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THE CITY CHALLENGES AND EXTERNAL AGENTS.
METHODS, TOOLS AND BEST PRACTICES

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The cover image shows a sea glacier ice that melts away.

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Prioritizing active transport network investment using locational accessibility

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Abstract

This research explores prioritizing network investment to improve walking and biking access in a suburban area with a poorly connected street network. This study's methods provide a systematic approach to design and prioritize the potential links to improve active travel in the suburban environment. An access-oriented ranking system is proposed to prioritize the contribution of links in two evaluation processes for different travel time thresholds. One of the developing suburbs in Sydney is selected as the case study, and a list of potential links is identified. Results indicate that links with the highest added access per unit of cost are the links that have the highest impact if all links are built. However, the locational network structure surrounding the point of interest may affect the order. For a radial network, closer links lead to higher access, while for a tree-like network structure, connecting branches improve access significantly. Also, farther potential links are significantly dependent on the closer links in increasing accessibility for a specific location. This suggests that in order to utilize the network, there should be a sequence in constructing the potential links. The application of access-oriented network investment is also discussed.

Keywords

Walking; Biking; Street network; Accessibility; Urban planning.

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1. Introduction

The success of transit nodes depends on how easily they are accessed, but business activities and education centers also rely on the walkability conditions around them (Lahoorpoor & Levinson, 2020; Padon & Iamtrakul, 2021; Papa et al., 2018; Shbeeb & Awad, 2013; Vale, 2015). This can be a significant issue where there is automobile dependency, and there often follows a loss of accessibility for pedestrians and cyclists (Badami, 2009; D'Orso & Migliore, 2018; Pirlone & Candia, 2015). In such an environment, users have to spend more time reaching their desired destination because of excess network circuity (Barthélemy & Flammini, 2008; Boeing, 2019; Lahoorpoor et al., 2022; Levinson, 2012; Yen et al., 2021), a design failure that also afflicts those using public transport and driving (Giacomin & Levinson, 2015; Huang & Levinson, 2015; Levinson & El-Geneidy, 2009). Having a more connected network reduces travel time, increases pedestrian access, and provides more alternatives to pedestrians to choose their routes (Guo & Loo, 2013). Accessibility is about how easily opportunities can be reached (Levinson & Wu, 2020; Wu & Levinson, 2020). There are several strategies that local municipalities can employ to improve accessibility. One is to place activities closer together, which is a land use issue. For example, building high rises around transport facilities or town centers. Another is to reconfigure the street network by adding additional links to reduce the travel distance between activities; in other words, reducing circuity and expanding the catchment area of those centers. Re-configuring the walking network can be a comparatively low-cost and short-run strategy. Hence, in developing urban areas, planners try to make key activities more accessible to dwellers by active modes, and they usually come up with a list of potential links that can improve the accessibility to certain locations. Town centers, business districts, hospitals, schools and education centers are activities that need social interactions and thus access to people. Local accessibility is a measure that can be used to evaluate the effect of adding a link on walkability (and of course, cycle-ability). Locational accessibility shows the number of opportunities that can be reached within a specific travel time (or distance) from a particular location (Lahoorpoor et al., 2022; Lahoorpoor & Levinson, 2022). For the purpose of this study, the term 'opportunities' refers to the location of employment and population. In previous studies, the walkability of a network has been investigated through various methods. Studies have evaluated the quality of walking on the pedestrian network (Badami, 2009; D'Orso & Migliore, 2018; Shinoda, 2019; Turner & Giannopoulos, 1974; Yuen & Chor, 1998), the equity perspective (Achuthan et al., 2010; Arellana et al., 2021; Gaglione et al., 2019), and the accessibility aspects of walking (Blanchard & Waddell, 2017; Cooper et al., 2019; Gehrke & Welch, 2017; Lyu et al., 2016; Manfredini & Di Rosa, 2018; Padon & Iamtrakul, 2021; Tal & Handy, 2012). Almost all of the studies have taken the pedestrian network to be a given static layer, while the pedestrian network can be retrofitted to increase walkability and accessibility in a region. However, little has been written on how to prioritize a set of potential connections and investments on the walking and cycling network. Not every potential link affects local accessibility at the same magnitude, and not all of them have the exact attributes (for example, length, cost and land acquisition).

Some links are longer, some cost more to build, and some may need property acquisition. Also, some links are beneficial only after a certain link is built, and the sequence of link construction is essential. Therefore, a series of research questions is established to better understand the investment for access-oriented pedestrian network.

1. Which potential links improve active transport accessibility for a particular point of interest?
2. Among a list of potential pedestrian links, which link produces the highest access per unit cost if only one link can be built?
3. Among a list of potential pedestrian and biking links, which link produces the highest (lowest) access per unit cost if all links are built?
4. Is there any systematic correlation between the contribution of links in the two evaluation processes above? i.e., does the link with the highest added access to the base network also have to the largest access reduction when it is removed from a complete network?

5. Is there any systematic correlation between links improving 5-minute and links improving 15-minute walk (bike) access?

To answer these research questions, this paper develops a systematic approach to prioritize investments on expanding the active transport network in an urban area. It proposes an access-oriented ranking to evaluate potential links on the accessibility they provide and finding the correlation between them. To investigate the different scenarios, the local accessibility of different time thresholds is measured for two key activity centers in one of Sydney's developing suburbs, considering potential links on the street network. The results are ranked and compared together.mThe remainder of this paper is organized as follows. In Section 2, the geographical definition of catchment areas, the mathematical definition of locational access, and the correlation test are stated. The results of the computational experiments are provided in Section 4. Finally, the concluding remarks are presented in Section 5.

2. Methodology

This study uses an access-oriented ranking to evaluate a set of potential links in a street network and prioritize them based on their impacts. This includes creating networks for every link in two circumstances. In the first (*adding*) scenario, each link is solely attached to the existing network. In the second (*removing*) scenario, each link is removed from a complete network where all other potential links are built.

The flowchart of the process is depicted in Fig.1. The methodological steps are described in the following subsections.

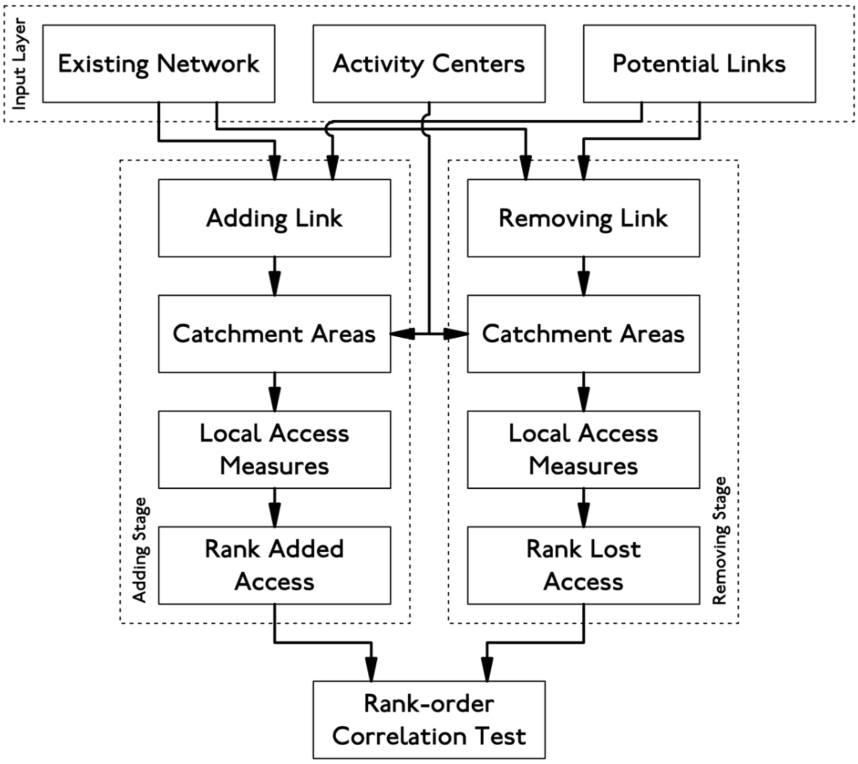

Fig.1 The access-oriented network's link-ranking flowchart

2.1 Catchment area

The catchment is an isochrone showing the area reachable (maximum extent) from an origin in a specific travel time. Generating catchment areas needs a location as the starting point, and a network to create the shortest path tree from that starting point. The method for generating isochrones is adapted from Lahoorpoor & Levinson (2020) to systematically generate 5-, 10-, 15-, 30-, and 45-minute catchment areas. It includes setting the buffer diameter, calculating the shortest path tree, and creating planar covered area. The walking speed equals 4.8 km/h (Walsh et al., 2019), so 15-, 30-, and 45-minute walking will be equivalent to 5-, 10-, and 15-minute biking, if biking speed equals 14.4 km/h.

2.2 Locational accessibility

Locational accessibility is the cumulative opportunities reachable from a location in a given time threshold. The value of locational accessibility can be, for instance, the number of residents or jobs. The access analysis here is conducted at the building structure level. A central point in that building footprint is identified (the centroid). The location of jobs and amenities are assumed to be located at the centroids of each building they are contained in. If a centroid is reachable, the jobs and amenities represented by the centroid are also considered reachable. The locational accessibility for adding and removing links can be expressed as Equation 1 and Equation 2, respectively. This concept of access can be visualized graphically, as the geographical area covered within a travel time threshold (as shown in Fig.3) and the number of opportunities (centroids) contained within that area.

$$A_{i,T,l} = \sum_{j=1}^{J} O_j \cdot f_T(C_{ij}) \,, l \in \Omega \tag{1}$$

$$A_{i,T,L-l} = \sum_{j=1}^{J} O_j \cdot f_T(C_{ij}) \,, \{L - l\} \in \Omega \tag{2}$$

$$f_T(C_{ij}) = \begin{cases} 1 \text{ if } C_{ij} \leq T \\ 0 \; if \; C_{ij} > T \end{cases} \tag{3}$$

where Ω is the road network; $\mathrm{L} = \{l_1, l_2, .., l_n\}$ is the set of potential links; $A_{i,T,l}$ is the cumulative opportunities from location (i) to every other locations reachable in time T with link l (adding scenarios); $A_{i,T,L-l}$ is the cumulative opportunities with all links in set L except l (removing scenarios); O_j is the number of opportunities (population or jobs) at location j; C_{ij} is travel time from point of interest i to location j; $f(C_{ij})$ is equal to 1 if $C_{ij} \leq T$ and 0 otherwise.

2.3 Benefit/Cost Test

The length of each link is measured in the GIS. This length is used as a surrogate for cost. The access produced by each link is divided by the length. The added and lost accessibility per unit length are ranked.

2.4 Correlation test

Two ordinal datasets are created from the added and lost access ranks. To measure the monotonicity between these two datasets, Spearman's correlation test is used without prior knowledge of the distribution of the ranks. The Spearman correlation coefficient (ρ) is a ranked-form of Pearson coefficient and varies between -1 and +1, which ranges from reverse to direct exact monotonic relationship. The correlation coefficient can be described as Equation 4 and Equation 5 (Griffiths, 1980).

$$\rho_{r_a, r_l} = \frac{cov(r_a, r_l)}{\sigma_{ra} \cdot \sigma_{rl}} \tag{4}$$

$$\rho_{r_a, r_l} = 1 - \frac{6 \sum d^2}{n(n^2 - 1)} \tag{5}$$

where r_a is rank of added access per unit length by adding a link; r_l is rank of lost access per unit length by removing a link; $cov(r_a, r_l)$ is the covariance of r_a and r_l; σ_{ra} and σ_{rl} are the standard deviations of r_a and r_l; d is the difference between corresponding ranks; n is the number of rank pairs.

3. Data

Miller, a suburb (i.e. neighborhood) of Sydney in the City of Liverpool local government area serves as the case study. According to 2016 census data, it is home to more than 3,000 people in an area of 1.25 km^2. Two key locations in this suburb are Miller Central, a shopping center, and TAFE, a community college campus. Fig.2 illustrates Miller's boundary and the location of Miller Central and TAFE. This section describes potential links to the walking and biking network around these two points of interests that can improve the poorly connected street network and subsequently local access to jobs and population in the near future.

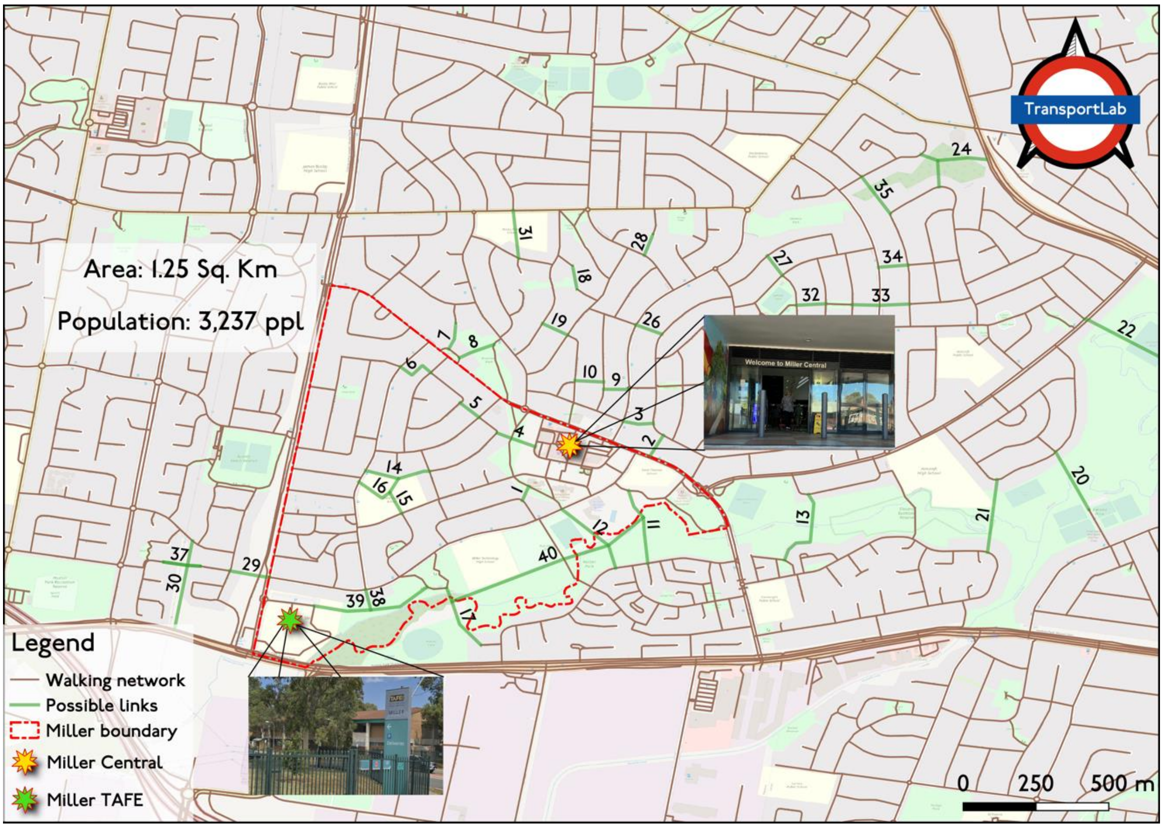

Fig.2 Potential links (green lines) in Miller labeled from 1 to 40. Basemap: OpenStreetMap.org

3.1 Network

Fig.2 marks possible new links in the walking (and biking) network around the Miller Central and TAFE. These links are proposed by the study team with consultation from staff of the local council. It is posited these new links will reduce network circuity and the walking and biking distance to/from Miller Central and TAFE. Some of the links are easy to build, while some might require future property acquisition. Although reducing circuity and avoiding building footprints were the selection criteria, the feasibility of these links requires more detailed evaluation beyond the scope of this article. The characteristics of the 40 proposed links in Miller and adjacent suburbs are available in (Levinson et al., 2020).

3.2 Census Data

The access calculations need the location of where people live and where they work. As this study is dealing with locational accessibility, higher resolution census data provides more accurate access measures. Therefore, in order to be precise in reflecting the effect of adding and removing each link, access calculations are conducted at the building level (building centroids).

To do so, the latest population and job numbers are obtained from the 2016 census data at the meshblock and the statistical area 2 (SA2) level, respectively.
The building data comes from Geoscape (Paull, 2020), which has estimated the height and footprint of every building in Australia from high resolution aerial photographs. The volume of a building equals the product of the footprint area and the average height of that building.
Then, in order to have finer block sizes for analysis, the population (mesh block) and employment (SA2) data are distributed proportionally to the volume of each building within the larger geographic area, while respecting control totals.
Equation 6 formulates how aggregated attribute's value is distributed over the building blocks, and Equation 7 checks control totals.

$$v_i = \frac{s_i \cdot h_i}{\sum_{j=1}^{i} s_j \cdot h_j} \times V_{P_j} : i \in I \qquad (6)$$

$$\sum_{k}^{I} v_k = V \qquad (7)$$

Where v_i is the value (attribute) of building i taken from the value of parcel j (V_{P_j}) by the ratio of its volume out of total building volume in the parcel j. s_i and h_i are footprint area and the average height of building i. The sum of buildings' values should be the total value V of that attribute.

4. Result

The study aims to prioritize potential links on the walking network based on the impacts they have on locational accessibility. An access-oriented ranking system is defined to rank the added access per unit of the cost when one link is supposed to be built at each time and rank the lost access when removing a link from a developed network as if all potential links are built. Two critical locations in Miller are considered as the points of interest, and 40 potential links are identified around these locations. The correlation between adding links to the extant network, and removing links from the complete (extant plus potential network) is compared for different time thresholds based on the Euclidean distances of those links to the center of activities. Since cycling speed is three times walking speed, the maps can be conceived as 5-, 10-, and 15-minutes walking (reflecting 400, 800, 1200 meters travel distance) and 5-, 10-, 15-minutes biking (reflecting 1200, 2400, 3600 meters distance).

4.1 Base and complete scenarios

The base scenario measures access isochrones from the points of interest without any network development. On the other hand, the complete scenario builds all the potential links, which gives the greatest accessibility at both locations.
These are the minimum and maximum range that locational accessibility could be. Fig.3 to Fig.6 compare the access isochrones before (base scenario) and after (complete scenario), adding potential links to the network around Miller Central and TAFE. In the case of Miller Central, results show that access can be increased approximately by 4% both for walking and biking.
The increase in 10-minute biking access to jobs is around 13%. The reason is the industrial area (south of Miller Central) would be much more accessible with potential links. The access increase is more significant for the Miller TAFE scenario (18% more jobs accessible in 10 minutes both for walking and biking), as the new links provide access to areas west of the Miller TAFE.

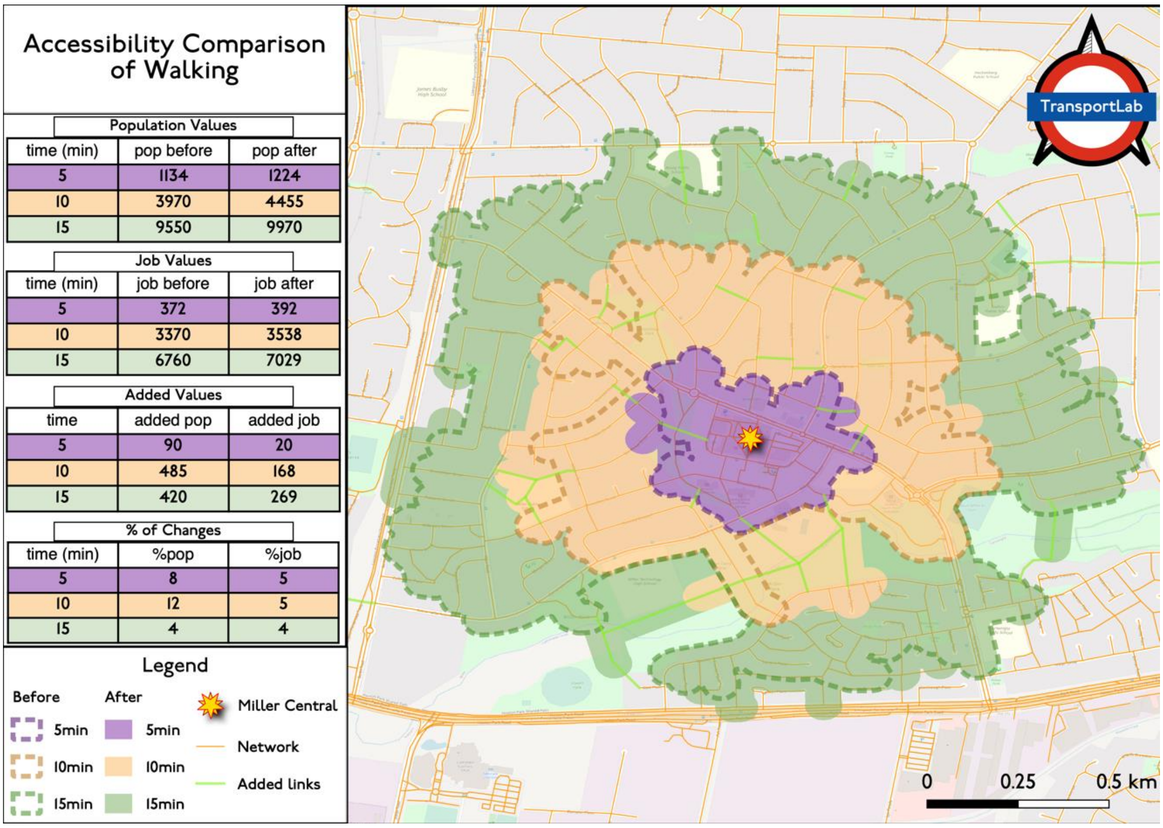

Fig.3 Miller Central Access Comparison of Walking Before and After Adding Potential Links. Basemap: OpenStreetMap.org

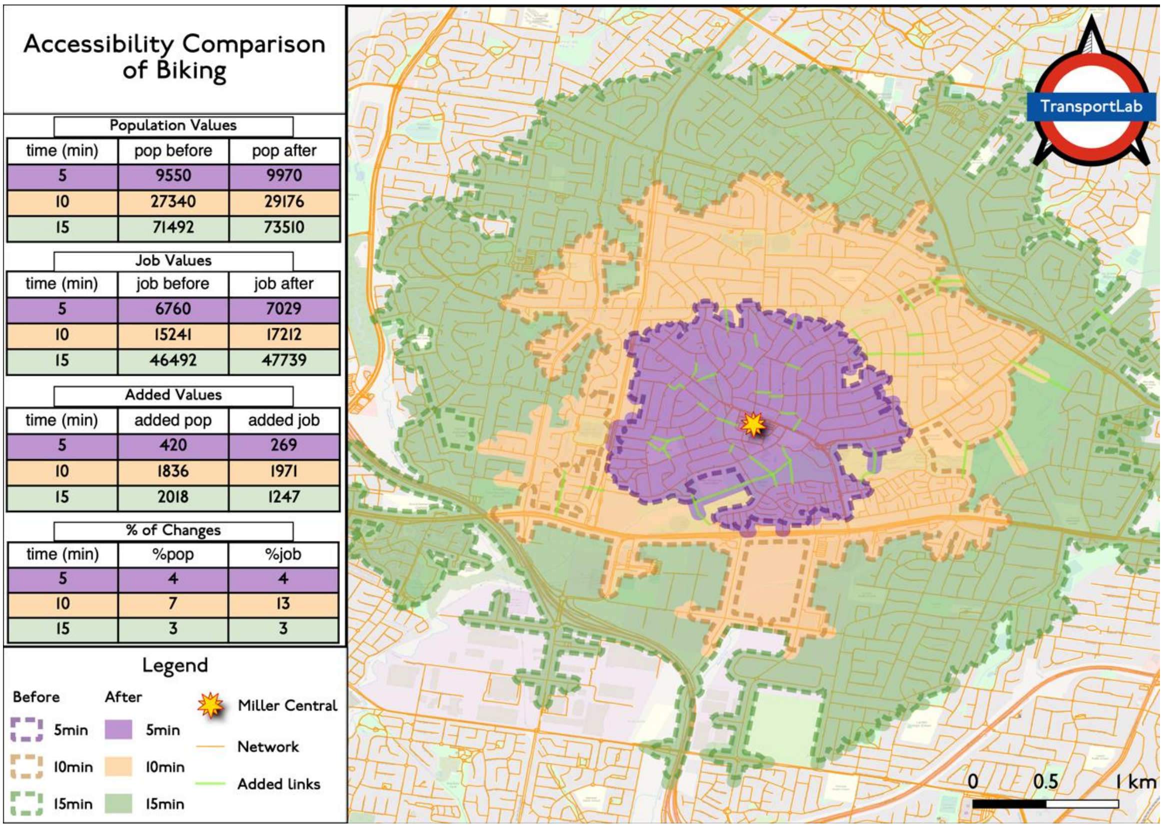

Fig.4 Miller Central Access Comparison of Biking Before and After Adding Potential Links. Basemap: OpenStreetMap.org

Accessibility Comparison of Walking

Population Values

time (min)	pop before	pop after
5	0	0
10	777	2121
15	2092	3636

Job Values

time (min)	job before	job after
5	338	338
10	405	478
15	806	885

Added Values

time	added pop	added job
5	0	0
10	1344	73
15	1544	79

% of Changes

time (min)	%pop	%job
5	0	0
10	173	18
15	74	10

Legend

Before: 5min, 10min, 15min
After: 5min, 10min, 15min
Miller TAFE
Network
Added links

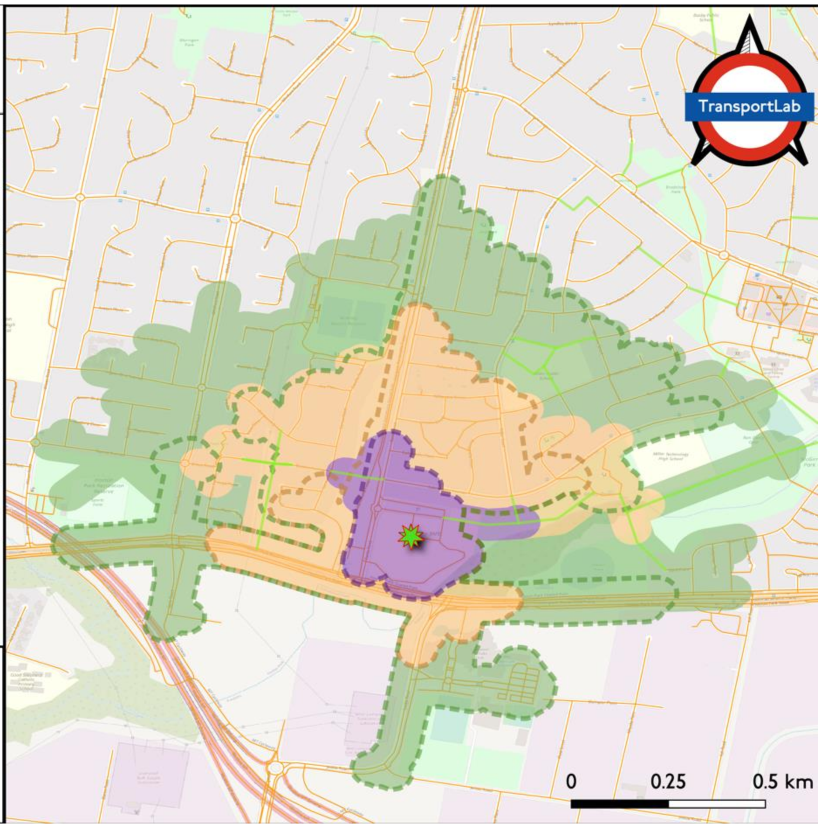

Fig.5 Miller TAFE Access Comparison of Walking Before and After Adding Potential Links. Basemap: OpenStreetMap.org

Accessibility Comparison of Biking

Population Values

time (min)	pop before	pop after
5	2092	3636
10	16651	19641
15	52816	56508

Job Values

time (min)	job before	job after
5	806	885
10	5100	5498
15	11605	11907

Added Values

time (min)	added pop	added job
5	1544	79
10	2990	398
15	3692	302

% of Changes

time (min)	%pop	%job
5	74	10
10	18	8
15	7	3

Legend

Before: 5min, 10min, 15min
After: 5min, 10min, 15min
Miller TAFE
Network
Added links

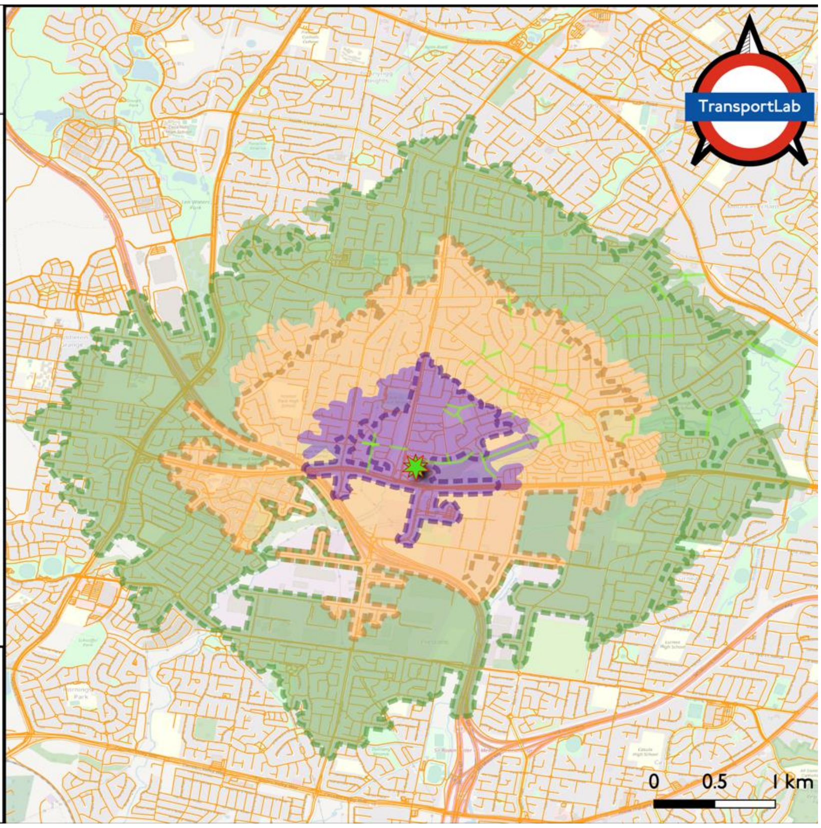

Fig.6 Miller TAFE Access Comparison of Biking Before and After Adding Potential Links. Basemap: OpenStreetMap.org

4.2 Ranking

Fig.3 through Fig.6 show the added accessibility for all the potential links attached to the existing network. However, this is not always the case, and with a fixed budget, links are built in order (not all at once) and prioritizing them requires a systematic ranking system. The benefit is the added access each link contributes in proportion to its length, which is the difference in access after building a link minus the base scenario, per unit cost. In the removal stage, the loss is the decrease in access per unit cost when a link is removed from the complete scenario. Cost is estimated as link length.

Does the link that gives the highest access when added to the extant network also cause the greatest access reduction when it is removed from the complete potential network?

To answer that question, the Spearman's correlation test is conducted for all time thresholds considering access to population, access to jobs, and the isochrone area Tab.1 summarizes the results for how much constructions and deconstructions are correlated.

Results indicate that the addition and removal of potential links are more correlated for Miller Central than Miller TAFE, which means the high ranked links in adding access are the ones that decrease the accessibility significantly when they are removed from the network. Miller TAFE's correlations are insignificant for short range distances.

The reason is two-fold. First, most of the links are spatially spread out around Miller Central. Second, the network around Miller Central is more locally radial, whereas around Miller TAFE is a tree-like structure with cul-de-sac branches. However, when the distance increases, the correlation decreases. Fig.7 illustrates the ranking of links that contributes to 15-minute walk access (to population) from Miller Central in adding and removing evaluation processes. By comparing the adding and removing processes, it can be seen the extent to which the rankings are correlated.

	Network distance (meters)	Walking time (minutes)	Biking time (minutes)	Miller Central		Miller TAFE	
				correlation	p-value	correlation	p-value
Access to population	400	5		1.000	0.000	0.400	0.600
	800	10		0.949	0.000	0.006	0.987
	1200	15	5	0.955	0.000	0.641	0.007
	2400	30	10	-0.445	0.004	0.256	0.164
	3600	45	15	0.087	0.592	0.482	0.002
Access to jobs	400	5		1.000	0.000	0.400	0.600
	800	10		0.847	0.000	0.018	0.960
	1200	15	5	0.935	0.000	0.368	0.161
	2400	30	10	-0.008	0.961	0.242	0.191
	3600	45	15	0.125	0.442	0.435	0.006
Isochrone area	400	5		0.762	0.028	-0.800	0.200
	800	10		0.645	0.002	0.552	0.098
	1200	15	5	0.498	0.0083	0.6206	0.010
	2400	30	10	-0.146	0.377	0.247	0.181
	3600	45	15	0.914	0.000	0.040	0.808

Tab.1 Spearman's correlation test results. 'Access to population' shows the correlation between construction and deconstruction accessibility to population and 'Access to jobs' illustrates the results for access to jobs from the activity centers. 'Isochrone area' denotes the added/removed coverage area

In Miller Central, the correlation between adding and removing links becomes insignificant and sometimes negative for distances over 10-minute biking. However, for Miller TAFE results become more correlated after 15-minute threshold. The reason can be due to the network topology. Fig.8 visualizes the adding and removal rank distribution for 5-, 15-minute walk, and 15-minute bike access to jobs from Miller Central and Miller TAFE.

As previously mentioned and depicted in the figure, the sparse points for long distances in Miller Central demonstrate lower and insignificant correlations.

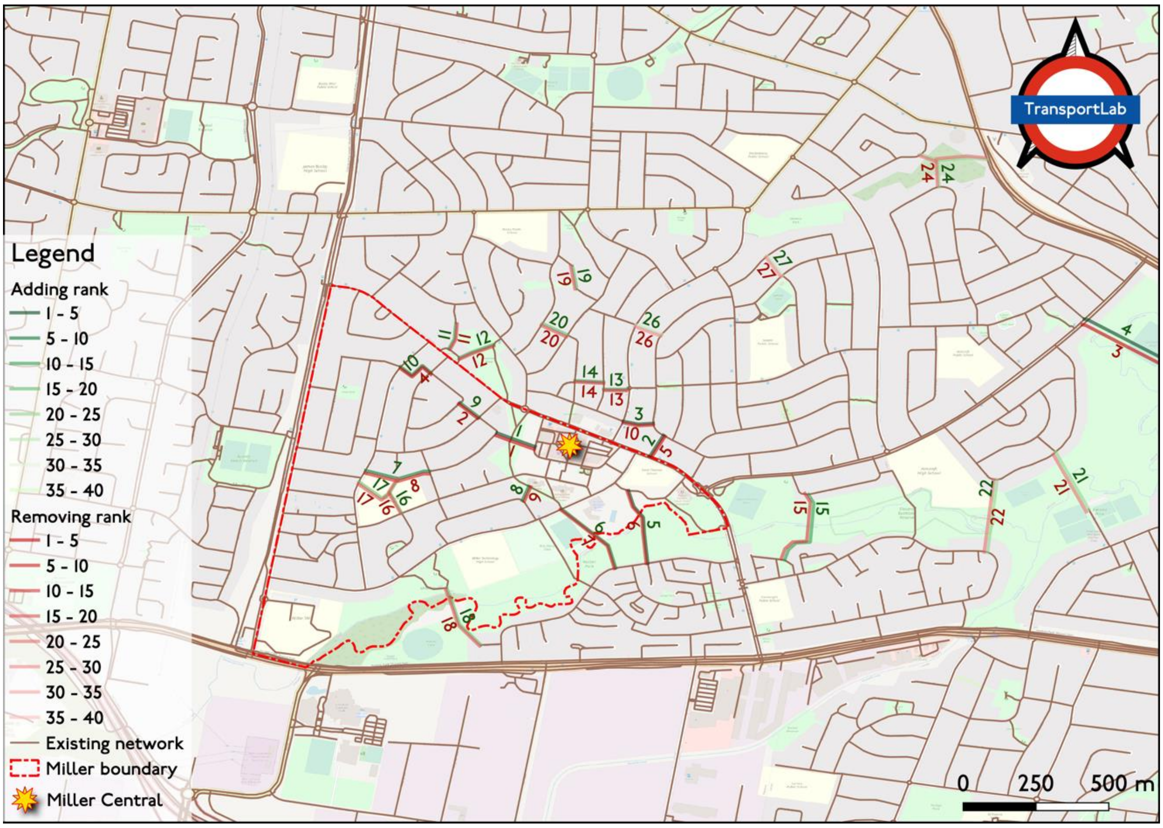

Fig.7 The rank of 15-minute walk potential links in the adding and removing stage from Miller Central. The dark green labels show the rank of adding and the dark red labels display the removing ranks. The benefit (access to population) to cost (length of link) ratio is used to determine rank

Furthermore, results show that in terms of access to jobs, the correlation is lower than access to population. The reason is the spatial distribution of opportunities. Dwellings are generally more evenly distributed than jobs. We also see that access to opportunities are more correlated than the coverage area. This corroborates the idea that transport links follow land use (Levinson, 2008), and links exist in places where people live and work.

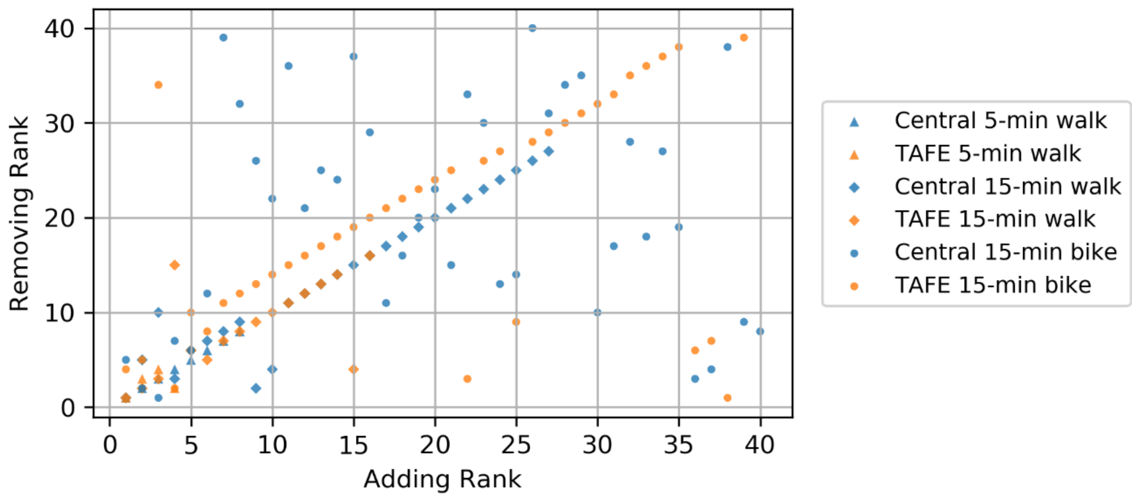

Fig.8 The rank distribution of added and lost access from Miller Central and Miller TAFE. 5-, 15-minute walk, and 15-minute bike access to jobs

4.3 Distance correlation

Another question that can be raised is whether a link with the top 5-minute access gives the highest access for other time thresholds. Due to the large combination of different time thresholds, only the 5-minute and 15-minute walk and 5-minute and 15-minute biking ranks are compared. The results are summarized in Tab.2 and Tab.3 for Miller Central and Miller TAFE respectively. Results indicate that in most cases, the rankings are significantly correlated and dependent. It can be inferred that links with the highest access in 5-minute travel time should be prioritized compared to links that increase 15-minute access. In other words, to gain benefits from farther potential links, closer links to the specific location should be constructed. It is important to note that Miller Central has weaker correlations when adding links and insignificant correlations when removing links when compared to Miller TAFE, which indicates that the network is more resilient and locally developed around Miller Central.

	Network distance (meters)	Time (minutes)	Adding correlation	p-value	Removing correlation	p-value
Access to	400-1200	5-15 walking	0.738	0.037	-0.106	0.600
population	1200-3600	5-15 biking	0.847	0.000	0.482	0.226
Access to	400-1200	5-15 walking	0.789	0.020	0.408	0.315
jobs	1200-3600	5-15 biking	0.499	0.008	0.172	0.391

Tab.2 Miller Central Distance Correlation

	Network distance (meters)	Time (minutes)	Adding correlation	p-value	Removing correlation	p-value
Access to	400-1200	5-15 walking	0.976	0.000	0.976	0.000
population	1200-3600	5-15 biking	0.781	0.000	0.985	0.000
Access to	400-1200	5-15 walking	0.976	0.000	0.976	0.000
jobs	1200-3600	5-15 biking	0.918	0.000	0.791	0.000

Tab.3 Miller TAFE Distance Correlation

5. Conclusion

Recognizing network development budgets are limited, this study systematically explores prioritizing network investment to improve walking and biking access in a suburban area with a poorly connected street network. The cul-de-sac street pattern leads to high network circuity in day-to-day travel and reduces accessibility. Using the methods outlined in this paper, planners can identify a list of potential links to add to the existing network and solve for pedestrian and cyclist access for a given land use pattern, here we use existing development patterns. In this research, an access-oriented ranking system is proposed to rate the potential links' impacts on the locational accessibility from a specific point using two scenarios: adding and removing, which allows for a more robust evaluation process that can identify which links are valuable independent of the construction of other proposed links.

A suburb in Sydney is selected as the case study, and a list of potential links with the local council's consultation is identified. Results indicate that links with the highest added access per unit of cost tend to retain their highest impact if all links are built, i.e. proposed links here largely do not substitute for each other in producing access and are instead mostly independent. Also, farther potential links depend on the closer links in increasing accessibility for a specific location. This suggests that in order to utilize the network, there should be a sequence in constructing the potential links.

The access-oriented ranking system provides a systematic tool for urban planners and policymakers to evaluate the alternatives in developing street networks. In developing the street network, a potential link may expand the catchment area for a specific point, but it does not necessarily increase access. It depends on the topology of the network and the land use (how the opportunities are dispersed). In the standard benefit/cost analysis framework, the best link is the one that improves access the most for the least cost.

This study draws conclusions from a ranked list of potential links. We suggest the links with the top access ranks in both the adding and removing processes should be prioritized, and that implies that links close to the desired location should be constructed first. However, prioritizing potential links with access-oriented ranks may have some limitations. In an urbanized area, for instance, the construction of active transport networks may conflict with existing land uses and right of ways. A multi-factor decision-making procedure may mitigate these deficiencies.

There are some methodological issues that must be addressed. The census data from large geographic units were first redistributed into building levels proportional to the volume of each building. The redistribution process can be obviated by higher resolution census data, which may also improve access accuracy. Second, it is assumed that the location of employment and population serves as a proxy for potential users or customers. It would be worthwhile to test out finding potential customers in location-based social networks. Third, this study considered length as a surrogate for cost. However, more sophisticated cost analysis is needed to evaluate property acquisitions, the actual cost of construction, and potential customers for interested activity centers. Furthermore, analyzing the correlation between network characteristics and access before and after the development could be another possible research direction. Also, future analysis should consider a low-stress biking network (limited to roads with low traffic or protected bike lanes) since not all cyclists are willing to bike on major roads, considered the available biking network in this analysis.

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