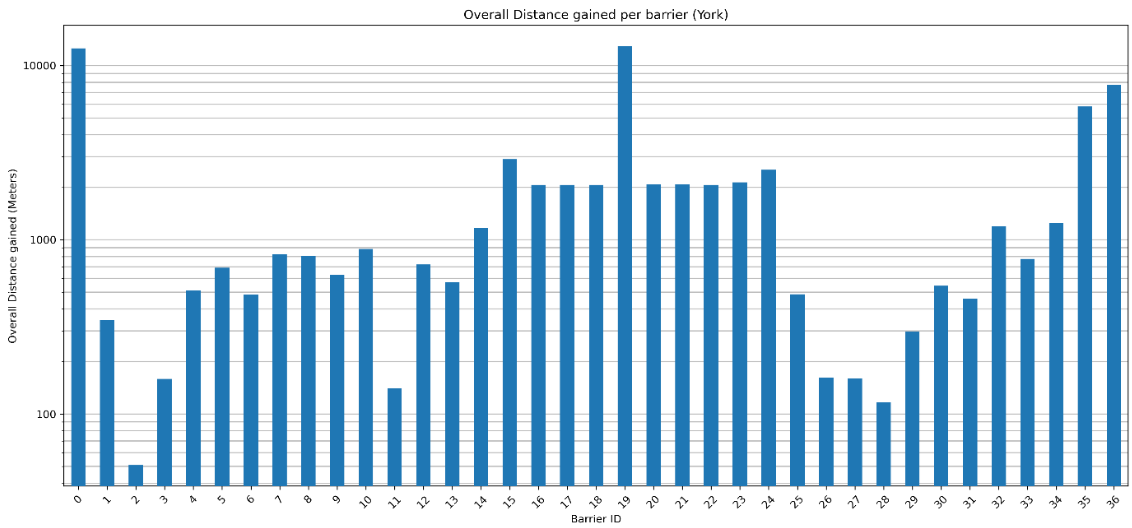


Figure 27 – Overall distance gain per barrier in York

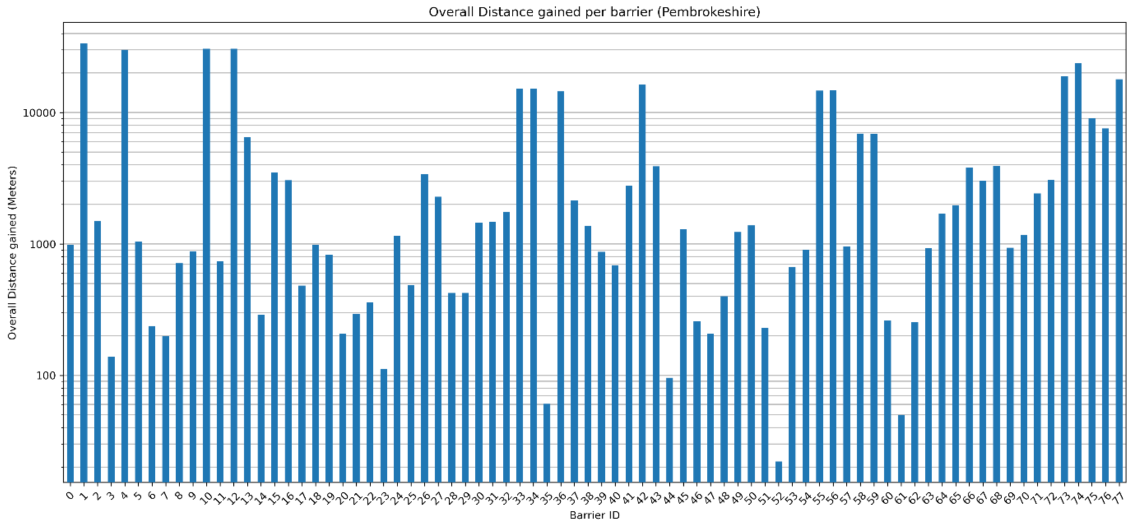


Figure 28 – Overall distance gain per barrier in Pembrokeshire

4.1.4 Route importance

4.1.4.1 Edge usage

Figure 29 displays the estimated edge usage within York. Dominant routes can be observed linking key areas of the city. High usage is found along the NCN route to the West of the city centre. Similarly, the NCN route over the Millennium bridge is found to have high levels of use (Figure 30, Figure 31). Overall the produced route choices are logical, following the major arterial active travel routes. Major roads and other non-traversable regions are not routed through.

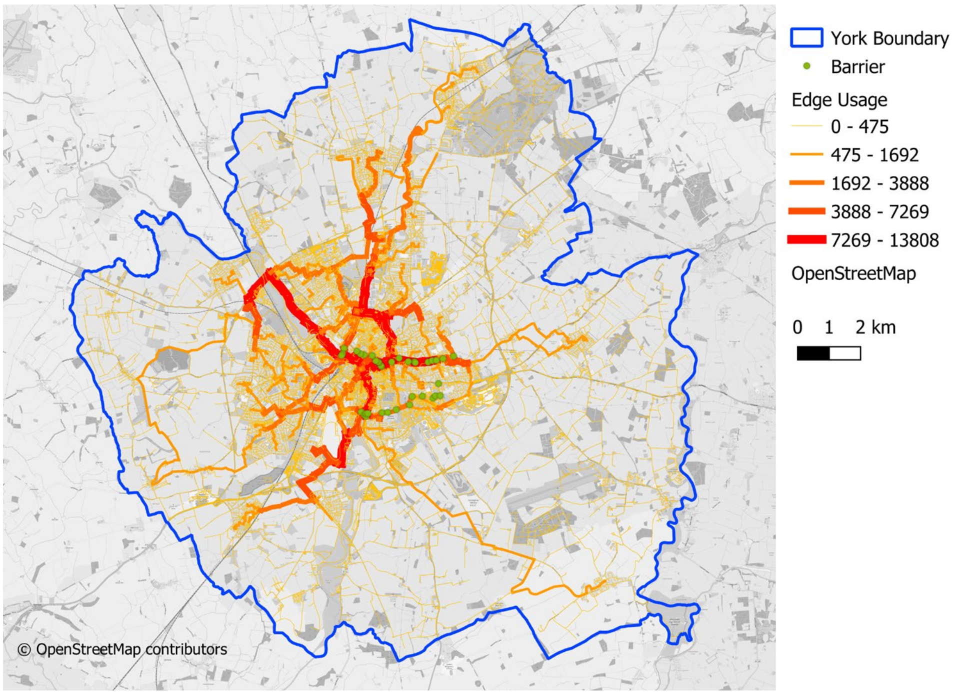


Figure 29 – Edge Usage within York

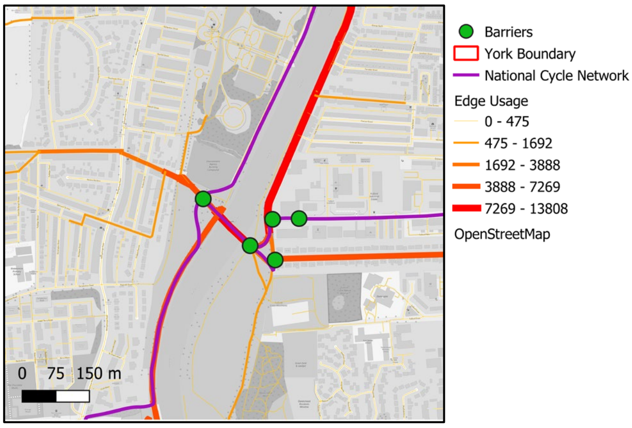


Figure 30 – High edge usage on the Millennium Bridge in York

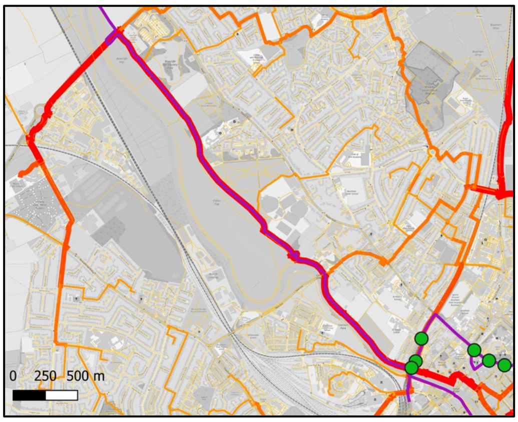


Figure 31 – High edge usage to the West of the city centre in York

Similar trends are found within Pembrokeshire. Particularly through built-up areas, the edge usage is highest on NCN routes (Figure 32). However, significant portions of the NCN are not on segregated bike paths within Pembrokeshire, rather located on minor roads. This means there is little overlap between the estimated route and the NCN route in sections where the NCN uses roads (Figure 33).

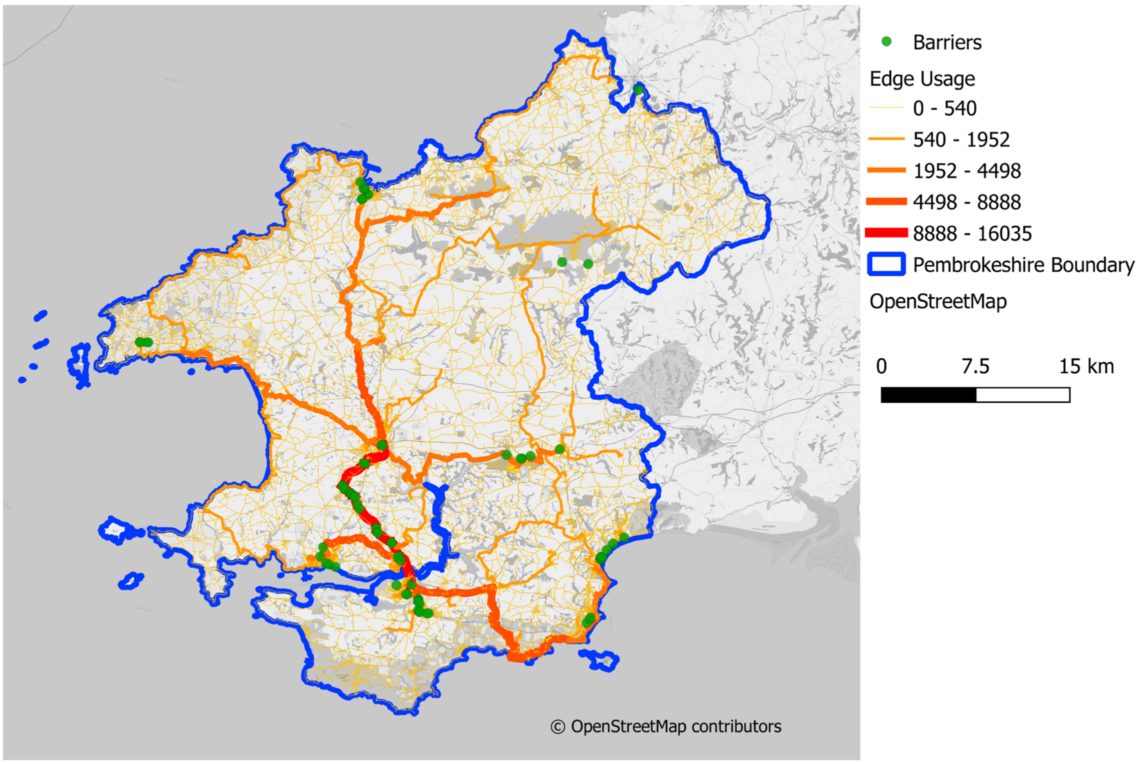


Figure 32- Edge usage in Pembrokeshire

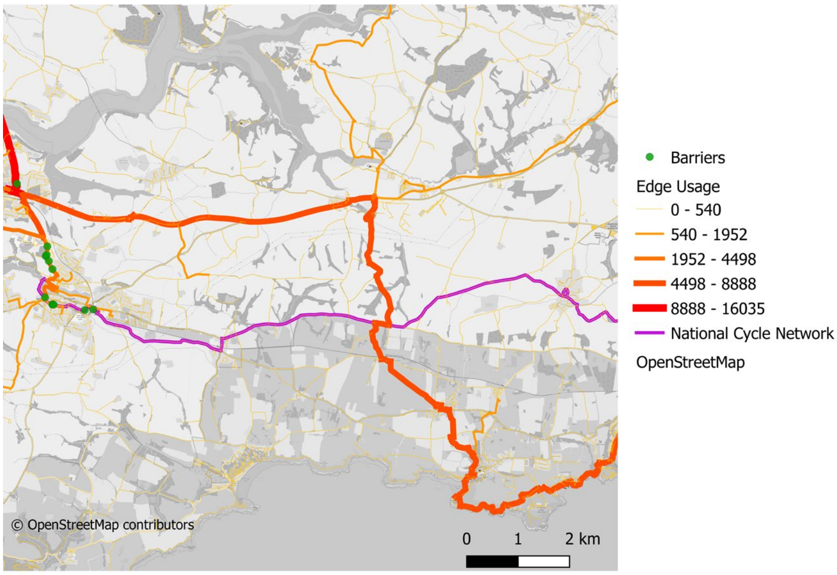


Figure 33 – Edge usage compared with the NCN

The edge usage per barrier in York is shown in Figure 34. Pembrokeshire is shown in Figure 35.

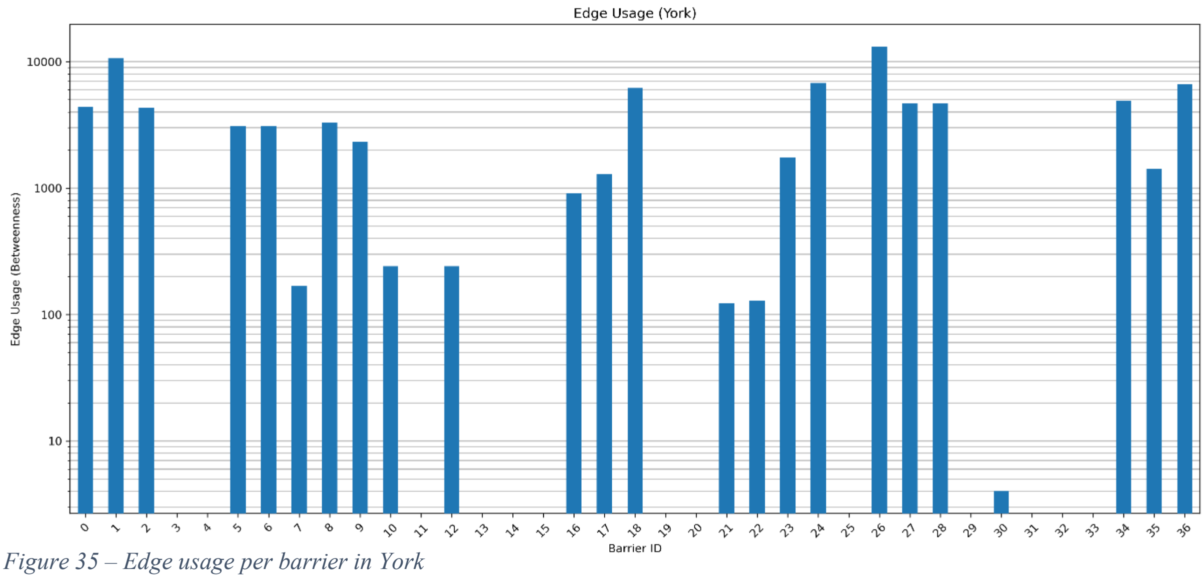


Figure 35 – Edge usage per barrier in York

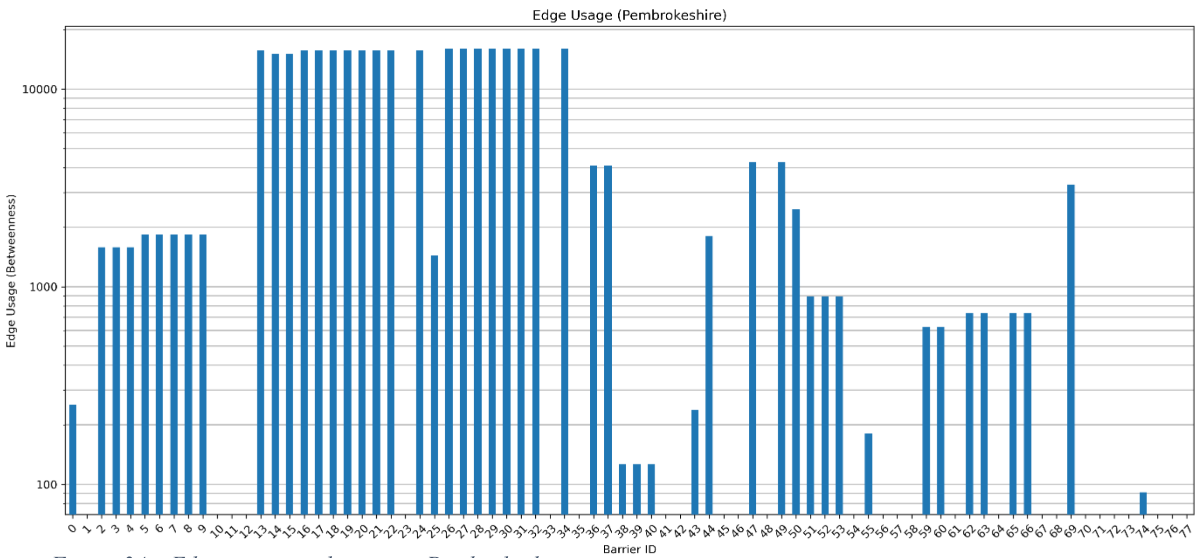


Figure 34 – Edge usage per barrier in Pembrokeshire

4.1.4.2 Edge betweenness centrality

Figure 36 shows the edge betweenness centrality values across York. Figure 37 shows the edge betweenness centrality values for Pembrokeshire. Betweenness values vary highly throughout both areas. This is to be expected due to the complex nature of road and path structures. York exhibits less coherent patterns, as the traversable network is denser within the city region than the rural paths and roads of Pembrokeshire.

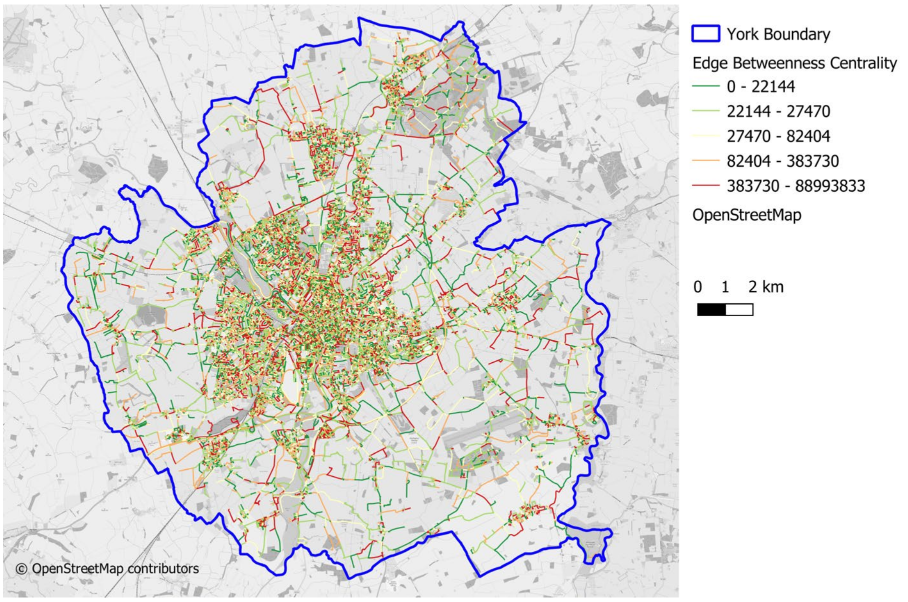


Figure 37 – Edge betweenness centrality in York

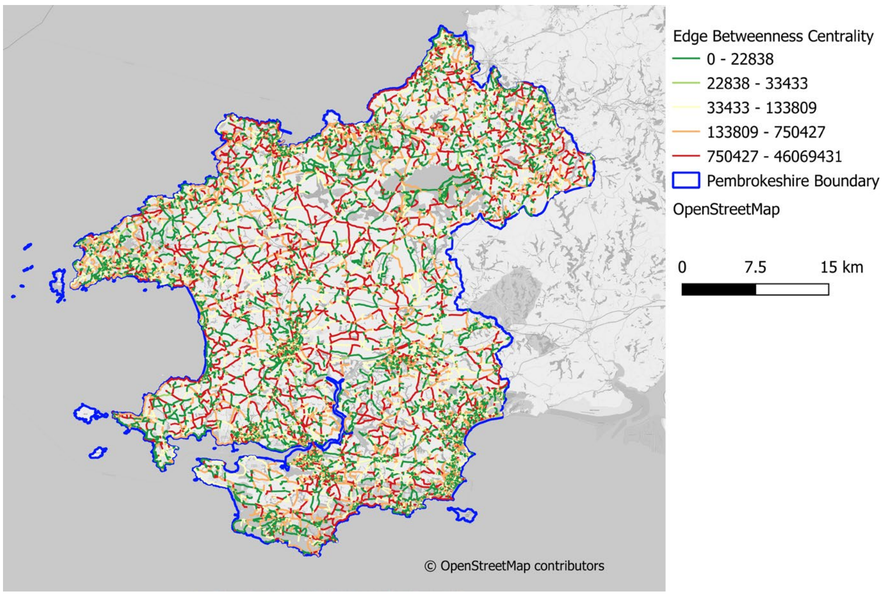


Figure 36 – Edge betweenness centrality in Pembrokeshire

The betweenness values per barrier can be seen in Figure 38 and Figure 39.

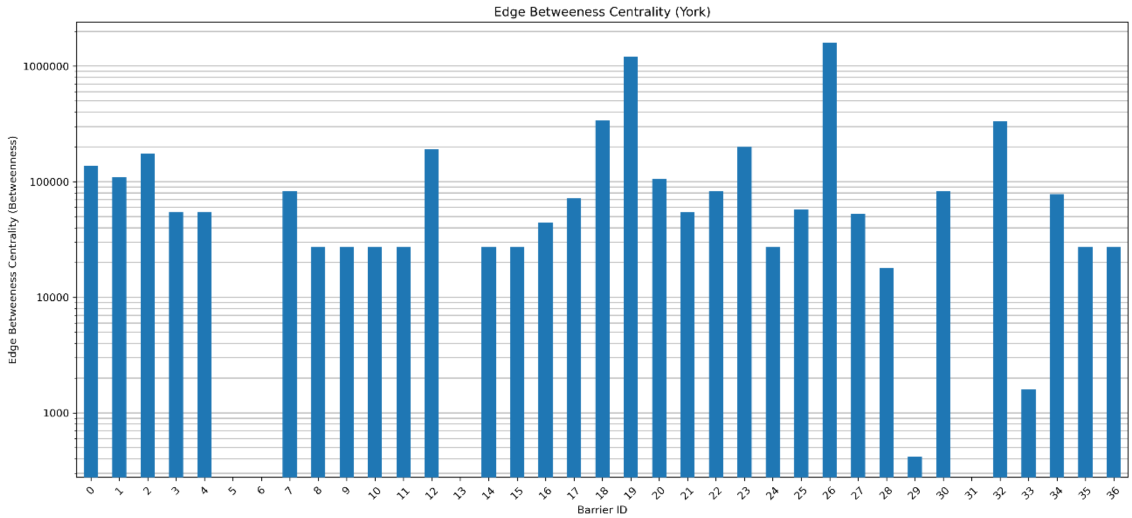


Figure 38 – Edge betweenness centrality per barrier in York

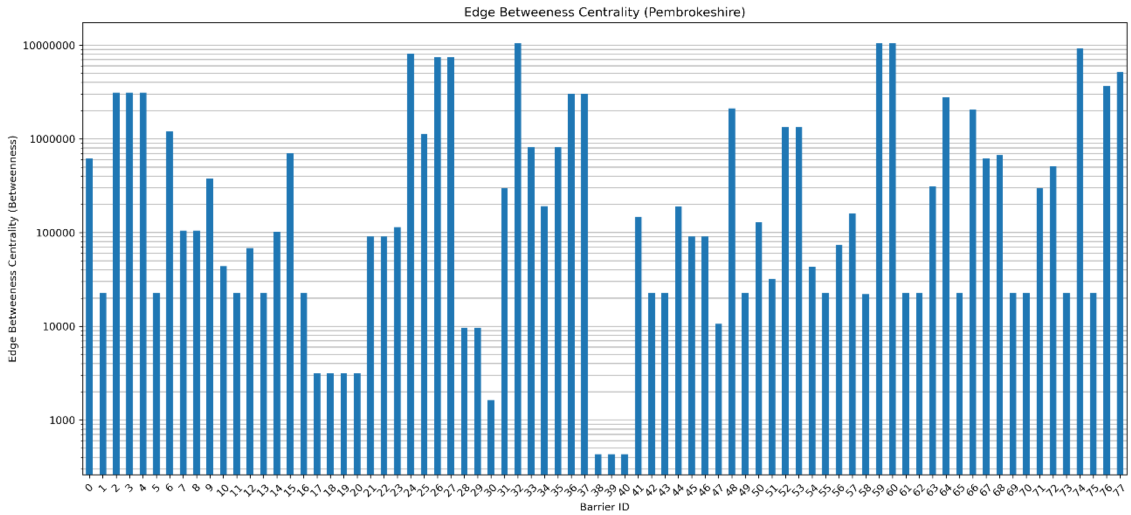


Figure 39 - Edge betweenness centrality per barrier in Pembrokeshire

4.1.5 Potential Accessibility gain

The minimum, maximum and range of accessibility change per transport type are found in Table 9.

Table 9 – Potential accessibility gain statistics per mode of travel

	Walking			**Biking**			**Mean**		
Study Area	Minimum amenity difference	Maximum amenity difference	Mean amenity difference	Minimum amenity difference	Maximum amenity difference	Mean amenity difference	Minimum amenity difference	Maximum amenity difference	Mean amenity difference
York	34	125	74	157	731	368	40	137	84
Pembrokeshire	0	11	1	0	3	26	0	11	1

The change in mean amenity accessibility between the network with barriers prevalent and with barriers removed is shown in Figure 40 for York and Figure 41 for Pembrokeshire. For York, barriers within the trip range of the city centre are most highly affected. Both barriers located within the city centre and those located further than average trip away see a comparatively low drop in amenity accessibility.

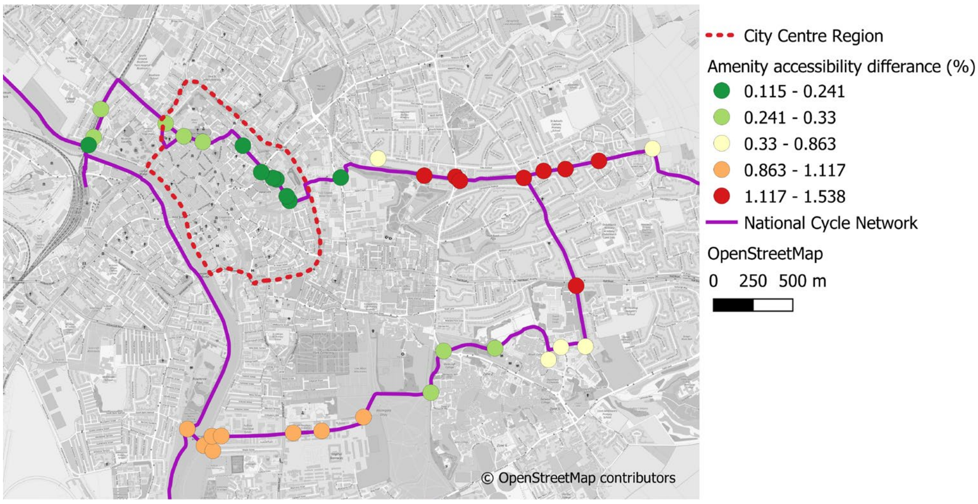


Figure 40 – Amenity accessibility improvement potential per barrier in York

Pembrokeshire displays different spatial patterns. Low amenity accessibility is found at barriers across most of the region.

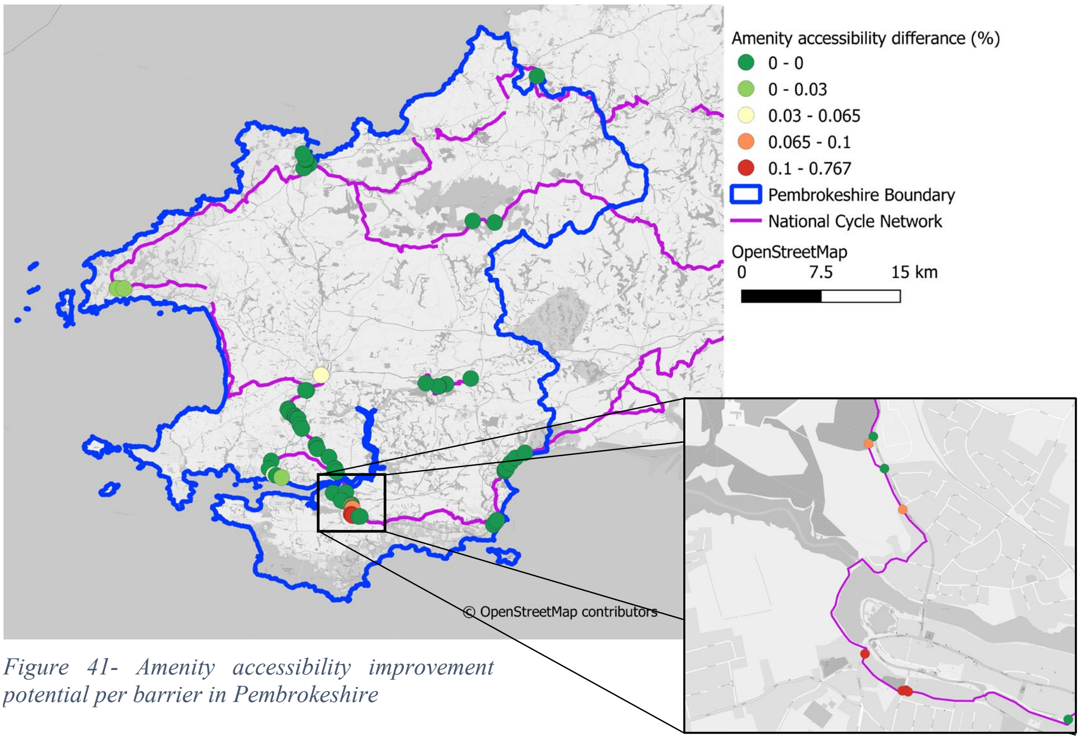


Figure 41- Amenity accessibility improvement potential per barrier in Pembrokeshire

Accessibility as a percentage of improvement overall improvement is shown in Table 10.

Table 10 – Percentage potential accessibility change

Study Area	Minimum amenity change (%)	Maximum amenity change (%)	Mean amenity change (%)
York	0.11	1.53	0.66
Pembrokeshire	0	0.78	0.04

A Spearman's rank correlation coefficient test is employed to test the relationship between the amenity change count and the amenity change as a percentage within both studies areas. The resulting rho value and p values are displayed in Table 11.

Table 11 – Spearman's rank correlation coefficient between amenity change count and amenity change percentage

Study Area	Spearman's rank (Rho)	p-value
York	0.704	1.334
Pembrokeshire	0.998	2.745

Both Rho values are close to +1, which indicates a high level of association of rank. However the p-value is greater than 0.05, which indicates that whilst an relationship is prevalent, it is not statistically significant. Thus there is insufficient evidence to say that barriers which cause the highest change impact to the count of amenities accessible also have the highest percentage impact on accessibility.

The amenity accessibility per barrier per study area is shown in Figure 42 and Figure 43.

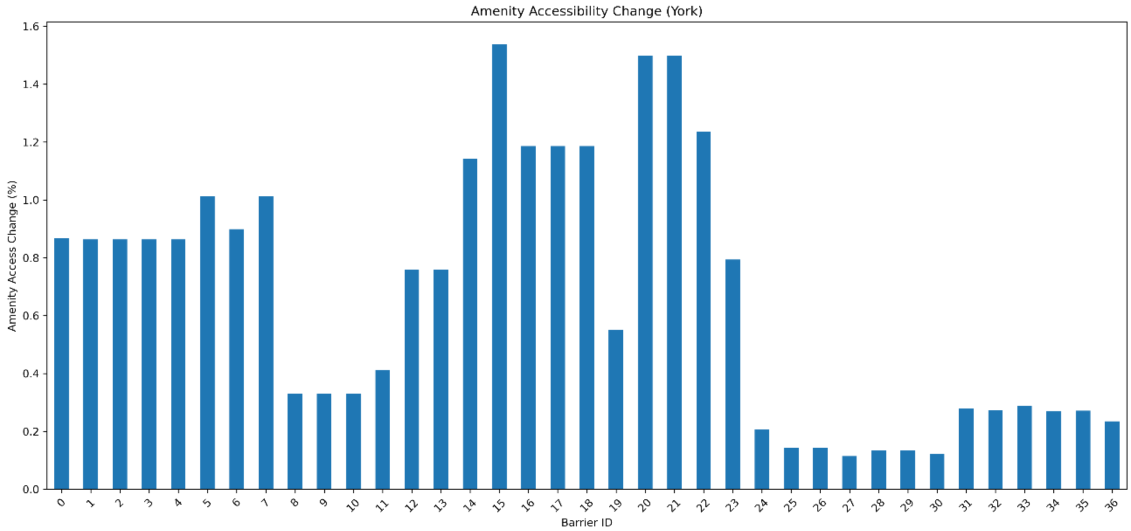


Figure 42 – Accessibility percentage change per barrier in York

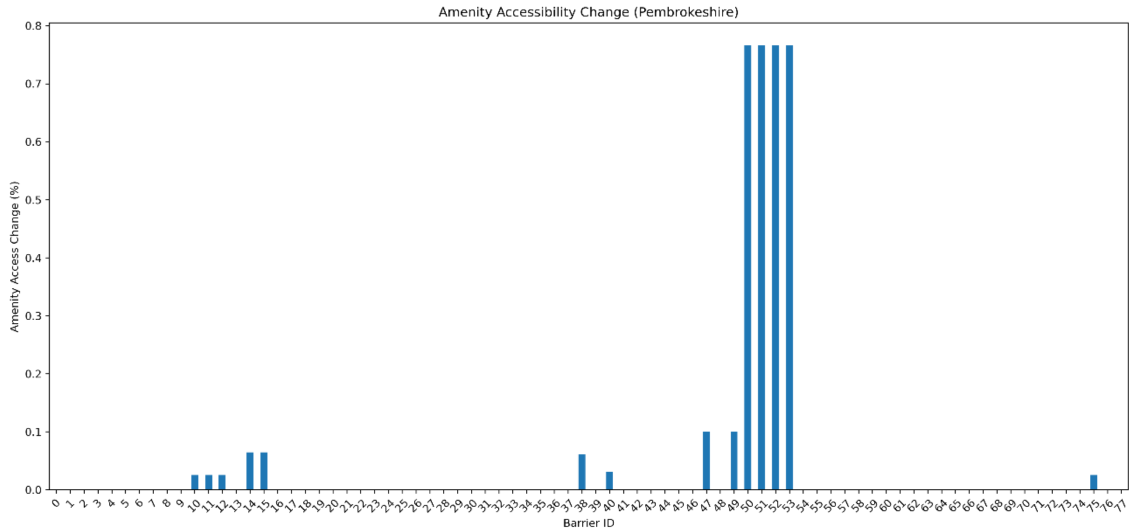


Figure 43 – Accessibility percentage change per barrier in Pembrokeshire

4.2 Unweighted overall scores

Figure 44 displays the barrier scores with respect to their spatial location within York. The highest ranked barriers are those located close to the city centre region.

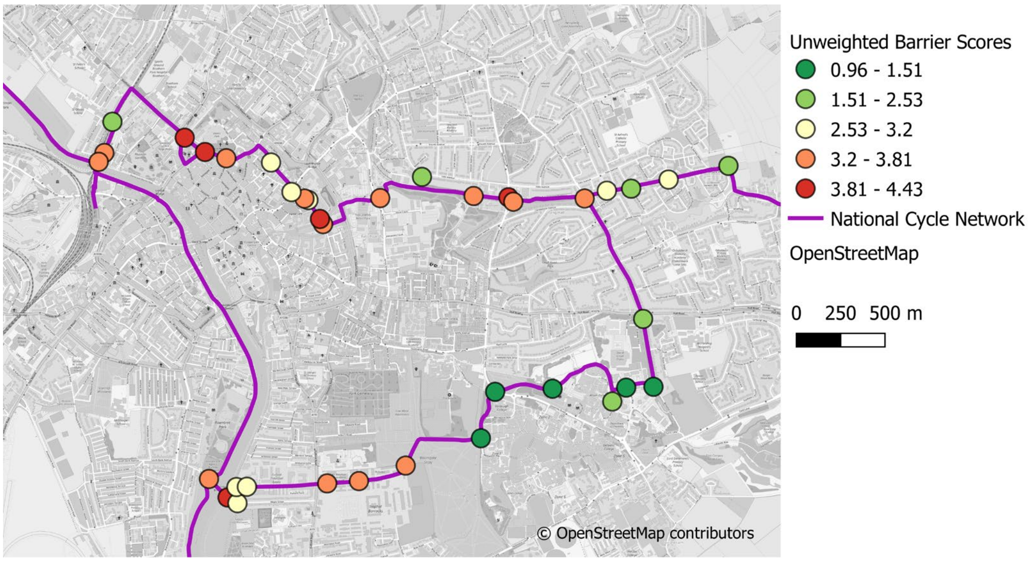


Figure 44 – Unweighted overall barrier scores in York

Figure 45 shows the overall unweighted barrier scores for Pembrokeshire. Rural barriers are scored low compared to those within built up areas. There is a central belt of high scoring barriers along the NCN section between Pembroke and Haverfordwest.

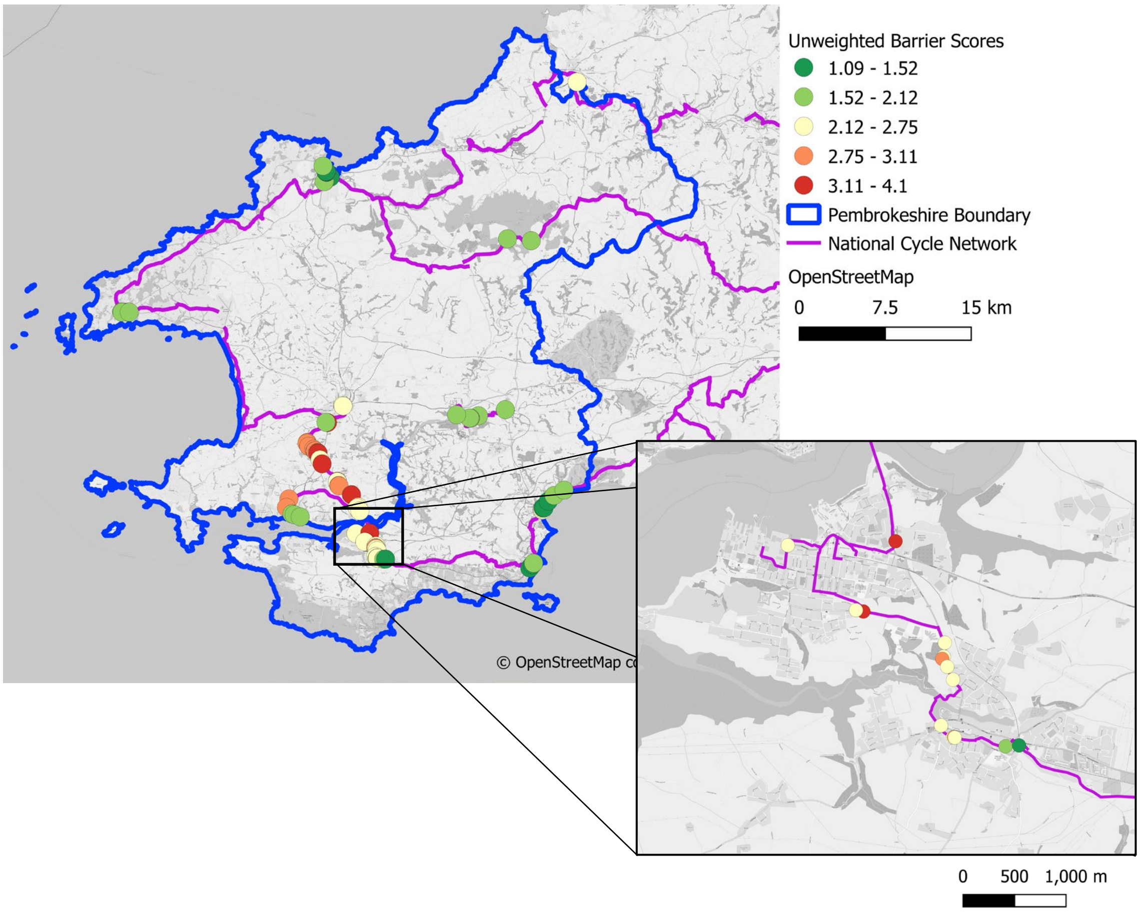


Figure 45 – Unweighted overall barrier scores in Pembrokeshire

4.3 Weightings

From each AHP questionnaire, the consistency ratio is checked to ensure valid answers. Of the completed questionaries, two responses gave consistency ratios greater than 0.1. These questionnaires were removed from the overall results accordingly. From the remaining responses, the linguistic scores were translated to numerical ratios (Table 4). The weights for the overall metrics are shown in Table 12:

Table 12 – AHP derived metric weights

Criterion	Weights	+/-
Relative transport poverty	9.3%	1.9%
Barrier width	41.2%	16.0%
Potential distance gained	7.2%	1.0%
Importance of route	6.4%	1.0%
Potential accessibility gained	35.9%	9.3%

The consistency ratio is 0.026, with an overall consensus of 90.4%. The consistency ratio is below the threshold value so therefore the determined weights can be accepted. The barrier critical width has been determined to have the highest priority in overall scores. Importance of the route on which the barrier is located is determined to be of lowest importance. The largest variance of opinion is with barrier critical width, whilst potential distance gained and importance of the route saw the lowest variance of opinion.

The weighting of the sub-metrics for importance of route, potential distance gained and relative transport poverty are found in Table 13, Table 14 and Table 15.

Table 13 – Importance of route sub-metric weights

Metric	Criterion	Weights	+/-
Importance of route	Edge betweenness centrality	83.3%	0.0%
	Edge usage	16.7%	0.0%

Table 14 – Distance gained sub-metric weights

Metric	Criterion	Weights	+/-
Distance gained	Minimum distance gained	20.5%	0.0%
	Overall distance gained	79.5%	0.0%

Table 15 – Relative transport poverty sub-metric weights

Metric	Criterion	Weights	+/-
Relative transport poverty	Vehicle ownership	18.5%	0.0%
	Index of multiple deprivation	81.5%	0.0%

Within all sub-metrics only two criteria are compared. Therefore the consistency ratio will always be a perfect 0.0. For the importance of route metric, all responses gave the exact same ranking to both criteria. This therefore provided a 100% consensus. Only one response differed from the mean in both the relative transport poverty ranking and distance gained ranking. This gave a consensus of 98.7% for each.

Shown in Table 16 are the derived weights from the AHP process. Sub-metric weights are calculated as a percentage of their respective metric's weighting.

Table 16 – Overall metric weights

Metric	Metric weight	Sub-metric	Sub-metric weight
Importance of route	6.4%	Edge betweenness centrality	5.3%
		Edge usage	1.1%

Potential accessibly gained	35.9%	*N/A*	*N/A*
Relative transport poverty	9.3%	Vehicle ownership	1.7%
		Index of multiple deprivation	7.6%
Distance gained	7.2%	Minimum distance gain	1.5%
		Overall distance gain	5.7%
Barrier width	41.2%	*N/A*	*N/A*

4.4 Weighted overall scores

Figure 46 displays the overall weighted scores per barrier for York. Once weighted, regions of highly score barriers have shifted from the city centre to those regions exterior to the centre. The city centre barriers now fall within the lowest scoring category.

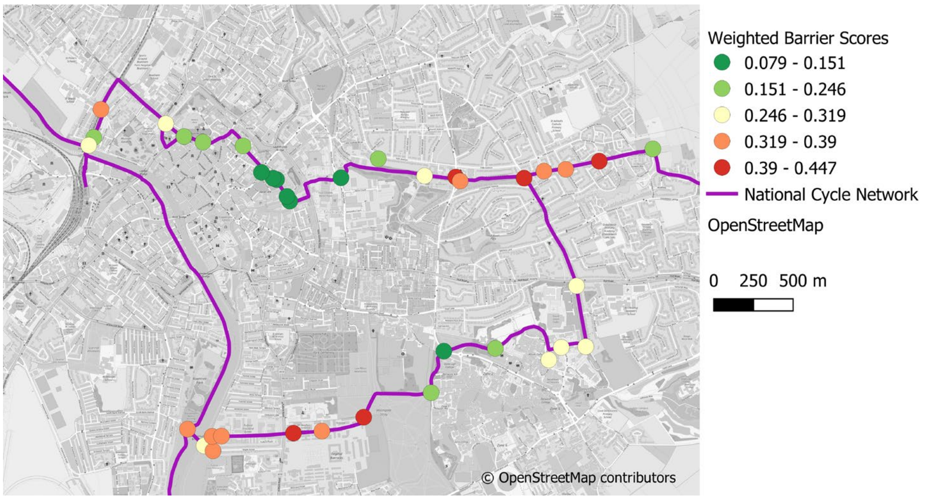


Figure 46 – Weighted barrier scores in York

Figure 47 displays the results for Pembrokeshire. High scoring barriers have remained within close proximity to urban areas. However, the central belt of high scoring barriers is no longer present. Barriers around Milford Haven in the South West of the area have seen large increase in relative score.

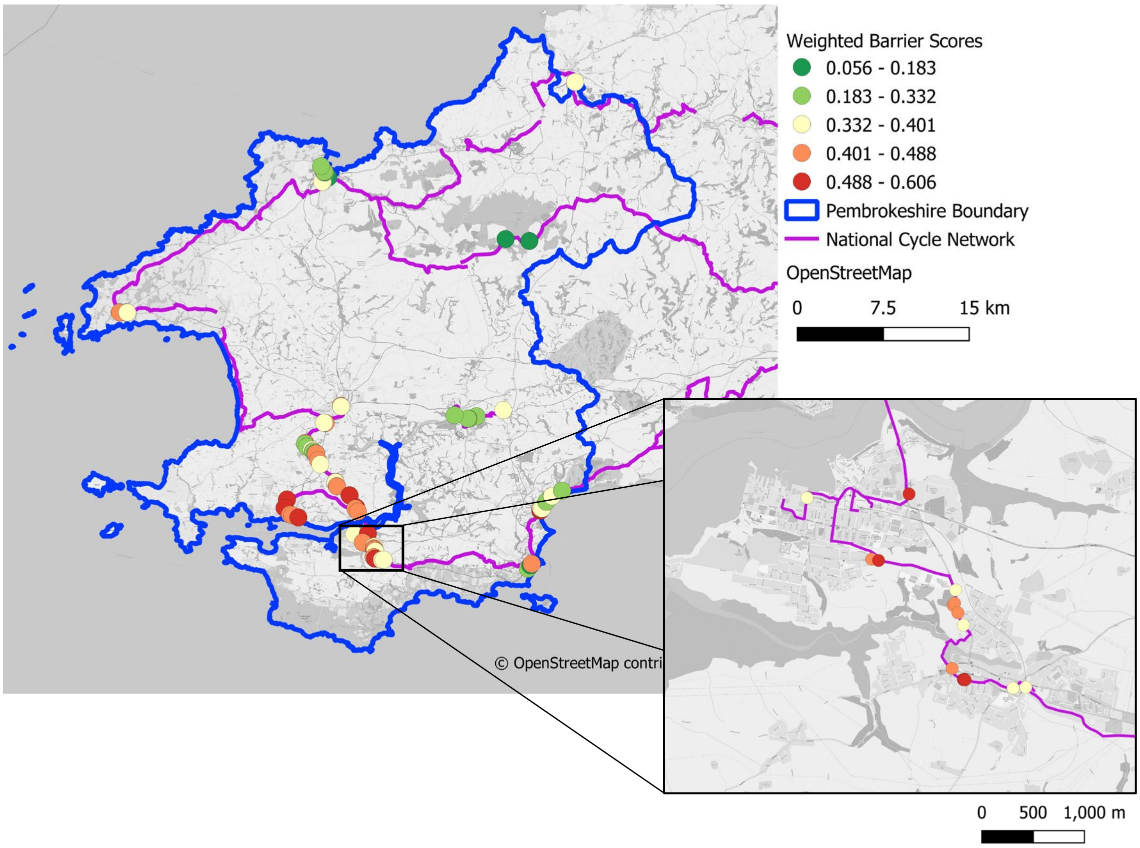


Figure 47 – Weighted barrier scores for Pembrokeshire

Through visual analysis of the scores, clear spatial patterns emerge. At a surface level, clusters appear in the north east and south west of Figure 46. Figure 47 suggests the presence of clustering with Pembrokeshire in south west. These clusters are confirmed or rejected through use of the Local Moran's I statistic of spatial association as outlined in section 3.2.8.

Figure 48 and Figure 49 shows the Local Moran's I clusters for both study areas. Clusters are found where $p < 0.05$ (95% confidence interval).

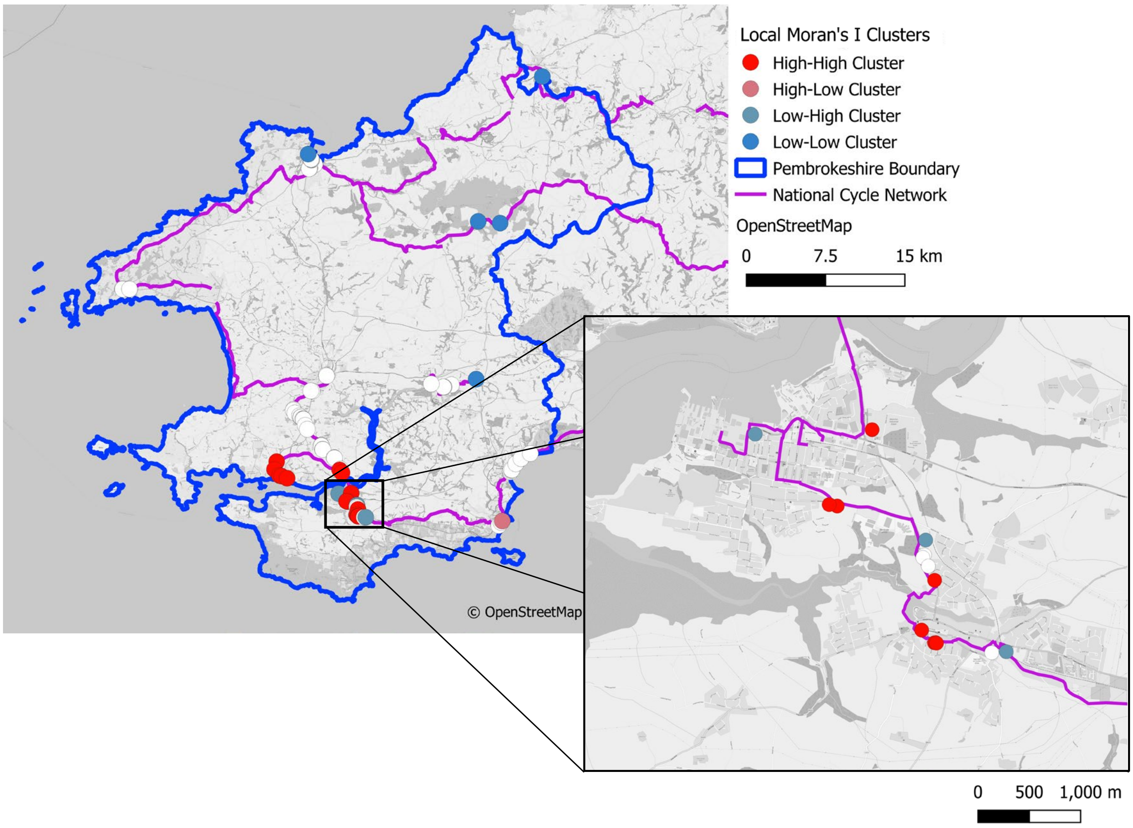


Figure 48 – Local Moran's I Clusters of weighted scores in Pembrokeshire

High-high clusters are most prevalent in Pembrokeshire, where distinct areas of high removal priority take up 11.7% of all barriers. These are predominately found near urban regions, where the highest proportion of potential users are found. Comparatively, low-low Clusters are generally found in rural regions. Four outliers are found in total, with three low-high outliers found in and around the town of Pembroke. The single high-low outlier is found the coastal town of Tenby in the south east.

York has no significant outliers, however does show signs of clustering. A section of 7 low-low clusters are found near the city centre (Figure 49), representing 21.6% of all barriers within this area. Three barriers within high-high clusters are found, two within the north east and one to the south west of the region.

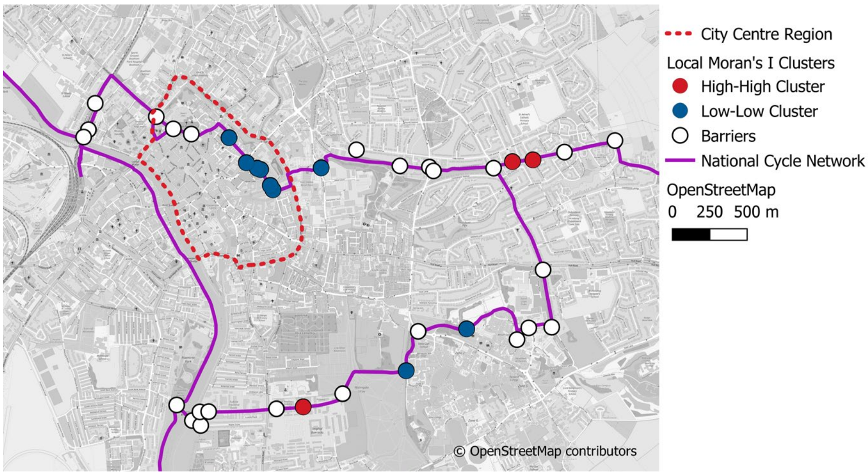


Figure 49 - Local Moran's I Clusters of weighted scores in York

4.5 Sensitivity analysis

To test if weighting of factors produces statistically different results to those obtained without weighting, a Spearman's rank correlation test is performed. Shown in Table 17 are the Spearman's rank correlations for the weighted and unweighted barriers from both study areas. The variables compared were the relative rank of removal importance.

Table 17 – Spearman's rank correlation coefficient between weighted and unweighted barrier scores

Study area	**Spearman's correlation Value**	**P-Value**
York	0.109	0.522
Pembrokeshire	0.581	2.399

Neither study area shows a significant relationship ($p > 0.05$). Therefore, no valid relationship exists between the weighted and unweighted barriers. Pembrokeshire does show a weak positive correlation, however the range for many individual barriers is large. This can be seen in Figure 50. York is also displayed for comparison (Figure 51).

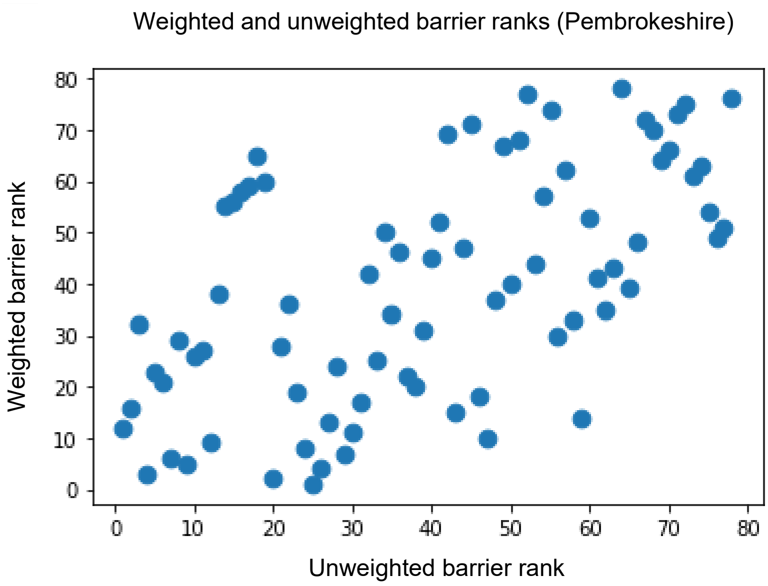


Figure 50 – Weighted and unweighted barrier ranks in Pembrokeshire

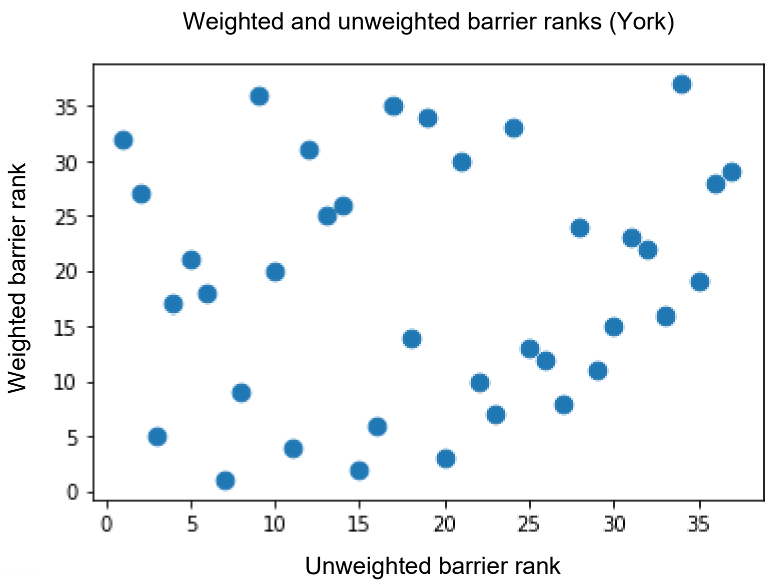


Figure 51 – Weighted and unweighted barrier ranks in York

DISCUSSION

This chapter discusses the findings from the results chapter and highlights the limitations of the study. Future works that would further benefit the research area are also suggested within this chapter.

5.1 Research findings

5.1.1 Overall findings

The methodology has produced an overall score to assess the removal priority of barriers across the NCN. Both study sites display separate spatial characteristics, however the overall pattern of high priority barriers remains similar. Obstructions which block movement in and out of areas are predominately the highest ranked. This is shown as linking areas of the city within York or linking towns together within Pembrokeshire (Figure 52). The potential reduction in community severance will provide better opportunities in terms of accessibility to those who live in and around the area of these barriers.

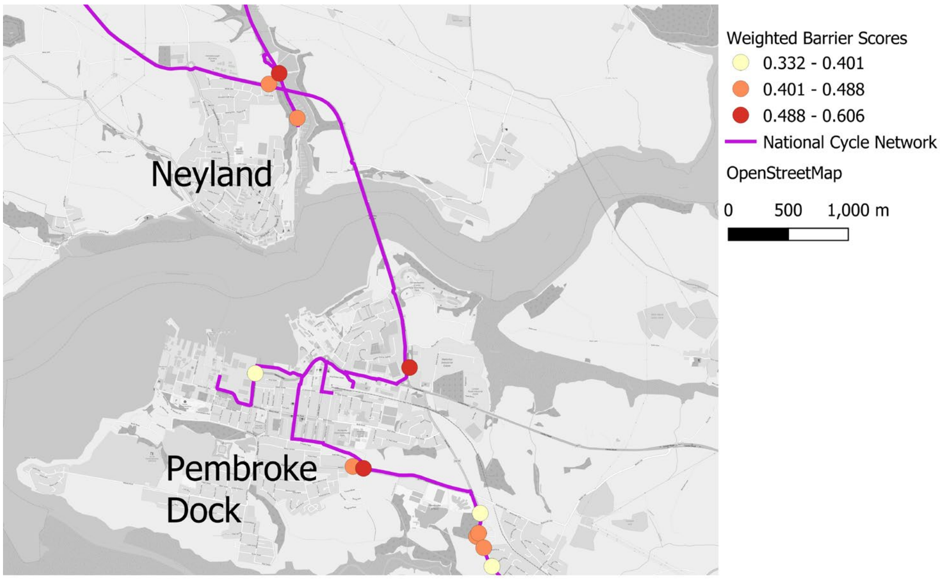


Figure 52 – High barrier scores on critical links

The simplistic nature of the overall score has provided an accessible tool for decision makers to use, regardless of their geospatial knowledge. There is sufficient variability between scores that barriers can be differentiated between. However, scores are not so widely spread that groups of barriers cannot be visually identified (Figure 46, Figure 47). The clustering of highly scored barriers provides a practical solution for decision makers, as rarely will a single barrier be removed in one location. The reality of removing obstructions is that removing a continuous set of obstructions is preferable in terms of labour and finances compared with moving between sites constantly. The high-high clusters indicate the areas in which it would be optimal to remove many barriers from as one overall removal project. This would achieve the most gain for users of the active travel network, whilst posing lower cost for the network custodian. The clustering affect is seen within and surrounding urban areas in Pembrokeshire. This result is largely expected as at a simplistic level the barriers are an example of Tobler's law (Tobler, 1970); barriers which are within greater proximity to where the population lives are more likely to have an influence on the populations movement. This trend is not visible within York as all barriers are located in urban areas. Clusters are still prevalent however. York's clusters highlight the areas where the access to the inner city is most improved. York does not exhibit this clustering around the high critical width values as this metric is spatially random within the area. This suggests that the other metrics provide sufficient impact for areas of high priority to still emerge.

5.1.2 Route importance

The methodology for simulating movement of users across the network has been effective, as the most utilised routes from the route choice analysis correlate with prior knowledge of travel routes within the study areas. Despite this, there are some inconsistencies between the modelled routes and the true routes taken. Issues with the routing comes not from the route choices but from the available routes. Using OSMnx's "bikeable" route network, some pathways are included which are not traversable by all users, such as uneven paths or major roads with no footpath. This can be observed in Figure 53, where the estimated route diverts from the NCN, only to re-join several meters later.

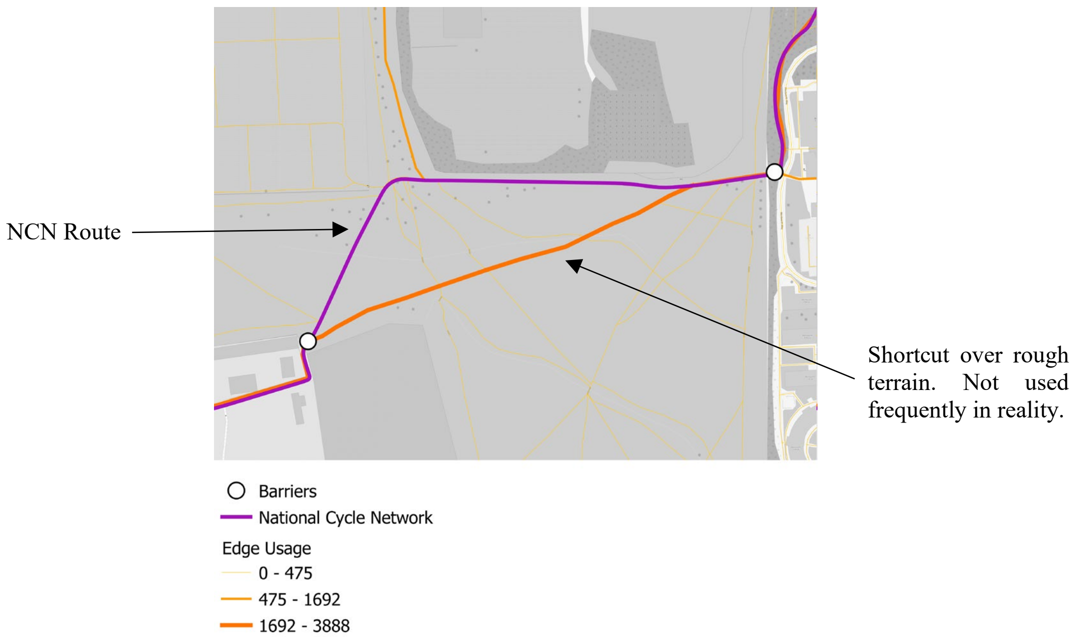


Figure 53 – Unrealistic route choice using OSM data

Whilst the shorter path does exist, and could be traversed by foot or bike, it is far more likely for the main path to be followed. The nature of volunteered geographic data such as OSM means there will always be issues with data quality, as edges are mis-attributed by users. Even if the edge is correctly categorised, the category definition can be too wide. The highway=”path” tag is a prime example of this, as what it means to be a path can be ambiguous.

Many of the barriers within both study areas exhibit equal edge usage values. This is due to barriers being part of the same route connecting two locations. As seen in Figure 33 and Figure 34, several barriers in both study areas are not passed through at all. This is due to the limited combinations of trips possible from the O-D data. As routes are only ever calculated between LSOA population weighted centroids, the subtlety of many journeys is lost. Whilst LSOA level journeys is the best estimation with the datasets available, the sub-LSOA trips which may pass through barriers is not modelled.

Edge betweenness has captured the key links between areas. As seen in Figure 54, bridges which link two sides of a river contain particularly high betweenness scores. The bike-path on the bridge has the highest centrality value in the figure (conversely, the road on the bridge has low centrally due to the higher impedance given to major roads). Barriers which provide access to these narrow links are scored accordingly high.

Figure 54 – High centrality values found on critical links

However, in areas where a shorter alternative route is present barriers have been scored lower than expected. Figure 55 displays this issue. The network dataset briefly splits to provide routes through the two barrier types present (Figure 56). As the left-hand route is shorter more shortest paths routes pass through the edge. This has led the shorter left hand route to have a higher centrality value. However, as the barriers locations are only recorded using mobile phone GNSS receivers, the barrier point is 2m to the righthand side of the network. Thus the centrality value at the barrier is lower than the true value, as it takes the value from the nearest edge.

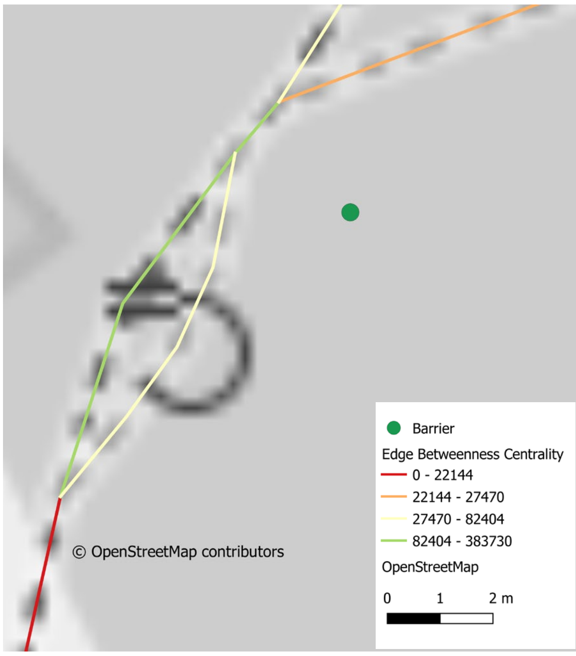


Figure 56 – Incorrect betweenness value assigned due to a split path

Figure 55 – A barrier at a split path
Two barriers are available for uses, either the cattle grid to the left, or the swinging gate to the right. Image sourced from the Sustrans barrier audit dataset

5.1.3 Amenity accessibility

Many barriers within Pembrokeshire had zero change in accessibility scores, as seen in Figure 43. This could be due to the remoteness of much of the area, as many barriers are simply not in a realistic walking/cycling range of any amenities. All barriers within York show a change in amenity accessibility, suggesting all barriers within York are currently discriminatory to anyone who cannot pass through any of the barriers. This highlights the importance of barrier removal schemes, as these barriers causing reduced accessibility to basic amenities.

As highlighted by the difference in the count of amenities accessible within the walk/cycle range of a barrier between York and Pembrokeshire, access to amenities varies dependant on location (Figure 40, Figure 41). This is to be expected as rural areas do have lower provisions of amenities and services compared to built-up areas (Vitale Brovarone & Cotella, 2020). However, it has been well documented that not all areas of OpenStreetMap are created to the same depth or detail (Haklay, 2010). Thus, it is to be expected that York contains better documentation of amenities than Pembrokeshire because of its urban density but also because that urban density leads to more potential OpenStreetMap users. Thus, whilst the results obtained in section 4.1.5 were expected, these results should not be taken as perfect findings.

The isochrones generated to calculate walk/cycle times from barriers were generated using convex hulls. This can lead to a margin of both under and over estimating the travel time radius. This is because straight lines are generated between the furthest points accessible within the given travel time. An example of this can be seen in Figure 57. The building point is outside of the isochrone, although part of the building is within. If the entrance is on any part of the building within the isochrone, then the amenity has been incorrectly excluded. This phenomenon may occur in reverse also, where the building point is within but the true entrance is out of the isochrone.

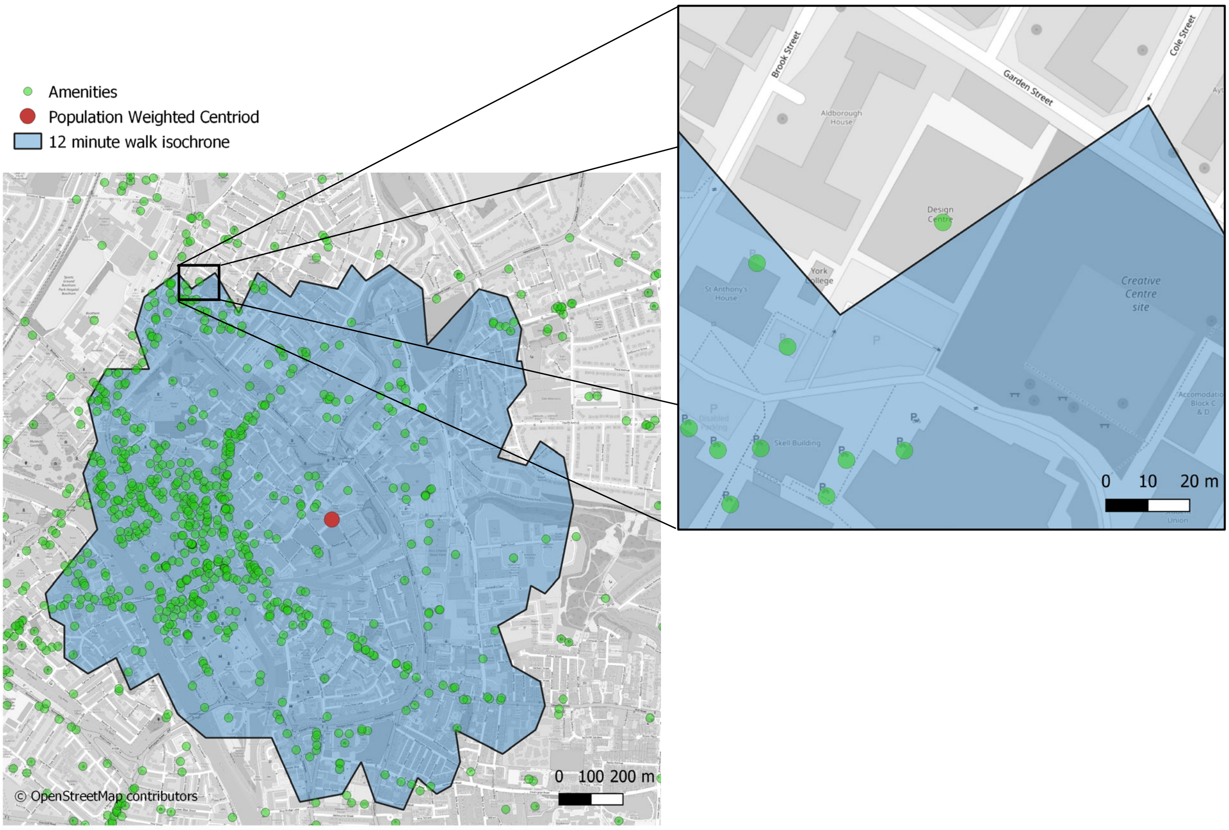


Figure 57 – Underestimation of amenities counts due to isochrone shape

5.1.4 Weightings

The results from the AHP have led to significant differences with the weighting of factors. The critical width and potential accessibility gained metrics account for the majority of the overall score at 77.1% of the weighting. This has naturally led to the most suitable barriers for removal being most influenced by their critical width and accessibility scores. Critical width saw the greatest difference in opinions from the respondents to the AHP, with some weighting critical width has high as 50.2% and low as 28.3%. The ranking of critical width as the highest score is perhaps unsurprising, as intuitively it is the largest factor in whether a barrier can be considered a negative to its users. A very wide critical width may not affect any users, thus if removal is to occur, the gains will be minimal compared to an largely impassable barrier. Feedback from the consulted stakeholders indicated that accessibility change was deemed to best measure latent demand. Thus the high weighting of accessibility scores with the overall index was also to be expected.

The lowest ranked factor is the edge usage, totalling just 1.1% of the overall ranking by the experts. From the open discussion with the topic experts, it was clear that this result is because the data source for this factor is sourced from travel to work data, which only captures a subset of the overall usage. Travel to work data also is only a measure of journeys which do occur, rather than journeys which could occur if the barrier was removed. Whilst no metrics are fully able to measure this latent demand, the edge usage is deemed to be less capable of measuring this than edge betweenness centrality. There was 100% consensus on the weighting of this metric from all questionnaires received, meaning all experts gave the exact same response. Vehicle ownership in an area was also deemed to have very low importance, also with just 1.7% of the overall rank. Similarly the minimum distance gained metric was ranked low, at just 1.5% of the overall rank. Given the low influence of these metrics, it is feasible that similar outputs could be achieved without them. This would reduce the overall holisticness of the metric, however would reduce the amount of data and pre-processing required to obtain an output. Further sensitivity analysis is required to assess how removing metrics could change the outputs.

The lack of correlation between the weighted vs unweighted barriers reported in Figure 50 and Figure 51 indicate a number of possibilities. It could indicate that without balancing, the score is too sensitive to individual metrics. Viewing of Figure 44, Figure 45 and Figure 46, Figure 47 shows that in many areas, clusters have reversed in their removal priority. However the weighted scores could also simply reflect that not all metrics should be considered equal. As discussed, not all metrics were deemed to be as effective as others by the experts consulted, thus naturally an adjustment in importance is to be expected. Weightings are inherently a reflection of what a given person perceives the value of active travel networks to be, and who/what the network is for. The weightings found with this study indicate the primary use for the network is to reach amenities. This is shown by the high critical width and accessibility weightings aforementioned. However, other stakeholder groups may value other weightings more significantly. Those interested in active travel for leisure may value distance gained and critical width with highest levels of importance as this would allow for the typically longer journeys brought by leisure activities to occur. City councils may value the route importance higher as they aim to improve commuting by active travel. The methodology created within this project allows for the alteration of weights at the end of the processing pipeline. If other stakeholder groups are to evaluate barrier with their own agenda in place, the metrics can simply be weighted according. Whilst the approaches taken in this project aimed to use quantifiable and measurable metrics, ultimately the true hinderance of a barrier can only be known through more qualitative measures. Extensive consultation with the people who currently use the active travel network and the people who may use the active travel network if changes were implemented would bring viewpoints and opinions which an index may not be able to convert to a number. However, it is these viewpoints that would paint the true picture of which barriers truly need to be removed first.

5.1.5 Transferability

The methodology provided within this work is highly transferable to any area of the UK. Aside from the barrier dataset provided by Sustrans, all data is sourced from publicly available data using API calls and scripting. Potential users of the tool simply need to change the area within the processing scripts to get an output for a new area. As shown with the two study areas selected, the method can be applied to areas with different spatial and social-economic characteristics without issue. Theoretically, the tool could be applied to not just the NCN but any active travel network. This would require minor adaptations to the underlying code. The only additional data required would be a barrier dataset.

Whilst theoretically applicable to significantly larger areas than the study areas in this project, the methods produced are limited by computational power and speed. Particularly with the network-based metrics (potential accessibility gain and route importance), processing times can take up to 24hrs on the current study areas. It is expected that this would increase significantly with larger regions. The longer processing time may coincide with hardware limitations, particularly with regard to memory usage. With this considered, it is recommended that study areas above the county level are not attempted with the current scripts. This does limit the transferability, as larger studies cannot feasibly be run without increased computing power.

CONCLUSION

This project has developed a methodology and analysis tool to determine the removal priority of obstructions across the NCN. The process can be implemented on any section of the NCN with barrier data within the UK. Decision makers can use the tool in order to support decisions about where to begin the process of making active travel networks accessible for all. This chapter will review the research aim and objectives set out at the start of this project and evidence the progress made to fulfil them. The limitations of this study and suggestions for future research will also be discussed. A summary of the overall work is provided to conclude the project.

6.1 Research aim and objectives review

The initial objective of this project was to determine the factors which influence removal priority of obstructions. This was determined through the literature review and through consultation with research area experts. Surprisingly, little literature has been written on the effects of obstructions in the context of active travel for all. The metrics devised provided an attempt at holistically scoring barriers by considering not just the physical impedance of the barrier, but the context surrounding it. Whilst all the metrics were deemed to have a level of importance, the weightings and feedback from topic area experts highlighted that the relative importance of different metrics did vary as not all measures have the same level of importance.

The second objective of this project was to source and process data relating to each factor. Aside from the barrier audit dataset provided by Sustrans, all data was sourced from open datasets. More specifically, street network data, amenity data and boundary data were sourced from OpenStreetMap using the OSMnx Python package. Census data was accessed through the Nomis census data portal and IMD scores were accessed through the Ministry of Housing, Communities and Local Government's ArcGIS Online web portal. Data was processed using Python primarily. The Geopandas, pandas, NetworkX, OMSnx, momepy and Pandana packages were used for manipulation of data and computation of metric scores. Processing is automated, provided the user inputs a valid location to the processing scripts. QGIS was used for any visualisations.

The third objective was the weight each factor and apply the developed index to an obstruction dataset. Weighting was achieved through use of an AHP. Industry experts and stakeholders in barrier removal projects were consulted to obtain data for the AHP. Critical width was deemed the most important factor, at 41.2% of the overall weighting. Potential accessibility gain had the second highest level of importance at 35.9%. Other factors ranged between 9.3% and 6.4% of the overall weighting. A normalisation function was applied to the metric scores prior to weighting. The weighted metrics per barrier were combined into an overall score. All metrics were calculated, weighted and combined for two study areas, York and Pembrokeshire respectively.

With the scores generated, the fourth objective could be met. This was to identify spatial patterns and trends within each factor and the scored obstructions. A variety of spatial statistics were applied, including local Moran's I, global Moran's I and Getis Ord Gi*. Non-spatial trends were identified using Spearman's rank correlation coefficient. This allowed the fourth objective to be satisfied. Key findings included the spatial clustering of high scoring barriers and the lack of statistically significant correlation between the unweighted barrier scores and the weighted scores.

The final objective was to automate this methodology to provide a decision support tool for stakeholders. This objective has mostly been met, with the majority of the methodology requiring little user input. Data collection and processing has largely been automated, with only minor intervention from the user required to input the study area of choice and select the correct data folder. However, currently the scripts must be individually run and do not link seamlessly. Further work will be required to fully automate the full process.

With all objectives met to a satisfactory standard, the overall aim of the project can be reviewed. The aim was "To produce a decision support tool to enable the prioritisation of obstruction removal". The methodology developed for this research has provided the tools to enable decision support with regard to prioritisation of obstruction removal. The metrics devised give any given obstruction a value which can be compared with others within a given study area. Decision makers can use this score as a part of the justification for a barrier removal scheme.

6.2 Limitations and future works

Whilst the methodology provided gives logical results within the study areas, the project is not without areas where additional work would benefit. A key limitation of the study is the lack of empirical data to perform validation with. Whilst the statistical validation used in the results section allows for trends to be confirmed, actual confirmation of if the correct barriers have been identified is limited. This applies to multiple sections of the project. Firstly, the weighting of the traversable network in section 3.2.2.2 is approached via a 'best estimate' approach. If walk and cycle count data was available to use instead this could provide validation of the modelled routes. Ideally, before and after barrier removal data could be provided at the barriers deemed most suitable for removal by this study. This would allow for the latent demand to be measured and confirm that removal has made a tangible difference to the locality. This could provide insights into the effectiveness of the proposed methodology for identifying removal priority.

A further limitation relates to the data available to study. Whilst the NCN represents a key backbone of active travel infrastructure, it by no means encompasses all possible routes. The barrier dataset used in this study only considers barriers either on the network or that provide access to the network. In an ideal study, all barriers across the full active travel network would be considered.

Similarly, the obstructions evaluated only form part of the large picture relating to accessibility issues on active travel networks. Research has shown surface type, slope angle and segregation from roads all encompass if a user is likely to choose to use active travel (Grond, 2016; Carroll *et al.,* 2019). The work developed in this project could form part of a larger tool to identify weakness in the current active travel infrastructure. Whilst the object being assessed would change, the metrics devised as part of this study could be applied with minimal alteration.

Additionally, the measure of accessibility could be expanded to measure more than just the number of amenities within a walkable/cyclable distance. The change in the type of amenities could be measured, thus allowing the importance of different amenities to be considered. Similarly changes in amenities already available could be discarded or reduced in importance, as it may not matter if there are four of the same amenities in a walkable areas or twelve. It simply matters that there is access to a single amenity of a given type, such as a hospital.

The modelling of the movement of people through the use of OD could be improved through use of jittering, as recently introduced by Lovelace *et al*., (2022). The jittering method would allow for trips to originate from more locations than simply the population weighted centroid within a LSOA area. Therefore a greater variety of routes could be generated, which should better model people's movement.

6.3 Thesis summary

This research project has developed a novel methodology for the prioritisation of obstruction removal on active travel networks. The metrics devised to score the obstructions provided a holistic approach to quantifying which barriers should be removed first from a given area. The methods developed for this project can be used by decision makers to identify the best short-term gains to the network. This will allow for better access to active travel for all, which in turn will help reduce greenhouse gas emissions, connect communities, and provide people with a healthier method of travel.

REFERENCES

Alattar, M.A., Cottrill, C. and Beecroft, M., 2021. Modelling cyclists' route choice using Strava and OSMnx: A case study of the City of Glasgow. *Transportation research interdisciplinary perspectives*, *9*, p.100301.

Aldred, R., 2019. Built environment interventions to increase active travel: A critical review and discussion. Current environmental health reports, 6(4), pp.309-315.

Apparicio, P., Abdelmajid, M., Riva, M. and Shearmur, R., 2008. Comparing alternative approaches to measuring the geographical accessibility of urban health services: Distance types and aggregation-error issues. *International journal of health geographics*, *7*(1), pp.1-14.

Anciaes, P.R., 2013. Measuring community severance for transport policy and project appraisal. *WIT Transactions on The Built Environment*, 130, pp.559-570.

Anselin, L., 2019. Local spatial autocorrelation. GeoDa. An introduction to spatial data analysis.

Arfat, Y., Suma, S., Mehmood, R. and Albeshri, A., 2020. Parallel shortest path big data graph computations of US road network using apache spark: survey, architecture, and evaluation. In *Smart Infrastructure and Applications* (pp. 185-214). Springer, Cham.

Aultman-Hall, L., Hall, F.L. and Baetz, B.B., 1997. Analysis of bicycle commuter routes using geographic information systems: implications for bicycle planning. *Transportation research record*, 1578(1), pp.102-110.

Brand, C., Götschi, T., Dons, E., Gerike, R., Anaya-Boig, E., Avila-Palencia, I., de Nazelle, A., Gascon, M., Gaupp-Berghausen, M., Iacorossi, F. and Kahlmeier, S., 2021. The climate change mitigation impacts of active travel: Evidence from a longitudinal panel study in seven European cities. *Global environmental change*, *67*, p.102224.

Bike Biz (2016) *Anti motorbike barriers to be removed from national cycle network.* Available at: https://bikebiz.com/anti-motorbike-barriers-to-be-removed-from-national-cycle-network/amp/ (Accessed: 08/06/2022)

Boeing, G., 2017. OSMnx: New methods for acquiring, constructing, analyzing, and visualizing complex street networks. Computers, *Environment and Urban Systems*, 65, pp.126-139.

Burns, T., Oram, M. M., Claris, S. (2019). *Cycling for Everyone*. 28 July. Available at: https://www.sustrans.org.uk/media/7377/cycling_for_everyone-sustrans-arup.pdf (Accessed 7 January 2022)

Cabinet Office (2009) *The wider costs of transport in English urban areas in 2009.* Available at: http://www.cabinetoffice.gov.uk/media/307739/wider-costs-transport.pdf (Accessed: 20/07/2022)

Calafiore, A., Dunning, R., Nurse, A. and Singleton, A., 2022. The 20-minute city: An equity analysis of Liverpool City Region. *Transportation Research Part D: Transport and Environment*, 102, p.103111.

Callister, D. and Lowry, M., 2013. Tools and strategies for wide-scale bicycle level-of-service analysis. *Journal of urban planning and development*, 139(4), pp.250-257.

Carroll, P., Caulfield, B. and Ahern, A., 2019. Modelling the potential benefits of increased active travel. *Transport Policy*, 79, pp.82-92.

Clark, J.M., 1991. The appraisal of community severance. Department for Transport, 135, ISSN: 0266-7045, (135).

Clayton, W. and Parkin, J., 2016. Cycling and disability: a review.
Clayton, W., Parkin, J. and Billington, C., 2017. Cycling and disability: A call for further research. *Journal of Transport & Health*, 6, pp.452-462.

City of Portland. 1998. Portland Pedestrian Master Plan. Portland: Portland Office of Transportation

Crossland, M.D., Wynne, B.E. and Perkins, W.C., 1995. Spatial decision support systems: An overview of technology and a test of efficacy. *Decision support systems*, 14(3), pp.219-235.

Curl, A., Clark, J. and Kearns, A., 2018. Household car adoption and financial distress in deprived urban communities: A case of forced car ownership?. *Transport Policy*, 65, pp.61-71.

Department for Transport (2017) *Cycling and Walking Investment Strategy*. URL https://assets. publishing. service. gov. uk/government/uploads/system/uploads/attachment_data/file/874708/cycling-walking-investment-strategy. pdf, p.38.

Department for Transport (2020) *Local Transport Note 1/20: Cycle Infrastructure Design.* Available at:https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/951074/cycle-infrastructure-design-ltn-1-20.pdf (Accessed: 19/07/2022)

Dong, X., Ben-Akiva, M.E., Bowman, J.L. and Walker, J.L., 2006. Moving from trip-based to activity-based measures of accessibility. *Transportation Research Part A: policy and practice*, 40(2), pp.163-180.

Dowling, R., Flannery, A., Landis, B., Petritsch, T., Rouphail, N. and Ryus, P., 2008. Multimodal level of service for urban streets. *Transportation Research Record*, 2071(1), pp.1-7.

Dulal, H.B., Brodnig, G. and Onoriose, C.G., 2011. Climate change mitigation in the transport sector through urban planning: A review. *Habitat International*, *35*(3), pp.494-500.

Duncan, D.T., Aldstadt, J., Whalen, J., Melly, S.J. and Gortmaker, S.L., 2011. Validation of Walk Score® for estimating neighbourhood walkability: an analysis of four US metropolitan areas. *International journal of environmental research and public health*, 8(11), pp.4160-4179.

Emery, J. and Crump, C., 2011. The WABSA project: assessing and improving your community's walkability & bikeability. 2003. *North Carolina Dep. Heal. Behav. Heal. Educ. Sch. Public Heal. Univ. North Carolina Chapel Hill*.

Grond, K., 2016. *Route choice modelling of cyclists in Toronto* (Doctoral dissertation, University of Toronto)

Fernández-Heredia, Á., Monzón, A. and Jara-Díaz, S., 2014. Understanding cyclists' perceptions, keys for a successful bicycle promotion. *Transportation research part A: policy and practice*, 63, pp.1-11.

Foda, M.A. and Osman, A.O., 2010. Using GIS for measuring transit stop accessibility considering actual pedestrian road network. *Journal of Public Transportation*, 13(4), p.2.

Foti, F., Waddell, P. and Luxen, D., 2012, April. A generalized computational framework for accessibility: from the pedestrian to the metropolitan scale. In *Proceedings of the 4th TRB Conference on Innovations in Travel Modeling. Transportation Research Board* (pp. 1-14).

Frank, L.D., Sallis, J.F., Saelens, B.E., Leary, L., Cain, K., Conway, T.L. and Hess, P.M., 2010. The development of a walkability index: application to the Neighborhood Quality of Life Study. *British journal of sports medicine*, 44(13), pp.924-933.

Furth, P.G., Mekuria, M.C. and Nixon, H., 2016. Network connectivity for low-stress bicycling. *Transportation research record*, 2587(1), pp.41-49.

Hagberg, A., Swart, P. and S Chult, D., 2008. Exploring network structure, dynamics, and function using NetworkX (No. LA-UR-08-05495; LA-UR-08-5495). Los Alamos National Lab.(LANL), Los Alamos, NM (United States).

Haklay, M., 2010. How good is volunteered geographical information? A comparative study of OpenStreetMap and Ordnance Survey datasets. *Environment and planning B: Planning and design*, 37(4), pp.682-703.

Halonen, J.I., Blangiardo, M., Toledano, M.B., Fecht, D., Gulliver, J., Ghosh, R., Anderson, H.R., Beevers, S.D., Dajnak, D., Kelly, F.J. and Wilkinson, P., 2016. Is long-term exposure to traffic pollution associated with mortality? A small-area study in London. *Environmental Pollution*, 208, pp.25-32.

Hansen, Walter G. How accessibility shapes land use. *Journal of the American Institute of planners* 25, no. 2 (1959): 73-76.

Harkey, D.L., Reinfurt, D.W. and Knuiman, M., 1998. Development of the bicycle compatibility index. *Transportation research record*, 1636(1), pp.13-20.

Heinen, E., Van Wee, B. and Maat, K., 2010. Commuting by bicycle: an overview of the literature. *Transport reviews*, 30(1), pp.59-96.

Herrmann-Lunecke, M.G., Mora, R. and Sagaris, L., 2020. Persistence of walking in Chile: lessons for urban sustainability. *Transport reviews*, *40*(2), pp.135-159.

Higgs, G., Fry, R. and Langford, M., 2012. Investigating the implications of using alternative GIS-based techniques to measure accessibility to green space. *Environment and Planning B: Planning and Design*, *39*(2), pp.326-343.

Hillnhütter, H., 2016. Pedestrian access to public transport. PhD Thesis, University of Stavanger.

Hoenke, K.M., Kumar, M. and Batt, L., 2014. A GIS based approach for prioritizing dams for potential removal. *Ecological Engineering*, 64, pp.27-36.

Hull, A., Silva, C. and Bertolini, L. eds., 2012. Accessibility instruments for planning practice (pp. 57-62). Brussels: Cost Office.

Jarlebring, I., Persson, S., Lindqvist, E., Eliasson, J., 2002. Beräkning av gångtrafikeffekter vid väginvesteringar - En handledning. Transek. Internal document Trafikverket.

Jarrett, J., Woodcock, J., Griffiths, U.K., Chalabi, Z., Edwards, P., Roberts, I. and Haines, A., 2012. Effect of increasing active travel in urban England and Wales on costs to the National Health Service. *The Lancet*, 379(9832), pp.2198-2205.

Jordahl, K., Van den Bossche, J., Fleischmann, M., Wasserman, J., McBride, J., Gerard, J., … Leblanc, F., 2020. *Geopandas/geopandas: v0.8.1 (Version v0.8.1).* Available at: https://geopandas.org/en/stable/)

Kesarovski, T. and Hernández-Palacio, F., 2022. Time, the other dimension of urban form: Measuring the relationship between urban density and accessibility to grocery shops in the 10-minute city. *Environment and Planning B: Urban Analytics and City Science.* DOI: https://doi.org/10.1177/23998083221103259

Khan, J., Ketzel, M., Kakosimos, K., Sørensen, M. and Jensen, S.S., 2018. Road traffic air and noise pollution exposure assessment–A review of tools and techniques. *Science of the total environment*, 634, pp.661-676.

Kong, F., Yin, H. and Nakagoshi, N., 2007. Using GIS and landscape metrics in the hedonic price modeling of the amenity value of urban green space: A case study in Jinan City, China. *Landscape and urban planning*, 79(3-4), pp.240-252.

Kounadi, O., 2009. Assessing the quality of OpenStreetMap data. *Msc geographical information science, University College of London Department of Civil, Environmental And Geomatic Engineering*, p.19.

Lamb, W. F., Wiedmann, T., Pongratz, J., Andrew, R., Crippa, M., Olivier, J. G., Wiedenhofer, D., Mattioli, G., Al Khourdajie, A., House, J. and Pachauri, S. (2021). A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. *Environmental research letters*, 16 (073005).

Longley, P.A., Goodchild, M.F., Maguire, D.J. and Rhind, D.W., 2015. Geographic information science and systems. John Wiley & Sons.

Lovelace, R., Goodman, A., Aldred, R., Berkoff, N., Abbas, A. and Woodcock, J., 2017. The Propensity to Cycle Tool: An open source online system for sustainable transport planning. *Journal of transport and land use*, 10(1), pp.505-528.

Lovelace, R., Félix, R. and Carlino, D., 2022. Exploring jittering and routing options for converting origin-destination data into route networks: towards accurate estimates of movement at the street level.

Lu, W., Scott, D.M. and Dalumpines, R., 2018. Understanding bike share cyclist route choice using GPS data: Comparing dominant routes and shortest paths. *Journal of transport geography*, 71, pp.172-181.

McDaniel, S., Lowry, M.B. and Dixon, M., 2014. Using origin–destination centrality to estimate directional bicycle volumes. *Transportation Research Record*, 2430(1), pp.12-19.

Manaugh, K. and El-Geneidy, A., 2011. Validating walkability indices: How do different households respond to the walkability of their neighbourhood?. *Transportation research part D: transport and environment*, 16(4), pp.309-315.

Mattioli, G., 2017. " Forced car ownership" in the UK and Germany: socio-spatial patterns and potential economic stress impacts. *Social Inclusion*, 5(4), pp.147-160.

Mavoa, S., Witten, K., McCreanor, T. and O'sullivan, D., 2012. GIS based destination accessibility via public transit and walking in Auckland, New Zealand. *Journal of transport geography*, 20(1), pp.15-22.

Nordström, T. and Manum, B., 2015. Measuring bikeability: Space syntax based methods applied in planning for improved conditions for bicycling in Oslo. *In SSS 2015-10th International Space Syntax Symposium* (pp. 1-14).

Norwood, P., Eberth, B., Farrar, S., Anable, J. and Ludbrook, A., 2014. Active travel intervention and physical activity behaviour: An evaluation. *Social science & medicine*, 113, pp.50-58.

Nyerges, T.L. and Jankowski, P., 2009. Regional and urban GIS: a decision support approach. Guilford Press.

Office for National Statistics, UK Goverment., 2015. *English indices of deprivation 2015*. URL: www.gov.uk/government/statistics/english-indices-of-deprivation-2015 (Accessed 24/07/2022).

Ohta, K., Kobashi, G., Takano, S., Kagaya, S., Yamada, H., Minakami, H. and Yamamura, E., 2007. Analysis of the geographical accessibility of neurosurgical emergency hospitals in Sapporo city using GIS and AHP. *International journal of geographical information science*, 21(6), pp.687-698.

Olsen, J.R., Mitchell, R., Mutrie, N., Foley, L. and Ogilvie, D., 2017. Population levels of, and inequalities in, active travel: a national, cross-sectional study of adults in Scotland. *Preventive Medicine Reports*, 8, pp.129-134.

Ord, J.K. and Getis, A., 1995. Local spatial autocorrelation statistics: distributional issues and an application. *Geographical analysis*, 27(4), pp.286-306.

Ørving, T., Fossheim, K. and Andersen, J., 2019. Public sector facilitation of cargo bike operations to improve city logistics. *In Autonomous Vehicles and Future Mobility* (pp. 141-154). Elsevier.

O'Sullivan, D., Morrison, A. and Shearer, J., 2000. Using desktop GIS for the investigation of accessibility by public transport: an isochrone approach. *International Journal of Geographical Information Science*, 14(1), pp.85-104.

Páez, A., Scott, D.M. and Morency, C., 2012. Measuring accessibility: positive and normative implementations of various accessibility indicators. *Journal of Transport Geography*, 25, pp.141-153.

Panahi, M., Rezaie, F. and Meshkani, S., 2013. Seismic vulnerability assessment of school buildings in Tehran city based on AHP and GIS. Nat. Hazards Earth Syst. Sci. Discuss, 1, pp.4511-4538.

Pirie, G.H., 1979. Measuring accessibility: a review and proposal. *Environment and planning A*, 11(3), pp.299-312.

Powell, J., Dalton, A., Brand, C. and Ogilvie, D., 2010. The health economic case for infrastructure to promote active travel: a critical review. Built Environment, 36(4), pp.504-518.

Pritchard, R., Frøyen, Y. and Snizek, B., 2019. Bicycle level of service for route choice—A GIS evaluation of four existing indicators with empirical data. *ISPRS International Journal of Geo-Information*, 8(5), p.214.

Pucher, J. and Buehler, R., 2008. Making cycling irresistible: lessons from the Netherlands, Denmark and Germany. *Transport reviews*, 28(4), pp.495-528.

QGIS.org (2022). QGIS Geographic Information System. QGIS Association. http://www.qgis.org

Rahman, M.A., Rusteberg, B., Gogu, R.C., Ferreira, J.L. and Sauter, M., 2012. A new spatial multi-criteria decision support tool for site selection for implementation of managed aquifer recharge. *Journal of environmental management*, 99, pp.61-75.

Ribeiro, A. and Antunes, A.P., 2002. A GIS-based decision-support tool for public facility planning. *Environment and Planning B: Planning and design*, 29(4), pp.553-569.

Rikalović, A., Ćosić, Đ., Popov, S. and Lazarević, Đ., 2013. Spatial multi-criteria decision analysis for industrial site selection: The state of the art. In XI *Balkan Conference on Operational Research.* Balcor.

Rind, E., Shortt, N., Mitchell, R., Richardson, E.A. and Pearce, J., 2015. Are income-related differences in active travel associated with physical environmental characteristics? A multi-level ecological approach. *International Journal of Behavioural Nutrition and Physical Activity*, 12(1), pp.1-10.

Reyier, J., 1987. 15E Calculation guide - Investments in roads and streets (No. 1986:1E). Swedish National Road Administration, Borlänge. Internal document Trafikverket.

Saaty, R.W., 1987. The analytic hierarchy process—what it is and how it is used. *Mathematical modelling*, 9(3-5), pp.161-176.

Saghapour, T., Moridpour, S. and Thompson, R.G., 2017. Measuring cycling accessibility in metropolitan areas. *International journal of sustainable transportation*, 11(5), pp.381-394.

Sałabun, W., Wątróbski, J. and Shekhovtsov, A., 2020. Are mcda methods benchmarkable? a comparative study of topsis, vikor, copras, and promethee ii methods. *Symmetry,* 12(9), p.1549.

Schaap, N., Harms, L., Kansen, M. and Wüst, H., 2016. Cycling and walking: the grease in our mobility chain. *Netherlands Institute for Transport Policy Analysis*.

Shimbel, A. (1953). Structural parameters of communication networks. *The bulletin of mathematical biophysics*, 15(4), 501-507.

Stinson, M.A. and Bhat, C.R., 2003. Commuter bicyclist route choice: Analysis using a stated preference survey. *Transportation research record*, 1828(1), pp.107-115.

Stojčić, M., Zavadskas, E.K., Pamučar, D., Stević, Ž. and Mardani, A., 2019. Application of MCDM methods in sustainability engineering: A literature review 2008–2018. *Symmetry*, 11(3), p.350.

Sun, G., H. Lin, and R. Li. 2012. Measuring the influence of built environment on walking behaviour: An accessibility approach. *Geographic Information Science* 7478: 187–197.

Sustrans (2018) *Paths for Everyone.* Available at: https://www.sustrans.org.uk/about-us/paths-for-everyone/ (Accessed: 22/05/2022)

Sustrans (2021) *How we remove barriers from the national cycle network.* Available at: https://www.sustrans.org.uk/our-blog/opinion/2021/november/how-we-remove-barriers-from-the-national-cycle-network/ (Accessed: 1 June 2022)

Sustrans (2020) *Why removing restrictive barriers must be part of our response to Covid-19*. Available at: https://www.sustrans.org.uk/our-blog/opinion/2020/june/why-removing-restrictive-barriers-must-be-part-of-our-response-to-covid-19/ (Accessed: 1 June 2022)

Team QW (2021) *QGIS Python Plugins Repository* - *QNEAT3.* Available at: https://plugins.qgis.org/plugins/QNEAT3 (Accessed: 30/07/2022)

Tobler, W.R., 1970. A computer movie simulating urban growth in the Detroit region. *Economic geography*, 46(sup1), pp.234-240.

Transport for London (2012) *Attitudes towards cycling Annual report 2012*. Available at: https://content.tfl.gov.uk/attitudes-towards-cycling-2012-report.pdf (Accessed: 28 April 2022)

Vale, D.S., Saraiva, M. and Pereira, M., 2016. Active accessibility: A review of operational measures of walking and cycling accessibility. *Journal of transport and land use*, 9(1), pp.209-235.

van Eldijk, J., Gil, J., Kuska, N. and Patro, R.S., 2020. Missing links–Quantifying barrier effects of transport infrastructure on local accessibility. *Transportation Research Part D: Transport and Environment*, 85, p.102410.

Van Rossum, G. & Drake Jr, F.L., 1995. *Python reference manual*, Centrum voor Wiskunde en Informatica Amsterdam.

Vitale Brovarone, E. and Cotella, G., 2020. Improving rural accessibility: A multilayer approach. *Sustainability*, 12(7), p.2876.

Vybornova, A., Cunha, T., Gühnemann, A. and Szell, M., 2022. Automated detection of missing links in bicycle networks. *Geographical Analysis*.

Wheels for Wellbeing (2022) *Infrastructure for All*. https://wheelsforwellbeing.org.uk/campaigning/infrastructure-for-all/ (Accessed: 23 April 2022)

Wei, S., Xu, J. and Ma, H., 2019. Exploring public bicycle network structure based on complex network theory and shortest path analysis: the public bicycle system in Yixing, China. *Transportation planning and technology*, 42(3), pp.293-307.

Yigitcanlar, T., Sipe, N., Evans, R. and Pitot, M., 2007. A GIS-based land use and public transport accessibility indexing model. Australian planner, 44(3), pp.30-37.

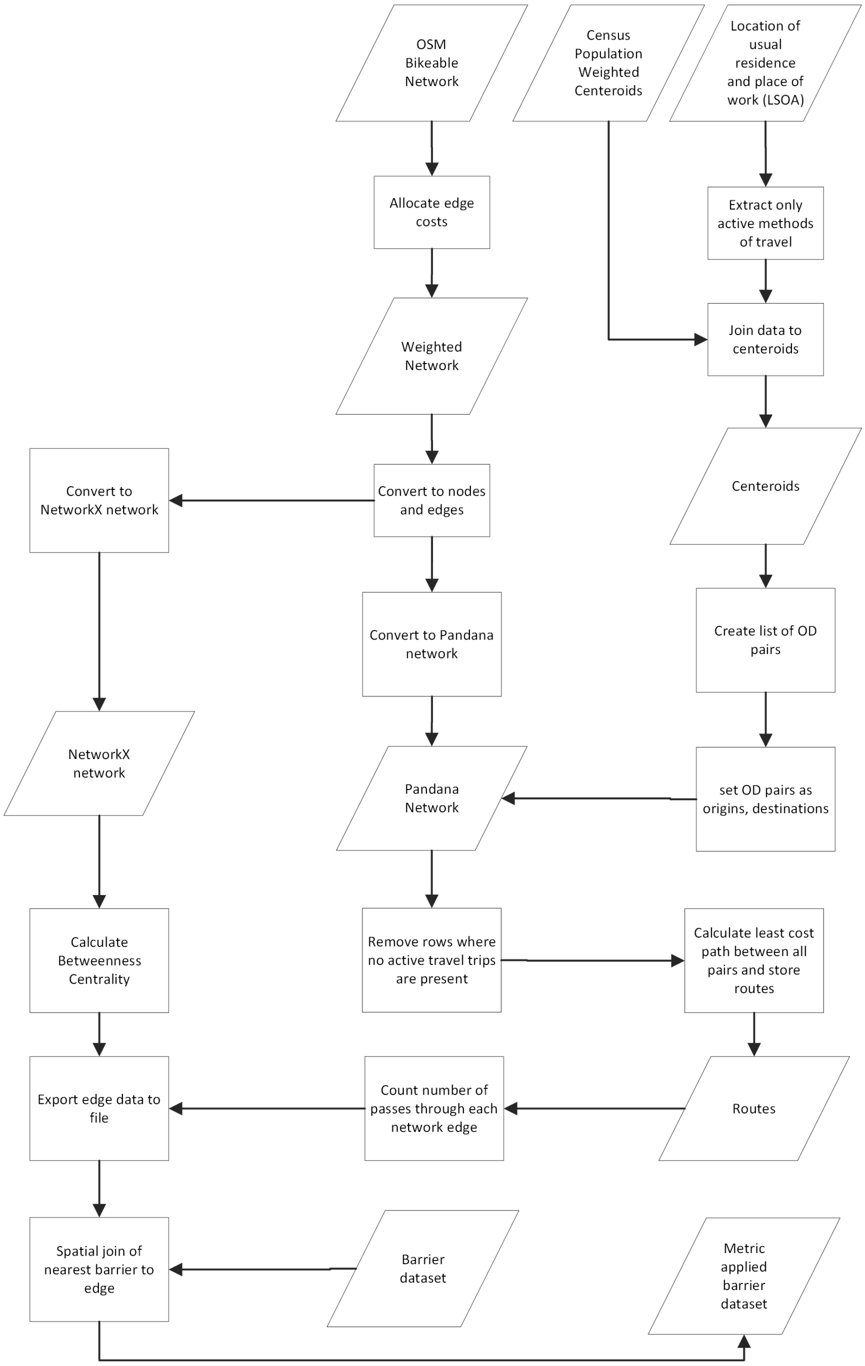
Zielstra, D. and Hochmair, H.H., 2011. Comparative study of pedestrian accessibility to transit stations using free and proprietary network data. *Transportation Research Record*, 2217(1), pp.145-152.

APPENDIX

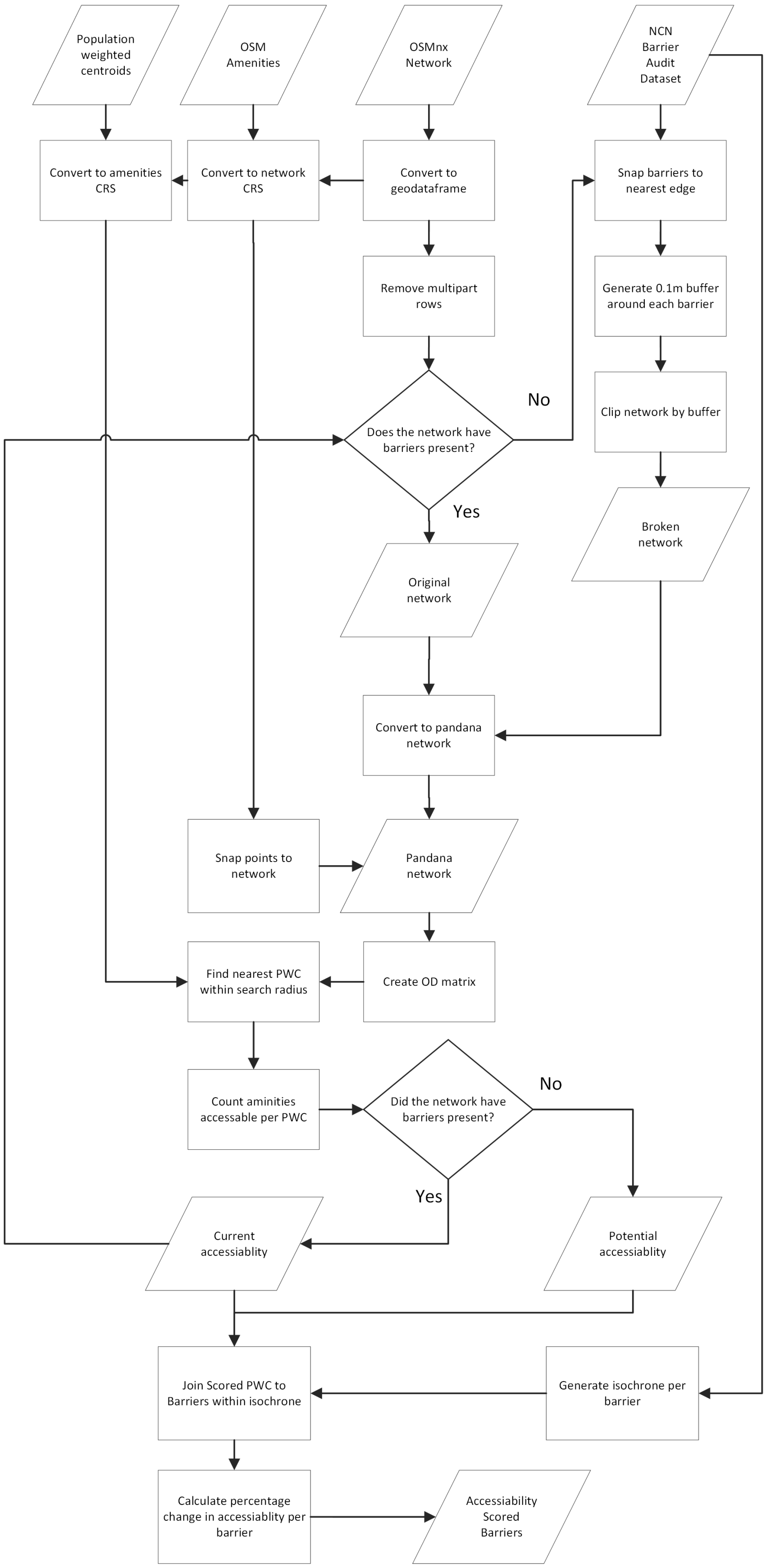
8.1 Github repository

The Github repository can be found at: https://github.com/Froguin99/BarrierRemoval

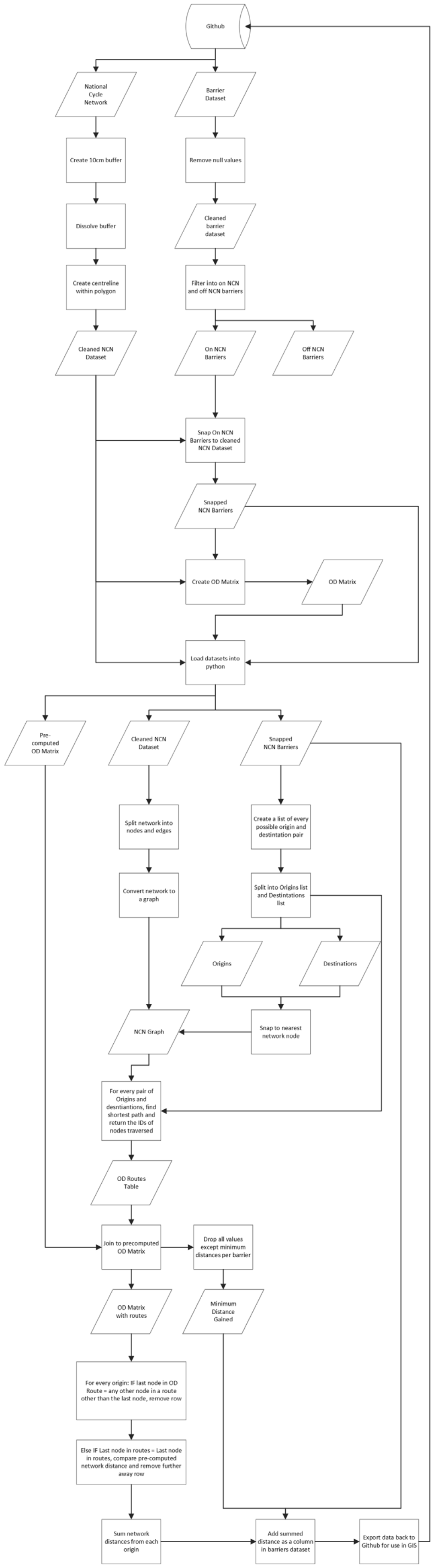
8.2 Route importance processing flowchart



8.3 Accessibility Score flowchart



8.4 Potential Distance gained flowchart



8.5 Relative transport poverty flowchart