Back on Track: Increasing Dutch Train Ridership using the Node-Place Model

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Colophon

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Abstract

The built environment of the area within walking and cycling distance of railway stations represents a finite public resource. This research investigates how this resource can be most effectively used by conducting a multilinear regression analysis of geospatial data of the areas surrounding 50 Dutch railway stations to determine which attributes of the built environment encourage rail ridership and higher degrees of customer satisfaction. To do this, indicators of rail service quality ("node") and those of the built environment ("place") were evaluated under Bertolini's Node-Place Framework. The potentially explanatory node indicators included train service frequency, for how much of the day service operates and the number of local bus connections. Place indicators evaluated included the degree of mix of land uses around a station, the possibility of walking and cycling in a neighbourhood and the population and local jobs. The research found that certain node and place indicators did have an effect on rail ridership. These included off-peak train frequency, number of bus, tram and metro connections, job density and street network permeability. However, node and place indicators were not found to have an effect on customer satisfaction scores. This research then applies these findings to various Dutch railway stations and describes remedial actions.

Key words: Railway stations, Urban design, Public Transportation, Node-Place Model, Ridership

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List of Abbreviations

Abbreviation	Full Version	Definition
CBS	Statistics Netherlands *(Centraal Bureau voor de Statistiek)*	A Dutch government agency with the statutory responsibility of compiling a range of statistics.
GCS	Geographic Coordinate System	A round (spheroid) system of coordinates which defines where on the earth's surface particular spatial data is located (Smith, 2020). Used by GIS. Uses angular units (e.g. degrees).
GIS	Geographic Information Systems	A computer system that analyses and displays spatial data. (U.S. Geological Survey, n.d.)
GTFS	General Transit Feed Specification (originally "Google Transit Feed Specification")	A common format for public transportation timetables and the relevant geographic information. The "Static" designation indicates that it refers to the scheduled timetables, which differentiates it from the "Dynamic" version, which concerns real-time data. GTFS allows public transportation agencies to publish timetable information in a format suitable for computer applications.
LISA	National Information System for Workplaces *(Landelijk Informatiesysteem van Arbeidsplaatsen)*	The national employment register *(Werkgelegenheidsregister)* offers spatial information about every place of where paid work is conducted in the Netherlands (Stichting LISA, n.d.).
NS	Dutch Railways *(Nederland Spoorwegen)*	Dutch state-owned rail operator of the main passenger rail concession in the Netherlands. (NS, n.d.b).
OLS	Ordinary Least Squares	A common method of linear regression used to generate models or predictions for a dependent variable from a set of explanatory (independent) variables (Pimpler, 2017).
OSM	OpenStreetMap	A crowd-sourced global map built by volunteers (Ferster et al., 2020). It offers a high level of detail.
PCS	Projected Coordinate System	Provides instructions on how to render geodata on a flat surface within a GIS (Smith, 2020). Uses linear units (e.g. metres).

Abbreviation	Full Version	Definition
RD	State Triangular (Rijksdriehoek) coordinate system	The cartesian coordinate system used by geospatial datasets in the European Netherlands, centred on the Onze Lieve Vrouwetoren in Amersfoort (Het Kadaster, 2020).
TAD	Transit-Adjacent Development	Neighbourhood within walking distance to transit (like TOD), but which fails to take advantage because of incompatible land use.
TOD	Transit-oriented development	Land-use planning concept which integrates public transportation facilities with walkable, diverse neighbourhoods (Jacobson & Forsyth, 2008).
VGI	Volunteered geographic information	Information about the spatial environment contributed to a geographic database by members of the public in an unofficial capacity (Goodchild, 2007).

1 Introduction

1.1 Societal Relevance

Passenger rail travel offers many benefits to society over travel by private automobile. It reduces traffic congestion, increases traffic safety, reduces greenhouse gas emissions and lowers consumer expenditures on transportation (Litman, 2021). In order to more fully realise these benefits, the railway network and its stations must attract a robust level of ridership. This raises the question of what role the choices made in the spatial environment can play in attracting ridership at railway stations.

In the distant past, particularly in North America, the construction of railway stations brought with it the development of the towns surrounding its stations. Later, during the streetcar and subway era, suburban development patterns often followed streetcar lines into the suburbs (Cervero & Seskin, 1995; Dittmar & Ohland, 2004) forming “streetcar suburbs.” Later, in the automobile era, railway trips decreased significantly because of developments in road and air transport (Brons et al., 2009). Throughout the second half of the twentieth century, automobile use increased because more people were able to afford their own cars. Additionally, development patterns in the built environment increased the geographic spread of land uses, which caused people to choose to travel farther between home and their daily destinations (Banister, 1999). During that era, railway stations were often built as a compliment to an automobile-based trip, i.e., surrounded by large amounts of car parking. These can be seen as lost opportunities because they were located away from activity centres, which makes the stations more difficult to use (Akabal et al., 2017).

The question of the spatial environment’s role in ridership also applies to the routings of new railways. In November 2022 the Dutch national government and the governments of the provinces of Friesland and Groningen announced that they had reached an agreement to map out all possible routings of the Lelylijn (Provinsje Fryslân, 2022), a proposed railway on a new alignment running from Lelystad in the southwest to the City of Groningen in the northeast. This new line would allow the construction of 75,000 new homes. Local media coverage has suggested an alignment closely following the A6 and A7 freeways (Omrop Fryslân, 2021). But that raises the question of whether that is a prudent choice and the consequences of that choice on ridership of the new line.

Since rail infrastructure and the layout of the built environment is fixed and difficult to shift (Van Wee et al., 2013), a long-term approach is needed, and a clearer understanding of the spatial factors that positively influence the volume of ridership at stations can help planners assess where best to deploy limited resources (Cummings & Mahmassani, 2022). The Node-place model helps with this assessment by helping to identify opportunities for intensification or an increase in density surrounding well-served public transportation nodes (Bertolini, 1999).

1.2 Academic Relevance and Research Gap

After several decades of academic debate, there remains a lack of consensus about whether land use patterns impact travel behaviour (Van Wee et al., 2013) and, by extension, rail ridership. Banister (1999) argues that it is essential to integrate land use and transportation planning because land use planning is just as important in travel outcomes as direct interventions in transportation services. We have underestimated the role that land use planning can play in reducing travel demand, and in particular levels of car dependency and automobile trip lengths. Martens (2000) holds a contrasting view, arguing that the Dutch Ministry of Spatial Planning ought to focus on influencing the quality and quantity of transportation infrastructure instead of trying to influence the configuration of the built environment. Boarnet and Crane (2001) are not quite as dismissive of the link between urban design and travel behaviour, but they cite price (economic and in terms of time) as the mechanism through which urban design and travel behaviour interact and which merits further study. They also argue for the importance of examining the link at various spatial scales. This research operates at the scale of the railway station level and an area of two-and-a-half kilometres surrounding it.

Previous research has considered what spatial qualities encourage effective use of transit investments. Perhaps the most well-known, transit-oriented development (TOD), has become a popular, but vague, concept since it was first discussed by Peter Calthorpe (1993). It generally refers to integrating public transportation facilities with walkable, diverse neighbourhoods (Jacobson & Forsyth, 2008). This research analyses rail ridership, a high level of which would suggest a successful integration between the built environment and the transportation system, which are also associated with high-quality TOD implementations.

The popularity of TOD does have merit. Cervero and Murakami (2009) examined the "railway + property" (R+P) developments of 51 MTR stations in Hong Kong and performed a qualitative assessment as to whether they featured a transit-oriented design. (It is worth noting that they only considered whether the station area had mixed land uses, a high-quality walking environment, and high walking connectivity. They did not consider the presence of density because the nature of this type of R+P development in Hong Kong is, by international standards, rather dense.) Those stations which did feature a TOD design attracted 35,000 additional riders per day.

Caset et al. (2019) list seven models which use quantifiable data to evaluate the area surrounding railway stations. The original of these, which is often mentioned in the literature, is the node-place model developed by Bertolini (1999). It offers a conceptual framework for considering the redevelopment of station areas and their transportation services, arguing that an important prerequisite for developing the full potential of public transportation nodes is that the node be considered in combination with its urban surroundings ("place"). He thus emphasises that such nodes should be highly connected in two senses: in the sense that it is easy for people to get there and in the sense that it should be very much a place of diverse activities. In essence, the node-place model is about matching the appropriate quality of transportation facilities with the appropriate intensity of urban activities. The "streetcar suburbs" mentioned earlier balance node and place well (Dittmar & Ohland, 2004).

Babb (2016) mentions a research gap regarding the effectiveness of railway stations which are placed next to major road infrastructure (e.g. within freeway medians), as this may inhibit pedestrian access to the station and undermine potential for local development. Such placement would have the potential to undermine the place values of the station area.

The research gap that this thesis seeks to address is a lack of assessment of railway stations in the Netherlands against a node-place model. There is also a research gap in the literature of applying the node-place model to investigate the ridership potential of new (potential) railway stations. When examining what explains transit ridership, Taylor and Fink (2013) cite many different factors, including fares, service routing, frequency, population density and land use. But the paper points out that the relationships between these factors, and how they influence each other is less well understood. This research will help address that gap by studying how various node and place values affect ridership. In their research on how off-peak frequencies affect rail ridership, Hansson et al. (2022) suggest further research into customer satisfaction, which will also be addressed in this research.

1.3 Research Aim and Research Questions

The purpose of this research is to contribute to the optimisation of railway infrastructure by modelling which factors within node, place and accessibility result in increased ridership.

This leads to the following research question: *What is the potential of applying the node-place value model to determine the optimal location of railway stations for the purposes of increasing both ridership and customer satisfaction?*

And the following sub-questions:

- **Sub-question 1:** What node characteristics increase ridership, and to what degree?
- **Sub-question 2:** What place characteristics increase ridership, and to what degree?
- **Sub-question 3:** What node characteristics increase customer satisfaction scores, and to what degree?
- **Sub-question 4:** What place characteristics increase customer satisfaction scores, and to what degree?
- **Sub-question 5:** What correlation exists between ridership and customer satisfaction?

1.4 Reading Guide

First a review of the literature on the factors affecting station ridership will be conducted. This will involve a more detailed review of the node-place model and updates to it from other scholars. In chapter 3 the methodology will be explored, starting with an examination of the existing situation. I will discuss the data to be used, which will include geodata and ridership data, and how that data and the indicators for node and place value were selected. Chapter 3 also features details of the linear regression analysis process used to answer the research questions. Chapter 4 will include a discussion of the results and chapter 5 examines how to apply the findings in practice. Chapter 6 concludes the thesis with policy implications, limitations, and future research directions.

2 Theoretical Framework

This section conducts a review of the existing literature by examining three topics: the motivation behind the decisions on whether to travel (particularly in a utilitarian context), how the built environment affects travel behaviour, and a conceptual model connecting the built environment to a specific metric of travel behaviour—ridership at rail stations and customer satisfaction scores.

2.1 Why we travel in general

What influences a person’s choice of mode of travel? One way to examine this question is to consider what motivates people undertake a journey in the first place. There are two main theoretical schools to answer this question: the theory of self-determination, which offers intrinsic and extrinsic motivations and the theory of utilitarian travel demand which focuses only on extrinsic motivations. Answering this question of travel motivation will help us when examining the indicators of node and place proposed by other researchers and help with our understanding of the built environment.

2.1.1 Theory of self-determination (Intrinsic and Extrinsic Motivations)

Most scholars see the demand for travel is derived from our desire to reach places (Cervero & Kockelman, 1997) for the purpose of reaching activities that are spatially separated (i.e. that the value of travel is *extrinsic* to the activity of travel itself) (Mokhtarian et al., 2015). Mokhtarian et al. (2015) counter this by examining travel through the lens of the theory of self-determination, which offers three motivations for human behaviour: extrinsic motivation (the value of an activity comes from outside the activity itself; usually the result), intrinsic motivation (the value of the activity comes from within the activity), and amotivation (where we do not perceive our behaviour to be connected with its outcomes.) They argue that by ignoring the intrinsic value of travel (i.e., the human need to travel for its own sake), we are significantly undercounting the potential demand for travel. It is difficult to link intrinsic motivations to travel with the built environment, which is why most theories about land use at stations rely on an extrinsic motivation to travel, such as the theory of utilitarian travel demand.

2.1.2 Theory of Utilitarian Travel Demand

Under this theory, travel is undertaken in order to satisfy a need. That is, individuals seek to maximise their utility given scarce resources and by expending the least possible cost, and hence, effort (Lucas et al., 2011; Pratt, 1970). The cost of travel, in terms of utility involves the hindrances involved such as economic and travel time cost. This theory fits with Allen and Farber’s (2020) view that the ability to participate in daily activities represents a basic function of urban transportation. Banister (2008) argues that this cost minimisation in the form of travel time minimisation should not be the primary policy objective for the transportation system. Today’s policies are not even consistent in their intention to minimise traffic speed—e.g., attempts to slow the speed of vehicular traffic for safety purposes. Instead, the utility of transportation comes from reliability in trip durations, and thus the policy focus should be on offering a reasonable and reliable travel time.

2.1.3 Customer Satisfaction and Rail Ridership

The literature does offer evidence that the degree of customer satisfaction may have an influence on ridership, particularly in the form of customer retention. Wang et al. (2020) used a structural equation model (a type of multivariable statistical technique) to assess how service quality and customer satisfaction impact the intention of rail customers to use the service again. In their study, service quality encompassed both node (e.g., punctuality) and place (e.g., ease of station access) values. They found that service quality itself is positively related to customer satisfaction and that customer satisfaction was positively related to the intention of customers to use the service again. Because of this, customer satisfaction was considered as an explanatory variable for ridership (addressing research sub-question 5) in addition to being considered as an independent variable.

The built environment itself can also play a role in customer satisfaction with transit services. Luo et al. (2023) argues that spatial interventions as part of transport policies play an important part in accommodating customers' heterogeneous travel needs. Their models suggested that travellers in the inner suburbs of Shenzhen, China were less satisfied with their public transportation service than those in the outer suburbs, despite the inner suburbs operating a higher quality service. This may be because inner suburban customers' higher performance expectations were not met. This points to a role for the built environment in customer satisfaction, and through that, resulting ridership. For this reason, Ibrahim et al. (2020) argue for the importance of identifying which factors in the passenger experience in particular influence customer satisfaction prior to developing strategies to address ridership.

2.2 Travel Behaviour and the Built Environment

Under the theory of utilitarian travel demand, features of the built environment can affect travel time costs, which affect travel behaviour (Mirzaei et al., 2018), including ridership. Thus, it is useful to introduce two lenses through which the built environment's effects on travel behaviour can be examined—namely the five Ds of travel behaviour and node-place theory. Accessibility provides another lens for examining travel behaviour because it reflects the choices that the built environment (among other factors) offers to the traveller.

The land-use transport feedback cycle models the interaction, in both directions, between land-use and the transportation system (Straatemeier & Bertolini, 2020). It posits that the spatial distribution of activities creates a utilitarian need for a transportation system (for people to reach the activities). And, conversely, that the transportation system enables (or constrains) opportunities for spatial interaction (i.e., *accessibility*, to be discussed in section 2.2.3.) (Wegener & Fürst, 1999). This distribution of accessibility is one of the determinants of land-uses, which, again, influences the spatial distribution of activities, thus beginning the cycle again (Straatemeier & Bertolini, 2020). The operation of the land-use transport feedback cycle forms part of the basis for the node-place theory framework, to be discussed in section 2.2.2.

Perceptions of safety can be altered by the built environment. For instance, optimising the built environment for walkability, such as by increasing pedestrian connections, improves users' perceptions of safety (Zeng et al., 2023). The perception of safety also has an influence on ridership, though Delbosc and Currie (2012) found it to be a relatively small effect, but greater than the influence of the distance from the city centre.

2.2.1 The Five Ds of Travel Behaviour

One influential framework for measuring the built environment involves the Five Ds: density, diversity, design, destination accessibility and distance to transit (Ewing & Cervero, 2010). These five Ds represent one way of considering the *place* factors in node-place theory. In this research, the *built environment* refers to the changed natural landscape which, taken together, define the physical urban public realm (Cervero & Kockelman, 1997). Chen and Lin (2015) argue that the five Ds framework is more commonly applied to metropolitan rail-based TOD implementations as opposed to intercity high-speed rail ones. This fits well in the Dutch context because Dutch railway stations are more likely to offer a metropolitan rail focus than a high-speed intercity focus.

Density can refer to multiple variables of interest per unit of area (Y. Zhang et al., 2014): population, number of dwelling units, jobs, built floor area. The implied theory being that the denser a place is, the more demand for vehicle trips will ‘degenerate’ (i.e., decrease) (Cervero & Kockelman, 1997), leading to more demand for public transit service. Consistent with this, Cervero and Dai (2014) found that doubling the population density of a bus rapid transit station area resulted in a nearly 40 percent increase in ridership. Density is a useful part of this model because higher density areas near railway stations more opportunities closer together, which makes transit more attractive to reach those opportunities (Ryan & Frank, 2009). In contrast, Handy (2018) argues that while density *does* influence the other ‘D’ criteria, which influences the choices available to travellers, density *does not* directly influence travel behaviour itself.

Diversity refers not to a demographic aspect, but to the diversity of land uses, and the degree to which they are represented in an area (Ewing & Cervero, 2010). This may be measured by examining entropy measures or ratios of jobs-to-housing or jobs-to-population (Y. Zhang et al., 2014).

The model considers the **design** of the street network in an area, particularly considerations such as average block size, the form of street networks (grids or cul-de-sacs) and building setbacks (Y. Zhang et al., 2014). The key considerations are what distinguishes a realm oriented towards pedestrians from one oriented towards automobile traffic (Ewing & Cervero, 2010).

The next two measures represent an extension of the original “three Ds” model. **Destination accessibility** measures things such as the distance to a central business district or the number of jobs within a specified travel time. It reflects the ease of access to trip attractions (Y. Zhang et al., 2014).

Finally, **Distance to transit** measures the average route to the nearest rail station or bus stop. An alternative is to measure the route number of kilometres of transit routes per square kilometre of the study area.

2.2.2 Node-place Theory

The likelihood that a person will use rail as a travel mode is a factor of three elements: the quality of the rail service, the accessibility of the station and the spatial and demographic characteristics of the surrounding area (Brons et al., 2009). In the Netherlands, we see evidence suggesting this because 47% of railway trips use a departure station which is not the closest to their residence (Debrezion et al., 2009), thus suggesting some other motivation. To further explore this phenomenon, the node-place framework intends to offer an evaluation of the quality of the rail service and the characteristics of the surrounding area.

Introduced in 1999, node-place theory attempts to answer the question of what makes railway stations attractive to (potential) users and to evaluate the performance of station areas (Yang et al., 2022). Following the logic behind the land-use transport feedback cycle (Chen & Lin, 2015), it posits that the transportation node (such as a railway station) should be considered holistically in combination with its surroundings (Bertolini, 1999). It aims for a balance between two factors: node and place under the assumption that improving the node value (i.e. the transportation supply) will create conditions favourable to intensifying and diversifying land uses, and vice versa (Vale, 2015). The practical application of this framework is to identify opportunities for spatial development surrounding railway stations, but at a regional scale (Caset et al., 2020). Today this is mostly applied in the context of transit-oriented development.

The node factor focuses on the connectedness of the railway station to other places of interest (Reusser et al., 2008) and thus to its “potential for physical human interaction” (Bertolini, 1999, p. 201). This is because a place with a high node value allows more people to reach a particular area, and thus, interact. The indicators of node values which were used in a selection of the literature are included in Appendix A.

The place factor focuses on the possible land use activities in the area surrounding the station (Reusser et al., 2008), which offer potential demand for transportation services (Dou et al., 2021). Ryan and Frank (2009) argue that place is a useful function because increased proximity to a diversity of land uses is thought to increase the likelihood that people will travel to those destinations using non-motorised vehicles. A survey of the specific indicators used in the literature for place values can be found in Appendix B. The specific node and place indicators used in this research will be examined in section 3.2.3.

Under this model, node and place values are plotted on a graph, with the node on the y-axis and the place on the x-axis (figure 2.1). The theory suggests that a balance should be pursued between these values and indicated by a position in the centre of the graph (Reusser et al., 2008), which would achieve a state of integration and cooperative development between them (Dou et al., 2021; Vale, 2015).

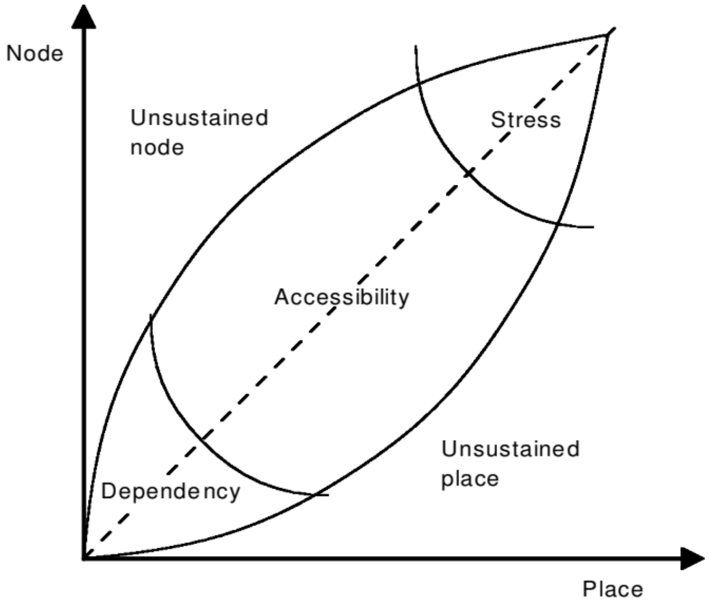
An unbalanced situation can result in one of four states:

- Areas under **stress** (top-right of figure 2.1): These areas are strong and balanced in the sense that there is a maximum diversity of land uses, and maximal passenger flows, providing maximum opportunity for human interaction (Vale, 2015). But this can create conflict because competition between land uses within limited space is very high.
- **Dependent** areas (bottom-left of figure 2.1): represent the opposite of the above. Since the land use is so limited, and the passenger services and flows so low, they are dependent on other factors to remain occupied, such as larger stations or government

subsidy (Reusser et al., 2008). Competition for space here remains very low (Vale, 2015).

- **Unsustained** (or unbalanced) **nodes** (top-left of figure 2.1): feature transportation facilities that are more developed than their surrounding land uses would warrant, representing wasted potential, which fails to meet the financial component of sustainability. This might be corrected by moving right along the x-axis (i.e., increasing its place index), for instance by adding more land use functions (Reusser et al., 2008) or by decreasing its node index value, for instance by cutting rail service (Vale, 2015). Both may be pursued at the same time.
- **Unsustained places** (bottom-right of figure 2.1): feature places with inadequate transportation options. Reusser et al. (2008) argue that this could be addressed by moving right along the x-axis (place), by, for example, adding more transportation services. This may be corrected by increasing its node index value or decreasing its place index value.

Figure 2.1: *The original node-place graph by Bertolini (1999).*



In contrast with most scholars, including Bertolini (1999) and Reusser et al. (2008), Olaru et al. (2019) argue that a balance between node and place is not desirable everywhere. For example, they found that station accessibility may be a better predictor of ridership than local density. Vale et al. (2018) found that even if node and place were balanced at a station area, that does not necessarily indicate that the area qualifies as TOD, and vice versa.

Cummings and Mahmassani (2022) expand this node-place model of examining station ridership by adding an *accessibility index*, i.e., how easy it is to actually access a station. They apply this in an American framework of 478 Amtrak stations. Node, place and accessibility were operationalised using 29 indicators for each station. Node indicators focused on Amtrak rail service levels only (and not connecting local transport), such as the number of trains per week and the number of different train routes serviced. Place measures focused on the demographics of the population within one mile of each station (such as age, education, and job details). Accessibility criteria focused on the number of residents, and jobs within a 30-

minute drive of the station, and their average travel time. (It is worth noting that these criteria are often classified as indicators of node in other studies.) Their research suggests the importance of all three aspects of their adapted node-place model, though they found the node aspect to have more impact on station ridership than the place or accessibility ones. Similarly, Cao et al. (2020) found node indicators to have five times the impact on ridership than place ones.

Zhang et al. (2014) considered the effect of various indicators of the built environment had on car use in the Chinese city of Zhongshan. They suggested an increase in land use density, improved public transportation service and less connectivity in the car road network. They suggest further research into the influence of the built environment on the modal choices made by individual travellers. They suggest that this be done by incorporating features of the built environment ("place") into models.

Caset et al. (2019) applied the node-place model to 259 railway stations in Flanders. Their paper is unique in that it expands on the node-place model with 360° circular 'rose' diagrams for each station, representing 16 indicators, thus providing an accessibility profile. These rose diagrams are divided into supply and demand halves, focusing on the station and its area, along with the users of the station (Figure 2.2). The indicators are then graded outwards from the centre of the diagram (Figure 2.3).

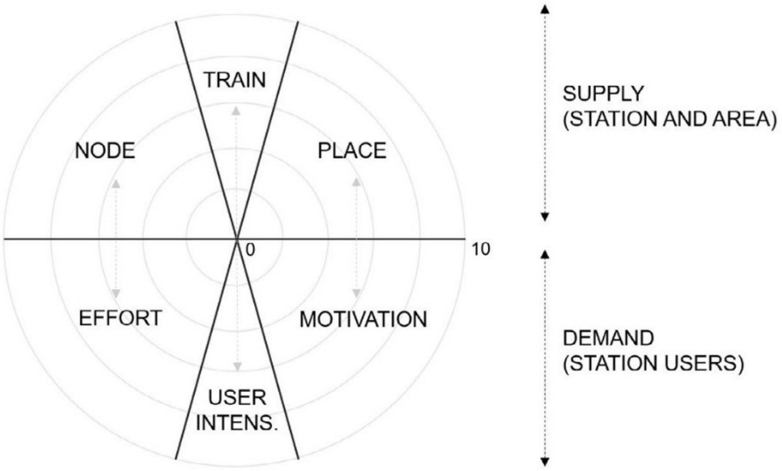
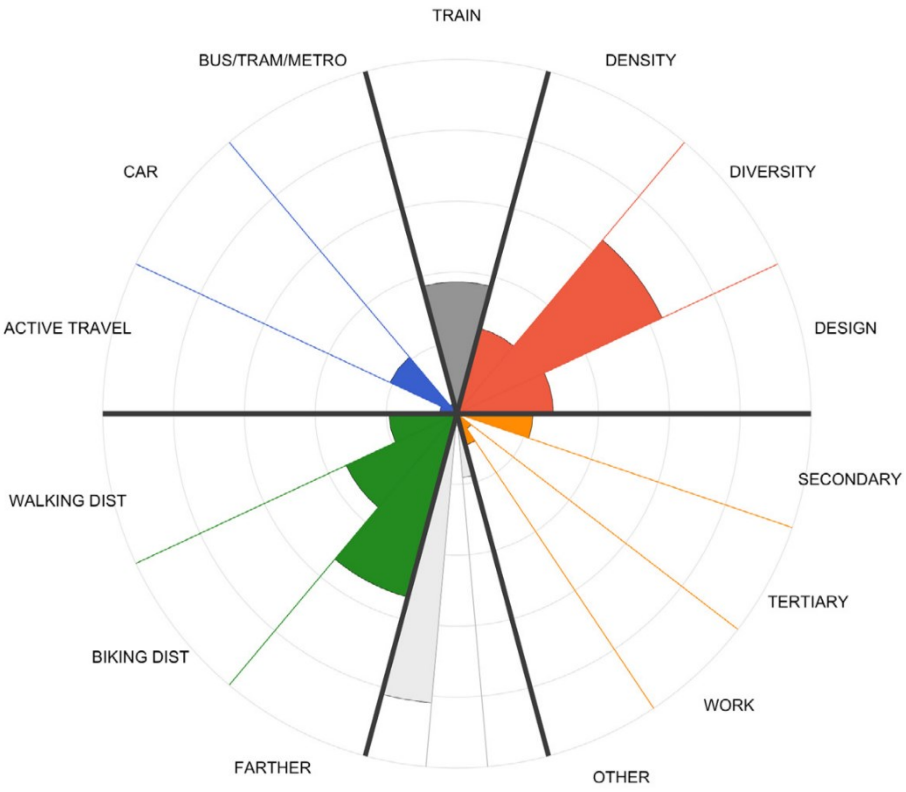


Figure 2.2: *Template for station area assessment using a flower diagram. (Caset et al., 2019)*

Figure 2.3: *Example station accessibility profile from Aalter Station, Belgium. (Caset et al., 2019)*



The advantages of the Node-place conceptual framework include that it offers a strong quantitative indicator for evaluating railway stations in terms of integrating land use and transportation over time (Dou et al., 2021; Reusser et al., 2008). It offers a method for identifying whether the development potential of station areas has been reached (Vale, 2015) and by producing index values for both node and place it allows comparison of different jurisdictions with each other (Ma et al., 2022; Vale, 2015). It also allows a categorisation of stations based on the situations mentioned earlier.

The Node-place framework does involve some limitations. It is unable to predict future developments but can instead only tell us where there is room for improvement in the current situation (Groenendijk et al., 2018). Olaru et al. (2019) note that changes to node and place are not limited to areas immediately surrounding a station, thus they recommend an analysis of stations in their role in the entire transportation network. Vale (2015) expands on this criticism by noting that the five archetypal forms of station areas (the four unbalanced states above, plus the balanced form) fail to capture the diverse implementations of TOD in reality (Su et al., 2021). Chen and Lin (2015) question the validity of the results of node-and-place studies because the indicators selected by researchers could be arbitrary. These potentially-arbitrary indicators may be missing important information, which may be better derived from, for example, interviews with experts (Reusser et al., 2008). Yang et al. (2022) feel that the original model fails to adequately cover the functional and morphological characteristics of station areas. In response to some of the above limitations, scholars have expanded on the original node-place theory, and these expansions will be covered in section 2.2.4.

Indicators of Node

The full extent of the node indicators encountered in the literature can be found in Appendix A. The following indicators featured prominently in the literature.

Frequency of train service may be one of the most important indicators of a successful node. Frequency effectively means freedom—imagine having a garage door at your house that only opened once every 30 minutes. Debrezion Andom (2006) found that frequency, when combined with proximity, was an important determinant in real estate prices, which suggests its value to consumers. Frequency as an indicator is consistent with Allen and Farber's (2020) view of transportation accessibility as a matter of social equity by enabling the participation in daily urban activities.

A related indicator is the service amplitude, or span, of the service offered in a day. A larger service span offers a greater potential to increase ridership is useful because it can accommodate a greater variety of trip purposes (Simmons & Haas, 2016). In particular, Simmons and Haas (2016) examined the routes of nine transit agencies in the western United States and found that routes with increased service span resulted ridership growth of 12.6%, while routes with decreased span saw ridership decrease by 6.1%. Though it is worth noting that routes which added or removed midday service (i.e., service between the morning and evening rush hours) experienced the greatest changes in ridership. This may not be applicable in the Netherlands because all rail services generally operate throughout the day. Caset et al. (2020) found that the span of train service did play a role in their ridership model of morning rush hour services. The span of service also played a large role in particular stations on the periphery of the Belgian railway network. In their examination of rail ridership, Hansson et al. (2022) found the service span and frequency of off-peak service were important indicators of the quality of service provided by regional public transportation. Consistent with Simmons and Haas (2016), a notable finding was that adding off-peak weekday service was correlated with an increase in demand for peak service, based on the hypothesis that additional off-peak departures provides customers with additional security about the timing of their return trips.

A significant part of a station's usefulness is determined by how many destinations can be reached from that station (Debrezion Andom, 2006). An application of the node-place framework to the Flemish railway network showed that transfer centrality (i.e., the number of transfers required to reach all other stations on the network) played an important part in ridership (Caset et al., 2020).

Brons et al. (2009) found that improving the quality of bicycle parking facilities at a station (by replacing unguarded bicycle parking facilities with guarded ones) or improving the car parking situation by designating car parks as Park & Ride was not likely to increase rail use at that station. They also found that increasing the frequency of connecting transit services (i.e., bus service) was more effective than reducing the travel time to the station. This is consistent with the theory that travel time budgets remain constant (Van Wee et al., 2013). For this reason, cycle and car parking capacities at stations was not selected for this research.

Indicators of Place

A survey of American transportation planning professionals who work with TOD found that the quality of the built environment along with the walkability of an area were just as important to the success of TOD as transit ridership (Renne et al., 2005). This fits with the pursuit of balance between node and place indicators by other scholars. The full extent of the place indicators encountered in the literature can be found in Appendix B.

The walkability of an area is a key component to a successful station area and ridership (Ryan & Frank, 2009). This can be measured in multiple ways, and three have come to the forefront of research and practice: catchments, network integration and permeability (Dovey et al., 2018). *Catchments* may use an “interface catchment” calculation, which measures the amount of public/private interface (Dovey et al., 2018) by totalling the length of all walkable street segments (representing the public part) that are also flanked by buildings (representing the private portion) (Caset et al., 2020). *Permeability* involves the extent to which the urban environment is permeated with public space. I.e., the degree to which publicly accessible walkways split urban blocks. It is a useful attribute as it reflects ease of movement within a station area and offers multiple route choices between any two points (Dovey et al., 2018). Another measurement of walkability involves tabulating the total length of walkable streets within a station area (Caset et al., 2020).

Guzman and Gomez Cardona (2021) studied the Transmilenio bus rapid transit system in Bogotá, Colombia and found a direct and synergistic relationship between job and population density and public transportation ridership. For this reason, they argue that transport planning should be integrated with land use. In Los Angeles, Kim et al. (2016) found the opposite—that *job density* itself does not contribute to ridership, but land uses related to jobs (such as office or retail space) *did* contribute positively to ridership. They offer an explanation for this by pointing out that public transportation ridership is generated both by visiting customers, as well as by employees. LeRoy (2011) examines this question from the reverse angle, arguing that urban density and the provision of public transportation bring with them more jobs. Mattson (2020) was more direct, and found that population density was positively associated with ridership with an estimated elasticity of 0.09. (Thus, if density increased 10%, it would be associated with a 0.9% increase in ridership.) Aston et al. (2021) found a similar elasticity at 0.10. This was also true for US Census block group (a geographical unit consisting of about 300 - 6,000 people)—the greater the block group’s population density, the more likely it was to have at least one person commuting by public transport, when all other factors are equal. An important caveat to these findings was that a balance between jobs and residential population was a negative influence on ridership (Kim et al., 2016). This is because locating workplaces near homes requires less commuting from employees. This situation can be applied to a transit system’s advantage to reduce unbalanced peak demand and relieve overcrowding (Guzman & Gomez Cardona, 2021).

The diversity of land uses in the built environment around station areas has also been shown to have a positive impact on transit ridership (Kim et al., 2016). Aston et al. (2021) did a meta-analysis of post-2010 studies on the impacts which the built environment has on ridership and found that land use mix had a positive association with ridership. A diverse land use mix also affects other factors affecting spatial quality, such as enhancing walkability (Mavoa et al., 2018) and reducing energy consumption for transportation (M. Zhang & Zhao, 2017).

2.2.3 Accessibility

Accessibility represents a way of characterising the choices the offered to travellers by the built environment (Handy, 2020). Walter Hansen was one of the first to define (1959) accessibility in the land use and transportation sense as “*potential* for opportunities for interaction” (Hansen, 1959, p. 73), emphasising the “intensity of the possibility of interaction” over the ease of interaction and. “It tells us something about the choices that the built environment offers to travellers” (Handy, 2018, p. 2). Lewis Mumford focused on this idea in a series of essays in the *New Yorker* magazine in the 1950s (Handy, 2020). Geurs and van Wee

(2004) distinguish *access* from *accessibility* by stating that access refers to the traveller's perspective, whereas accessibility refers to the perspective of the location. This leads them to define accessibility as "the extent to which land-use and transport systems enable (groups of) individuals to reach activities or destinations by means of a combination of) transport mode(s)." (Geurs & van Wee, 2004, p. 128)

Accessibility has an effect on customer satisfaction of riders of public transportation. Pawlasová (2015) surveyed customer satisfaction in a survey of public transportation customers in Ostrava, Czechia. It was found that what they referred to as "station proximity" was found to be a key indicator of customer satisfaction. But they defined "station proximity" more broadly as "The public transport stations are accessible without any problem." (Pawlasová, 2015, p. 25) The other determinants of customer satisfaction were related to node values, specifically service frequency and service continuity.

Susan Handy (2020, 2018) has been an ongoing proponent of utilising accessibility as a measure, both in research and practice, saying it remains the most useful framework for analysing the built environment because the ease of accessing what they need is what the public truly cares about. She cites the German phrase "*ein Stadt de kürzen wegen*", meaning "a city of short distances" as an ambition on which everyone can agree (Handy, 2018). This fits with the utilitarian view of travel demand expressed in section 2.1. Brons et al. (2009) confirmed the importance of the accessibility of a rail station through a survey of customer satisfaction and the importance of various attributes of the railway journey in the Netherlands by finding that an increase in accessibility is likely to lead to an increase in rail use. This was especially true when taking into account the costs involved.

Poor levels of accessibility bring with it the risk of social exclusion (i.e., being unable to participate in desired activities) (Allen & Farber, 2020), which may have a negative impact on people's subjective quality of life (De Vos, 2022). Allen & Farber (2020) found a positive relationship between the accessibility of transit and participation of activities outside of the home. More specifically, they found that improving the accessibility of transit, by adjusting components of node or place led to increased activity participation amongst socioeconomically deprived communities. One way of demonstrating that such improved access is truly making a difference is by measuring ridership directly.

But, despite its long history, an accessibility-based approach does not dominate transportation and land use planning with only 55% of planning practitioners stating that they used such metrics in their work. (Boisjoly & El-Geneidy, 2017; Handy, 2020). Relying on accessibility as a measure does bring with it some disadvantages. One is the lack of a uniform definition, which often results in it being confused with mobility (De Vos, 2022), even though good mobility represents only one way of bringing about good accessibility (Handy, 2020). Standardised measures would be useful to ensure that everyone is talking about the same thing. Another challenge relates to the measurement of accessibility, which makes it difficult to implement in practice when compared to mobility (Handy, 2020). Unlike accessibility measures, mobility measures, such as level-of-service for vehicular traffic are common and well established in planning practice with official guidance available to practitioners. In a survey of planning practitioners, most responded that the use of accessibility metrics came from their own initiative and that such metrics were not present before their arrival (Boisjoly

& El-Geneidy, 2017). Those measures which are easy to understand and calculate lack a deeper theoretical foundation, but those which have such a foundation are difficult to understand and communicate (De Vos, 2022). Accessibility may also be confused with the related concept of universal accessibility for disabled people (Handy, 2020). A final challenge is attracting the interest of policy makers as they often receive complaints from the public about congestion (i.e., poor mobility) and not so much about a lack of accessibility.

2.2.4 Expansions on Node-place framework

Several researchers have expanded on the Node-place framework because its two axes fail to sufficiently capture the performance of station areas (Yang et al., 2022). Table 2.1 offers an overview of these expansions from the literature.

***Table 2.1:** Summary of the indicators added to the base node-place model.*

Indicator Added	Description	Author(s)
Design index	Urban design elements which contribute to the pedestrian experience of the station itself.	Vale (2015); Vale et al. (2018)
System support	Importance of the station in the overall transportation network.	Ma et al. (2022)
Experience	Passenger comfort, ambient elements, and social safety.	Groenendijk et al. (2018); Du et al. (2021)
Oriented	To what degree are transit and development components of TOD oriented toward each other.	Lyu et al. (2016)
Criticality	A centrality analysis of the network.	Zhang et al. (2019)
Ridership	How node and place affect ridership.	Cao et al. (2020)
Network	The network indicators examine centrality, i.e., the degree of connection of nodes.	Dou et al. (2021)
Link	Link-place framework categorises streets.	Jones et al. (2008)
Proximity to CBD	Proximity to Central Business District (added as node indicator.)	Chorus and Bertolini (2011)
Background Traffic	Various indicators of road traffic within the station area.	Babb et al. (2016); Olaru et al. (2019)
Accessibility Index	Index showing how easy it is to access a station.	Cummings and Mahmassani (2022)
Accessibility Profile	Station-specific accessibility characteristics.	Caset et al. (2019)
Compactness	Local building morphology and design.	Yang et al. (2022)
Urban Vibrancy	Daily outflows and inflows from the station, plus night time activity.	Yang et al. (2022)
Functionality	How residents walk and ride in station areas.	Su et al. (2021)

Jones et al. (2008) proposed a new link-place framework, which focuses on the dual nature of streets as both a link, acting as a conduit providing through movement and as a place where activities occur (a destination in its own right.) This framework categorises streets in a five-by-five matrix, with link status levels on the y-axis and place status levels on the x-axis. This particular framework is deeply concerned with the quality of street design, though declares itself not anti-private vehicle because it also recognises the needs of those who use the street as a link (Jones & Boujenko, 2009). The intent of this framework is similar to that of the node-place framework in that it offers the opportunity for a shared dialogue between professionals.

The node-place model does not take the rail passenger's experience into account. The portion of the journey with the greatest disutility is the process of transferring between services, which occurs within the transit node. Station areas exhibit characteristics of both a node and an urban place with economic development (Du et al., 2021). That is why Groenendijk et al. (2018) used a process of Best Worst Method, which is a form of multi-criteria decision making to develop the node-place-experience model. Under this model, the design characteristics of the station environment are considered (Dammers et al., 2005). The station elements of comfort (e.g., a comfortable waiting room), ambient qualities (e.g., architecture) and presence of personnel for social safety were assigned a weight through a passenger survey. Du et al. (2021) considered such elements through an importance vs. satisfaction analysis of a passenger survey at Amsterdam Central station and found that customers were generally satisfied with the station's place quality but disliked the square outside. Women in particular found social safety in the station area important but dissatisfactory. These elements have mostly to do with the station environment at the node itself, and thus the main application of this framework is indicating in which stations passenger amenities should be improved. The largest caveat with the node-place-experience model is that the value of each criterion will vary across cultures, thus local research is needed.

The node-place-system support model adds a link with the overall urban transportation system in the form of system support (Ma et al., 2022). This is intended to describe the significance of the station in the overall transportation system instead of the local area using the traditional node-place model. They measured this by considering the "betweenness" of the station (i.e. the number of shortest paths through the node) and the closeness centrality (an index which reflects how easy it is to reach a node) (Cao et al., 2020). They also considered whether the land surrounding the station was considered a "core" plot of land in the city (Ma et al., 2022). These measures of centrality are similar to those added by Cao et al. (2020) to the node-place model.

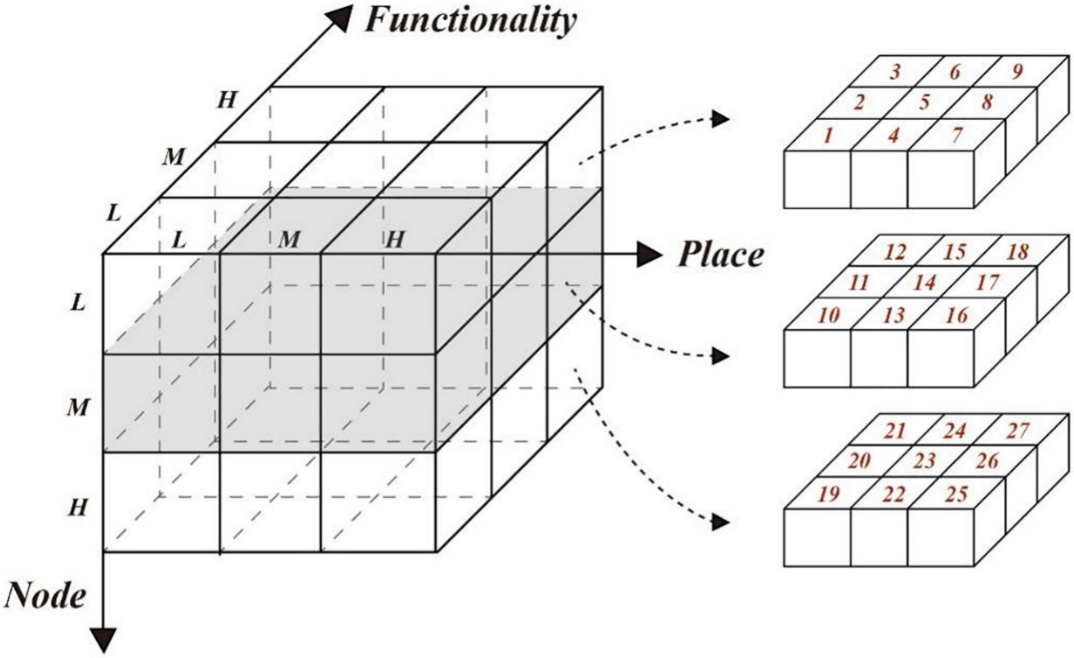
Olaru et al. (2019) note that some node indicators may present conflicting roles in the station environment. They offer the example of providing park and ride facilities may increase ridership from people driving to the station, but it conflicts with a built environment that is conducive to walking and cycling. This is why they added a background (non-station) traffic indicator to measure the interaction between road traffic and node values (i.e., the impact of railway station activity on the surrounding road network.) They examined this effect by considering the classification of the road in front of the station (e.g., primary distributor or collector), the interaction between park and ride facilities, bus services and local roads. They also considered traditional congestion evaluation measures such as level of service at key intersections.

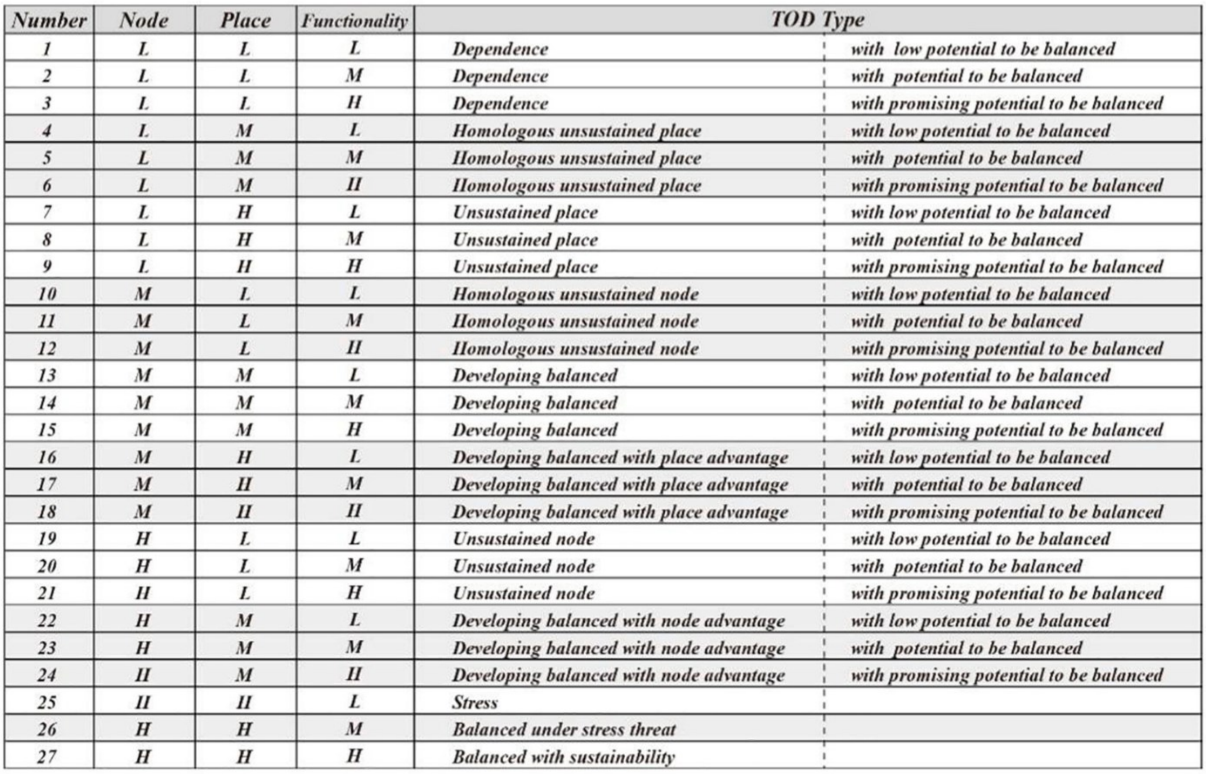
Urban vibrancy, defined as the intensity of human interactions, is important to a city because it encourages engagement in activities and human contact (Yang et al., 2022). Yang et al.

(2022) measured this by examining the number of trips from the entire city to and from the station, plus considered trips at night. They also consider the design and morphology of the area surrounding the station through a “compactness” indicator, though I question the measures they use. For example, they evaluate the morphology of an area by examining the average floor space of local buildings in square metres and their heights. A suburban big box store and a block of flats may have the similar floor space, but their morphologies and design languages are entirely different. Similarly, a six-storey car parking garage and a cathedral may have similar heights but offer entirely different experiences of the spatial environment.

Accessibility and walkability are incorporated into a new dimension to the node-place model, that of *functionality* (Su et al., 2021). This presents a 3-dimensional graph in figure 2.4, where the added z-axis (functionality) shows the *potential* for the node and place indicators to be balanced. This functionality considers ordinary walkability measures, such as intersection density and walk score, but also “accessibility” indicators, which they operationalise as distance from various points to metro stations and bus stops. While the 3-dimensional model is indeed unique, it remains unclear why indicators like distance to a metro station are determinative of whether or not node and place can be balanced. For example, if a place has a high node value and low place value (an unsustained node, such as cube numbers 19-21 in figure 2.4), it is not clear why reducing the distance to metro stations would achieve balance, because the cause of the misbalance is place values, not node values.

Figure 2.4: *The node-functionality-place model, which considers the possibility of balancing node and place values. (Su et al., 2021)*





Number	Node	Place	Functionality	TOD Type	
1	L	L	L	Dependence	with low potential to be balanced
2	L	L	M	Dependence	with potential to be balanced
3	L	L	H	Dependence	with promising potential to be balanced
4	L	M	L	Homologous unsustained place	with low potential to be balanced
5	L	M	M	Homologous unsustained place	with potential to be balanced
6	L	M	H	Homologous unsustained place	with promising potential to be balanced
7	L	H	L	Unsustained place	with low potential to be balanced
8	L	H	M	Unsustained place	with potential to be balanced
9	L	H	H	Unsustained place	with promising potential to be balanced
10	M	L	L	Homologous unsustained node	with low potential to be balanced
11	M	L	M	Homologous unsustained node	with potential to be balanced
12	M	L	H	Homologous unsustained node	with promising potential to be balanced
13	M	M	L	Developing balanced	with low potential to be balanced
14	M	M	M	Developing balanced	with potential to be balanced
15	M	M	H	Developing balanced	with promising potential to be balanced
16	M	H	L	Developing balanced with place advantage	with low potential to be balanced
17	M	H	M	Developing balanced with place advantage	with potential to be balanced
18	M	H	H	Developing balanced with place advantage	with promising potential to be balanced
19	H	L	L	Unsustained node	with low potential to be balanced
20	H	L	M	Unsustained node	with potential to be balanced
21	H	L	H	Unsustained node	with promising potential to be balanced
22	H	M	L	Developing balanced with node advantage	with low potential to be balanced
23	H	M	M	Developing balanced with node advantage	with potential to be balanced
24	H	M	H	Developing balanced with node advantage	with promising potential to be balanced
25	H	H	L	Stress	
26	H	H	M	Balanced under stress threat	
27	H	H	H	Balanced with sustainability	

2.2.5 Transit-Oriented Development vs. Transit-Adjacent Development

Perhaps the most popular application of frameworks concerning the use of land surrounding rapid transit stations is Transit-Oriented Development (TOD.) First discussed by Peter Calthorpe in the late 1980s and later defined in The New American Metropolis as (Carlton, 2009), it lacks a universal definition, but Calthorpe saw it as a mixed use community that encourages people to live near, and use, transit (1993). TOD usually focuses on maximising the quality of the five Ds mentioned earlier, which, from the perspective of the built environment, results in the area adjacent to stations being hospitable to pedestrians (Dorsey, 2016). TOD has three objectives: trip degeneration (i.e., reduce the number and length of motor vehicle trips), increase the share of remaining that are conducted without motor vehicles, and of the remaining motor vehicle trips, increase vehicle occupancy levels (e.g., by encouraging more trips via public transit.) (Cervero & Kockelman, 1997)

Benefits of TOD include increased ridership and transit system revenue (both from ridership and from the sale of transit system assets), revitalisation of marginal neighbourhoods, additional affordable housing and increased foot traffic for local businesses (Transportation Research Board, 2004). By mixing land uses, TOD aims to reduce vehicle kilometres travelled (VKT), which will result in a reduced environmental footprint. Green TOD (Cervero & Sullivan, 2011) or 'TOD-Plus' (Babb et al., 2016) is designed to take this further and capture the synergy of TOD and green urbanism by combining TOD with improved building designs and resource management systems. For example, reduced surface parking will reduce the heat island effect.

TOD does face some barriers in its implementation (Transportation Research Board, 2004). In addition to fiscal barriers and institutional barriers (such as exclusionary zoning, coordination difficulty amongst competing interests, and "not-in-my-backyard" opposition to higher density.) These include what is called the "congestion conundrum" where the improved nodal quality (i.e., better transportation service) results in congestion at that spot. This suggests a mismatch in the balance between node and place factors—in this case the area is seen to be under stress because of conflicting land uses (Vale, 2015). Another dilemma of TOD implementation involves providing for access between modes, particularly accommodating automobile access to station areas. Accommodating automobile access through large amounts of road space and parking can compromise the "place" qualities of an area, such as walkability. Li et al. (2019) point out a lack of literature in non-Western countries, and suggests qualitative studies in non-Western countries.

Similar to TOD, TAD (Transit-Adjacent Development) refers to an area within walking distance to a transit station. However, in contrast with TOD, TAD suffers from what are effectively low place values, and incompatibility with the five Ds mentioned earlier, particularly the diversity of land uses, design of the street grid and an unnecessarily great distance to transit (i.e., problems with problems with station access and site design.) Renne (2009) offers a spectrum between TOD-favouring land uses and street design (mixed use and walkable) to TAD-favouring (segregated land uses with suburban street pattern.) It is also possible that a station features a high node-place balance (and a dense area) but the distribution of such densities may not gravitate towards the station itself, thus the development merely being "adjacent to" transit (Lyu et al., 2016). Hale (2014) believes that a TOD ought to achieve at least 50% modal share by sustainable transport to be granted the designation, otherwise it being mere TAD.

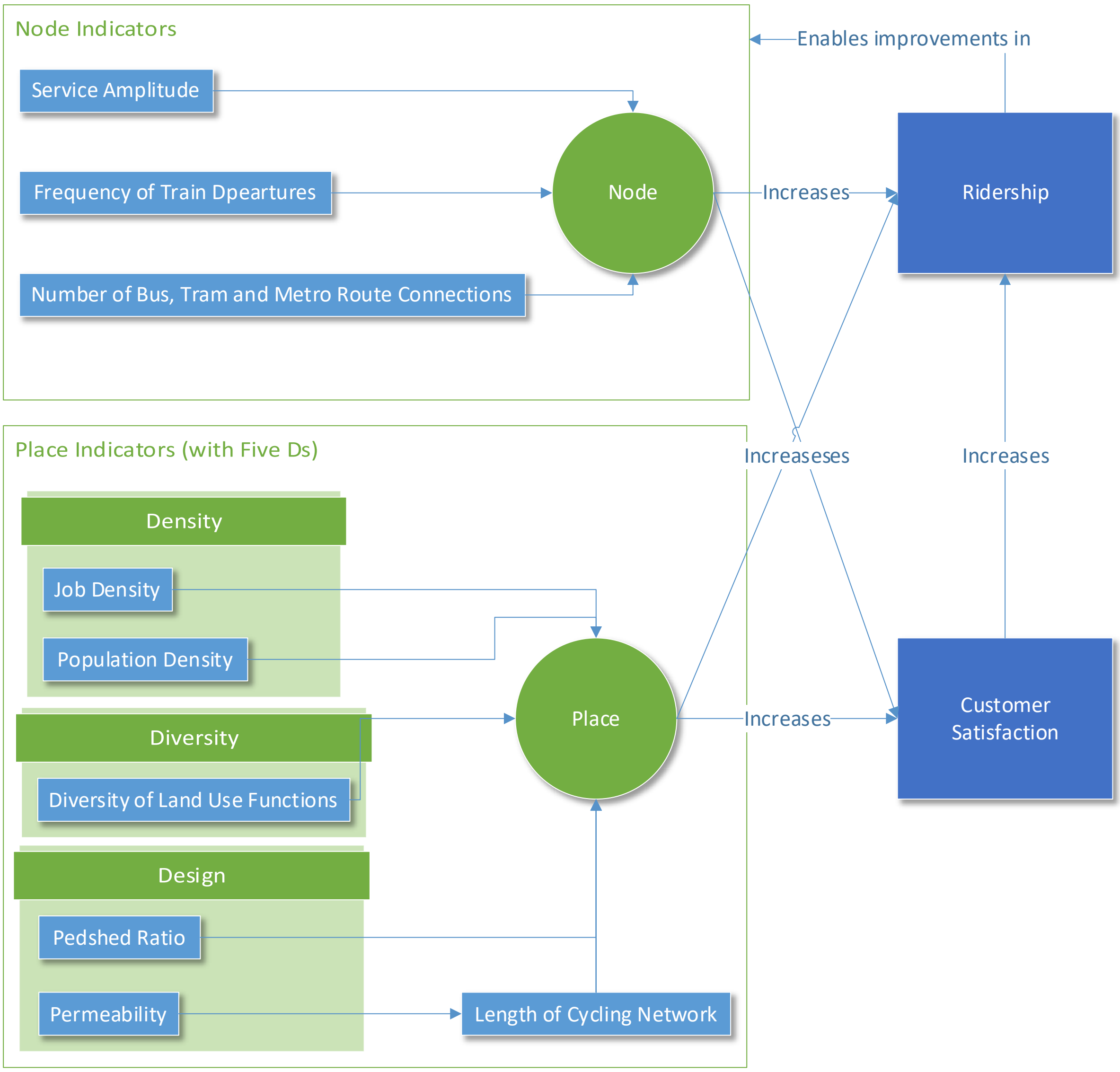
Vale (2015) considers this TAD phenomenon by combining node and place with an evaluation of pedestrian connectivity (particularly the pedestrian shed ratio) of a station. Three different aspects are evaluated: land use, transportation conditions and local walkability. Lyu et al. (2016) expand on Vale's work by adding a examining the "oriented" dimension of a station area, which reflects the degree to which the "transit" and "development" aspects of TOD are actually oriented towards each other. Li et al. (2019) synthesise these two works by categorising TOD implementations by node, place, and a third dimension, “tie,” which incorporates the “orientation” of the area in terms of whether its nodal properties are really in synch with its place ones, thus making it TOD as opposed to TOD. The distinction being that TOD feeds back into the land-use transport feedback cycle discussed earlier. This results in eight TOD classifications.

2.3 Conceptual Model and Hypothesis

The hypothesis of this research is that station areas which feature higher node and place indicator values will have higher customer satisfaction scores. This higher level of customer satisfaction will lead to increased ridership. This increased ridership will also enable (by providing both the economic and political space) to improve node indicator values. It is worth noting that the improvement of node values may be undesirable in areas under stress (as illustrated in the top-right corner of figure 2.1.)

Consistent with that, it is also hypothesised that station areas which reflect the qualities of the five Ds framework mentioned earlier will also feature higher ridership and customer satisfaction scores. In this conceptual model (figure 2.5), the node and place indicators both act to increase ridership and customer satisfaction. Some of the place indicators fall under the five Ds framework, but only the density, diversity and design components.

Figure 2.5: *Conceptual model of this research*



3 Methodology

This chapter elaborates on the epistemological approach to this research. It then examines the quantitative approach used in this research, the indicators to be considered, the selection of railway stations to be sampled, the selection and collection of geospatial data and its analysis through a process of multivariate Ordinary Least Squares regression.

3.1 Research Approach

Overall, this research uses a mix of methods as its approach by combining a review of the academic literature (to build a background of the theories and indicators which are most suitable for operationalisation of the node-place framework) with quantitative geographical analysis.

As stated earlier, the aim of this research is to consider the possible relationships between variables, particularly those included within the node-place framework, such as land use diversity, and ridership. Quantitative research in general offers an approach for testing objective theories (such as the node-place framework) by examining the relationships between variables (Creswell, 2014), which is suitable for this research.

A subset of quantitative research, quantitative geography, involves the analysis of numerical spatial data for the purpose of adding to our understanding of spatial processes (Fotheringham et al., 2007), with an objective of delivering a maximum of knowledge about spatial processes with a minimum of error. These techniques are most often used because of a belief that quantitative data analysis and theoretical reasoning provide an efficient and reliable way of exploring spatial processes (Fotheringham et al., 2007, p. 6). Additionally, since inference is a key part of any quantitative study (Fotheringham et al., 2007), a classical inferential statistical approach will be used in this study. The statistical methods in this research were executed based on the output of the GIS analysis. These methods include linear regression with a check for collinearity.

Quantitative geographical methods offer four main advantages (Fotheringham et al., 2007):

- Large datasets can be reduced to smaller and more meaningful information.
- Visualising data through *exploratory data analysis* allows easier recognition of errors.
- Statistical tests allow the examination of the role of randomness in generating spatial patterns.
- Mathematical models of spatial processes allow predictions to be made.

In their survey of the literature which attempts to explain transit ridership, Taylor and Fink (2013) propose a taxonomy of two categories of studies: research that focuses on attitudes and perceptions of operators or travellers (“descriptive analyses”), and research that seeks to develop explanatory models by examining the environmental, system and behavioural characteristics (what they term “causal analyses”.) In examining characteristics of the built environment, this research falls into the latter category. Though statistical methods in general do carry some limitations, particular caution should be exercised when attempting to understand causal relationships between any two phenomena. It may be difficult to prove that one phenomenon causes another phenomenon because there might be multiple causes or explanations for the observed outcome (Harris, 2016).

Within the "causal analysis" category they define aggregate studies, which use geographic area data as explanatory variables; and disaggregate studies, which focus on the mode chose of individual travellers. In focusing on the geographic area surrounding stations, this research is an aggregate study under their taxonomy.

Descriptive analyses have the advantage of using rich qualitative data which allows for the identification of common factors affecting ridership (Taylor & Fink, 2013). They suffer from two disadvantages in the areas of methodology and interpretation. The methodology can be problematic because the data collection process tends to be vague regarding the methods used. In terms of interpretation, the data can be highly subjective because it is often dependent on the respondents' perceptions.

The analyses of transit ridership (like this one) which Taylor and Fink (2013) would classify in their typology as "causal analyses" analyse a wider array of data than most descriptive analyses, which makes them more sophisticated empirically. A limitation of causal analyses is the lack of consistency in the variables operationalised across studies. Consider the heterogeneity of the indicators found in the literature in appendices 1, 2 and 3 as an example of this phenomenon.

Taylor and Fink (2013) point out one further relevant limitation; the loss of some information can occur due to the effects of geographical aggregation over a large area. This is because indicators such as building density, service frequency, etc. can vary over a transit agency's service area. This research does not suffer from this limitation because its geographical scale of focus is at the station area. However, they also argue that analysis should be disaggregated to the individual trip level, and then re-aggregated to draw conclusions. This level of detail is not practicable in this research.

3.2 Data Collection

3.2.1 Station Classification and Selection

The geographic scope of this research is the European portion of the Netherlands as a whole. Thus any references to "the Netherlands" in this research refer only to the European portion of the Kingdom of the Netherlands. In the Netherlands there are over 400 passenger rail stations owned and managed by NS Stations, a business unit of Nederland Spoorwegen, the operator of the main passenger rail concession in the Netherlands. (NS, n.d.b). These organisations are separate from ProRail, which is a state-owned company responsible for maintenance of the entire rail network in the Netherlands.

For this research, 50 railway stations were selected, in equal measure, from different categories. (These selected stations and applicable reasons for their selection are listed in full in Appendix E.) Reusser et al. (2008) argues that a taxonomy of railway stations would be a useful addition to the development process for TOD because certain measures may be effective only in certain types of stations and not others. In their research on British rail stations, Crockett and Hounsell (2005) decided that it was necessary to categorise stations because a 'one size fits all' approach would be inappropriate, given the large diversity in size, usage and facilities of Britain's 2,500 stations. Despite the usefulness of a classification system, there is no universally-accepted categorisation method for railway stations in the literature.

Table 3.1 offers a summary of the classification models offered in the literature. In the Dutch context, ProRail designates five categories of stations for purposes of calculating tariffs paid by rail operators (ProRail, 2022). These are, classified by descending order of ridership, Cathedral, mega, plus, basic and stop. Other classification systems in the literature examining the Swiss railway system considered other factors, such as their use primarily by tourists, their isolation from the road network, or the presence of station staff. These factors are not applicable in the Netherlands due to its physical geography.

Table 3.1: *Railway station categorisation schemes used in the literature.*

ProRail (2022) (Netherlands)	Zemp et al. (2011) (Switzerland)	Reusser et al. (2008) (Switzerland)	Stoilova and Nikolova (2016) (Bulgaria)	Caset et al. (2019) (Belgium)	Example Station (from the Netherlands)
Cathedral	C1 "Largest and most central stations"	C5 Large to very large stations	Group 1: The biggest passenger rail station (Sofia)	International Nodes	Amsterdam Centraal
Mega	C2 "Large connectors"	C5 Large to very large stations	Group 3: Within cities with > 100,000 inhabitants	Metropolitan nodes	Amsterdam Sloterdijk
Plus	C3 "Medium commuter feeders"	C3 Mid-size stations and C4 Mid-size, unstaffed stations	Group 5: regional centres	Urban-regional nodes	Ede-Wageningen
Basic	C4 "Small commuter feeders"	C2 Small stations	Group 6b: cities which are municipal centres	Urban-regional nodes	Houten
Stop	C5 "Tiny touristy stations"	C1 Smallest stations	Group 6a: not municipal centres	Rural-regional nodes	Soestdijk
No equivalent in ProRail classification	C6 "Isolated tourism nodes"				
No equivalent in ProRail classification	C7 "Remote destinations"				

ProRail (2022) (Netherlands)	Zemp et al. (2011) (Switzerland)	Reusser et al. (2008) (Switzerland)	Stoilova and Nikolova (2016) (Bulgaria)	Caset et al. (2019) (Belgium)	Example Station (from the Netherlands)
No equivalent in ProRail classification			Group 2: Small junction stations		

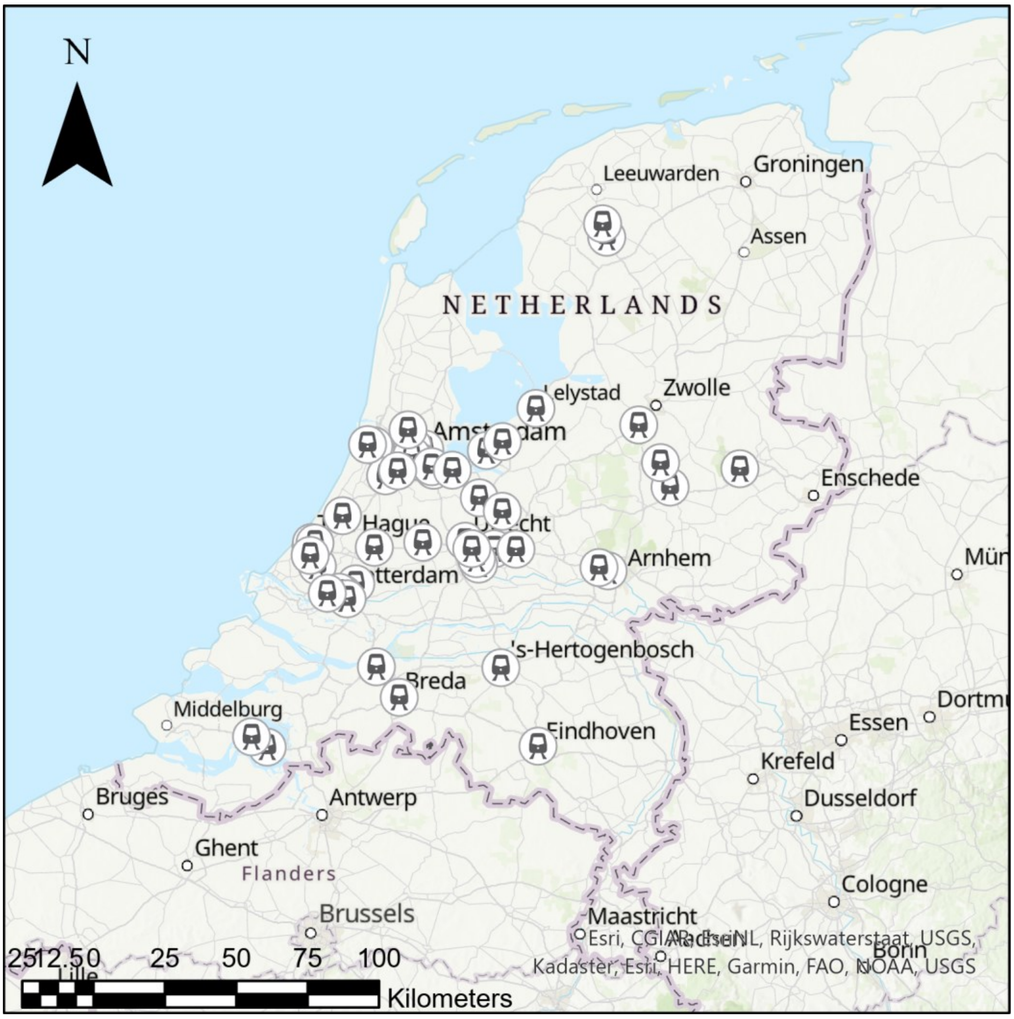
Since this research examined station areas, individual railway stations represent the potential set of cases for closer examination. To select the 50 stations used, an intentional case selection was made using multiple criteria. Consistent with this, Drozdova and Gaubatz (2017, p. 14) argue that an appropriate intentional case selection can offer “significant research leverage.” Though they caution that the intentional selection of cases which confirm the researcher’s prior theory can produce skewed results (for example, by missing cases which refute the theory.) They emphasise that researchers must be transparent about the selection method and its implications.

In terms of the criteria for the station selection, first, ridership and customer satisfaction data were readily available for NS-operated services only (as opposed to services operated by local third-party train operators, such as Arriva and Qbuzz. Thus, only stations which were (almost entirely) operated with NS train services were eligible for section. One implication of this is that regional operators tend to operate less popular routes (and thus stations with lower ridership). Further to that, ten stations were chosen from each of the five ProRail categories listed in table 3.2. Since there are only seven stations in the Netherlands which are classified as ‘cathedral’ stations, these seven were selected along with an additional three ‘mega’ stations.

A third consideration was customer satisfaction scores; included in the 50 stations, three stations which met the other criteria and were amongst the best performing, plus three amongst the poorest performing stations in 2021 and 2022 were selected. Lage Zwaluwe in North Brabant is an example of a station with poor customer satisfaction scores in both years. Interestingly its place values would also be quite lacking in the node-place framework because it lies next to the A16 freeway at some distance (3 km) from the town after which it is named.

This leads into the final consideration when choosing the stations: the intention to offer a contrast between areas which are expected to do well in terms of place values and those which are expected to do poorly. For example, Houten and Houten Castellum were chosen because they were developed intentionally to complement the railway and were expected to perform in terms of permeability. Lage Zwaluwe, on the other hand, was chosen because its street network is non-existent. It is unnecessarily difficult to reach the station from the town of the same name. For each of the 50 stations, Appendix E offers a brief note on why it was selected.

Figure 3.1: *Map of the 50 stations selected for study. The full list can be found in appendix E.*



3.2.2 The Importance of Ridership and its Limitations

This research considers ridership as its dependent variable, and thus as a sign of "success." Professionals in the field agree with its importance. Renne et al. (2005) surveyed thirty American transportation planning professionals and 70% listed number of transit boardings (effectively ridership) as a 'very useful' indicator of the success of TOD. They also considered it easy to collect with 61% listing it as 'very easy' to collect, which suggests that it will be more commonly available, allowing for easier comparisons with other jurisdictions.

Olaru et al. (2019) is more cautious about the sole importance of ridership, arguing that good urban design (even in TODs) may shorten distances between activities, thus enhancing opportunities for active transport, which may not lead to increased transit ridership. Such a scenario could hardly be described as a *failure* of a TOD. It then calls for a balance between ridership and other secondary outcomes of node-place functions, such as creating liveable places with enhanced amenity or good job accessibility. Secondary functions may not translate directly into increased ridership but may still be desirable.

Given its acceptance by industry professionals and its ease of comparison, this research will use average daily ridership as its dependent variable to be examined.

3.2.3 Selection of Node and Place Indicators

This section discusses the node and place indicator values used in this research. Table 3.2 offers a full listing of the nine indicators of node or place values which were selected from the literature. Indicators of node or place are often classified in the literature as a third category, accessibility. These accessibility indicators are listed in full in Appendix C. The literature also features indicators which do not fit into the above three indicators, which are listed in Appendix D. For clarity, in this research they are classified as either node or place. A literature review for specific node and place indicators is available in section 2.2.2.

Given time and resource constraints, it would be impractical and wasteful to gather entirely new geospatial datasets (Harris, 2016). Thus, in geospatial research, datasets often are reused for a purpose other than their original task. This makes the availability of datasets a key consideration in their selection. This lack of availability played a role in the decision to not select some datasets. An example of this is a breakdown of customer satisfaction scores as used by Groenendijk et al. (2018) and Du et al. (2021)—NS Stations does not offer a breakdown of specific customer satisfaction metrics per station, such as perceptions of social safety or cleanliness.

Table 3.2: *Indicators of node and place selected for this research.*

Indicator	How to measure	Units	Source(s)	Type of Indicator
Customer Satisfaction	Survey of customers by NS Stations group.	Score out of 10	Groenendijk et al. (2018); (2021)	Node
Service amplitude	The portion of the day between the first and the last train service at the station	Hours (time)	Caset et al. (2020); Caset et al. (2019)	Node
Frequency of departures	Frequency of scheduled departures on weekdays between 07:00 and 20:00.	Trains per hour	Caset et al. (2020); Bertolini (1999); Brons et al. (2009); Vale (2015); Dou et al. (2021); Chen and Lin (2015); Su et al. (2021); Li et al. (2019)	Node
Number of bus, tram, and metro connections	Number of unique bus, tram, and metro routes to and from the railway station on a Tuesday (stops within 300 m walking from the station are included)	Routes	Caset et al. (2020); Cummings & Mahmassani (2022); Chorus and Bertolini (2011)	Node

Indicator	How to measure	Units	Source(s)	Type of Indicator
Permeability	Total number of street crossings per station area	Street Crossings	Caset et al. (2020); Babb et al. (2016)	Place
Cycling Network	Total length of walkable and bikeable street networks within the station area	Kilometres	Caset et al. (2020); Chen and Lin (2015)	Place
Job Density	The number of workers per each of four economic clusters (retail/hotel and catering, education/health/culture, administration and services, industry and distribution)	Jobs per hectare	Bertolini (1999); Vale (2015); Olaru et al. (2019)	Place
Population Density	People per square mile within a one-mile radius of each station	Ratio	Cummings and Mahmassani (2022); Dou et al. (2021); Olaru et al. (2019)	Place
Land use Diversity /Degree of functional mix	Mixing entropy of land use within 500 m	Ratio	Ma et al. (2022); Kamruzzaman et al. (2014); Bertolini (1999); Reusser et al. (2008); Chorus and Bertolini (2011); Zemp et al. (2011); Li et al. (2019)	Place
Pedshed (pedestrian shed) ratio or walkable catchment	Dividing the area accessible by walking within 1 km using the cycling network by the Euclidean area of a 1 km radial circle	Ratio	Vale (2015); Zhang et al. (2019); Seeger et al. (2018)	Place

3.2.4 Timetable Data

Appendix F contains the full node value dataset which was collected from timetable and line network maps to produce frequency, service amplitude and the number of possible connecting directions by bus, tram, metro and ferry.

A decision was taken to define train service frequency was as the number of train departures per hour, in any direction, in ordinary off-peak service (on weekdays from 07:00 to 20:00.) The use of off-peak data is consistent with the view of Ferguson et al. (2012) that equity concerns mean that public transportation service should be considered for more uses than employment, grocery shopping and medical care. This information was gathered by examining the Spoorkaart line network map showing all passenger train services (and their hourly frequencies) published by NS in 2021 and 2022 (NS, 2021, 2022b).

The service amplitude was applied to mean the amount of time, in hours, between the scheduled departure of the first and last domestic NS train services, in any direction, from that station. Service amplitude varies from day-to-day, with services often starting later on Saturdays, and especially Sundays, and often ending later on Saturday and Sunday mornings. For this research, Tuesday was selected as the day of the week to be measured, following the example from the literature (Caset et al., 2018, 2019, 2020). For stations with services departing 24 hours per day, the same method was applied, with the service amplitude totalling to nearly 24 hours (often 23 and a half hours.) Nearly all NS train stations in the Netherlands receive services from at least six o'clock in the morning through midnight (18 hours). In the sample of 50 stations for this research, the mean span of service was 19 hours and 51 minutes.

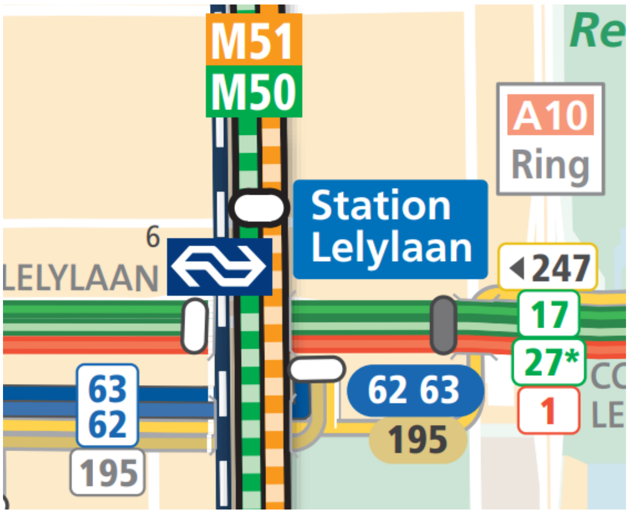
The service amplitude (span of service) data were collected using published timetables from NS in the years 2021 and 2022. Changes to railway timetables across Europe are made at midnight on the second Saturday in December (Directive 2012/34/EU, 2019). Thus, the "2021" NS timetable applied between 13 December 2020 through the end of 11 December 2021. The "2022" NS timetable applied between 12 December 2021 to the end of 10 December 2022.

Another node-related explanatory variable was the number of directions in which it was possible to travel by bus, tram, ferry or metro from the station. This was tabulated in Appendix G. Here I decided to consider each potential direction of travel separately, because each additional direction effectively offers double the opportunities for spatial interaction. Lines which followed each other and terminated at the same or a closer location were deemed redundant and only counted once, similar to the approach taken by Ingvardson and Nielsen (2018).

Figure 3.2 offers an example of the assessment of Amsterdam's Station Lelylaan (Carto Studio & Cartonext, 2022):

- Metro lines M51 and M50 were counted once to the north because they follow the same route and terminate at Isolatorweg. In the southerly direction they were counted as 2 because they terminate at different stations.
- Trams 1 and 17 pass through the station and terminate at different locations, thus counting as 4.
- Tram 27 follows the same path as 17 (terminating earlier), so it was not counted.

Figure 3.2: *GVB line network map showing Amsterdam Lelylaan station with connecting bus, tram and metro routes (Carto Studio & Cartonext, 2022)*



- Bus lines 62, 63 and 195 all terminate at the station, so were counted as one each.
- Bus line 247 only connects with the station in one direction, so it was counted as one.

Connecting route data was gathered from the line network maps offered by the relevant local bus operator for 2021 and 2022. Some more rural stations were gathered using OpenStreetMap data (2023) because the operators do not produce local network maps.

3.2.5 Geospatial Datasets

A full listing of the geospatial datasets which were used is available in Appendix H. To aid reproducibility, a listing of the exact steps taken during the GIS analysis are listed in in Appendix I. Brunsdon (2016) argues in favour of providing precise details of the analysis process for two reasons: aiding a useful academic discourse and because such transparency in methods enables public discussion and debate. This section will reflect on the on noteworthy details of, and decisions made regarding, the geospatial datasets used in this research.

Population Data

The CBS demographic data in the Netherlands is offered as a grid of 100 m^2 squares throughout the country. In areas with no residents, the squares are omitted. An ethical consideration of this geospatial data is that it should not allow the identification of any particular individual. To avoid this, the Dutch statistical agency, CBS, only releases demographic geospatial datasets that are broad enough to not identify any individual household (the threshold they use is five residents per 100 m^2 square.) The Urban and Regional Information Systems Association (URISA) developed a code of ethics (2003), which insists on the projection of individual privacy, particularly when information is discovered through GIS manipulations. Since I did not collect this data myself and this secondary data contains no personal data, the privacy of individual residents is not a relevant issue in this research. To maintain this anonymity, CBS lists the population of those 100 m^2 squares as "-99997" (Centraal Bureau voor de Statistiek, 2022b). Since the presence of a 100 m^2 square indicates that at least one, but fewer five residents live in that square, the mean of 2.5 was chosen.

Employment Location Data

The LISA employment locations geospatial dataset does provide the specific locations of places of employment, including individual entrepreneurs (registered with the national Chamber of Commerce) conducting business out of their homes. It does not, however, include the names of the individuals or businesses at such locations. In this research, such locations were aggregated into the area within one kilometre of the fifty selected railway stations to determine job density, thus making the identification of individual firms impossible. Because the LISA employment locations covers all areas of the country, including residential areas, this research's method for calculating job density differs from Kamruzzama et al. (2014) in that they divide the number of jobs by the area of *employment-generating* land uses only (thus excluding residential areas.) By contrast, this research divides job density by the area reachable within 1 km of the stations.

The Network Dataset

It is helpful to clarify what exactly is meant by the “cycling network” around a railway station. In this research, it is taken to mean the roads, paths and cycleways on which it is reasonably possible and lawful to cycle, and not to refer exclusively to infrastructure dedicated to cycling, or to designated cycle routes, such as the *Knooppuntennetwerk* of recreational cycling routes in the Netherlands, Belgium and small portions of Germany. This “cycling network” was chosen to represent the pedestrian network because pedestrians are often allowed on routes where cycling is permitted, or at least very close by. Additionally, when creating the network dataset, I assumed that all links which cross each other actually intersect (i.e., height differences were ignored) because such obstructions are less applicable to pedestrians and cyclists than to motorists. (E.g., where roadway bridge where walking and cycling is allowed crosses another roadway, a connection between the two is usually provided nearby.)

The underlying roadway data was obtained using the OpenStreetMap project, which is a worldwide voluntary geographic information (VGI) database with data contributed by users and the largest of its kind (Klinkhardt et al., 2021). A general advantage of using OSM data is that it provides a single, global source of up-to-date data, leading to Ferster et al. (2020) recommending its use by researchers. OSM provides a worldwide homogeneous tagging structure, which allows international comparison, interoperability and aids future reuse (Hochmair et al., 2013). In contrast, data provided by local agencies present a variety of classification and attribute schemes, hindering interoperability. Ferster et al. (2020) conducted an evaluation of OSM data by comparing it with that from official (usually municipal) sources for various Canadian cities. They generally found high levels of concordance in the length of cycling infrastructure, between official data sources and OSM data, with differences ranging from as low as ±2% to as much as ±30%. On-street bicycle lanes were particularly well represented with newer cycle tracks being less so. Hochmair et al. (2013) similarly compared OSM data of bicycle lanes and dedicate paths with the Google Maps bicycling layer and found OSM quality to be high.

Ferster et al. (2020) did find labelling problems, which are common in citizen participatory mapping. This was particularly true in more obscure types of cycling infrastructure. To correct this, they suggest further effort be expended to develop a uniform international definition of cycling infrastructure types, which is easy for users to identify and apply (Ferster et al., 2020).

It is unlikely that a lack of concordance would affect this research because it utilises the cycling and road networks as a combined network dataset (removing obviously incompatible items as described below), and it is extremely likely that the connections can still be made, thus affecting the extent of the station service catchment area polygons very little, if at all.

To reduce the chance of inappropriate paths being included in the network dataset, the following classifications of roadways were excluded from the network dataset:

- Motorways and their links
- Trunk roads and their links
- Primary roads and their links
- Bridle paths (because they are often unpaved)

- Service roads. These were excluded because they too often provided misleading connections through inaccessible, privately-owned land and were often redundant to nearby connections. Their presence would also unduly distort the length of the local cycling network by including the length of individual rows of car parking lots.

3.2.6 Time Period

The time period covered in this research is the years 2021 and 2022. The average weekday ridership and customer satisfaction scores for the fifty stations were provided by NS is from those years (NS, n.d.a). The *Werkgelegenheidsregister* (LISA) dataset of all locations of paid employment in the Netherlands was the latest available version of 2021. In keeping with that, timetable data from those periods was compared. Additionally, the network dataset for the network analysis in ArcGIS Pro was generated using an OpenStreetMap dataset from 2021. Data from 2021 was intentionally chosen to best reflect the effect of the built environment on pedestrian movements during the period of study. A contemporary street network dataset might have been expanded since the ridership and customer satisfaction figures were gathered. CBS population data from 2021 was also intentionally selected for similar reasons.

The Covid-19 pandemic had a severe effect on ridership. In 2021, ridership of NS services was only 48% of pre-pandemic levels (NS, 2022a). This can be partly explained by a nationwide curfew in place from the beginning of the year through to the end of April, with work-from-home orders in place on-and-off throughout the year. In 2022, weekend ridership had returned to pre-pandemic levels, but only 75% of pre-pandemic ridership had returned on working days (NS, 2023).

3.3 GIS Analysis Process

Table 3.3 provides an overview of the steps which were taken to analyse the indicators of node and place. Given the spatial nature of the data sought, the analysis was conducted using Geographic Information System (GIS) software and geospatial datasets, specifically ESRI ArcGIS Pro 3.0.0 with the following general choices made during the analysis:

- The software's Model Builder feature was used to operationalise the analysis workflow, and was then executed for each indicator.
- ArcGIS offers some of its tools in pairwise and classic versions. The biggest difference is normally that pairwise tools are more efficient because they use multi-threading to distribute the workload over multiple logical processors (Esri, 2022a), but they can lead to a different output, as is the case with Pairwise Intersect (Esri, 2022c).
- Most Dutch geospatial datasets are use the Amersfoort/RD New (*Rijksdriehoek* or State Triangular) **projected coordinate system** (PCS) (EPSG code 28992), which is based on 5,600 points installed across the Netherlands (Het Kadaster, 2020) and thus that is the coordinate system chosen for this research. A PCS instructs the system on how to render geodata on a flat surface (such as a computer screen) (Smith, 2020).
- By contrast, **a geographic coordinate system** (GCS) is a round (spheroid) system which indicates where spatial data is located on the earth's surface (Smith, 2020). Similar to the above, this research uses the Amersfoort GCS (EPSG code 4289.)
- The Service Area Analysis Solver tool was used to generate polygons representing the area reachable from the stations at a 1 km distance (representing walking distance) and a 2.5 km distance (representing cycling distance.) This tool is similar to an Euclidian

radius (using an ordinary Buffer), but it represents the maximum distance that can be travelled using the network dataset (Esri, 2022d).

- Kim et al. (2016) argues for the importance of choosing a proper transit catchment area reflecting the job and population density characteristics surrounding each station. Since this research analyses 50 stations, this was not feasible. Instead a 1 km distance was selected based on guidance from Transport for London (Transport for London, 2015; Y. Zhang et al., 2019), representing a 12-minute walk from the railway station. It was suggested that 400 m was too small of a radius to properly capture the complete influence of the built environment (Kim et al., 2016). Other transit catchment area values used in the literature include 700 m (Vale, 2015; Vale et al., 2018), 800 m (Kim et al., 2016) and 1,200 m (15-minutes) (Caset et al., 2020). Stations in close proximity with catchment areas which overlap were split into separate polygons so that there was no overlap. (An example of this is shown in figure 4.2 with Houten and Houten Castellum.)
- When reviewing cycling trips which connected with the metro in Shenzhen, China, Wu et al. (2019) found that 95% of such trips fell within a distance of 2.5 km, representing up to a 12-minute cycle trip for a casual rider. Thus, this cut-off was selected for this research.

Table 3.3: *List of analysis steps taken.*

Indicator	Type of Indicator	Analysis Process
Service amplitude	Node	Examine timetable data to calculate the length of time between the first and last train departures of the day scheduled for Tuesdays in during the 2021 and 2022 NS timetables.
Frequency of departures	Node	Choose one hour and examine the GTFS timetable data to calculate the number of train departures in any direction, per hour.
Number of bus, tram, and metro connections	Node	Examine OpenStreetMap data or the regional network maps to count the number of possible bus, tram, and metro connections at a stop.
Permeability	Place	Within a 1 km radius from the station, count the number of intersections.
Cycling network	Place	Add up the distance of the cycling network within a 1 km radius of the station.
Job density	Place	Within a 1 km radius from the station, count the number of jobs, then divide by the area. Specifically, the LISA *Werkgelegenheidsregister* dataset of all locations in the Netherlands where paid work is performed, including in non-employment areas such as . (Stichting LISA, n.d.)
Population density	Place	Within a 1 km radius from the station, find the population using cadastral data. Specifically, the *Basisregistratie Adressen en Gebouwen* dataset of address registrations.

Indicator	Type of Indicator	Analysis Process
Land use diversity /degree of functional mix	Place	Calculate Simpson's Diversity Index (Kamruzzaman et al., 2014)
Pedshed (pedestrian shed) ratio	Place	Dividing the area accessible by walking within 1 km using the cycling network by the Euclidean area of a 1 km radial circle

The results of this analysis can be found in Appendix J.

3.4 Regression Analysis Process

Causal analyses of ridership most often use regression analysis (Taylor & Fink, 2013) and that was similarly selected for this research. The data input for the regression process is listed in appendices E (place values) and I (node values.) For each of the independent variables (ridership and customer satisfaction score), a process of Ordinary Least Squares (OLS) regression was executed four times using two years of data: 2021 and 2022. For each of the two years, it was again executed using a 1 km and 2.5 km radius from the stations. As no convincing weighting scheme could be found, the indicators were each given equal weight. Different node indicator data was collected for both years, while the same place value indicator data was used for both years. This resulted in eight data configurations:

- Ridership:
    - A 1 km radius in 2021
    - A 1 km radius in 2022
    - A 2.5 km radius in 2021
    - A 2.5 km radius in 2022
- Customer Satisfaction Scores:
    - A 1 km radius in 2021
    - A 1 km radius in 2022
    - A 2.5 km radius in 2021
    - A 2.5 km radius in 2022

In order to counter excessive skewness, the dependent variables and the following explanatory variables were log-transformed (base 10):

- Number of connecting bus, tram and metro directions
- Customer satisfaction score
- Job density
- PedShed ratio
- Service Span
- Trains per hour (off-peak)

(Thus permeability, bike network length, land use mix and population density were left untransformed.) The explanatory variables which were subject to this transformation were selected by importing the dataset into SPSS 28 and running the Skewness Test via the Descriptive Statistics function. A score less than -1 or greater than 1 were considered excessively skewed. This is consistent with the approach taken in multiple other node-place studies which use regression (Caset et al., 2020; Cummings & Mahmassani, 2022; Monajem & Ekram Nosratian, 2015; Reusser et al., 2008; Vale, 2015).

For each of the eight data configurations, the indicators from table 3.2 were analysed as explanatory variables using the Exploratory Regression tool in ArcGIS Pro. This data-mining tool (partially) automates the process of finding a properly-specified OLS model which best explains the dependent variable (Kauhl et al., 2015; Pimpler, 2017). Applied to this research, this tool makes it possible to identify statistically significant node and place factors while avoiding multicollinearity and redundancy (Feng & Tong, 2017). Its output is a list of potential OLS models which pass the following tests (Esri, 2022b; Kauhl et al., 2015):

- The model exceeds the Adjusted R^2 threshold of 0.5, evaluating model performance at explaining the dependent variable.
- Coefficient p-values for all explanatory variables are statistically significant (threshold of 0.05), indicating that they are helping the model.
- Coefficient Variable Inflation Factor (VIF) values less than 7.5, indicating that the variables are not redundant.
- Jarque-Bera test p-value larger than 0.1, indicating that the model was not detected to be biased (i.e., that it can be assumed to be normally distributed with a 0 mean).
- Because the 50 stations were examined as separate and distinct areas, the Global Moran's I Spatial Autocorrelation test was not run.

As an added check, the variables of the models proposed by the Exploratory Regression tool were entered into IBM SPSS 28 using its Multilinear Regression function to verify that it produced the same adjusted R^2 figure.

The proposed models offered by the Exploratory Regression tool were then filtered to select those which passed under the eight situations mentioned above and featured the highest Adjusted R^2 figures. The same model in each of the four situations produced a slightly different Adjusted R^2 figure, but they were relatively close. These models are shown in Chapter 4.

4 Results of the Regression Process

Overall, one of the most striking results it that the node and place values appeared to have no correlation with the customer satisfaction scores (as an independent variable). This was true of both the non-transformed variables and the log-transformed variables described in section 3.4. But customer satisfaction scores did appear to offer explanatory value for ridership, and thus were incorporated as an independent variable.

Table 4.1: *Summary table of key regression coefficient results.*

Dependent Variables	Unstandardised Beta	Sig	95% Confidence: Lower Bound	95% Confidence: Upper Bound
(Constant)		0.696971	-2.162307	3.202890
Customer Service Score 2022 (Log-Transformed)	0.072241	0.186029	-0.793671	3.952058
Span of Service 2022 (Log-Transformed)	-0.031220	0.702947	-5.240348	3.567514
Off-peak trains per hour 2022 (Log-Transformed)	0.465936	0.000026	0.584776	1.448206
Number of connecting bus directions 2022 (Log-Transformed)	0.206976	0.018898	0.064980	0.680795
Bike Network Length (m)	0.150898	0.511068	-0.000010	0.000019
Job Density (Log-Transformed)	0.281814	0.004288	0.129469	0.647700
Land use mix (entropy)	-0.002049	0.971752	-0.975385	0.941609
PedShed Ratio (Log-Transformed)	-0.024902	0.781875	-1.387843	1.051605
Permeability (Number of junctions)	-0.001979	0.991946	-0.000514	0.000508
Population Density	0.002522	0.975116	-0.035672	0.036797

Table 4.1 offers a summary of the key coefficient figures in terms of the relationship between the explanatory variables (using data from 2022 and a service area of 1,000 m) and the independent variable of ridership. These include the unstandardised Beta, p-value and 95% confidence band. The full table can be found in Appendix K.

Appendix J includes the full output from the ArcGIS Exploratory Data tool, including tests addressing bias and redundancy. Additionally, the descriptive statistics from the node and place values can be found at the bottom of Appendices E and J, respectively. The top-five OLS models for ridership resulting from the process described in section 3.4 are presented in table 4.2.

Table 4.2: *Top five OLS models which passed under all four data configurations*

Model	Adjusted R^2 Range	Variable 1	Variable 2	Variable 3
A	0.896221 - 0.922961	Off-peak trains per hour (log-transformed)	Number of bus, metro, tram and ferry directions (log-transformed)	Job density (log-transformed)
B	0.861463 - 0.872335	Permeability (number of junctions)	Number of bus, metro, tram and ferry directions (log-transformed)	Job density (log-transformed)
C	0.796814 - 0.821182	Permeability (number of junctions)	Number of bus, metro, tram and ferry directions (log-transformed)	Customer Satisfaction Score (log-transformed)
D	0.796823 - 0.809286	Bike Network Length	PedShed Ratio	Job density (log-transformed)
E	0.787812- 0.807506	Population Density	Number of bus, metro, tram and ferry directions (log-transformed)	Customer Satisfaction Score (log-transformed)

Many of the variables appear in multiple models. Three in particular were consistently labelled as significant in the Exploratory Regression for all four of the ridership data configurations:

- Off peak trains per hour (log-transformed)
- Number of bus, metro, tram, and ferry directions (log-transformed)
- Job density (per km^2) (log-transformed)

In the interests of manageability, it was decided that the 2022 data is the dataset of primary interest with the 2021 data offering the opportunity for further verification. In general, the results between the two years were very similar.

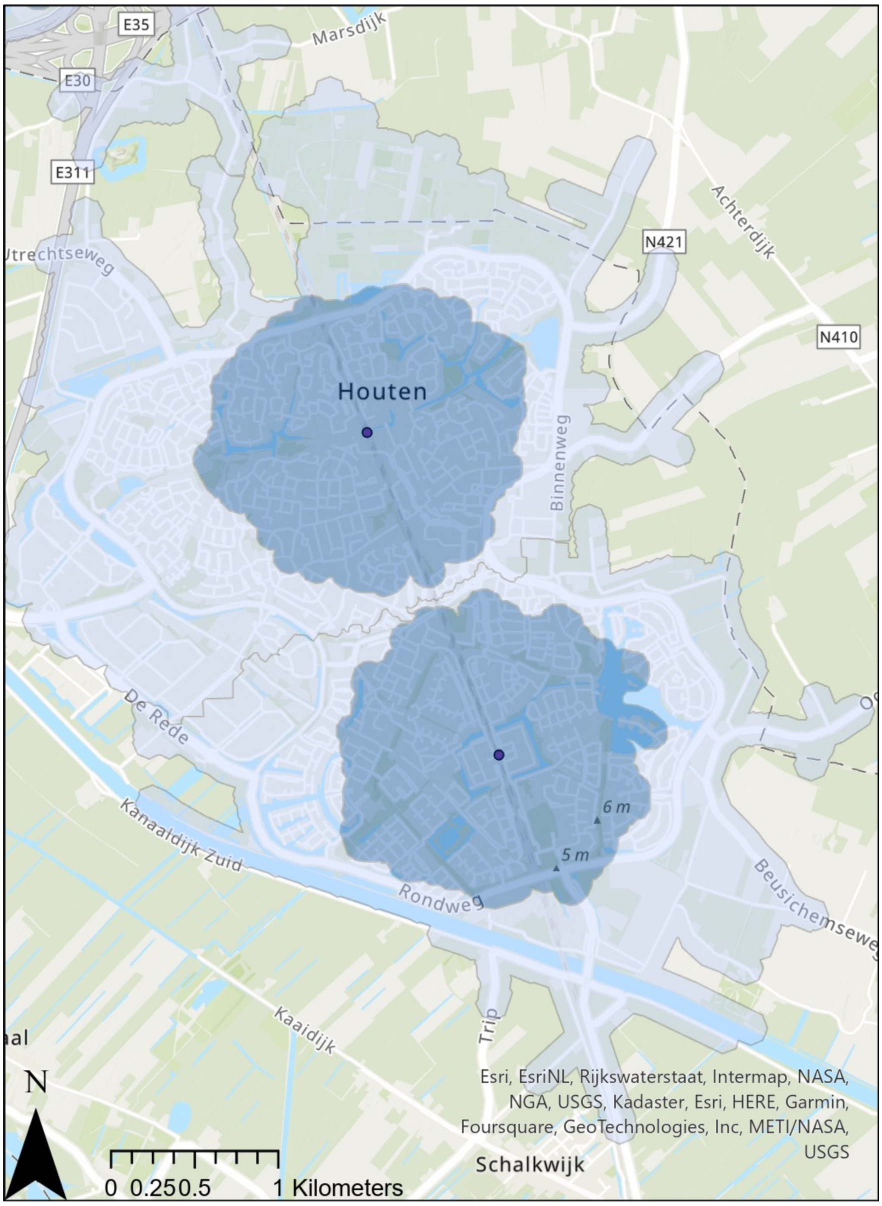
Only two of the exploratory variables suffered issues from multicollinearity: the length of the pedestrian/cycling network and the permeability (measured by the number of junctions.) This was not unexpected as the two datasets are closely related. It is very likely that as the length of the cycling network grows, there will be more junctions within it.

For all 50 stations ridership increased from 2021 to 2022 by at least 24.76% with a mean of a 47.70% increase. The highest increase was Schiphol Airport station with 101.45%. This increase is likely because of the Covid-19 restrictions which included work-from-home orders, curfews, and particularly in the case of Schiphol Airport station, international travel restrictions. Amsterdam Biljmer ArenA station saw a similar 97% increase in ridership in 2022, likely because events at the nearby Johan Cruyff Arena resumed. In general, amongst the 50 stations the node and place indicators did not substantially change between the two years, so they cannot explain the increase. The ridership increase was matched with a mean off-peak service increase of 4.19%, mostly as part of the 10-minute network in the Randstad, implying that there was a high amount of unused train capacity in 2021.

Figure 4.1: *Map of the Lage Zwaluwe station area showing the 1,000 m distance (dark blue) and 2,500 distance (light blue).*

Customer satisfaction (measured on a scale out of 10) was broadly steady between the two years, with a standard deviation 0.5/10 but decreased by 19% at Lage Zwaluwe, which was just below one standard deviation from the mean in 2021. It is curious that Lage Zwaluwe underperforms significantly in its place values, with the lowest job and population density and lowest pedestrian and cycling network length (for both the 1,000 model and 2,500 models). This is likely because it is, in reality in the "middle of nowhere." Figure 4.1 illustrates this with both the 1,000 m (green) and 2,500 m (green) network distances falling well outside the built-up area to the east (indicated by a red arrow.)

Figure 4.2: *Map of the Houten (top) and Houten Castellum (bottom) station areas showing the 1,000 m distance (dark blue) and 2,500 distance (light blue).*



Esri, EsriNL, Rijkswaterstaat, Intermap, NASA, NGA, USGS, Kadaster, Esri, HERE, Garmin, Foursquare, GeoTechnologies, Inc, METI/NASA, USGS

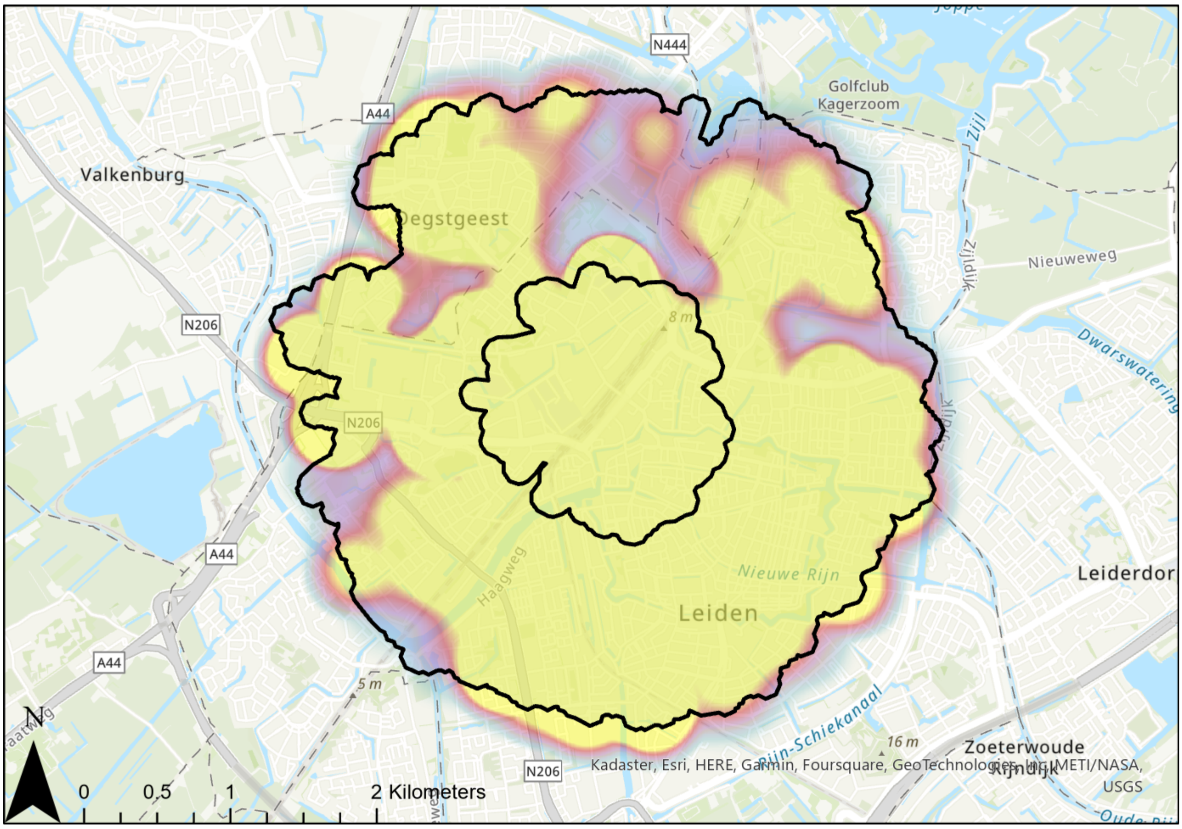
This could be most starkly contrasted with Houten and Houten Castellum in the province of Utrecht, both shown in figure 4.2. They feature the highest PedShed ratios of the 50 stations (which means that it has the greatest area reachable from the respective stations via the pedestrian and cycling networks. This stems from the fact that these residential areas were intentionally designed to facilitate easy access to the rail stations. Both stations boast roughly the mean customer satisfaction scores of the 50 stations. Because the Houten area is almost exclusively residential, it has a relatively low job density.

Table 4.2 shows the top 10 stations in terms of surrounding job density. These tend to be in large city centres with dedicated office space sectors, which means that they also have the highest ridership. Within 1 km of the station these tended to have job densities above 20 per square kilometre. These tended to drop off substantially (up to 69%) at the 2.5 km distance from stations, suggesting that employers wish to be close to railway stations. Figure 4.3 illustrates this phenomenon with a heat map of job density surrounding Leiden Centraal station (with a 67% decrease in job density from 1,000 m to 2,500 m.) The black lines represent the 1,000 m and 2,500 m radii. The area within the 1,000 m radius is almost entirely yellow, but there are significant gaps in the 2,500 m radius. It is interesting to note that population density does not face a similar drop off when going from 1,000 m to 2,500 m catchment areas, perhaps suggesting that residential uses are more dispersed than commercial ones.

Table 4.3: *Top 10 stations by job density at both 1,000 m and 2,500 m from the station.*

Station Name	Job Density at 1,000 m distance (per km2)	Job Density at 2,500 m distance (per km^2)	% Change from 1,000 m to 2,500 m
Den Haag Centraal	27.98097	13.03290	-53%
Utrecht Centraal	26.97645	8.32915	-69%
Amsterdam Bijlmer ArenA	21.25966	9.04579	-57%
Amsterdam Centraal	20.49165	14.25296	-30%
Amsterdam Zuid	19.15836	8.61536	-55%
Rotterdam Blaak	17.66554	8.35212	-53%
Rotterdam Centraal	15.95689	7.78228	-51%
Schiphol Airport	13.74517	8.38801	-39%
Amsterdam Sloterdijk	13.52135	5.53855	-59%
Leiden Centraal	13.24881	4.42062	-67%

Figure 4.3: *Heat map of jobs around Leiden Centraal with 1,000 m and 2,500 m distances outlined in black.*



Kadaster, Esri, HERE, Garmin, Foursquare, GeoTechnologies, Inc, METI/NASA, USGS

5 Discussion and Conclusion

5.1 Summary of Findings

This study aimed to find what factors of node and place affected ridership and customer satisfaction at railway stations in the Netherlands. The research question was: *What is the potential of applying the node-place value model to determine the optimal location of railway stations for the purposes of increasing both ridership and customer satisfaction?*

Briefly, the results suggest that the node-place value model does indeed have the potential for determining the optimal location of railway stations for purposes of *increasing ridership*. However, the results suggest that the node-place value model has little or no potential to determine the optimal location of railway stations for purposes of *increasing customer satisfaction*. This makes intuitive sense when it comes to place values, because these do not exhibit themselves in the railway stations in which customer satisfaction was surveyed. To reflect this, a revised conceptual model is included in figure 5.1. This revised model changes customer satisfaction scores to a strictly dependent variable and removes its role as an independent one. Thus, the answers for research **sub-questions 3 and 4** (regarding which node and place factors increase customer satisfaction scores) is none. To summarise, in this updated conceptual model, the indicators of node, place and customer satisfaction influence ridership, which economically and politically help advance improvements in node values.

Broadly, the results point to the utilitarian approach to travel, and with it, an extrinsic demand for travel (Cervero & Kockelman, 1997). E.g., the importance of job density on ridership indicates that passengers travel because experience greater benefits than the cost (in terms of time and hassle) of not travelling. In their survey of public transportation ridership studies, Taylor and Fink (2013) found that ridership studies which were considered to be causal analyses (as opposed to descriptive analyses; see section 3.1) found factors external to the journey had greater influence than inherent ones. Broadly, this research is in line with that finding, with off-peak frequency and customer satisfaction being the only significant factors internal to NS.

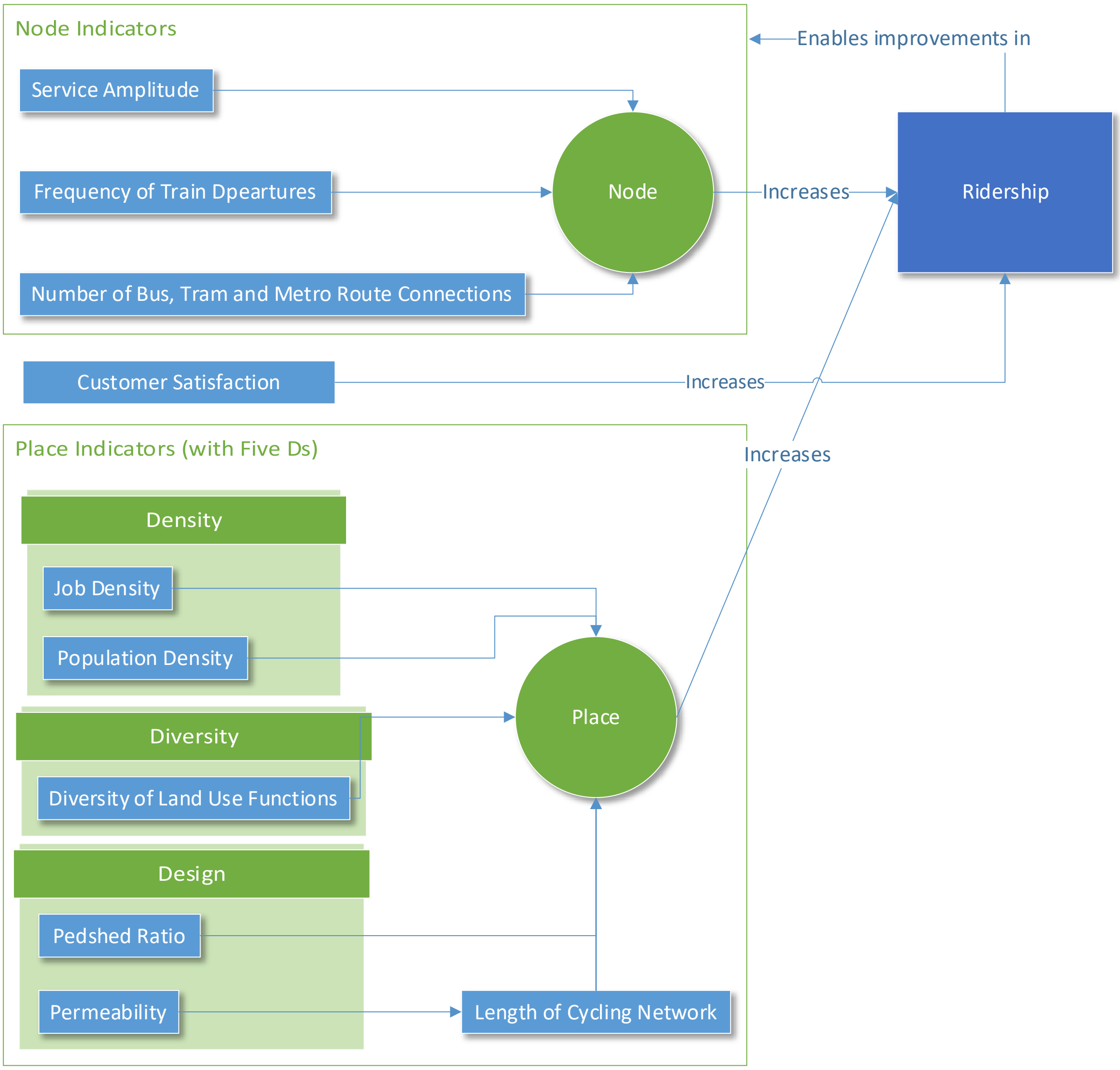
The following sub-sections will answer the other three sub-questions posed in section 1.3.

5.1.1 Sub-question 1: What node characteristics increase ridership, and to what degree?

Number of trains per hour, off-peak (Frequency) showed a correlation with ridership with a standardised coefficient of 0.466, the highest of the explanatory variables. Ferguson et al. (2012) took considerations of frequency in an equitable access direction by proposing a framework to incorporate equity into public transportation timetabling decisions. As part of this, they argue for the consideration of transportation needs other than employment, groceries and supermarkets, which relates to off-peak frequency. Taylor and Flink (2013) also call for considering trips beyond those for work. This is contrast to the analysis at the Dutch postcode level conducted by Brons et al. (2009) which suggests that additional resources should be directed at areas which already have strong rail service and access to it.

Number of bus, metro, tram and ferry directions (log-transformed). With a standardised coefficient of 0.207, this is consistent with Ingvardson and Nielsen (2018) who examined network topology in 48 European cities and found that the number of stations at which transfers were possible to be more important than the number of fundamental circuits (the cyclomatic nature) of the network. Many studies found that the possibility to transfer was a significant parameter because it offers higher robustness of the network (Ingvardson & Nielsen, 2018). More possibilities for transfers increased the mobility of passengers, which made the system as a whole more attractive (which would increase ridership.)

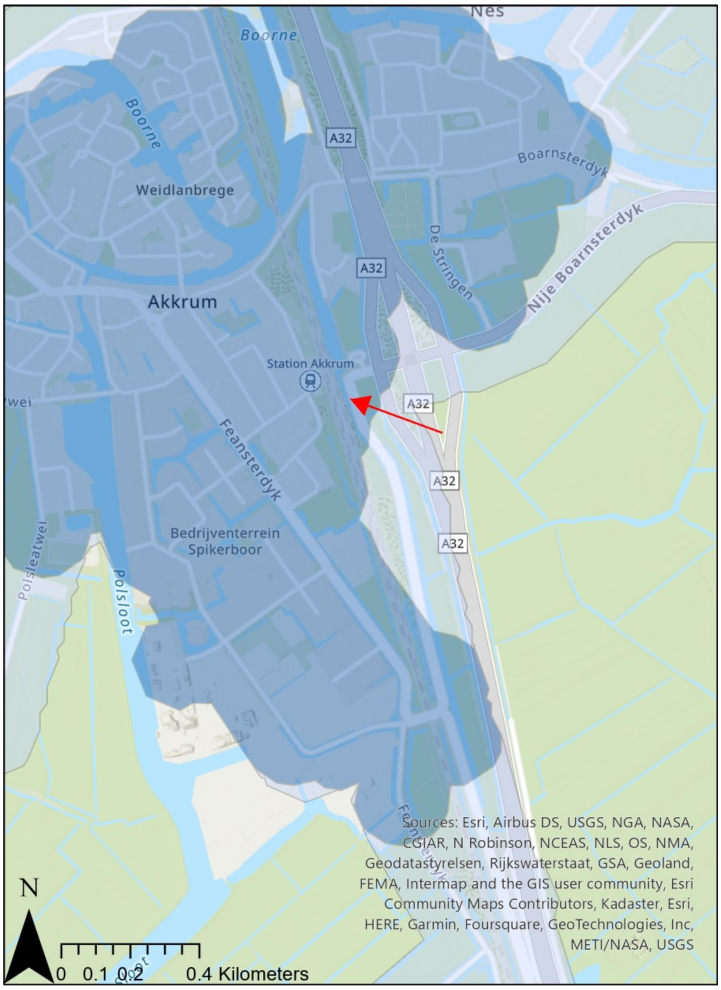
Figure 5.1: *Revised Conceptual Framework showing the updated role of customer satisfaction as an explanatory variable instead of an independent one.*



5.1.2 Sub-question 2: What place characteristics increase ridership, and to what degree?

One interesting finding about the **bike and pedestrian network length** surrounding stations is that it would appear that the areas with the longest bike and pedestrian networks were present in neighbourhoods constructed after World War II. This may be because such areas tend to have larger distances between buildings. (This standardised coefficient was 0.151.)

Figure 5.2: *Akkrum station where a canal and freeway east of the station (red arrow) block passengers from walking east.*



Sources: Esri, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap and the GIS user community, Esri Community Maps Contributors, Kadaster, Esri, HERE, Garmin, Foursquare, GeoTechnologies, Inc, METI/NASA, USGS

PedShed Ratio and permeability: Population density and intersection density were both important factors in an analysis of rail-based rapid transit systems in Canada (Durning & Townsend, 2015). This indicates that for ridership there is importance both in having a built-in local user base (through population and job density) and an ease of accessing the station from elsewhere. This makes intuitive sense with public transportation as pedestrians are less able to divert around obstructions than drivers are. It also increases the catchment area that can be reached from a station within a given distance or time. Akkrum in Friesland (figure 5.2) shows a good example of this phenomenon. A canal and freeway prevent passengers from walking east from the station, which significantly reduces the potential catchment area. A counter example to this is Houten (figure 4.2) which offers very good opportunities for dispersion and the highest PedShed ratio of the studied stations.

Place values relate to the question of whether or not to provide park-and-ride facilities for riders. Some authors argue against the provision of park-and-ride facilities for several reasons. These facilities may increase ridership, but they come at the cost of not generating tax revenue and forgoing the opportunity for TOD by occupying land that could otherwise be developed (Durning & Townsend, 2015). Such facilities would also decrease the explanatory variables offered in this research, particularly **population and job density**. Parkhurst (1995) examined the issue of Park and Ride facilities outside of British cities and argued that they could end up drawing users who would have otherwise completed their journeys by bus.

The example of the two main stations in the Hague may give some insight into how job density has more effect on ridership than population density. Den Haag Holland Spoor (HS) has daily ridership of around 30,000 and the highest population density of the 50 stations at 13.67

persons per square kilometre. Den Haag Centraal, on the other hand, has approximately 69,000 riders but less than half the population density at 5.92. The key difference appears to be that Den Haag Centraal has a higher job density (28 jobs per square km) vs Den Haag HS (8 jobs per square km.)

Brons et al. (2009) found that improving access to the railway (i.e., improving place values around stations) to be more cost effective at increasing ridership than improving service on the railway itself. The indicators they used suggested that improving access would be a more efficient use of resources to increase ridership.

5.1.3 **Sub-question 5:** What correlation exists between ridership and customer satisfaction?

Customer satisfaction did seem to have a relationship as an explanatory variable for ridership, consistent with the findings of Wang et al. (2020). It's unclear whether, as in Wang et al. (2020), improved customer satisfaction scores made customers more likely to choose to travel by train in the future. Future research might involve surveying customers about their satisfaction with the place aspects of the station environment. This might fit well with the five five generic functions of stations (as more than simply being places to board a train) have been devised. These are: linking the relevant catchment area to the actual transportation network, supporting transfer between modes of transport, facilitating commercial use of real estate, providing public space, and contributing to the identity of the surrounding area (Zemp et al., 2011). These generic station functions shed further light on the functional goals of a railway station beyond train passenger conveyance and provide opportunities to improve upon node and place indicators, and possibly customer satisfaction.

In terms of the studied stations, those with the highest satisfaction scores vary from the "basic" to "cathedral" classifications, suggesting that the size of the station does not relate directly to satisfaction. But a curious thing is that several of the top stations, including Utrecht Centraal, Rotterdam Centraal, Delft and Driebergen-Ziest were recently renovated. Therefore, it would be interesting to see if recent station renovation influences customer satisfaction scores, and, perhaps, ridership.

5.2 How do these concepts apply in practice?

Ferguson et al. (2012) propose applying their equity in public transportation frequency framework mentioned earlier to future land use planning. I.e., they propose incorporating the level of access to be provided under a fixed public transportation budget into the evaluation of potential land use scenarios. In a Dutch context, this may result in development permission being withheld in more isolated and less well-connected stations.

When considering the number of off-peak train services (48) Amsterdam Sloterdijk offers more than Amsterdam Centraal (45) but underperforms in terms of ridership at only 46,362 in 2022. Amsterdam Centraal achieved more than three times as much. At the 1000 m catchment area, it also has a low population density at one standard deviation lower than the mean. This puts it on par with Akkrum in Friesland, which has one quarter of its land designated for agriculture. According to node-place theory, this suggests that Sloterdijk is an **unsustained node** (see figure 2.1) (Reusser et al., 2008; Vale, 2015). This offers an interesting opportunity to apply the node–functionality–place 3D model (figure 2.4) (Su et al., 2021). The functionality dimension relates to how local residents get around within the station area. The node-functionality-place model also includes an evaluation of the potential for remediation, which is rather high in this area. Thus, Amsterdam Sloterdijk might be classified on the model's "magic cube" as number 20: high node values, low place values, with a medium potential for remediation.

In contrast, Amsterdam Centraal offers a prominent example of a station under **stress** (cube position 25). It has some of the highest ridership in the country, along with some of the highest levels of service. Additionally, it acts as a hub for 11 bus services from both sides of the IJ river, 8 tram routes 3 ferries and 2 metro lines serving 5 different termini. In terms of place values, the centre of Amsterdam is known worldwide for its charming streetscape. As a centre of commerce and employment, it features high job density, with many of those employees and visitors passing through Amsterdam Centraal itself. The station area has been undergoing renovation for many years, and additional rail-related improvements are underway.

Amsterdam Zuid is a good example of an **unsustained place** (cube 11). It features a high job density as a Dutch financial hub, generating around 50,000 riders per day, but with only 16 trains per hour it has a service comparable to Haarlem and Breda with only around 33,000 riders per day. The constraints here are because of the four-track layout, which prevents adding additional service. This is to be addressed with an ongoing construction project to add an additional two tracks.

In Friesland, Grou-Jirnsum could be considered a **dependent** area, with four Sprinter trains per hour (two in each direction) it has a low level of daily boardings of around 500 per day. It also offers a connection to one bus line. This area is dependent on being between Leeuwarden and Zwolle so that a train service is viable.

In the five Ds model, **Density** in land use has the benefit of supporting a high level of public transportation network coverage (Ingvardson & Nielsen, 2018), which, in turn, drives ridership. Kim et al. (2016) makes a key point regarding job density: they argue that governments should shift their focus to pursue *employment land uses* over a specific number of jobs around. This is because these places of employment attract visitors (e.g., commerce.) The case of Amsterdam Sloterdijk (described above) may be an example of an area lacking density, particularly in terms of residential population.

For this reason, Durning and Townsend (2015) argue that higher ridership could be achieved by promoting a **diversity** of land uses around existing and new stations. But it should be noted that a balance between land uses has the potential to actually reduce ridership (Guzman & Gomez Cardona, 2021; Kim et al., 2016). This is because a balance between jobs and residential population at a certain location would reduce demand for commuting. Guzman and Gomez Cardona (2021) propose this balance as a way to manage areas that are under stress in the node-place model (see the top-right of figure 2.1.)

6 Final Reflections

This research contributes to the field of public transportation and spatial development by confirming that the node-place model framework does have a correlation with ridership and by indicating which node and place values to pursue improvements in. Like all research, it comes with some limitations, which will be addressed below.

6.1 Limitations

Studying multiple transit agencies produces more robust results which are more generalisable to other jurisdictions, and thus a limitation of this study is that it relies exclusively on NS ridership figures. However, it is worth noting that NS is the principal passenger rail operator in the Netherlands, operating the largest and most important parts of the network, and thus including other carriers would bring limited insight.

In their study, Cummings and Mahmassani (2022) found using annual ridership at the station level to be a limitation of their research because it did not capture day-to-day decisions of individuals as to whether or not to ride. Applying this finding to this research, average daily ridership figures were provided by NS, but there has been a recent trend on the Dutch passenger rail network for peak days to now be on Tuesdays and Thursdays as opposed to all five working days before the Covid-19 pandemic (OV-Magazine, 2023). As a result, for the 2023 timetable, NS decided to only run its 10-minute service in the Randstad from Monday through Thursday and not on Fridays (NS, 2022c). This raises questions about how to account for this. Cao et al. (2020) suggest hourly ridership data so that both peak and off-peak ridership can be considered. This would have to be matched with similar timetable data for service throughout the day. The data in this research did not break down by day of the week, nor was the average off-peak number of trains per hour broken down by day of the week.

Talor and Flink (2013) identified several weaknesses with causal analyses of public transportation ridership. Their biggest criticism was that generalisability value of the research was limited because of data problems. The two most relevant to this research involve relying on readily available data (provided by the rail carrier) and considering unlinked train trips instead of the entire door-to-door journey. This research examines the ease witch which journeys between the origin/destination and station can be made (by considering the place values), but it fails to quantify how passengers make use of the connecting bus and street network. This relates to the issue that some variables are difficult to quantify (Taylor & Fink, 2013), e.g., how can street networks amongst cities be compared?

Cross-temporal data errors could be relevant to this study because the ridership and customer satisfaction data are from 2021 and 2022, but the latest geospatial dataset on the built environment (BBG) is from 2017 (Centraal Bureau voor de Statistiek, 2022a). One mitigating factor to this is that spatial change occurs slowly. I attempted to minimise this by sourcing the timetables and network line diagrams from 2021 and 2022.

As shown in figure 3.1, stations in this study tended to be clustered in the west. This is because the station selection process (from section 3.2.1) excluded stations with significant passengers using regional carriers. These services are most often found in the north, east and southeast of the country.

6.2 Further Research

Given high-profile incidents of unreliability on the Dutch railway network over the past few years, one potentially interesting area of further research involves examining reliability as a dependent variable for both ridership and customer service. Brons et al. (2009) found that customer perception of service reliability did impact Dutch rail customer satisfaction, but curiously did not seem to impact the customers' level of rail or car use. In their study of customer satisfaction expressed by Chinese microblogs on Sina Wibo, Luo et al. (2023) A related question is how much of the timetabled service actually operated? (I.e., How many trains were cancelled?) Do customers base their utilitarian travel decisions on the timetabled service or on the service levels that they actually experience?

This research considers travel from a mostly utilitarian perspective—balancing benefits and costs. But it does not account for economic costs, which may become more important in Dutch travel decisions as Outgoing State Secretary Vivianne Heijnen has announced that train tickets will increase by 3.5% plus already-high inflation (Merrienboer, 2023).

Some of the literature calls for cogent regional transportation visions (World Bank, 2021) and it is unclear how this could be operationalised. The World Bank (2021) cites Copenhagen and Stockholm as examples with such visions which match transit capacity improvements with spatial developments. Applied specifically to this research, this would relate to measuring the "door-to-door" journey mentioned earlier. Perhaps considering ridership on all public transportation operators in the Netherlands would be a suitable point of further research.

Olaru et al. (2019) found that railway corridors exhibit spatial patterns and studying individual railway stations will not uncover that nor offer help in developing strategies at that level. They therefore recommend analysing the role of stations in the regional transportation system. Some of the extensions to the node-place framework mentioned in section 2.2.4 attempted to consider this scale through "betweeness" and centrality (Cao et al., 2020; Ma et al., 2022). The check-in and check-out data from the Dutch public transport card (OV-Chipkaart) may provide insight into this question because it offers origin and destination data.

Another potentially insightful avenue of investigation is expanding from studying the land use mix to including the job-housing ratio in an area (Cao et al., 2020). Network coverage of a public transportation network was found to have a positive relationship with ridership and more frequent use of the system by individuals (Ingvardson & Nielsen, 2018). Good network coverage additionally improves customer satisfaction levels (Ibrahim et al., 2020). Thus, it would be insightful to evaluate network coverage as an explanatory variable.

The Netherlands is known for its high-quality and comprehensive cycling network, but that is not the case in other countries. A potential for further research would involve testing the length of the cycling network against ridership in the context of other countries where safe cycling networks are much less common. Similar to this, much of the research about the built environment and travel behaviour is conducted from a Western perspective, which means that their findings may not be translatable into an Asian context (Y. Zhang et al., 2014). This provides additional opportunity for further research.

Station areas constitute a useful public resource which should be laid out to maximise ridership. This research confirms that the node-place framework can aid in this endeavour. Place-related interventions include maximising walking and cycling convenience and concentrating employment at public transportation nodes. Node-related interventions include off-peak service improvements and easy connections to other forms of public transportation.

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Appendix A: Indicators of Node

Indicator	How to measure	Units	Source(s)
Service amplitude	The proportion of the day between the first and the last train service at the station	Minutes (time)	Caset et al. (2020); Caset et al. (2019)
Frequency of departures	Frequency of departures on a chosen day (e.g., Tuesday)	Trains per hour	Caset et al. (2020); Bertolini (1999); Brons et al. (2009); Vale (2015); Dou et al. (2021); Chen and Lin (2015); Su et al. (2021); Li et al. (2019)
Frequency of departures	Frequency of departures off-peak (e.g., for one hour between 10 and 11 AM on a Tuesday)	trains per hour	Caset et al. (2020)
Travel time centrality	Minimum cumulative impediment in terms of travel time and service frequency, between station *i* and all other stations in the Dutch railway network	Minutes (time)	Caset et al. (2020); Caset et al. (2019)
Transfer time centrality	Minimum cumulative impediment in terms of transfers needed, between station *i* and all other stations in the Belgian railway network	Minutes (time)	Caset et al. (2019)
Transfer centrality	Number of transfers required to reach all other stations in the networks.	Transfers	Caset et al. (2020)
Rail Service Quality Index			Brons et al. (2009);
Reachable Stations	Number of stations reachable within a certain time (e.g., 45 minutes of travel)	Stations	Bertolini (1999); Vale (2015); Dou et al. (2021); Chen and Lin (2015); Zemp et al. (2011); Li et al. (2019)

Number of bus, tram and metro connections	Number of unique bus, tram and metro routes to and from the railway station on a Tuesday (stops within 300 m walking from the station are included)	Routes	Caset et al. (2020); Cummings & Mahmassani (2022); Chorus and Bertolini (2011)
Number of train connections	Number of train routes available at a station.	Routes	Chorus and Bertolini (2011)
Directions served	Number of directions served by train	Directions	Vale (2015); Dou et al. (2021); Dou et al. (2021); Chen and Lin (2015); Li et al. (2019)
Directions served	Number of directions served by connecting bus, metro or tram	Directions	Bertolini (1999); Vale (2015); Chen and Lin (2015); Ma et al. (2022); Yang et al. (2022); Su et al. (2021)
Frequency of connecting services	Frequency of bus, tram and metro departures on a Tuesday (stops within 300 m walking from the station are included)	Minutes (time)	Caset et al. (2020); Vale (2015); Chen and Lin (2015)
Car Parking capacity	Total number of car parking spots	Parking Spots	Caset et al. (2020); Bertolini (1999); Brons et al. (2009); Vale (2015); Dou et al. (2021)
Car parking utilisation	Average percentage of car parking spots in use on a weekday.	Percentage	Babb et al. (2016)
Motorway accessibility	Distance from the closest motorway access	Metres	Vale (2015); Dou et al. (2021); Chen and Lin (2015)
Trains per Week	Count of train stops made at each station per week	Trains per week	Cummings and Mahmassani (2022)
Direct Stops	Count of other stations served directly (no transfers) from each station	Stops	Cummings and Mahmassani (2022)

Bike Parking capacity	Total number of bike parking spots	Parking Spots	Caset et al. (2020); Bertolini (1999); Babb et al. (2016); Brons et al. (2009)
Size of cycling network	Number of free-standing cycling paths	Cycling paths	Bertolini (1999); Babb et al. (2016)
Potential demand for station access	Regional travel time from the stations and feeder bus catchment area	Travel Time	Babb et al. (2016)
Quality of feeder bus and rail services	Unspecified	Index	Babb et al. (2016)
Journey-to-work data			Babb et al. (2016)
Kiss-and-ride facilities	Presence of facilities to drop off and pick up passengers	Binary	Babb et al. (2016)
Bike mode share	Percentage of customers accessing the station by bike.	Percentage	Babb et al. (2016)
Type of Train Services	Number of long distance services/number of regional services	Routes	Chen and Lin (2015); Chorus and Bertolini (2011)
Proximity to CBD	Proximity to central business district	Kilometres	Chorus and Bertolini (2011)
Road network accessibility	Maximum road accessibility within 500 m	Index	Ma et al. (2022)
Station entrances	number of station entrances	Entrances	Ma et al. (2022); Su et al. (2021); Li et al. (2019)
Station capacity (area)	Area of the station building	Square metres	Ma et al. (2022)
Betweenness centrality	Local betweenness centrality weighted by straight-line distance between stations	Index	Yang et al. (2022)
Closeness centrality	Local closeness centrality weighted by straight-line distance between stations	Index	Yang et al. (2022)

Number of bus stops	Number of bus stops around the station	Bus stops	Yang et al. (2022)
Number of "compartments"	Number of train cars going through the metro station per hour.	Train cars	Su et al. (2021); Li et al. (2019)
Distance to next station	The average distance from the current metro station to each service direction to the next station	Metres	Li et al. (2019)
Maximum Passenger Flow	Maximum number of passengers which can pass through a station in a given time.	Passengers	Li et al. (2019)
Rail transit network integration	Degree of integration from space syntax theory	Index	Li et al. (2019)
Proximity to CBD	Proximity to Central Business District (added as node indicator.)	Kilometres	Chorus and Bertolini (2011)

Appendix B: Indicators of Place

Indicator	How to measure	Units	Source
Population	The total number of residents living in the station area	Inhabitants	Caset et al. (2020); Bertolini (1999); Vale (2015); Chorus and Bertolini (2011); Chen and Lin (2015); Yang et al. (2022)
Number of residences	Number of residential units within 600 m	Residences	Dou et al. (2021); Li et al. (2019)
Diversity of land use--functionally	Shannon Diversity Index calculated using Fragstats software	Index	Caset et al. (2020); Caset et al. (2019); Bertolini (1999); Babb et al. (2016); Vale (2015); Dou et al. (2021)
Diversity of land use--spatially	Interspersion and Juxtaposition index calculated using Fragstats software	Index	Caset et al. (2020)
Permeability	Total number of street crossings per station area	Street Crossings	Caset et al. (2020); Babb et al. (2016)
Interface Catchment	The sum of the length of all walkable street segments that are also flanked by buildings.	Metres	Caset et al. (2020); Dovey et al. (2018)
Pedestrian shed ('pedshed') Ratio	Dividing the 700 m pedestrian catchment area calculated with ArcGIS Network Analyst with the maximum theoretical area given by a circle with 700 m radius.	Ratio	Vale (2015)
Cycling Network	Total length of walkable and bikeable street networks within the station area	Kilometres	Caset et al. (2020); Chen and Lin (2015)

Jobs	The total number of jobs located in the station area	Jobs	Caset et al. (2020); Caset et al. (2019); Cummings and Mahmassani (2022); Vale (2015); Zemp et al. (2011)
Job Density	The number of workers per each of four economic clusters (retail/hotel and catering, education/health/culture, administration and services, industry and distribution)	Jobs per hectare	Bertolini (1999); Vale (2015); Olaru et al. (2019)
Population Density	People per square mile within a one-mile radius of each station	Ratio	Cummings and Mahmassani (2022); Dou et al. (2021); Olaru et al. (2019)
Median HH Income	Median household income within a one-mile radius of each station		Cummings and Mahmassani (2022)
Job Mix (Degree of multifunctionality)	Job-type diversity index, where higher values indicate more diverse job types		Cummings and Mahmassani (2022); Chen and Lin (2015); Chorus and Bertolini (2011)
Job-to-Population Ratio	Ratio of jobs to population within a one-mile radius of each station		Cummings and Mahmassani (2022)
Under 18	Average percent of population under 18 years old within a one-mile radius of each station		Cummings and Mahmassani (2022)

Over 65	Average percent of population over 65 years old within a one-mile radius of each station		Cummings and Mahmassani (2022)
Male	Average percent of population that is male within a one-mile radius of each station		Cummings and Mahmassani (2022)
Commute Drive	Average percent of workers within a one-mile radius of each station who commute to work by car		Cummings and Mahmassani (2022)
Commute Transit	Average percent of workers within a one-mile radius of each station who commute to work by transit (bus, light rail, or subway)		Cummings and Mahmassani (2022)
Commute Bike or Walk	Average percent of workers within a one-mile radius of each station who walk or bicycle to work		Cummings and Mahmassani (2022)
High School	Average percent of population over 25 years old within a one-mile radius of each station that holds a high school diploma or equivalent		Cummings and Mahmassani (2022)
Bachelors	Average percent of population over 25 years old within a one-mile radius of each station that holds a bachelor's degree		Cummings and Mahmassani (2022)
Masters	Average percent of population over 25 years old within a one-mile radius of each station that holds master's degree		Cummings and Mahmassani (2022)
Doctorate or Professional Degree	Average percent of population over 25 years old within a one-mile radius of each station that holds a PhD or professional degree		Cummings and Mahmassani (2022)
Poverty	Average poverty rate within a one-mile radius of each station		Cummings and Mahmassani (2022)
Unemployed	Average unemployment rate within a one-mile radius of each station		Cummings and Mahmassani (2022)
Rentals	Average percent of housing units within a one-mile radius of each station that is under a rental contract		Cummings and Mahmassani (2022)

Rent	Average dollar value of rent for rented housing units within a one-mile radius of each station		Cummings and Mahmassani (2022)
Home Price	Average dollar value of housing units within a one-mile radius of each station		Cummings and Mahmassani (2022)
Presence of developable sites			Babb et al. (2016)
Socio-economic characteristics of the immediate station precinct			Babb et al. (2016)
Level of background noise			Babb et al. (2016)
Presence of shade			Babb et al. (2016)
Thermal comfort			Babb et al. (2016)
Public spaces			Babb et al. (2016)
Degree of road space			Babb et al. (2016)
Presence of landmarks			Babb et al. (2016); Dou et al. (2021)
Destinations to walk to			Babb et al. (2016)
Number of workers in business	Number of workers at establishments in business within 600 m		Dou et al. (2021)
Intersection density	Density of intersections per hectare	Index	Dou et al. (2021); Yang et al. (2022); Lyu et al. (2016)
Average Block Size	Average size of each street block in the station area	Metres	Lyu et al. (2016)
Accessible Network Length	Length of Accessible Network	kilometres	Dou et al. (2021)
Number of workers in green space	Number of establishments in green space within 600 m		Dou et al. (2021)
Number of workers in transportation	Number of establishments in transportation within 600 m		Dou et al. (2021)
Number of workers in public service	Number of establishments in public service within 600 m		Dou et al. (2021);

Number of workers in industry	Number of establishments in industry within 600 m		Dou et al. (2021); Chorus and Bertolini (2011)
Number of workers in services and administration			Chorus and Bertolini (2011)
Number of workers in retail			Chorus and Bertolini (2011)
Number of workers in education, health and culture			Chorus and Bertolini (2011)
Distance to town centre			Chen and Lin (2015)
Conference rooms and educational facilities			Chen and Lin (2015)
Intensity	Average plot ratio within 500 m	Ratio	Ma et al. (2022)
Land use Diversity /Degree of functional mix	Mixing entropy of land use within 500 m	Ratio	Ma et al. (2022); Kamruzzaman et al. (2014); Bertolini (1999); Reusser et al. (2008); Chorus and Bertolini (2011); Zemp et al. (2011); Li et al. (2019)
Residential Capacity	Area zoned for residential use within 500 m	Square Metres	Ma et al. (2022); Li et al. (2019)
Commercial Capacity	Area zoned for commercial use within 500 m	Square Metres	Ma et al. (2022)
"Establishment" Facilities	Assumed to mean number of business establishments.	Establishments	Yang et al. (2022)
Leisure Facilities	Number of leisure points of interest.	Establishments	Yang et al. (2022)
Catering Facilities	Number of catering points of interest.	Establishments	Yang et al. (2022); Li et al. (2019)
Administration Facilities	Number of Administration points of interest.	Establishments	Yang et al. (2022)
Education Facilities	Number of education points of interest.	Establishments	Yang et al. (2022); Li et al. (2019)

Retail Facilities	Number of retail points of interest.	Establishments	Yang et al. (2022); Li et al. (2019)
Hotel Facilities	Number of hotel points of interest.	Establishments	Yang et al. (2022)
Pedestrian network	Length of pedestrian paths	Metres	Yang et al. (2022)
Walkability	Proportion of walkable blocks within a set walking distance from the station	Index	Li et al. (2019)
Revised Walk Score	Average walkability of residential quarters according to the revised Walk Score metric	Index	Li et al. (2019)
Road walkability	Ratio between width of pedestrian space and of attached green spaces	Index	Li et al. (2019)

Appendix C: Indicators of Accessibility

Indicator	How to measure	Units	Source
Jobs within 30-min Drive	Count of jobs within a 30-min drive of each station	Jobs	Cummings and Mahmassani (2022)
Pop within 30-min Drive	Count of people within a 30-min drive of each station	Inhabitants	Cummings and Mahmassani (2022)
Pop within 10-min Walk	Count of people within a 10-min walk of each station	Inhabitants	Cummings and Mahmassani (2022)
Mobility	Average travel time (in minutes) to each station for the people within a 30-min drive	Minutes	Cummings and Mahmassani (2022)
Bus Connection	Binary variable, 1 if station is also served by a bus network, 0 otherwise	Binary	Cummings and Mahmassani (2022)
Air Connection	Binary variable, 1 if station is located at an airport, 0 otherwise	Binary	Cummings and Mahmassani (2022)
Bikeshare Connection	Binary variable, 1 if station is also served by a bikeshare location, 0 otherwise	Binary	Cummings and Mahmassani (2022)
Rail Connection	Binary variable, 1 if station is also served by a local, non-Amtrak rail service, 0 otherwise	Binary	Cummings and Mahmassani (2022)
Road Congestion and Performance	Level-of-service (delays)		Babb et al. (2016)
Road Congestion and Performance	volume/capacity ratios at key intersections in the AM and PM peak hour.		Babb et al. (2016)

Existing Road Capacity	number of lanes and intersection spacing along major parallel and perpendicular roads.		Babb et al. (2016)
Pedestrian access	Pedestrian access to the station via prominent and direct radial routes.		Babb et al. (2016)
Average distance to workplace	Average distance from the metro station to this category of points of interest within a set travel time radius of the station.		Li et al. (2019)
Average distance to medical facilities	Average distance from the metro station to this category of points of interest within a set travel time radius of the station.		Li et al. (2019)
Average distance to educational venues	Average distance from the metro station to this category of points of interest within a set travel time radius of the station.		Li et al. (2019)
Average distance to nursing homes	Average distance from the metro station to this category of points of interest within a set travel time radius of the station.		Li et al. (2019)
Average distance to recreation areas	Average distance from the metro station to this category of points of interest within a set travel time radius of the station.		Li et al. (2019)
Average distance to residential areas	Average distance from the metro station to this category of points of interest within a set travel time radius of the station.		Li et al. (2019)
Average distance to bus stations	Average distance from the metro station to this category of points of interest within a set travel time radius of the station.		Li et al. (2019)
Passengers within walking distance	% of people using the station as origin station who live within walking distance (< 900 m)		Caset et al. (2019)
Passengers within cycling distance	% of people using the station as origin station who live within cycling distance (900 m - 3000 m)		Caset et al. (2019)

Passengers farther than 3 km	% of people using the station as origin station who live more than 3 km away		Caset et al. (2019)
Accessibility Index	Index showing how easy it is to access a station.	Index	Cummings and Mahmassani (2022)

Appendix D: Miscellaneous Indicators

Indicator	How to measure	Units	Source(s)
Design index	Urban design elements which contribute to the pedestrian experience of the station itself.	Index	Vale (2015); Vale et al. (2018)
Oriented	To what degree are transit and development components of TOD oriented toward each other.	Index	Lyu et al. (2016)
Link	Link-place framework categorises streets.	Categories	Jones et al. (2008)
Pedshed (pedestrian shed) ratio	Dividing 1 km radius of walkable area by the area of a 1 km radiial circle.	Ratio	Vale (2015); Zhang et al. (2019)
Compactness	Local building morphology and design.	Index	Yang et al. (2022)
Network	The network indicators examine centrality, i.e., the degree of connection of nodes.	Index	Dou et al. (2021)
Background Traffic	Various indicators of road traffic within the station area.	Volume of traffic	Babb et al. (2016); Olaru et al. (2019)
Urban Vibrancy	Daily outflows and inflows from the station, plus night time activity.	Passenger volume	Yang et al. (2022)
Functionality	How residents walk and ride in station areas.	Categories	Su et al. (2021)
Ridership	How node and place affect ridership.	Passenger volume	Cao et al. (2020)
System support	Importance of the station in the overall transportation network.	Index	Ma et al. (2022)
Experience	Survey results about passenger comfort, ambient elements and social safety.	Percentages of customers	Groenendijk et al. (2018); Du et al. (2021)
Motivation for travel	The percentage of passengers using the station for secondary education, tertiary education, work or other purposes.	Percentages of customers	Caset et al. (2019)
Origin station	Percentage of passengers using station as the origin station for their journey.	Percentages of customers	Caset et al. (2019)
Destination station	Percentage of passengers using station as the destination station for their journey.	Percentages of customers	Caset et al. (2019)

Appendix E: Stations Selected for this Research and Reasons

Station Name	ProRail Classification	Why station was selected
Akkrum	Stop	Small town with A32 next to it.
Almere Centrum	Mega	Almere was intentionally designed to complement railway access to Amsterdam.
Almere Oostvaarders	Basic	Almere was intentionally designed to complement railway access to Amsterdam.
Amsterdam Bijlmer ArenA	Mega	TOD nearby, but a lot of land occupied by stadium. Ridership may have been affected by a lack of events at the adjacent stadium in 2021.
Amsterdam Centraal	Cathedral	One of the seven 'Cathedral' stations in the Netherlands.
Amsterdam Lelylaan	Plus	Built in 1986 to serve a neighbourhood in western Amsterdam which was itself built in the 1970s.
Amsterdam Sloterdijk	Mega	A lot of space occupied by freeways and railways.
Amsterdam Zuid	Mega	In the middle of the A10 freeway but also next to Amsterdam's business district.
Boskoop Snijdelwijk	Stop	A residential area close to agricultural areas.
Breda	Mega	Selected because there are only seven 'Cathedral' stations in the Netherlands.
Delft	Mega	The railway through this station was recently burried in a tunnel.
Den Haag Centraal	Cathedral	One of the seven 'Cathedral' stations in the Netherlands.
Den Haag HS	Mega	Selected because there are only seven 'Cathedral' stations in the Netherlands.
Den Haag Laan van NOI	Plus	High density residential and offices nearby.
Deventer	Mega	A traditional Dutch mixed use city.
Driebergen-Zeist	Plus	High customer satisfaction scores in 2021 & 2022. Far from Driebergen and Ziest.
Duivendrecht	Plus	Little development immediately nearby.
Eindhoven Centraal	Cathedral	One of the seven 'Cathedral' stations in the Netherlands.
Grou-Jirnsum	Stop	Next to A32 freeway on edge of town.
Haarlem	Mega	Selected because there are only seven 'Cathedral' stations in the Netherlands.
Hilversum	Mega	A traditional Dutch mixed use city.
Hoofddorp	Plus	Next to a business park.
Houten	Basic	The surrounding community was designed in the 1980s as a TOD
Houten Castellum	Basic	The surrounding community was designed as a sequel to Houten's TOD.
Krabbendijke	Stop	Next station from Kruiningen-Yerseke, but next to a residential area.

Station Name	ProRail Classification	Why station was selected
Kruiningen-Yerseke	Stop	In an industrial area.
Lage Zwaluwe	Stop	Station with the lowest customer satisfaction in the country in 2022. Used as a transfer station--very little development nearby.
Leiden Centraal	Cathedral	One of the seven 'Cathedral' stations in the Netherlands.
Lelystad Centrum	Plus	Lelystad was intentionally designed to complement railway access to Amsterdam.
Maarn	Basic	Adjacent to A12 freeway.
Olst	Basic	Small town with its centre near the station and low-density residential surrounding.
Oosterbeek	Stop	Half the catchment area is not built upon.
Overveen	Basic	Highest customer score in 2021. Next to nature area.
Rijssen	Stop	Industrial development to the north and mixed use to the south.
Rijswijk	Basic	Underground station in a suburb of Den Haag built in the late 1960s.
Rotterdam Alexander	Plus	Station with the lowest customer satisfaction in the country in 2022. Used as a transfer station--very little development nearby.
Rotterdam Blaak	Mega	High density and modern architecture surrounded by wide boulevards.
Rotterdam Centraal	Cathedral	One of the seven 'Cathedral' stations in the Netherlands.
Rotterdam Zuid	Basic	Poor customer experience scores in 2021 and 2022.
Schiedam Centrum	Plus	Next to the A20 freeway with an industrial area and some vacant land to the north.
Schiphol Airport	Cathedral	Ridership at this station may have been particularly affected by Covid-19 related travel restrictions, particularly outside of the European Economic Area (EEA).
Hertogenbosch ('s)	Mega	Next to N3 expressway
Soestdijk	Stop	Mostly residential with some retail and agriculture.
Utrecht Centraal	Cathedral	One of the seven 'Cathedral' stations in the Netherlands.
Utrecht Lunetten	Basic	Close to A12 & A27 freeways.
Weesp	Plus	Somewhat outside of the city centre.
Wezep	Basic	High customer satisfaction scores in 2021 & 2022.
Woerden	Plus	A traditional Dutch mixed use city.
Wolfheze	Stop	Quite a small built-up area.
Zaandam	Mega	New TOD commuter town project from 1980s

Appendix F: Node Indicator Values and Descriptive Statistics for Stations 2021-2022

Station Name	Ridership (2021)	Ridership (2022)	% Change in Ridership	Customer Satisfaction Score (2021)	Customer Satisfaction Score (2022)	% Change in Customer Satisfaction	Service Span (Amplitude) (2021)	Service Span (Amplitude) (2022)	% Change in Service Span	Trains per hour (off-peak) 2021	Trains per hour (off-peak) 2022	% Change in Off Peak Service
Akkrum	477	626	31.24%	7.3	7.21	-1.23%	19:15:00	19:15:00	0.00%	4	4	0.00%
Almere Centrum	16,834	23,861	41.74%	6.1	6.79	11.31%	19:49:00	19:49:00	0.00%	18	18	0.00%
Almere Oostvaarders	2,495	3,157	26.53%	6.9	7.19	4.20%	20:09:00	20:10:00	0.08%	6	6	0.00%
Amsterdam Bijlmer ArenA	10,489	20,739	97.72%	7.2	7.1	-1.39%	19:05:00	19:29:00	2.10%	16	20	25.00%
Amsterdam Centraal	86,202	151,112	75.30%	7.5	7.51	0.13%	23:31:00	23:31:00	0.00%	45	45	0.00%
Amsterdam Lelylaan	7,322	11,268	53.89%	6.4	6.34	-0.94%	19:26:00	19:26:00	0.00%	12	12	0.00%
Amsterdam Sloterdijk	29,649	46,362	56.37%	6.7	6.84	2.09%	20:15:00	20:09:00	-0.49%	48	48	0.00%
Amsterdam Zuid	31,603	50,262	59.04%	6.9	6.91	0.14%	19:21:00	19:12:00	-0.78%	16	16	0.00%
Boskoop Snijdelwijk	406	563	38.67%	7.9	7.62	-3.54%	19:32:00	19:32:00	0.00%	8	8	0.00%
Breda	21,712	32,844	51.27%	7.5	7.53	0.40%	19:10:00	19:10:00	0.00%	14	14	0.00%
Delft	20,176	31,737	57.30%	7.8	7.84	0.51%	23:32:00	23:32:00	0.00%	20	24	20.00%
Den Haag Centraal	40,213	68,972	71.52%	7.6	7.64	0.53%	19:14:00	19:14:00	0.00%	22	22	0.00%

Station Name	Ridership (2021)	Ridership (2022)	% Change in Ridership	Customer Satisfaction Score (2021)	Customer Satisfaction Score (2022)	% Change in Customer Satisfaction	Service Span (Amplitude) (2021)	Service Span (Amplitude) (2022)	% Change in Service Span	Trains per hour (off-peak) 2021	Trains per hour (off-peak) 2022	% Change in Off Peak Service
Den Haag HS	20,287	29,974	47.75%	7.2	7.18	-0.28%	23:24:00	23:16:00	-0.57%	20	24	20.00%
Den Haag Laan van NOI	7,075	11,608	64.07%	6.9	7	1.45%	20:28:00	20:20:00	-0.65%	16	20	25.00%
Deventer	12,661	17,564	38.73%	7.5	7.45	-0.67%	18:44:00	18:58:00	1.25%	12	12	0.00%
Driebergen-Zeist	4,258	7,084	66.37%	8	7.84	-2.00%	19:00:00	19:00:00	0.00%	8	10	25.00%
Duivendrecht	6,707	9,408	40.27%	7	6.8	-2.86%	19:22:00	19:20:00	-0.17%	24	24	0.00%
Eindhoven Centraal	36,450	56,113	53.95%	7.4	7.48	1.08%	19:21:00	19:21:00	0.00%	22	22	0.00%
Grou-Jirnsum	513	652	27.10%	7.2	7.43	3.19%	19:26:00	19:26:00	0.00%	4	4	0.00%
Haarlem	22,496	33,456	48.72%	7.7	7.69	-0.13%	19:37:00	19:45:00	0.68%	18	18	0.00%
Hilversum	14,694	21,933	49.27%	7.2	6.97	-3.19%	19:46:00	19:46:00	0.00%	20	20	0.00%
Hoofddorp	7,757	12,473	60.80%	6.9	6.93	0.43%	19:09:00	19:16:00	0.61%	14	14	0.00%
Houten	3,986	5,727	43.68%	7.6	7.48	-1.58%	18:49:00	18:48:00	-0.09%	8	8	0.00%
Houten Castellum	2,891	4,232	46.39%	7.5	7.54	0.53%	18:50:00	18:48:00	-0.18%	8	8	0.00%
Krabbendijke	525	655	24.76%	6.5	7.28	12.00%	18:31:00	18:29:00	-0.18%	4	4	0.00%
Kruiningen-Yerseke	518	659	27.22%	6.2	6.98	12.58%	18:41:00	18:39:00	-0.18%	4	4	0.00%
Lage Zwaluwe	544	764	40.44%	6.5	5.22	-19.69%	19:00:00	19:00:00	0.00%	8	8	0.00%
Leiden Centraal	48,046	72,162	50.19%	7.6	7.55	-0.66%	23:38:00	20:39:00	-12.62%	28	32	14.29%

Station Name	Ridership (2021)	Ridership (2022)	% Change in Ridership	Customer Satisfaction Score (2021)	Customer Satisfaction Score (2022)	% Change in Customer Satisfaction	Service Span (Amplitude) (2021)	Service Span (Amplitude) (2022)	% Change in Service Span	Trains per hour (off-peak) 2021	Trains per hour (off-peak) 2022	% Change in Off Peak Service
Lelystad Centrum	8,279	10,395	25.56%	6.8	6.65	-2.21%	20:31:00	20:36:00	0.41%	10	10	0.00%
Maarn	813	1,211	48.95%	7.4	7.48	1.08%	18:19:00	18:16:00	-0.27%	4	4	0.00%
Olst	814	1,019	25.18%	7.5	7.48	-0.27%	18:00:00	18:00:00	0.00%	4	4	0.00%
Oosterbeek	248	397	60.08%	7.7	8.04	4.42%	18:30:00	18:30:00	0.00%	4	4	0.00%
Overveen	1,262	1,604	27.10%	8.2	7.85	-4.27%	19:20:00	18:37:00	-3.71%	4	4	0.00%
Rijssen	1,383	1,825	31.96%	7.1	7.11	0.14%	18:00:00	18:00:00	0.00%	4	4	0.00%
Rijswijk	3,237	4,532	40.01%	6.6	6.08	-7.88%	20:34:00	20:15:00	-1.54%	8	8	0.00%
Rotterdam Alexander	8,125	12,275	51.08%	7.3	7.19	-1.51%	19:20:00	19:20:00	0.00%	12	12	0.00%
Rotterdam Blaak	11,890	17,976	51.19%	6.9	6.87	-0.43%	19:48:00	19:48:00	0.00%	16	20	25.00%
Rotterdam Centraal	55,553	88,983	60.18%	8	8.03	0.37%	23:00:00	23:00:00	0.00%	34	38	11.76%
Rotterdam Zuid	2,155	2,769	28.49%	5.8	5.88	1.38%	19:54:00	19:54:00	0.00%	8	12	50.00%
Schiedam Centrum	12,579	17,476	38.93%	6.8	6.7	-1.47%	20:27:00	20:32:00	0.41%	16	20	25.00%
Schiphol Airport	36,649	73,830	101.45%	7.7	7.6	-1.30%	23:04:00	19:40:00	-14.74%	46	48	4.35%
Hertogenbosch ('s)	31,996	48,895	52.82%	7.5	7.37	-1.73%	19:10:00	19:10:00	0.00%	24	24	0.00%
Soestdijk	440	613	39.32%	7.7	7.87	2.21%	18:41:00	18:39:00	-0.18%	4	4	0.00%
Utrecht Centraal	114,243	188,933	65.38%	7.9	7.8	-1.27%	22:57:00	23:06:00	0.65%	57	65	14.04%

Station Name	Ridership (2021)	Ridership (2022)	% Change in Ridership	Customer Satisfaction Score (2021)	Customer Satisfaction Score (2022)	% Change in Customer Satisfaction	Service Span (Amplitude) (2021)	Service Span (Amplitude) (2022)	% Change in Service Span	Trains per hour (off-peak) 2021	Trains per hour (off-peak) 2022	% Change in Off Peak Service
Utrecht Lunetten	1,915	2,621	36.87%	7.1	7.06	-0.56%	18:57:00	18:57:00	0.00%	8	8	0.00%
Weesp	8,199	11,460	39.77%	7	6.9	-1.43%	19:30:00	19:30:00	0.00%	12	12	0.00%
Wezep	582	839	44.16%	7.1	7.53	6.06%	18:59:00	18:59:00	0.00%	4	4	0.00%
Woerden	8,110	11,835	45.93%	7.2	7.15	-0.69%	19:27:00	19:27:00	0.00%	14	14	0.00%
Wolfheze	354	468	32.20%	6.8	7.12	4.71%	18:30:00	18:30:00	0.00%	4	4	0.00%
Zaandam	12,409	18,395	48.24%	7.2	7.11	-1.25%	19:35:00	19:28:00	-0.60%	20	20	0.00%
Mean	**15,564**	**24,886**	**47.70%**	**7.2**	**7.2042**	**0.13%**	**19:51:10**	**19:42:41**	**-0.62%**	**15.28**	**16.08**	**4.19%**
Standard Deviation	**22,372**	**37,571**	**16.70%**	**0.519**	**0.543**	**4.70%**	**01:31:39**	**01:21:19**	**2.80%**	**12.464**	**13.478**	**13.25%**
Min	**248**	**397**	**24.76%**	**5.8**	**5.22**	**-19.69%**	**18:00:00**	**18:00:00**	**-14.74%**	**4**	**4**	**-50.0%**
Max	**114,243**	**188,933**	**101.45%**	**8.2**	**8.04**	**12.58%**	**23:38:00**	**23:32:00**	**2.10%**	**57**	**65**	**50.00%**

Appendix G: Tabulation of Bus, Tram, Ferry and Metro connecting directions of travel

Station Name	Number of Bus Directions 2021	Number of Tram Directions 2021	Number of Ferry Directions 2021	Number of Metro Directions 2021	Connecting Bus, Tram & Metro Directions 2021	Number of Bus Directions 2022	Number of Tram Directions 2022	Number of Ferry Directions 2022	Number of Metro Directions 2022	Connecting Bus, Tram & Metro Directions 2022
Akkrum	4				**4**	4				**4**
Almere Centrum	10				**10**	10				**10**
Almere Oostvaarders	3				**3**	3				**3**
Amsterdam Bijlmer ArenA	14			3	**17**	14			3	**17**
Amsterdam Centraal	11	8	3	5	**27**	11	8	3	5	**27**
Amsterdam Lelylaan	4	4	0	3	**11**	4	4	0	3	**11**
Amsterdam Sloterdijk	10	1	0	3	**14**	12	1		3	**16**
Amsterdam Zuid	9	3			**12**	9	3			**12**
Boskoop Snijdelwijk	2				**2**	2				**2**
Breda	26				**26**	26				**26**
Delft	12	3			**15**	12	3			**15**
Den Haag Centraal	9	14		1	**24**	9	14		1	**24**
Den Haag HS	0	9			**9**	0	9			**9**

Station Name	Number of Bus Directions 2021	Number of Tram Directions 2021	Number of Ferry Directions 2021	Number of Metro Directions 2021	Connecting Bus, Tram & Metro Directions 2021	Number of Bus Directions 2022	Number of Tram Directions 2022	Number of Ferry Directions 2022	Number of Metro Directions 2022	Connecting Bus, Tram & Metro Directions 2022
Den Haag Laan van NOI	2	6		2	**10**	2	6		2	**10**
Deventer	16				**16**	16				**16**
Driebergen-Zeist	10				**10**	10				**10**
Duivendrecht	2			5	**7**	2			5	**7**
Eindhoven Centraal	18				**18**	18				**18**
Grou-Jirnsum	2				**2**	2				**2**
Haarlem	20				**20**	20				**20**
Hilversum	15				**15**	15				**15**
Hoofddorp	15				**15**	15				**15**
Houten	4				**4**	4				**4**
Houten Castellum	0				**0**	0				**0**
Krabbendijke	10				**10**	10				**10**
Kruiningen-Yerseke	3				**3**	3				**3**
Lage Zwaluwe	5				**5**	5				**5**
Leiden Centraal	32				**32**	32				**32**
Lelystad Centrum	19				**19**	19				**19**
Maarn	2				**2**	2				**2**
Olst	3				**3**	3				**3**

Station Name	Number of Bus Directions 2021	Number of Tram Directions 2021	Number of Ferry Directions 2021	Number of Metro Directions 2021	Connecting Bus, Tram & Metro Directions 2021	Number of Bus Directions 2022	Number of Tram Directions 2022	Number of Ferry Directions 2022	Number of Metro Directions 2022	Connecting Bus, Tram & Metro Directions 2022
Oosterbeek	2				**2**	2				**2**
Overveen	2				**2**	2				**2**
Rijssen	2				**2**	2				**2**
Rijswijk	10	2			**12**	10	2			**12**
Rotterdam Alexander	5			4	**9**	5			4	**9**
Rotterdam Blaak	6			6	**12**	6			6	**12**
Rotterdam Centraal	4	14			**18**	4	14			**18**
Rotterdam Zuid	3	6			**9**	3	6			**9**
Schiedam Centrum	7	4		5	**16**	7	4		5	**16**
Schiphol Airport	36				**36**	35				**35**
"s-Hertogenbosch	34				**34**	34				**34**
Soestdijk	2				**2**	2				**2**
Utrecht Centraal	35	3			**38**	35	3			**38**
Utrecht Lunetten	3				**3**	3				**3**
Weesp	4				**4**	4				**4**
Wezep	2				**2**	2				**2**
Woerden	15				**15**	15				**15**

Station Name	Number of Bus Directions 2021	Number of Tram Directions 2021	Number of Ferry Directions 2021	Number of Metro Directions 2021	Connecting Bus, Tram & Metro Directions 2021	Number of Bus Directions 2022	Number of Tram Directions 2022	Number of Ferry Directions 2022	Number of Metro Directions 2022	Connecting Bus, Tram & Metro Directions 2022
Wolfheze	3				**3**	3				**3**
Zaandam	9				**9**	9				**9**

Appendix H: Datasets used in this research

Requirement	Relevant Sub-Question(s)	Format of the data (including spatial features)	Relevant attribute(s)	Name dataset	Year of dataset	Source of dataset
Population density	2 & 4	Polygons in 100 m^2 grid with population of each square.	Total inhabitants (aantal_inwoners)	*Statistische gegevens per vierkant 2022*	2021	CBS: https://www.cbs.nl/nl-nl/dossier/nederland-regionaal/geografische-data/kaart-van-100-meter-bij-100-meter-met-statistieken
Land uses	2 & 4	Polygons of land use classifications	BBG2017 classification	Soil use: *Bestand bodemgebruik (BBG)*	2017	CBS: https://www.cbs.nl/nl-nl/dossier/nederland-regionaal/geografische-data/natuur-en-milieu/bestand-bodemgebruik
Length of cycling network	2 & 4	Network dataset of local cycling network	Classification of network link	netherlands-210101-free.shp.zip	2021	OpenStreetMap capture from Geofabrik: https://download.geofabrik.de/europe/netherlands.html
Ridership at NS Stations	1, 2 & 5	Average number of trips per working day	Number of riders at each station	*Reizigersgedrag*	2021 & 2022	NS: https://dashboards.nsjaarverslag.nl/reizigersgedrag
Customer satisfaction survey scores	3, 4 & 5	Station experience score for each station in the Netherlands	Score (out of 10) at each station	*Stationsbelevingsmonitor (SBM)*	2021 & 2022	NS Stations: https://stations.nl/wp-content/uploads/2021/12/SBM-jaarcijfer-2021-4.pdf

Requirement	Relevant Sub-Question(s)	Format of the data (including spatial features)	Relevant attribute(s)	Name dataset	Year of dataset	Source of dataset
Locations of Railway Stations in the Netherlands	1, 2, 3 & 4	Point data of stations within the Netherlands	Location, Station Name	*Stations (NS)*	2023	ESRI Nederland: https://www.arcgis.com/home/item.html?id=822b7e9ad10e476e9092265416ad484d
Job density	2 & 4	Point data of all employment locations	Location, Number of Jobs	*(Werkgelegenheidsregister)*	2021	Stitching LISA: https://www.lisadata.nl/

Appendix I: GIS Analysis Steps

This appendix describes the routine analysis steps completed in ArcGIS Pro 3.0.0. The regression process completed in ArcGIS and SPSS is described in section 3.4.

Data Preparation

1. **Inner Join** between my table of selected stations and the “naam” attribute of the ESRI Stations (NS) dataset.

Generate Local Pedestrian and Cycling Network

1. **Downloaded** 2021 OSM Shapefile from Geofabrik.
2. **Removed** roads with the following values for fclass attribute:
    - Motorway
    - Motorway-link
    - Trunk
    - Trunk-link
    - Primary
    - Primary-link
    - Bridlepath
    - Service
3. Created a **network dataset** with the following options:
    - Height: assumed that all links that cross each other actually intersected (i.e., ignored height differences)
    - Service-area index used
    - No hierarchy selected
    - Disregarded one-way flows.
4. Imported **facilities** (the 50 stations from ESRI) into the network dataset.
    - Snap to network enabled
    - Snap offset set to 5m
    - Search tolerance set to 5000 m
5. Generated **Service Areas** of 1km walking distance and 2,500 m cycling distance for the 50 selected stations using the Network Analyst tool.
    - Vertical connectivity & high precision enabled.

Length of Pedestrian and Cycling Network in Station Area

1. **Intersect** the station area polygons (1,000 m and 2,500 m) with the cycling network.
2. **Summary Statistics** to sum the length of the edges.

Permeability

1. **Intersect** the road junctions generated by the network dataset with the station area polygons.
2. **Sum** the number of junctions.

PedShed Ratio

1. Find the **area** of the station area polygons (1,000 m and 2,500 m).
2. **Divide** the area of a Euclidian circle around the station (1,000 m and 2,500 m).

Population Density

1. Using the CBS population demographic 100 m squares data from 2021.
2. Use the **field calculator** to change the values of "-99997" (i.e. between 1 and 4 residents) (Centraal Bureau voor de Statistiek, 2022b) to 2.5.
3. Intersect the service areas generated in the previous section with the CBS population squares.
4. Use the **Apportion Polygon** tool to proportionally assign the population from the CBS 100 metre squares to the service area surrounding the stations.
5. Use field calculator to take antaal_inwoners (total residents) (w/ correction from step 2) and divide by area_shape (in square metres) and multiply by 1000 for persons per square kilometre. Result: population_density column in population_proportional feature class.

Job Density

1. Extracted table from LISA 2021 dataset.
2. Used **XY Table to Point tool** to convert columns of X & Y coordinates into spatial data
    - Selected RD_New and Amersfoort coordinate system.
    - Result: Pins on a map w/ a # of jobs for each point.
3. Use **Pairwise Intersect** to find all of the job location points within the service area radius of the 50 stations. (Each point representing one location with a number of job
4. Use the **Summarize Within** tool to sum the Baan field (I.e., to find total the number of jobs at all points within the service area).
5. Use the **field calculator** to divide step 4 by the area of the service area polygon. Multiply by 1000 for a per-square kilometre figure.

Land Use Mix

1. Run **Intersect** of the land uses plus the 1km station service areas generated earlier.
    - Esri recommends Intersect as a default.
2. Use the **Pairwise Dissolve** tool to remove the borders between land uses.
    - Result: One polygon for each type of land use in each station catchment area.
    - Pairwise dissolve can be used interchangeably with Dissolve, so it was chosen to increase performance.
3. **Join field** to get the station names
4. Use **summary statistics** to count the number of different types of land uses in each station area and calculate the area of each station catchment area and join those to the table.
5. Calculate the **first part** of the **entropy index** using the following formula:
$$\frac{\text{area of one land use}}{\text{area of station catchment area}} \times \ln\left(\frac{\text{area of one land use}}{\text{area of station catchment area}}\right)$$
6. **Sum** the entropy index for each station catchment area and join that to the table.
7. Calculate the rest of the **entropy index** using the following formula:
$$\frac{\text{sum of entropy in station catchment area}}{\ln(\text{number of different land uses in station catchment area})}$$

Appendix J: Results of GIS Analysis (Place Values) Fed into Regression Analysis

Using the 1,000 m service area

Station Name	Bike Network Length (m)	Job Density (per km^2)	Log of Job Density	Land use mix (entropy)	PedShed Ratio	Log of PedShed Ratio	Permeability (Number of junctions)	Population Density
Akkrum	38906.43	0.85212	-0.06950	0.70469	0.49271	-0.30741	652	1.886265
Almere Centrum	103944.50	8.49522	0.92917	0.79101	0.84370	-0.07381	1894	4.770539
Almere Oostvaarders	83507.77	1.15184	0.06139	0.63216	0.79588	-0.09915	1261	5.948704
Amsterdam Bijlmer ArenA	67311.26	21.25966	1.32756	0.81832	0.70369	-0.15262	1114	4.521371
Amsterdam Centraal	73950.45	20.49165	1.31158	0.79039	0.63189	-0.19936	1888	8.937817
Amsterdam Lelylaan	87794.24	4.82122	0.68316	0.68534	0.78587	-0.10465	1468	10.420231
Amsterdam Sloterdijk	61666.42	13.52135	1.13102	0.70360	0.72714	-0.13838	1069	1.888907
Amsterdam Zuid	66905.10	19.15836	1.28236	0.74258	0.65032	-0.18688	1210	6.120372
Boskoop Snijdelwijk	51920.72	0.54510	-0.26352	0.66137	0.63825	-0.19501	1067	3.255383
Breda	76396.89	5.92213	0.77248	0.82570	0.78248	-0.10653	1397	5.527919
Delft	95284.67	5.40145	0.73251	0.64110	0.76763	-0.11485	2114	10.533935
Den Haag Centraal	93099.68	27.98097	1.44686	0.89459	0.74360	-0.12866	1900	5.621959
Den Haag HS	66375.15	8.43897	0.92629	0.71809	0.59264	-0.22721	1317	13.647364
Den Haag Laan v NOI	74981.23	10.02128	1.00092	0.60527	0.68256	-0.16586	1308	9.684891
Deventer	80389.75	4.87115	0.68763	0.65230	0.80800	-0.09259	1230	7.051173
Driebergen-Zeist	26090.64	2.69234	0.43013	0.83824	0.52316	-0.28137	304	0.259869
Duivendrecht	45080.78	2.67922	0.42801	0.76555	0.60437	-0.21870	776	4.783201
Eindhoven Centraal	72431.48	10.97080	1.04024	0.82126	0.71413	-0.14622	1408	4.938502
Grou-Jirnsum	24735.79	1.11562	0.04752	0.77124	0.47220	-0.32587	314	1.396151

Station Name	Bike Network Length (m)	Job Density (per km^2)	Log of Job Density	Land use mix (entropy)	PedShed Ratio	Log of PedShed Ratio	Permeability (Number of junctions)	Population Density
Haarlem	66928.63	5.33847	0.72742	0.63972	0.62738	-0.20247	1107	8.943668
Hilversum	76426.43	4.63574	0.66612	0.52526	0.87211	-0.05943	997	8.342481
Hoofddorp	64030.85	7.26237	0.86108	0.76849	0.70124	-0.15414	1074	1.531872
Houten	87359.21	2.21826	0.34601	0.49108	0.86973	-0.06062	1695	5.278335
Houten Castellum	95124.60	1.90874	0.28075	0.63805	0.87418	-0.05840	1716	5.433772
Krabbendijke	25723.36	0.65924	-0.18096	0.61716	0.50747	-0.29459	266	2.420452
Kruiningen-Yerseke	12404.92	1.11957	0.04905	0.58949	0.36620	-0.43629	84	0.019938
Lage Zwaluwe	11182.66	0.06834	-1.16530	0.60166	0.27479	-0.56100	81	0.005191
Leiden Centraal	82377.64	13.24881	1.12218	0.80305	0.75695	-0.12093	1738	6.335819
Lelystad Centrum	99462.63	3.64997	0.56229	0.73259	0.79953	-0.09716	1928	3.957827
Maarn	42463.43	0.42794	-0.36861	0.63084	0.78472	-0.10528	427	1.607725
Olst	35407.17	0.91302	-0.03952	0.60853	0.60802	-0.21609	489	2.545434
Oosterbeek	36886.94	1.04261	0.01812	0.68318	0.67838	-0.16853	346	1.994542
Overveen	41564.34	1.83881	0.26454	0.68996	0.61366	-0.21207	451	2.869882
Rijssen	47243.66	2.91381	0.46446	0.54599	0.77758	-0.10925	654	2.864154
Rijswijk	86848.11	4.38120	0.64159	0.67419	0.73678	-0.13266	1460	6.363163
Rotterdam Alexander	70031.10	9.50059	0.97775	0.70301	0.67729	-0.16923	1081	5.186355
Rotterdam Blaak	96560.87	17.66554	1.24713	0.74138	0.70743	-0.15032	2120	10.894993
Rotterdam Centraal	79780.19	15.95689	1.20295	0.73556	0.73842	-0.13170	1528	11.921296
Rotterdam Zuid	70318.74	3.83809	0.58411	0.69585	0.66812	-0.17515	957	10.983383
Schiedam Centrum	79898.26	4.02385	0.60464	0.71199	0.79549	-0.09937	1287	8.540408
Schiphol Airport	21641.20	13.74517	1.13815	0.76168	0.23999	-0.61981	406	0.046423
's-Hertogenbosch	88577.26	9.47828	0.97673	0.81740	0.81778	-0.08736	1588	5.941333
Soestdijk	40130.23	1.16510	0.06636	0.53532	0.69176	-0.16005	434	3.320562
Utrecht Centraal	87410.45	26.97645	1.43098	0.83246	0.67679	-0.16955	2246	7.870483
Utrecht Lunetten	53119.40	1.87456	0.27290	0.76040	0.61639	-0.21014	988	4.260916

Station Name	Bike Network Length (m)	Job Density (per km^2)	Log of Job Density	Land use mix (entropy)	PedShed Ratio	Log of PedShed Ratio	Permeability (Number of junctions)	Population Density
Weesp	48726.30	1.97872	0.29638	0.72719	0.59987	-0.22194	718	5.504357
Wezep	35901.45	0.83746	-0.07704	0.59061	0.66136	-0.17956	371	2.069391
Woerden	58799.36	3.92598	0.59395	0.79427	0.76464	-0.11654	1021	3.581572
Wolfheze	32962.37	0.66233	-0.17893	0.77865	0.61275	-0.21271	273	0.739672
Zaandam	63004.86	5.09078	0.70678	0.77676	0.80166	-0.09601	1208	5.251474
Mean	**62,581**	**6.77474**	**0.55996**	**0.70529**	**0.67757**	**-0.18107**	**1,089**	**5.15643**
Standard Deviation	**24,711**	**7.11979**	**0.55115**	**0.09220**	**0.13868**	**0.11257**	**586**	**3.40823**
Min	**11,183**	**0.06834**	**-1.16530**	**0.49108**	**0.23999**	**-0.61981**	**81**	**0.00519**
Max	**103,945**	**27.98097**	**1.44686**	**0.89459**	**0.87418**	**-0.05840**	**2,246**	**13.64736**

Using the 2,500 m service area

Station Name	Bike Network Length (m)	Job Density (per km^2)	Log of Job Density	Land use mix (entropy)	PedShed Ratio	Log of PedShed Ratio	Permeability (Number of junctions)	Population Density
Akkrum	72247.04	0.31274	-0.50482	0.59415	0.25535	-0.59287	863	0.80604
Almere Centrum	505635.02	2.38570	0.37762	0.65853	0.69987	-0.15498	9141	4.16279
Almere Oostvaarders	302502.96	0.81746	-0.08753	0.69964	0.59250	-0.22732	4156	3.52333
Amsterdam Bijlmer ArenA	244408.89	9.04579	0.95645	0.80350	0.44826	-0.34847	4147	4.70714
Amsterdam Centraal	353493.85	14.25296	1.15391	0.65348	0.55356	-0.25684	7367	11.77177
Amsterdam Lelylaan	385589.17	5.99112	0.77751	0.65855	0.58680	-0.23151	6387	10.32118
Amsterdam Sloterdijk	296675.57	5.53855	0.74340	0.72956	0.57280	-0.24200	4537	5.09356
Amsterdam Zuid	388734.72	8.61536	0.93527	0.69920	0.66028	-0.18027	6141	7.37022
Boskoop Snijdelwijk	175994.04	0.57668	-0.23906	0.60708	0.51955	-0.28437	2721	2.14355
Breda	376312.83	3.67617	0.56540	0.65731	0.72434	-0.14006	5544	4.67227
Delft	437073.87	3.18477	0.50308	0.64696	0.69167	-0.16010	8459	6.74993
Den Haag Centraal	251767.70	13.03290	1.11504	0.75111	0.39897	-0.39906	4272	6.73544
Den Haag HS	270914.02	5.60351	0.74846	0.61524	0.39114	-0.40767	4841	13.98418
Den Haag Laan van NOI	274660.56	4.58050	0.66091	0.65422	0.40220	-0.39556	5372	6.91356
Deventer	333853.88	2.23308	0.34890	0.71591	0.70044	-0.15463	4608	3.76177
Driebergen-Zeist	217613.77	1.07425	0.03111	0.65694	0.61049	-0.21432	2611	1.69198
Duivendrecht	192116.83	3.56295	0.55181	0.82779	0.42039	-0.37634	3332	3.81649

Station Name	Bike Network Length (m)	Job Density (per km^2)	Log of Job Density	Land use mix (entropy)	PedShed Ratio	Log of PedShed Ratio	Permeability (Number of junctions)	Population Density
Eindhoven Centraal	438410.81	4.70380	0.67245	0.66413	0.77647	-0.10987	6841	5.26669
Grou-Jirnsum	73563.44	0.42760	-0.36896	0.61664	0.32385	-0.48966	787	0.91190
Haarlem	298037.27	4.20747	0.62402	0.57410	0.52932	-0.27628	4379	7.91076
Hilversum	342760.72	2.62728	0.41951	0.59229	0.79868	-0.09763	3683	4.62036
Hoofddorp	229831.74	3.35862	0.52616	0.72642	0.50459	-0.29706	3353	2.40387
Houten	215863.82	1.69572	0.22935	0.65926	0.47442	-0.32384	3359	2.58112
Houten Castellum	176233.18	1.09477	0.03932	0.69167	0.40087	-0.39700	2599	2.82503
Krabbendijke	61312.57	0.25494	-0.59356	0.47262	0.32542	-0.48755	385	0.67442
Kruiningen-Yerseke	70524.75	0.30062	-0.52199	0.44142	0.41863	-0.37817	382	0.16496
Lage Zwaluwe	39906.04	0.06974	-1.15650	0.44549	0.24828	-0.60506	308	0.14426
Leiden Centraal	487750.73	4.42062	0.64548	0.68223	0.75024	-0.12480	9314	6.24789
Lelystad Centrum	485097.19	1.54703	0.18950	0.64917	0.71089	-0.14820	8763	3.74919
Maarn	142105.38	0.14686	-0.83311	0.56071	0.59476	-0.22566	1044	0.38529
Olst	71317.03	0.38610	-0.41330	0.51114	0.32686	-0.48563	756	0.99753
Oosterbeek	201124.75	0.61358	-0.21213	0.64508	0.64585	-0.18987	1700	0.86992
Overveen	177583.29	0.71329	-0.14673	0.68356	0.51216	-0.29060	1838	1.71128
Rijssen	239272.37	1.16710	0.06711	0.67663	0.71946	-0.14300	2452	1.96020
Rijswijk	377796.36	2.37899	0.37639	0.68991	0.63678	-0.19601	5507	5.30446
Rotterdam Alexander	398159.76	3.59364	0.55554	0.62084	0.66731	-0.17567	5878	5.38351
Rotterdam Blaak	253338.59	8.35212	0.92180	0.72909	0.38776	-0.41144	4570	9.81058
Rotterdam Centraal	296342.11	7.78228	0.89111	0.71358	0.49384	-0.30641	4821	10.38359
Rotterdam Zuid	253264.30	5.32045	0.72595	0.71059	0.42578	-0.37081	3330	9.62261
Schiedam Centrum	352409.95	3.03617	0.48233	0.69298	0.68568	-0.16388	4617	5.36080
Schiphol Airport	41012.70	8.38801	0.92366	0.73727	0.09726	-1.01205	636	0.01833
Hertogenbosch ('s)	356105.50	3.74684	0.57367	0.77401	0.65734	-0.18221	5705	3.70670
Soestdijk	173280.56	0.93217	-0.03050	0.61736	0.56783	-0.24578	1815	2.52087

Station Name	Bike Network Length (m)	Job Density (per km^2)	Log of Job Density	Land use mix (entropy)	PedShed Ratio	Log of PedShed Ratio	Permeability (Number of junctions)	Population Density
Utrecht Centraal	449511.39	8.32915	0.92060	0.63700	0.67792	-0.16882	8511	9.61156
Utrecht Lunetten	236660.99	1.77127	0.24828	0.80205	0.50982	-0.29258	3998	3.85814
Weesp	142362.22	1.15701	0.06334	0.70979	0.39467	-0.40377	1934	2.54054
Wezep	138661.84	0.45305	-0.34386	0.60060	0.48485	-0.31439	1166	1.22418
Woerden	226924.89	2.02252	0.30589	0.69340	0.55656	-0.25449	3329	2.95457
Wolfheze	120439.73	0.15324	-0.81462	0.66600	0.55735	-0.25387	690	0.14673
Zaandam	299216.10	2.46248	0.39137	0.70499	0.61159	-0.21354	5018	4.76557
Mean	**258,916**	**3.44198**	**0.27990**	**0.66042**	**0.53403**	**-0.29604**	**3,959**	**4.37725**
Standard Deviation	**125,379**	**3.34306**	**0.55102**	**0.08129**	**0.15315**	**0.16053**	**2,486**	**3.37054**
Min	**39,906**	**0.06974**	**-1.15650**	**0.44142**	**0.09726**	**-1.01205**	**308**	**0.01833**
Max	**505,635**	**14.25296**	**1.15391**	**0.82779**	**0.79868**	**-0.09763**	**9,314**	**13.98418**

Appendix K: Full Coefficients Output from SPSS

This output reflects the 1,000 m model using 2022 data.

	Unstandardized Coefficients		Standardized Coefficients			95.0% Confidence Interval for B		Correlations			Collinearity Statistics	
	B	Std. Error	Beta	t	Sig.	Lower Bound	Upper Bound	Zero-order	Partial	Part	Tolerance	VIF
(Constant)	0.520	1.326		0.392	0.697	-2.162	3.203					
Log(CSScore2022)	1.579	1.173	0.072	1.346	0.186	-0.794	3.952	0.125	0.211	0.057	0.631	1.584
Log(Span2022)]	-0.836	2.177	-0.031	-0.384	0.703	-5.240	3.568	0.617	-0.061	-0.016	0.275	3.632
Log(trainsPerHour2022)	1.016	0.213	0.466	4.763	0.000	0.585	1.448	0.911	0.606	0.203	0.190	5.264
Log (connections 2022)	0.373	0.152	0.207	2.450	0.019	0.065	0.681	0.850	0.365	0.104	0.255	3.926
Bike Network Length (m)	4.641E-06	0.000	0.151	0.663	0.511	0.000	0.000	0.638	0.106	0.028	0.035	28.465
Log(JobDensity)	0.389	0.128	0.282	3.033	0.004	0.129	0.648	0.888	0.437	0.129	0.211	4.747
Land use mix (entropy)	-0.017	0.474	-0.002	-0.036	0.972	-0.975	0.942	0.516	-0.006	-0.002	0.550	1.818
Log(PedShed)	-0.168	0.603	-0.025	-0.279	0.782	-1.388	1.052	0.266	-0.045	-0.012	0.228	4.387
Permeability (Number of junctions)	-2.57E-06	0.000	-0.002	-0.010	0.992	-0.001	0.001	0.721	-0.002	0.000	0.048	20.871
Population_density	0.001	0.018	0.003	0.031	0.975	-0.036	0.037	0.558	0.005	0.001	0.282	3.550

Appendix L: Full Output of Top-Five Models from Exploratory Regression Tool

Model	Year	Catchment Area Radius	Adjusted R-Squared	Akaike's Information Criterion (AICc)	Jarque-Bera p-value	Koenker (BP) Statistic p-value	Max Variance Inflation Factor (VIF)	Explanatory Variable 1	Explanatory Variable 2	Explanatory Variable 3
A	2021	1000 m	0.922961	-10.478327	0.41739	0.10446	3.898736	+LOG_TRAINSPERHOUR2021***	+LOG_JOBDENSITY_***	+LOG__CONNECTIONS_2021_**
	2021	2500 m	0.908222	-1.725182	0.37081	0.030014	4.437969	+LOG_TPH2021_***	+LOG_CONNECTIONS_2021_**	+LOG_JOBDENSITY_***
	2022	1000 m	0.913239	-0.590187	0.88537	0.280903	3.750484	+LOG_TRAINSPERHOUR2022_***	+LOG_JOBDENSITY_***	+LOG__CONNECTIONS_2022_**
	2022	2500 m	0.896221	8.365185	0.49345	0.071731	4.323637	+LOG_TPH2022_***	+LOG_CONNECTIONS2022_**	+LOG_JOBDENSITY_***
B	2021	1000 m	0.869354	15.930717	0.75523	0.614835	3.091919	+PERMEABILITY***	+LOG_JOBDENSITY_***	+LOG__CONNECTIONS_2021_***
	2021	2500 m	0.861463	18.863015	0.79277	0.145085	2.575973	+PERMEABILITY**	+LOG_CONNECTIONS_2021_***	+LOG_JOBDENSITY_***
	2022	1000 m	0.872335	18.722342	0.79783	0.311816	3.108009	+PERMEABILITY**	+LOG_JOBDENSITY_***	+LOG__CONNECTIONS_2022_***
	2022	2500 m	0.864673	21.636682	0.64417	0.276509	2.58067	+PERMEABILITY**	+LOG_CONNECTIONS2022_***	+LOG_JOBDENSITY_***
C	2021	1000 m	0.821182	31.624366	0.98014	0.724741	1.461529	+PERMEABILITY***	+LOG_CSSCORE2021_**	+LOG__CONNECTIONS_2021_***
	2021	2500 m	0.803984	36.215767	0.85852	0.488051	1.702122	+PERMEABILITY***	+LOG_CSSCORE2021_**	+LOG_CONNECTIONS_2021_***

Model	Year	Catchment Area Radius	Adjusted R-Squared	Akaike's Information Criterion (AICc)	Jarque-Bera p-value	Koenker (BP) Statistic p-value	Max Variance Inflation Factor (VIF)	Explanatory Variable 1	Explanatory Variable 2	Explanatory Variable 3
	2022	1000 m	0.81844	36.331256	0.85311	0.818839	1.466114	+PERMEABILITY***	+LOG_CSSCORE2022_**	+LOG__CONNECTIONS_2022_***
	2022	2500 m	0.796814	41.957998	0.69744	0.583229	1.711602	+PERMEABILITY***	+LOG_CSSCORE2022_**	+LOG_CONNECTIONS2022_***
D	2021	1000 m	0.803108	36.438761	0.35188	0.332486	3.671835	+BIKE_NETWORK_LENGTH***	+LOG_JOBDENSITY_***	-LOG_PEDSHED_**
	2021	2500 m	0.796823	38.009781	0.285	0.869506	5.04148	+BIKE_NETWORK_LENGTH***	+LOG_JOBDENSITY_***	-LOG_PEDSHED_**
	2022	1000 m	0.809286	38.790634	0.4088	0.10541	3.671835	+BIKE_NETWORK_LENGTH***	+LOG_JOBDENSITY_***	-LOG_PEDSHED_**
	2022	2500 m	0.798663	41.501049	0.35021	0.962899	5.04148	+BIKE_NETWORK_LENGTH***	+LOG_JOBDENSITY_***	-LOG_PEDSHED_**
E	2021	1000 m	0.787812	40.179489	0.55306	0.077749	1.216282	+POPULATION_DENSITY***	+LOG_CSSCORE2021_**	+LOG__CONNECTIONS_2021_***
	2021	2500 m	0.807083	35.419062	0.39327	0.031522	1.409688	+POPULATION_DENSITY***	+LOG_CSSCORE2021_**	+LOG_CONNECTIONS_2021_***
	2022	1000 m	0.788262	44.01937	0.17829	0.595918	1.212849	+POPULATION_DENSITY***	+LOG_CSSCORE2022_**	+LOG__CONNECTIONS_2022_***
	2022	2500 m	0.807506	39.255235	0.21535	0.232883	1.409257	+POPULATION_DENSITY***	+LOG_CSSCORE2022_***	+LOG_CONNECTIONS2022_***