A nodal approach for estimating potential cycling demand★

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Abstract

Establishing cycling as a prominent utility mode is recognised as central to creating sustainable transport systems in many cities around the world. Strategies of starter cycling cities are often biased to the supply of infrastructure along prominent corridors without acknowledging the nature, quantum or location of potential demand for cycling. Decisions are frequently left to local knowledge and experience of local needs, resulting in a bias with little opportunity for repeatability or reproducibility. This study proposes a data-driven approach to estimate the potential market for cycling geographically. Estimates are based on the number of potential cyclists in close proximity to the destinations they want to access. The paper demonstrates the method using Cape Town, South Africa as a case study. Given the virtual absence of utility cycling in the city, characteristics of cyclists in cities where cycling is popular are used to identify potential cyclists. Destination nodes are stratified in terms of the characteristics of their users, while home locations of persons with these characteristics are identified from a publicly available synthetic population for Cape Town. Analysis provides an order of magnitude indication of the cycling potential of selected nodes. It also shows areas with many potential cyclists that are not in proximity of desired destination. The results enable city authorities to focus detailed investigations and interventions where a critical mass of cycling may be achieved with the least effort and in the shortest time.

Keywords: Cycling potential, high potential zones, target population, travel behaviour, synthetic population

1. Introduction

Increasing the number of utility cyclists is progressively being promoted as a core strategy of transport plans in major cities around the world [13, 24]. Benefits of cycling include not contributing to emissions, having substantial health benefits as an active mode, lowest energy use per kilometre, low cost of travel, social inclusion for those without access to motorised transport, faster than motorised modes over short distances and requires among the least space per person travelling. The Netherlands, having the highest use of bicycles as a nation at about 25% of all trips, experiences these benefits. In recent years, utility cycling range between 30% and 40% in Utrecht and Amsterdam, but reach almost 50% in cities like Zwolle and Leiden [25]. In Copenhagen, the share of utility cycling exceeds 45% on average and reaches 63% in the

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central city [18]. In contrast, and despite its policy priority in many developing countries, cycling constitutes an almost negligible share of commuter, or utility modes, in some major African cities. For example, the share of cycling trips in Nairobi, Dar es Salaam and Cape Town ranged between 0,05% and 2% at around 2015 [31].

Since there is nothing novel about cycling, given the technology has evolved over more than 200 years, the question is why it is not an obvious choice of transport for more people in many more cities around the world. Several studies have demonstrated a strong correlation between the increase of cycling infrastructure and the increase of cycling as a utility mode [5, 30]. However, the simplification to believe in the mantra of *"if we build it, they will come"*, or providing infrastructure alone, is not enough to raise levels of cycling [24, 27]. Infrastructure is, therefore, a necessary, but not sufficient intervention to achieve more utility cycling. For a significant number of people to adopt cycling, one has to remove all the barriers that result in the current low uptake. People cannot cycle if they do not have access to a bicycle. People do not cycle when they feel vulnerable, sharing a road with higher speed mixed traffic. People would cycle up to a threshold distance, after which the effort and time travelling make other modes more attractive. People will also not adopt cycling if the norms, culture and acceptance of their community do not support or encourage it [47]. On the contrary, and somewhat counter-intuitively, an increase in cyclists in the streets typically reduce the percentage and number of cycling-related accidents [46].

Behaviour change requires a multi-pronged approach of *hard* and *soft* measures. Firstly, one must influence a community or individuals' ability to cycle and the benefits this hold for people directly or indirectly. Secondly, landowners or business owners have to integrate cycling facilities at the trip destinations, either on their properties or inside their buildings. Finally, authorities have to build the necessary infrastructure to keep cyclists safe from traffic, all while attracting an adequate number of cyclists to warrant the investment in these interventions. The premise of this article is that one achieves a critical mass of cycling in the shortest time when all necessary interventions are concentrated within the catchment area of a node of high cycling potential, to maximise the adoption of cycling at a significant scale.

A cycling mode share of say 10% of commuter trips will not be evenly distributed across a city [18] (accessed 2020). Cycling mode share could therefore follow a distribution that ranges from below 1% in some areas to more than 30% in others [48]. One can attribute the differences to the number of trip attractions (activity density), the population profile (potential cyclists) in the catchment, the extent of cycling infrastructure, local community preferences and others.

The contribution of this paper is methodological and aims to quantify a potential market for utility cycling. The focus is not on the interventions necessary to convert the potential. Instead, the three-step methodology to quantify the potential starts with identifying market segments based on rich, disaggregate descriptions of both households and individuals. Secondly, the proposed approach selects nodes with substantial trip attraction land uses for the target market segments. Finally, calculate the potential market using a synthetic population that represents the study area.

A case study in the City of Cape Town, South Africa, demonstrates the approach using publicly available data. The results show how authorities can effectively rank nodes based on their potential for utility cycling. The ranking would enable authorities to design more focussed and targeted interventions to both change and behavioural attitudes and enable different actions.

The paper is structured as follows. The next section reviews the underlying theories that drive people's behaviour to consider utility cycling as a viable choice. Section 3 provides the context for cycling in the City of Cape Town and introduces the market segment based on established literature. The results of the case study to estimate cycling potential, in Section 4, discuss the significance of ranking nodes. We conclude the paper in Section 5 and suggest a research agenda to further the body of knowledge.

2. Increased cycling as a change in travel behaviour

Observing a significant increase in cycling trips is the result of a large number of persons changing their travel behaviour from a prevailing mode to cycling. A variety of theories exist about the underlying cognitive process that influences the travel choices people make [1]. Rational Choice Theory suggests that people choose the mode that yields the highest utility, which typically translates to reaching a chosen destination in the shortest time, at the lowest cost and highest convenience while feeling safe and secure [29, 33, 41]. Cycling should therefore be the preferred mode for shorter trips where it is faster than driving, finding parking and walking to the final destination; where adequate infrastructure is available for safe and continuous travel [26]; ambient conditions are amenable to cycling and; people feel secure while travelling or storing their bicycles at both origin and destinations.

In contrast, Habit Formation Theories [20, 21] contest that people stop searching for superior alternatives when previous choices continue to yield desirable results. This has the implication that cycling might not be selected as a preferred mode by many, even when conditions become favourable. Behrens et al. [3] demonstrate that travel choices are more likely to be reviewed with life changing events, such as getting married, changing jobs and gaining or loosing access to a car. They also found a much greater likelihood to change between non-car modes than between car and other modes. The target market for taking up cycling as a new mode would therefore be greater amongst younger people who are leaving home, people who are becoming students, will start or change jobs more often and have a lower income where use of a private car is not (yet) embedded (habitual).

Women are more likely than men to benefit from the freedom cycling offers when they do not have regular access to a private car [34, 43]. While women are less likely to have permanent employment for which public transport is suitable, women typically have lower disposable income and greater family responsibilities than men. These gender-based roles range from travelling with parents and children or running other errands for the household.

Bamberg et al. [2] found that a person's attitude, subjective norms and perceived behavioural control influence their travel behaviour. Attitude is influenced by knowledge and expectations about the outcome of a choice, which can be influenced by targeted marketing. Subjective norms are influenced by a community and peers' perceptions, which may be influenced by campaigns, including leadership by public figures. The ability to act on the intention to cycle would be influenced by the physical environment, access to a bicycle and ability to ride. Strategies that aim to achieve substantial selection of cycling as a utility mode therefore needs to i) create a desire to want to benefit from cycling, ii) ensure the broader community accept or even encourage cycling as a mode and, iii) create the infrastructure and systems necessary to accommodate cyclists.

This paper's aim is to quantify a potential market for utility cycling and not on the interventions necessary to convert this potential. Interventions would take a variety of forms, will require budgets and adequate resources and would be exerted over different time periods to be effective. Appropriate knowledge sharing and marketing campaigns would be required to change the attitude of individuals and communities towards the benefits of cycling. Perceived behavioural control is influenced by access to a bicycle, trip distance, safety from traffic, ability to safely store it, topography, ambient temperature and wind factors [26, 36, 38]. Many barriers could be mitigated by technology such as e-bikes and clothing, but against the hurdle of additional cost. For instance, longer trip distances become attainable with e-bikes, despite wind and extreme temperatures. Data is emerging that demonstrates how electric bicycles not only increase the average trip distance, but also result in more bicycle trips [44].

Finally, while the premise of estimating the market for cycling is that an equilibrium is reached, Chatterjee [6], Saleh & Farrell [37] show that it is much more likely that a system experiences a degree of churn, where individuals swop between different modes on a continuous basis. Equilibrium should therefore be viewed as the point where the asymmetric churn that resulted in a substantial shift from prevailing modes to cycling, has slowed down to marginal levels. It is further believed that the principle for observing induced traffic for the car is likely to apply equally to cycling. It can therefore be expected that additional demand is likely to be induced when the infrastructure capacity and related conditions for cycling is improved [23]. It could be anticipated that the newly induced trips, as well as secondary trips also made by bicycle, will raise the total share of cycling trips over time.

The literature guides the selection of targeted individuals or groups by interrogating the profile of users more likely to shift to cycling from their current modes. The individual characteristics will be contextualised for Cape Town, where population data is available and the authors have local knowledge of the topography and ambient conditions.

3. Cycling potential in Cape Town

Cape Town has a population of about 4 million people living on an area of about 80 000 ha, at a relatively low density of about 15 dwelling units per hectare (du/ha). The low density and sprawling nature of the city result in average daily commute distance to work exceeding 15km per direction, with many exceeding 25km. While it still has a predominant central business district (CBD), as shown in Figure 1, there are several other

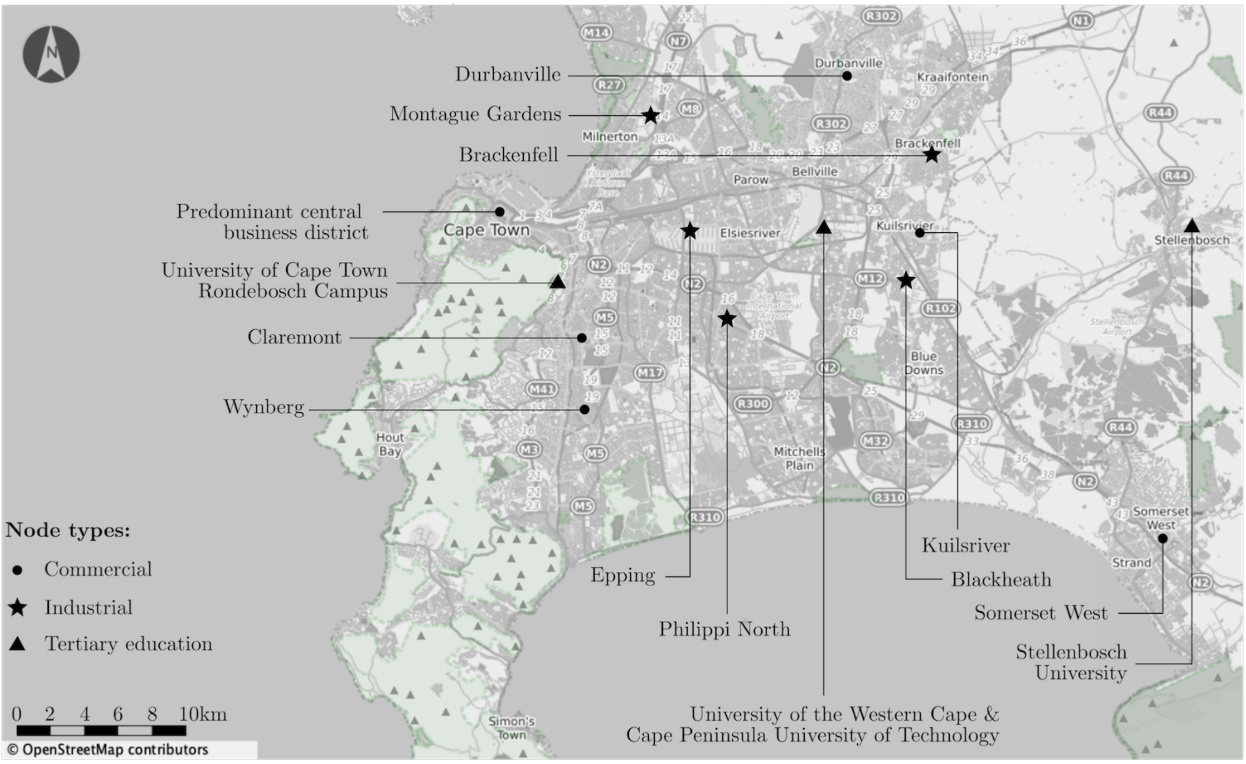

Figure 1: City of Cape Town with a few highlighted nodes.

strong nodes that serve local communities or have regional functions. Commercial nodes (denoted by the ● symbol) include the Central Business District (CBD), Claremont, Wynberg, Durbanville, Kuilsriver and Somerset West; Industrial nodes (denoted by ★) include Epping, Montague Gardens, Blackheath, Philippi North and Brackenfell; while tertiary education nodes (denoted by ▲) include the Universities of Cape

Town (UCT) and the Western Cape (UWC) as well as the Cape Peninsula University of Technology (CPUT) campuses. The campuses of UWC and CPUT lie adjacent to each other, and could be viewed as a single node for tertiary education trips.

3.1. Cycling context

South Africa has a strong policy framework to promote the increased use of cycling as a preferred mode of transport [15, 16]. The City of Cape Town published its first non-motorised transport (NMT) policy and strategy in 2005 and followed it up with a cycling strategy in 2016 [8, 12]. The 2016 Cycling Strategy sets a target for utility cycling to contribute a share of 8% to the daily commute by 2030. However, cycling as a commuter mode in Cape Town was about 0.7% in 2013 [10], and still only contributed up to 3% of commute trips in the highest use areas in 2016 [12].

In absolute terms there were about 1-million home-based work trips (one direction) in Cape Town in 2013. The strategy therefore aims to increase the number of daily cyclists from the current nearly 10 000 to about 80 000 bicycle trips per day by 2030. With population growth and achieving the targets set to lower unemployment, this target number is more likely to reach 90 000 by 2030. By the time of writing there is little evidence to indicate that any progress has been made towards the target over the first four years since this strategy was adopted.

Despite its moderate climate, Cape Town is renowned for extreme wind speeds during summer months, especially along the Atlantic sea board which includes the central business district (CBD). The CBD is also famous for being located on the foothill of Table Mountain, which is characterised by steep grades in some directions. However, cycling infrastructure has been provided at very flat grades around the mountain and along the north western coastline. Large parts of the city, where more than half the population live, is known as the *Cape Flats* due to its flat topography, as the name suggests. This area is largely shielded from the brunt of coastal winds and therefore offers a relatively attractive environment for cycling over an extended area.

Despite the almost negligible presence of utility cycling, Cape Town has an established culture of sport cycling, including hosting the world's largest annual timed cycle race for the 42$^{\text{nd}}$ time in 2020 [14]. Sport cycling supports a strong bicycling sales and service industry which is spread across all suburbs in the metropolitan area. Likewise, neighbouring Stellenbosch has been host to world class mountain biking competitions.

3.2. Synthetic populations

The more unequal a society, the more critical it becomes to work with disaggregate models that can discriminate and distinguish between entities at a low(er) level than, for example, suburbs or transport analysis zones (TAZs). There are many unique attributes and attribute combinations that affect individuals' travel behaviour. Consequently, advances in activity-based transport models required more detailed demographic/socioeconomic descriptions of the travelling population.

This paper benefits from publicly available synthetic populations generated using a Bayesian network approach [28]. Similar to earlier approaches like Iterative Proportional Fitting and Iterative Proportional Updating, a Bayesian network uses the detailed Public Use Micro Sample (PUMS) data and improves its geographic granularity by using the Community Profiles data, which is spatially more detailed but aggregated, as control totals. The result is a richly described and representative synthetic population. The City of Cape Town is one of the nine areas for which 100 such populations are available that are accurate at both household and individual levels. The multiple populations result from the inherent randomness in the generation procedure. Each population is available as a compressed extensible markup language (XML) file that, in turn, contains two separate XML files. The first describes the household with a unique (sequential) identifier and a list of all household members. The second describes each person in the population using a unique identifier for each; the same identifier listed in the household file.

Every household has several attributes, one of which is the household income that is expressed in South African Rand (ZAR) using 2011 values from which the Census-based synthetic populations originate. For each household, we also know the main dwelling and housing type, the tenure status and the number of rooms. For every person, we also have several attributes including age, gender, race, state of employment, level of completed education and the individual's current level of education.

3.3. Target market for cycling

The virtual absence of utility cycling means that revealed data is not available to describe distinguishing characteristics of utility cyclists in Cape Town. Instead, Travel Behaviour Theory is used as the basis for building a profile of characteristics that make individuals more likely to cycle than others, given the necessary interventions.

Shay & Khattak [39] found the factors most likely to influence travel decisions include household composition (number and type of dependents), type of dwelling, income and car ownership. Attributes are therefore borrowed from cities where cycling is substantial, or even a dominant mode.

3.3.1. Age

Copenhagen data shows that persons aged 18 to 25 years cycle the most, with the age group 26 to 35 a little less. Age group 36 to 59 still cycle a fair amount, but thereafter the contribution declines fast.

Behrens et al. [3] describe a strong correlation between mode change and what they refer to as *life-events*. Significant life events occur around the age of 18 when many individuals leave school and either start to work or embark on tertiary education. Life events also include getting married, having children, changing jobs or homes, etc. The frequency at which major life changing events occur decreases with age.

Until more data becomes available it is assumed that the likelihood of shifting to cycling is 100% for ages 18 to 25, 80% for ages 26 to 35, and 40% for ages 36 to 59. It is assumed that it would be much more difficult for people above the age of 60 to take up cycling, as their habits would be deeply entrenched, and their most common expected life event is to stop working (full time). Schools are typically spread uniformly throughout a community, and not concentrated within a node. While any school would not warrant the infrastructure investment intended here, learners would benefit from a cycling culture once warranted by the primary target groups identified in this paper.

Cape Town's population in 2011 consisted of 22% persons in the age group 6 to 18, 36% from 19 to 34, 33% from 35 to 59 and 9% above 60 years of age. The potential market for cycling is therefore initially well below 69% of the total population.

3.3.2. Gender

Gender refers to the roles, behaviours, activities, attributes and opportunities that any society considers appropriate for girls and boys, and women and men. Gender interacts with, but is different from the binary categories of biological sex.

While slightly more women than men cycle in Copenhagen (53% : 47%), men cycle longer distances. Cape Town's population in 2011 consisted of 51% female and 49% male [42]. Sustainable Mobility for All [45] highlight that women from lower income areas are less likely to travel by car, have more family responsibility, therefore less freedom of choice to travel. It is assumed that the freedom afforded by a bicycle would be more attractive to women than men in the Cape Town context. We therefore assume that all eligible women (100% chance) will take up cycling, but only 80% of men would. At this point we acknowledge that there may indeed exist negative cultural attitudes towards female cycling that may make it hard to unlock the calculated potential. In the absence of quantitative evidence to support the varying attitudes towards cycling, we do not provide diminishing factors to account for attitudes among the diverse population in South Africa.

3.3.3. Primary activity: tertiary education/employment

Since real market potential is being tested, it is assumed that current trip purposes will drive decisions. A total of 64% of peak hour trips in Cape Town are home-based work trips, with a further 33% being home-based trips to education (CCT, 2013b). Tertiary education students are possibly the most uniform group to target. These are mostly persons in the 18 to 25 year age group who receive grants, and possibly a nominal extra income, travelling in large numbers to a single destination (campus). It is assumed that all tertiary education students (100%) could cycle, regardless of their household income. Recall that the goal is to calculate total *potential*.

It is assumed that unemployed people would not be able to afford either obtaining or maintaining a bicycle, and are excluded from the initial potential market. The potential market therefore consists of people in formal employment; persons aged between the ages of 18 and 65. For the purpose of being conservative and ease of modelling, secondary activities and a complex trip chains are not considered.

3.3.4. Household composition

One or two person households with independent persons have the greatest freedom to choose their modes. In terms of rational choice theories, these depend mainly on their own intention, which is a factor of their personal preferences, the norms their communities exert on them and their perceived ability to use the mode [19, 41]. Informal enquiries among professional workers and academics in Cape Town revealed that the need to escort children to day care or school was a leading reason for not using public transport or cycling to work.

It is assumed that, all else being equal, members from one or two-person adult households have a 100% chance of cycling, while those with dependents have a 50% chance. Dependent children is likely to have a greater impact on travel decision than elderly dependents, but data is not available to refine these assumptions.

Physical ability, or prevalence of disabilities, may differ between different areas but are often reported as aggregated numbers within a community. It is assumed that the people with disabilities that would prevent them from cycling are uniformly distributed, and would result in a small reduction of the overall potential market.

3.3.5. Household income

More than 85% of Capetonians are members of Low and Low-Middle income households. 47% of Cape Town households fall in the low income group that earned under R3 200 (about USD 210) per month in 2012. Another 39% earned in the low-middle income bracket of R3 200 and R25 600 per month (USD 210 to USD 1 700). The City of Cape Town reports [11] that up to 45% of lower-income households' income could go towards transport. Because of trip suppression and latent demand, these households tend to spend much less on transport in practice, and therefore they would greatly benefit from the relatively low cost of cycling. More than 50% of these households make use of some form of public transport at least once a week, with fewer than 30% never using it.

The exact affordability point for bicycles would differ based on actual income, household size and travel distance (saving in public transport fares). A survey among low and low-middle income household members in Cape Town revealed a reluctance to purchase a bicycle when the benefits of cycling is not clear (survey under a 2017 project, no report). However, several programmes exist to distribute subsidised or free bicycles to communities where affordability is a barrier to cycling [4, 17, 35].

Only 13% of households in Cape Town are in the high-middle and high income bracket where affordability would not be a constraint to cycling. However, car ownership and usage is very high, with less than 36% making any trip without a car, and less than 25% use alternative modes at least once a week [9].

Higher income earners in the professional and service economy not only commute by car, but are also more likely to use the car for business trips throughout the day. On the other hand, lower and lower-middle income workers tend to spend more time at their work stations, and travel with senior staff (middle-high to higher income) for business trips. The low potential contribution to a shift to cycling in the short to medium term may not warrant the marketing effort to target the high-middle and high income groups in the initial stages. Work trips from these income groups are therefore excluded from the initial target market. This paper aims to quantify the high-probability target market. Excluding middle-high and high-income earners therefore does not imply that NMT is portrayed as a mode only for the poor. Once the high-potential areas are identified, authorities need to design the actual intervention(s), and here they need to ensure that the targeted interventions are inclusive across a broader demographic while still catering for those that can benefit most. The intervention design will dictate the most appropriate communication message for the different target groups.

Working class families were excluded from economic opportunities under apartheid. This also meant an inability to own cars, which was viewed as a privilege for disadvantaged communities. It may be prudent to include middle-high income groups during implementation to avoid cycling being viewed as a discriminatory tool to again prevent previously marginalised communities from purchasing cars.

3.3.6. Dwelling type

Bicycles need to be securely stored at or near the home. There is an inverse correlation between household size and income, while a positive correlation exists between dwelling size and income [42]. It is therefore argued that informal settlements, with low income households and relatively larger families do not have the space to securely store bicycles. Members from these households are excluded from the target market estimation of this study. This does not imply that innovative solutions can not be introduced to overcome this barrier.

3.4. A nodal approach

An assessment of its strategy, as well as completed and proposed cycling projects, reveal that Cape Town's approach focuses on the provision of infrastructure along corridors [12]. Cities where cycling constitutes a very low share as commuter mode, could benefit by assessing the potential market share of cycles before deciding where to prioritise interventions. Some of the main interventions to enable cycling are: infrastructure, cycle lanes and bicycle parking; access to bicycles and their maintenance and repair; information and marketing to make the mode socially acceptable. Both infrastructure and the places where bicycles can be purchased and maintained must be geographically linked to the destinations and origins of the target market segments.

In addition, while marketing through social and conventional media is not limited in space, the power of following early adopters by copying their example, has proven a powerful way to establish trends which, if sustained, could achieve the critical mass, or tipping point to mainstream using cycling as a mode [22]. Achieving such critical mass in one location confirms the value of the investment and would garner political support for further investment in consecutive areas.

In many instances, the selection of nodes to implement strategies to increase cycling are left to historic perceptions and individuals' personal experience of local needs [24]. However, recent examples exist where data-driven approaches were used to identify areas of high potential for new cycling demand and intervention. For example, [48] uses demographic data from transport zones and prevalence of cycling to understand the difference between potential and revealed demand for cycling. Silva et al. [40] uses both demographic data and proximity to priority land uses to estimate potential demand for cycling across a city, while [32] use data collected by tracking current cyclists to estimate potential demand on new bike paths. This study makes use of highly disaggregated population data to not only identify key user groups, but also the impact of household characteristics on the propensity to cycle.

Based on the analysis of market segments, students and low-middle income workers would gain most from using cycling as a main mode. Land uses that attract a significant proportion from these groups include tertiary academic institutions, industrial areas and business nodes. For this study, the nodes shown in Figure 1 were selected based on their mostly distinct primary land use, as well as local knowledge of key differences in the population profile in their catchments.

In cities where cycling is a regular and popular mode of transport, it is attractive as a utility mode for distances up to about 10km [24]. However, propensity to cycle declines with an increase in distance. Data for DTU [18] shows that the majority of people cycle between 5 and 8km for regular commutes. While 87% of distance by bicycle in Copenhagen is less than 5km, the majority are about 2km in length, with only 4% exceeding 11km. Data collected in 2009 among students in Valencia also revealed a reduction in cycling trips with increasing distance, and a threshold cycling distance of 5.1km [7].

Catchment areas increase from 7 854 m^2 to 20 106 m^2, or 2.5 times when the radius increases from 5 to 8 km. Travel paths are not radial, and typically include sections of grid-type streets, which could increase actual travel distances for 5km and 8km radii up to 7km ($5^2 = 4^2 + 3^2$) and 11.2km respectively. To account for the difference between catchment radius and travel distance, a catchment radius of 4km is used in this research, since that results in a maximum travel distance of 5.6km.

Furthermore, the circumferences of 4 and 8km radius catchments are 25 and 50km respectively. Should infrastructure be provided within 2.5km of a point of origin, then the length of cycle lanes required would increase from 20km to about 85km, or more than fourfold. Infrastructure can therefore be provided at four nodes up to a 4km radius, rather than one node at an 8km radius.

3.5. *Determining NMT potential*

We denote with set $\boldsymbol{P}$ the population. For each individual, $p \in \boldsymbol{P}$, we first determine if the s/he falls in the category of potential users. This paper considers three *hurdles*, treating each as a binary variable. The first, h^{edu}, is defined as 1 if the person is currently a tertiary level student, and 0 otherwise. The argument here is that all tertiary students can be considered, in principle, given the available attributes, as cycling potentials.

The second hurdle, h^{inc}, is defined as 1 if an employed person's household falls in the *low-middle* income category, and again 0 otherwise. Here the argument is that the low-middle income group would benefit most from the modest cost of cycling and would be most perceptible to shift from using their current modes.

The third hurdle, h^{inf}, is defined as 1 if a person resides in an informal dwelling, and 0 otherwise. The argument for this (negated) hurdle is that the owner of a bicycle should store it securely at home. There is an inverse correlation between household size and income in South Africa, as well as dwelling type and household size. This paper argues that informal settlements with low-income households and relatively larger families do not have space to store bicycles securely.

We use the expression in (1) to check if a person is indeed a potential user,

$$h_i = \left(h^{\text{edu}} \vee h^{\text{inc}}\right) \wedge \left(\neg\, h^{\text{inf}}\right) \qquad \forall i \in \boldsymbol{P} \tag{1}$$

where '$\vee$' denotes an inclusive OR, '$\wedge$' an AND, and '$\neg$' the negation. The expression translates into a person i being an NMT potential, $h_i = 1$, if s/he is either a student or from a low-middle income household, but then only if the family does not reside in an informal dwelling. We conservatively assume that any person not passing the hurdles has a zero probability to use NMT in the short term.

A person flagged as NMT potential may also have other attributes that act as diminishing factors, lowering the probability that the person will choose NMT as a mode. Table 1 shows the four elements we consider in this paper, the categories and factor values for each. Person i, being an NMT potential, then has

Table 1: Diminishing factor values.

Diminishing factor		**Factor values**	
j	**Description**	**Value**	**Description**
1	Gender	1.0	female
		0.8	male
2	Age	1.0	aged 18–25
		0.8	aged 26–35
		0.3	aged 36–60
		0.0	any other age
3	Household size	1.0	1 or 2 members
		0.4	3+ members
4	Car access	1.0	no car access
		0.0	have car access

a probability, p_i, which is the product of the four factor values as per (2), given the person's attributes

$$p_i = \prod_{j \in \boldsymbol{J}} f_i^j \qquad \forall i \in \boldsymbol{P} \tag{2}$$

where f_i^j denotes person i's diminishing factor value for factor j.

As an example, consider Deborah, a 28-year old female who lives with her husband and child in a small apartment. A low-middle-income family without having access to a private car. Their low-middle income status qualifies her as an NMT potential. Her gender-based factor is 1.0; age-factor is 0.8; household size-factor is 0.4; and car access-factor is 1.0. Her overall probability of using NMT is then $p_i = 1.0 \times 0.8 \times 0.4 \times 1.0 = 0.32$ or 32%. Since the proposed methodology aims to calculate discrete potential, we sample a random value, r_i, from a uniform distribution between 0 and 1. If, in this example, $r_i < p_i$, Deborah becomes an NMT potential. If $r_i \geq p_i$, she is ignored.

There are two sources of randomness. First, there are multiple synthetic populations. Secondly, the sampling regime to discretely identify individuals as either being an NMT potential or not can also lead to variance in calculating the overall potential of a node. To overcome this, we take multiple samples for each synthetic population and report a node's NMT potential as a distribution instead of a point-value.

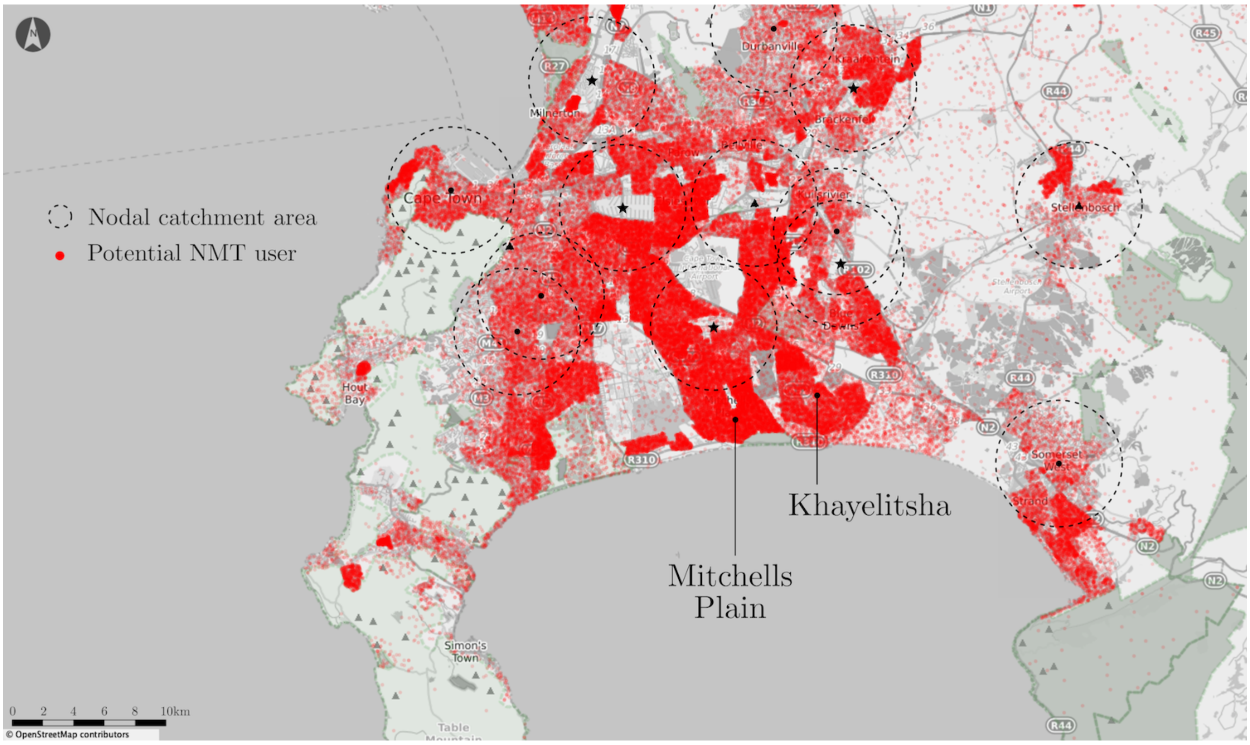

Figure 2: Density of potential market.

4. Discussion of results

4.1. Results

Figure 2 shows the density distribution of the target market across the study area, while Table 2 shows the Average probable target population for the nodes identified in Section 3.3. While the density of potential cyclists is very large in the south-east corner of the metro area (Khayelitsha and Mitchells Plain), these are largely residential suburbs with very few trip-attracting land uses.

The top three nodes have a significantly higher proportion of the target market living within their own unique catchments than the others. However, there is significant overlap between the catchment of both the Claremont & Wynberg nodes and the Kuislriver & Blackheath nodes. If combined, these pairs contain a similar potential demand for cycling to the top three nodes. Prominent cycle lanes have been provided in recent years in the CBD and along the coast north of the CBD. However the table shows that the potential demand in the CBD and Montague Gardens, through which catchment the lanes run, is relatively low compared to most other nodes.

Figure 3 shows the 4km radius catchment areas around the three zones with the highest potential target markets. The analysis indicates that, based on the chosen users profiles, the greatest potential for cycling sits within the zone wedged between the N1 to the north and R300 to the east and south and the M7 to the west. Between the selected nodes are additional significant trip generators for the same low-middle income group and students. These include the Bellville-South and Airport Industrial areas, as well as the Tygerberg Campus of the University of Stellenbosch.

The three catchment areas with highest potential have a combined pool of more than 40 000 potential cyclists in a zone of roughly 15 000 ha. A successful shift from current modes would constitute 5% of total

Table 2: Cycling potential of selected Cape Town nodes

Rank	Node		Type	Average
1	Philippi North	★	Industrial	15 584
2	Epping	★	Industrial	14 762
3	University of the Western Cape & Cape Peninsula University of Technology	▲	Tertiary education	12 028
4	Claremont	●	Commercial	8 921
5	Blackheath	★	Industrial	8 059
6	Wynberg	●	Commercial	7 622
7	Brackenfell	★	Industrial	7 046
8	Kuilsriver	●	Commercial	6 856
9	University of Cape Town, Rondebosch	▲	Tertiary education	5 998
10	Montague Gardens	★	Industrial	4 794
11	Somerset West	●	Commercial	3 970
12	Cape Town	●	Commercial	3 611
13	Durbanville	●	Commercial	3 150
14	Stellenbosch University	▲	Tertiary education	2 171

AM peak trips in Cape Town. However, given that the area constitutes about 19% of the total area of 80 000 ha, this results in a cycling density of up to 8% for the combined catchment zone. In addition, if one keeps the reference to Cape Town's strategy target, 8% of about 1mil trips = 80 000. Therefore, achieving this 40 000 trips would constitute almost 45% of the City of Cape Town's 2030 target of 90 000 utility cycling trips during the morning peak.

4.2. Discussion

More targeted interventions allow an authority to achieve demonstrable success, i.e. *early wins*. Success in one area does not detract existing efforts in promoting cycling in another area. In fact, this paper argues that substantially increasing cycling in one zone of the city is likely to raise awareness and positively affect future interventions.

Being able to prioritise nodes in a city according to cycling potential does not necessarily indicate which nodes to target first. If the number of people that can be convinced to cycle constitutes the *Benefit* (through reduced emissions, lower costs, better health, etc), the *Cost* of convincing them should also be calculated. Costs include the provision of infrastructure, the possible supply of or subsidising of bicycles, provision of safe storage facilities, marketing campaigns, training programmes and driver education. Whereas targeting the area of highest potential at any cost may not yield success, achieving cycling in a node with low potential would not deliver the mode-share target for cycling.

The fact that the three top zones lie in such close proximity motivates that these could be treated as a single study area. The infrastructure provided for one can easily be extended to join that of an adjacent zone, thereby greatly increase the catchment size of both zones. Similarly, a marketing campaign targeting students may be adapted and expanded to also target workers in industrial areas within the same community.

Finally, the availability of a synthetic population based on census provides an intuitively accurate indication of the location of potential cyclists, given the selected criteria. More importantly, it also quantifies the relevant market segments within the catchments of zones with relevant primary destination activities.

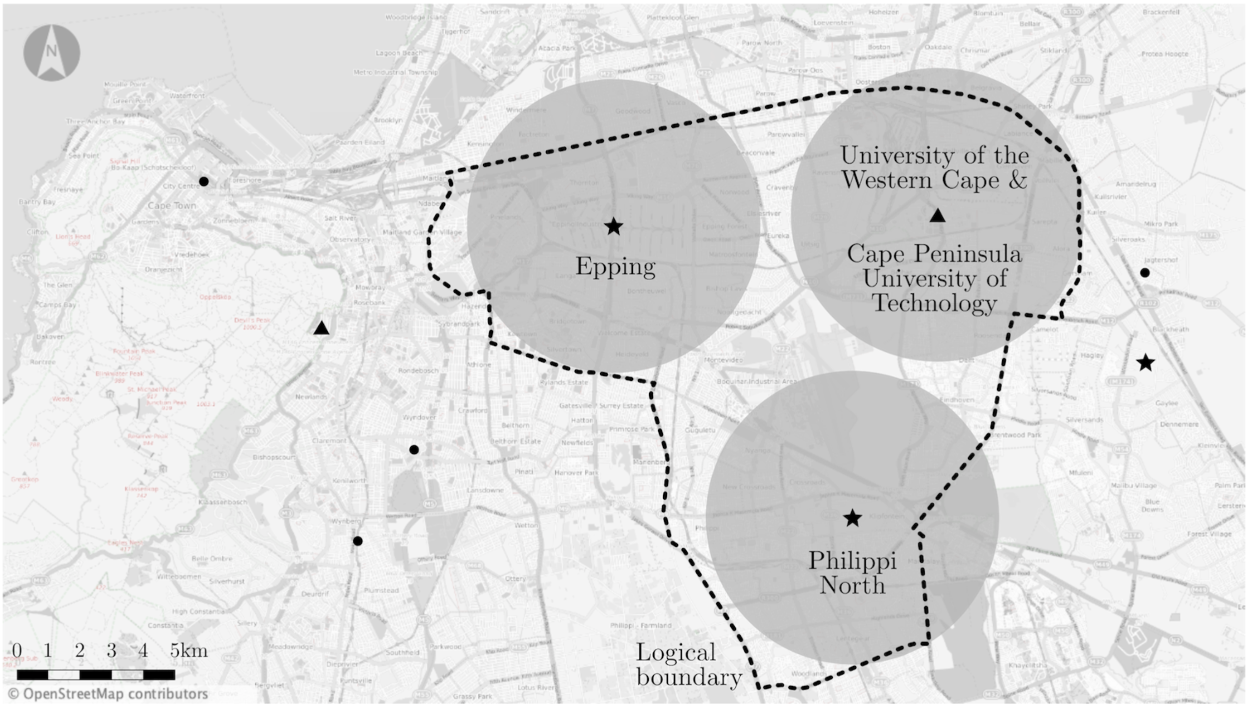

Figure 3: Zones of highest cycling potential

While travel behaviour theory was used to estimate the potential market segments in the absence of data of actual cyclists, the assumptions made in the process can be tested when the strategy is implemented and cyclists can be observed. Observing revealed demand would also highlight the impact on secondary trips in a travel chain, and the factors that led to the uptake of persons that did not fit the target market segments. A large body of work is available to inform such strategies.

5. Conclusion

The objective of the study was to determine cycling potential to a destination type, based on the size of the target market living within its catchment area using a representative synthetic population for the city. The results demonstrate that this objective has been met. Estimating the potential is the first step. The next step, which we leave for future work, is the actual design of interventions. And here it will be necessary to consider emerging research that look at attitudinal factors that may influence the ease with which the potential can be unlocked. And these interventions will (and should) remain context-specific. Three specific areas that require refinement, as highlighted in this paper, include the way an intervention is presented and marketed to different income groups; cultural attitudes towards cycling (be it race or gender); and age of a household's dependents, for example when travelling with infants or elderly.

One key benefit of the proposed methodology is that it accounts for multiple sources of uncertainty. Since populations are dynamic and individuals' behaviour may be erratic, this paper accounts for the uncertainty by using multiple samples over one hundred different synthetic populations. Consequently, the reported potential is calculated and reported as a distribution and not a scalar point-value. The programmatic implementation using publicly-available data makes the methodology *repeatable*, meaning that researchers can be confident that, amidst the uncertainty, the same conclusion (ranking of potential areas) will be reached when repeating the exercise.

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