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Abstract

The aim of this paper is to develop a non-motorised transport (NMT, covering walking and cycling) prioritisation model using Geographic Information System (GIS) which can be used for planning as well as auditing existing NMT infrastructure. The study used ArcGIS 10.1 ModelBuilder for designing NMT prioritisation using the cases of Sembawang and Yishun residential townships in Singapore. The concept of spatial intelligence is used to predict the NMT prioritisation scheme; spatial intelligence is the ability to visualise spatial features and apply spatial judgement for mobility problems involving navigation or to identify fine details or patterns. Herein, an NMT prioritisation model is developed based on NMT movements in relation to spatial features such as residential buildings, community centres, schools & hospitals, recreation & sports centres, economic zones, transport hubs, bus stops, and green spaces. The designed NMT prioritisation map is the weighted sum of Euclidean distance rasters of 8 spatial layers. The results of this study are subsequently used to assess the existing NMT facilities in the Sembawang and Yishun townships.

Keywords: GIS model; NMT; ModelBuilder; spatial intelligence; walking and cycling; transport planning; infrastructure planning; sustainability

1. Introduction

Developed countries, in experiencing the Motordom's problems, are searching for efficient and sustainable transport alternatives (Koh & Wong, 2012). As such, non-motorised transport (NMT – mainly walking and cycling) is gaining importance as a healthy and environmentally friendly transport. Understanding what pedestrians and/or cyclists consider as an “attractive commuting route” can allow planners to build appealing NMT networks and liveable cities, resulting in elevated number of walking and cycling trips among residents (Koh & Wong, 2013). Providing suitable and comfortable infrastructure at key location is imminent considering the goal to increase walking and cycling rates while catering for safety of users and efficient use of space. It has been observed that there is variation in perception towards impacts of improved infrastructure and its effect on travel behaviour (Jain & Tiwari, 2016). A systemic audit and transformation of the urban network should be performed in order to diminish conflicts between different transport users, and enhance trip connectivity. Special consideration shall be taken at areas of high NMT presence and activity (Victoria et al., 2012; Poyil et al., 2014).

To enhance NMT movements, some countries are decentralising urban areas and “bringing jobs closer to home” and implementing strategies to constrain car use. Planning for transport is even more challenging in highly urbanised countries where available land space is limited such as in Singapore where the current study is based. The Land Transport Authority (LTA) of Singapore announced that the Government will cut the annual growth rate for cars and motorcycles to zero, from 0.25 percent, starting in February 2018 (Tong, 2017). Along with these developments, measures to enhance NMT movement efficiency and connectivity need to be developed. Amsterdam and Copenhagen are best examples for the vigorous development of NMT infrastructure, noting that there is much cycling activity that takes place on the road. A recent study investigated cycling level for four cities, including Singapore, and the study pointed out that urban structure, transport policy, public transport service and infrastructure provision affect cycling and walking activities (Meng et al., 2014).

The purpose of this paper is to develop an NMT prioritisation scheme taking various factors into consideration, with the main focus on spatial and planning characteristics of a selected study area. The proposed NMT prioritisation model is a model which indicates the degree-of-importance of particular areas for NMT priority. Among developed economies, a substantial body of research suggests that built environments are good predictors of non-motorised travel (Handy et al., 2002; Frumpkin et al., 2004; Cervero et al., 2008). In terms of application, the NMT prioritisation model is developed based on NMT movements in relation to spatial features such as: residential buildings, community centres, schools & hospitals, transport hubs and others. The concept of spatial intelligence is used to design the NMT prioritisation model. Spatial intelligence is the ability to visualise spatial features and make a spatial judgement for problems involving navigation or to identify fine details or patterns. It includes the capacity to visualise, to graphically represent visual or spatial ideas, and to orient oneself appropriately in a spatial matrix (Armstrong, 2000; Musliman et al., 2013).

Following this introductory section, relevant findings from the literature review are highlighted. Then, in Section 3 characteristics of the NMT formal and informal NMT network in Singapore are described, followed by a description of the methodology of the study in Section 4. Methodology section includes details on the selection of study area and

the empirical design of research for development of the NMT prioritisation model. Moreover, Section 5 presents the generated results. The study is summed up with a discussion and conclusion based on the results as well as the scope of future research in Section 6.

2. Literature review

Researchers and planners have proposed a variety of approaches to evaluate and maintain different transport infrastructure, with most of these models and frameworks being focused on motorised transport infrastructure (Mackie and Preston, 1998; Giorgi and Tandon, 2002; Sinha and Zongzhi, 2014; Pantha et al., 2010). Most of these evaluation methods take into consideration Multiple Criteria Analysis and most of the time include Cost Benefit Analysis as one of the criteria (Iniestra, 2009; Tsamboulas, 2007). However, more research is needed to explore the capabilities of spatial intelligence regarding navigation and routing. Innovative approaches with multiple criteria should be considered and introduced as part of urban planning and management (Nijkamp et al., 1998; Gaytán-Iniestra & Garcia-Gutierrez, 2009; Tsamboulas, 2007).

A case study in Cape Town, South Africa describes the application of a statistical clustering method to the results of a GIS-based Spatial Multiple Criteria Assessment (SMCA) of contextual data in a city or town to identify areas that are most suited for walking and cycling infrastructure (Beukes et al., 2013). Yelda and Shrestha (2003) used multi-criteria approach in the decision-making process for prioritising alternative transport options in Delhi, India. Moreover, a 5-step framework for assessing the prioritisation of green infrastructure to mitigate high temperatures in urban landscapes has been proposed recently (Norton et al., 2015). The framework is developed at a neighbourhood level and it considered different urban factors such as geometry and green infrastructure. In addition, similar alternatives can be utilised to determine and prioritise investment for different kinds of infrastructure such as already being done in London with the Pedestrian Environment Review System (Davies & Clark, 2009), which is also developed with aid of spatial intelligent systems. Also in Brazil, a study developed a systematic framework to prioritise transportation infrastructure investments based on the application of Analytic Hierarchy Process - AHP (Quadros and Nassi, 2015). It has been highlighted that findings from studies/frameworks should be considered in parallel with policies or programmes to foster the usage of NMT (Jonietz et al., 2013; Jonietz & Timpf, 2013).

Geographic Information Systems (GIS) in combination with spatial intelligence, such as those provided by the ModelBuilder tool, offer a unique possibility to operationalise the depiction of the physical environment from the stand-point of everyday life and individual experiences (Kahila & Kytta, 2009). Furthermore, these features can be easily explored using specific location-based methodologies (McCoy 2003; Salonen et al., 2014), which alternatively can be made by specific site visits and audits which require extensive time and manpower investment to create output datasets using geo-processing tools, scripts or models (Schaller, 2009).

3. Non-motorised transport's formal and informal network in Singapore

Singapore is a small 719 km² island nation. The reduced land area and the burgeoning population, today at 5.6 million inhabitants (SINGSTATS, 2017), calls for innovative and detailed urban and transport planning. The country has often been ranked to be one of the most walkable cities in the world, having a good public transport system and adequate facilities for pedestrians (Ng et al., 2012; Sanyal, 2013; UN Habitat, 2013; Koh et al., 2014). The transport system comprises Mass Rapid Transit (MRT) rail and comprehensive bus service system. As the country is moving towards the goal of “car-lite” Singapore, infrastructure planning is implemented to optimise land use, alleviate traffic congestion, encourage walking and cycling, and protect the environment (Nguyen et al., 2015). In addition, programmes and policies are being implemented to enhance NMT trip comfort and safety (LTA, 2014).

In Singapore, most cycling activity takes place off-road, thus, pedestrians and cyclists commonly share mobility facilities. Regarding NMT infrastructure provision, footpaths (also now used by cyclists since late 2016 (Active Mobility Act, 2016)) are readily available alongside majority of the roads in the nation. Due to the increased NMT traffic, some footpaths are being widened to enhance “sharing experience” among the different types of NMT users. Space permitting, delineated or segregated paths are provided, comprising footpath and adjacent cycling path (LTA, 2016). In general, footpaths are 1.5 metres wide, widened paths are between 2 to 2.5 metres and in cases where delineated and/or segregated paths are provided, pedestrian and cyclists paths are of no less than a metre wide each (Rojas Lopez & Wong, 2017). Other facilities such as signalised and zebra crossings and overhead bridges are also available to enhance NMT trip quality and accessibility (Chin & Menon, 2015). These facilities (see Figure 1) are known as the NMT “formal network” and it can be shared by pedestrians, cyclists and other Personal Mobility Device (PMD) riders within appropriate speed limit (Active Mobility Act, 2016).

Moreover, unlike many other cities, there exists much scope in Singapore for unrestricted NMT movements in residential neighbourhoods due to the ubiquitous presence of void decks in public housing clusters. A void deck is an open space typically found on the ground floor of public housing blocks in Singapore (Koh & Wong, 2015). It is pertinent to note that in Singapore, over 80% of the population live in public housing flats (Housing & Development Board, 2017). Although originally designed to enhance social interaction among residents, it readily permits NMT movements across blocks, instead of circumnavigating them, thereby directly connecting such informal NMT mobility facilities with the formal walking and cycling network. Herein, a pedestrian or a cyclist can move from one point to another in an almost straight line manner by cutting across the void decks and other freely navigable areas of the “informal network”, such as car-parks and green-spaces in the neighbourhoods (see Figure 2.). The basis of this research is thus anchored on the fact that NMT movement can be in any direction from a point, rather than following a fixed network pattern.

Local research has highlighted that the decision to walk and cycle and the perceived importance of infrastructural compatibility factors differ under different land use environments (Koh & Wong, 2013; Rojas López & Wong, 2017). Regarding route choice for home-bound (last-mile) NMT trip stages, Koh and Wong (2014) found that pedestrians

favour routes with good scenery, availability of convenience shops on the way, and presence of other people, while cyclists favour routes with presence of other people, flat terrain (characteristic of Singapore), and riding on footpath adjacent to the roadways. These identified factors provide areas and scope of infrastructural improvements to encourage greater walking and cycling activities, as Singapore continues to expand its NMT network. It must be highlighted that levels of personal safety in Singapore is normatively at an elevated level (MFA, 2015). Thus, concerns about personal safety (either day or night) are rarely mentioned when discussing factors that affect active mobility. It is also important to understand how land uses influence routing and navigation pattern, which can be modelled by means of a NMT prioritisation model. Furthermore, while at a first glance the hot and humid weather in Singapore might be a deterrent for NMT trips, research focused on cycling behaviour has shown that travellers most commonly adjust their travel plan (e.g. travel time, travel path) rather than avoiding active trips (Meng et al., 2016). Thus, it is important to determine where to provide quality commuting infrastructure to ensure sufficient provision under favourable as well as adverse weather conditions.

4. Methodology

4.1. The study area: Sembawang and Yishun townships

The townships of Sembawang and Yishun are selected as study locations as these towns are deemed to have fully-implemented NMT infrastructure and no further NMT network enhancement is planned in the near future. Footpaths and cycling paths characteristics in these towns are as described in Section 3, with mostly extended paths of 2 to 2.5 metres wide. Sembawang and Yishun are residential towns with individual planning areas located in the northern part of Singapore. According to Singapore's Department of Statistics, the total area, residential area, population, population density, dwelling units and projected estimate of dwelling units of Sembawang and Yishun are as shown in Table 1.

Figure 3 represents the study area showing spatial features used in the study. This is developed by overlaying the GIS spatial layers such as buildings, cycling paths, footpaths, roads, bus stops, MRT stations and greenways layers adapted from MyTransport.SG website of Land Transport Authority of Singapore. MyTransport.SG, among other features, provides useful and updated land transport information and data for research purposes and development of applications (MyTransport.SG, 2017). The length of transport network in Sembawang and Yishun consisting of road, footpath and cycling path are as given in Table 2. Characteristics of the networks are considered in a general way as the developed NMT prioritisation model analyses transport at a macro-level, and micro-level details such as specific width of each segment of the paths are not considered.

4.2. Development of NMT prioritisation model

The study used ArcGIS 10.1 ModelBuilder to aid in the design of NMT prioritisation model of Sembawang and Yishun townships. The GIS offers a unique possibility to operationalise the depiction of the physical environment. Though GIS is not an objective representation of the environment, it is by far the most useful description of the physical qualities of the settings that one can trace from the stand-point of everyday life and individual experiences

(Kahila & Kytta, 2009). Figure 4 illustrates the methodology adopted with the specific steps being described in following sections.

Recent developments in Geographic Information System (GIS) have created new possibilities for extensive computational analysis and the use of location-based methodologies (Salonen et al., 2014). Actual regional planning activity requirements necessitate intensive geo-data processing in which many existing geo-datasets must be processed to create output datasets using geo-processing tools, scripts or models (Schaller, 2009). The ModelBuilder constructs geo-processing workflows using visual programming language and represents a model as a diagram that chains processes' sequences and geo-processing tools. Geo-processing models automate and document the spatial analysis and data management processes. Analyst can create and modify geo-processing models in ModelBuilder using the output of one process as the input to another process (ESRI, 2011). During 'normal' GIS work in a planning process, GIS analysts use one tool after another to complete their task(s) and must always be aware which working step they are completing at any one time. In contrast, the ModelBuilder technology opens up a workspace in which the analyst can 'plan' the GIS jobs to be carried out, and ultimately run them (Schaller, 2009). Figure 5 depicts the specific ModelBuilder tool used in this study.

4.2.1. Spatial features in the study area

As mentioned, spatial data used in the study was obtained from MyTransport.SG website. The polygon spatial data layer for buildings (see Table 3) consists of residential buildings, community centres, schools & hospitals, recreation & sports centres, economic zones (include commercial buildings and industries), and transport hubs (i.e. MRT stations and bus interchanges). The second layer, which is a point data layer (consists of 302 points), is that of bus stops and the third one is green spaces which is a polygon layer containing 24 polygons. A total of 8 spatial features on 3 layers were available for the study. The NMT facilities layer is not utilised for model development as they clearly affect NMT movements by routing users through specific areas. On the contrary, NMT facilities layer is used at a later stage to evaluate the accuracy and estimate the usefulness of the NMT prioritisation model.

4.2.2. Extracting the layers

For determining the NMT prioritisation, the model should predict the NMT movements of study area based on the NMT movements in relation to certain spatial features such as residential buildings, community centres, schools & hospitals, recreation & sports centres, economic zones, transport hubs, bus stops, and green spaces. To do so, the buildings layer obtained from MyTransport.SG website is classified into residential buildings, community centres, schools & hospitals, recreation & sports centres and economic zones as separate polygon layers using the extraction tool. Altogether, a total of 8 spatial features on 8 layers were applied in this study.

4.2.3. Euclidean distance raster for each class

The Euclidean distance is the straight-line distance from the centre of the source cell in the raster to the centre of each of the surrounding cells in matrix space and the process is as illustrated in Figure 6. Euclidean distance rasters are developed for each of the layers mentioned in Section 4.2.2. When the input source data is a feature class, the source locations are converted internally to a raster before performing the analysis (ESRI, 2011). Euclidean distance raster is the measure of NMT movement or, in other words, it is the map showing the presence of NMT in relation to spatial features. Processing extent for the Euclidean distance raster is the boundary of Sembawang and Yishun townships.

4.2.4. Weighted sum raster

This tool overlays various rasters, multiply each of them by their assigned weight and add them together. In this study, equal weight is given to all the spatial features as all the parameters are given equal priority. In fact, priority is being given to spatial locations of NMT based on these factors. A similar study can be carried out in future by assigning differential weights for parameters using a perception survey on sample population of study area.

4.2.5. NMT prioritisation map

NMT prioritisation map is generated from weighted sum raster using the Clip tool. Here, the weighted sum raster is the input feature and boundary layer that form the clip feature. The final output raster generated is thus the NMT prioritisation map of Sembawang and Yishun townships.

4.2.6. Evaluation of accuracy

The predicted NMT prioritisation map shows the level of priority for NMT infrastructure to be given to different areas of the towns under study. To evaluate the accuracy of the current model, and as an alternative for validation, the existing NMT infrastructure layers (i.e. GIS layers of actual footpath and cycling path infrastructure in the towns) are used to map the existing NMT prioritisation. Sembawang and Yishun are well-suited for study as these residential towns are deemed to have full active mobility infrastructure. In addition, no major active mobility transport network improvements are planned for these towns in the near future. Thus, they can be considered as relatively matured towns in terms of non-motorised infrastructure. The same procedure mentioned in the methodology flowchart is used to create existing NMT prioritisation map considering the weighted sum of Euclidean distance rasters of both footpaths and cycling paths.

5. Results and discussion

The results of this study are used to assess the existing NMT facilities in Sembawang and Yishun townships. The initial model yields the Euclidean distance rasters representing the NMT movement with respect to residential buildings, community centres, schools & hospitals, recreation & sports centres, economic zones, transport hubs, bus stops, and green spaces. These rasters are individually illustrated in Figure 7. The white shades indicate relatively more NMT presence or more intense movement and the red regions indicate the opposite.

The Euclidean distance raster for the residential buildings layer in the study area is covered by white, violet and blue shades indicating relatively denser NMT movement. At community centres layer, several white shades can be seen covering extreme north, north east, centre, south east and south west areas of the townships. For schools & hospitals layer, the Euclidean distance raster shows relatively lesser density towards south eastern region but otherwise, shows a dense pattern. A similar trend can be seen in the case of economic zones with relatively more NMT movements towards the north western region as compared with the schools & hospitals layer. In the case of recreation & sports layer, Euclidean distance raster shows denser NMT movements in the north eastern and south western parts; and less dense towards the north west and south-east sectors. Three white shades can be seen in the Euclidean distance raster representing transport hubs. NMT density decreases towards the boundary away from MRT stations and bus interchanges. In addition, distance raster for bus stops is relatively dense. Approximately 75% of the raster representing green spaces is covered by white shade; the north western portion is relatively less dense, even reaching the minimum in some areas. This is because green spaces play a critical role in cooling cities, and also provide safe routes for walking and cycling for transport purposes as well as sites for physical activity, social interaction and for recreation (World Health Organization, 2017).

The combination of the Euclidean distance rasters for the 8 different spatial layers created the final NMT prioritisation map. Here again, the highest NMT priority areas are represented by white shading. The model builder result is stored and can be used as a tool for infrastructure planners and designers for future applications concerning similar planning requirements with different Geo-Databases, for example, as a template for necessary modifications (McCoy 2003; Schaller, 2009).

The features of the footpaths and cycling paths in the study area were digitised based on information obtained from MyTransport.sg webpage and site audit, and these were then saved as shape files layers for visualisation and analysis using GIS (see Figure 8). The existing NMT facilities, i.e. currently available footpaths and bicycle paths in the selected study area are used to develop the existing prioritisation map.

Figure 9 shows the comparison between existing and predicted NMT prioritisation for Sembawang and Yishun townships. It can be seen that priority for NMT facilities provision (white shades) should be more towards the central region of study area whereas priority decreases as one moves towards the boundary. The least NMT priority is seen towards the south eastern portion of the study area and this area is verified as being part of Lower Seletar Water Reservoir in Singapore.

In Singapore, conflicts between pedestrians and cyclists do arise on sidewalks as the dedicated cycling infrastructure is still limited. While on-street cycling, conflicts between drivers of motorised vehicles and cyclists are becoming more common. The prioritisation model helps to plan and manage road systems for the convenience of active mobility users. The key benefits of the study are:

- The NMT prioritisation model helps to consider the relationship between people, land use and transport network when developing an active mobility strategy.
- The model raises the importance of developing and implementing a coordinated set of priorities for non-motorised transport.

6. Conclusions

It is clearly evident from the comparison that existing NMT facilities in Sembawang and Yishun townships are almost following the priority sectors predicted by the GIS-enabled prioritisation model. At present, the cycling path network is not complete; however, existing cycling path which is represented using red line is already present in areas having high priority. Footpath network also follows the same trend; footpath network density is more towards high priority areas while being less dense or sometimes non-existent towards relatively low priority areas.

Here in this study, Euclidean distance is used to represent NMT density. The distance categories used in this research are based on previous studies that have integrated distance as a measure of accessibility and a predictor of travel behaviour (Bopp et al., 2011; Delmelle & Delmelle, 2012; Molina-Garcia et al., 2010; Parkin et al., 2008; Shannon et al., 2006; Rybarczyk & Gallagher, 2014). NMT movements and interactions are greater in areas where distance towards spatial features considered in the study is lower. By overlaying the boundary layer and Euclidean distance raster, it is possible to study the NMT density in relation to spatial features.

In future, NMT prioritisation model can be used for planning as well as auditing the existing NMT infrastructure. It can then be used as input for determining investment prioritisation for different areas of the town based on outputs. Similar model can be used to develop inventory and comprehensively taken into consideration while planning for the informal network. The success and impact of the GIS approach in the planning processes ultimately depend on the willingness of the planners and decision-makers to use the produced experiential knowledge and the new methods in their work (Kahila & Kytta, 2009).

The current study is being done at a mesoscopic level. Further to this study, the model will be improved by incorporating more spatial data such as width (capacity), sheltered and unsheltered walkways (comfort), crossing structures (overpass, underpass, junctions etc.) and accessibility (distance) to MRT stations and bus stops, and this shall improve the utility of the GIS-enabled approach in planning NMT network. Based on geomorphology, Singapore is more or less a flat terrain and as a result terrain will not be considered as a factor. Also, comparison will be done for before and after implementing bicycle centric infrastructure in the townships.

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References

- Anon, (2013). *State of the World's Cities 2012/2013, Prosperity of cities*, Nairobi, Kenya: Routledge.
- Anon, (2017). [online] Available at: <https://www.mytransport.sg/content/mytransport/home/toolbar/aboutus.html> [Accessed 26 Oct. 2017].
- Anon, Urban green spaces. *World Health Organization*. Available at: <http://www.who.int/sustainable-development/cities/health-risks/urban-green-space/en/> [Accessed November 16, 2017].
- ArcGIS Desktop: Release 10. (2011). Redlands, CA: Environmental Systems Research Institute.
- Armstrong, T. (2003). *The multiple intelligences of reading and writing*. Alexandria, Va.: Association
- Beukes, E., Vanderschuren, M., Vanderschuren, M. J. W. A., & Zuidgeest, M. H. P. (2013). Using an area wide analysis of contextual data to prioritize NMT infrastructure projects: case study Cape Town, South Africa. In Proceedings of CODATU XV, The role of urban mobility in (re)shaping cities, 22-25 October 2012, Addis Ababa, Ethiopia (pp. -). Addis Ababa, Ethiopia.
- Bopp, M., Kaczynski, A. and Wittman, P. (2011). Active Commuting Patterns at a Large, Midwestern College Campus. *Journal of American College Health*, 59(7), pp.605-611.
- Chin, K. and Menon, G. (2015). Transport accessibility and infrastructure in Singapore – pedestrian facilities. *Proceedings of the Institution of Civil Engineers - Municipal Engineer*, 168(2), pp.133-139.
- Citypopulation.de. (2018). City Population - Population Statistics in Maps and Charts for Cities, Agglomerations and Administrative Divisions of all Countries of the World. [online] Available at: <http://www.citypopulation.de/> [Accessed 13 Mar. 2018].
- Davies A. and Clark S. (2009). Identifying and prioritising walking investment through the PERS audit tool, Walk 21 Proceedings, 10th International Conference for Walking, New York, USA, October 2009.
- Delmelle, E. and Delmelle, E. (2012). Exploring spatio-temporal commuting patterns in a university environment. *Transport Policy*, 21, pp.1-9.

- Department of Statistics and Kim, W.W. (2017). *Population Trends 2017*, Singapore Department of Statistics. Available at: http://www.singstat.gov.sg/docs/default-source/default-document-library/publications/publications_and_papers/population_and_population_structure/population2017.pdf [Accessed October 16, 2017].
- Frumkin, H., Frank, L. and Jackson, R. (2004). *Urban Sprawl and Public Health*. Washington, DC: Island Press.
- Gaytán-Iniestra, J. & Garcia-Gutierrez, J. (2009). Multicriteria decisions on interdependent infrastructure transportation projects using an evolutionary-based framework. *Applied Soft Computing*, 9, pp. 512-526.
- Giorgi, L. and Tandon, A. (2002). Introduction: the theory and practice of evaluation. In: *Project and Policy Evaluation in Transportation*. Ashgate, England, pp. 1–13.
- Handy, S., Boarnet, M., Ewing, R. and Killingsworth, R. (2002). How the built environment affects physical activity. *American Journal of Preventive Medicine*, 23(2), pp.64-73.
- Jain, D. and Tiwari, G. (2016). How the present would have looked like? Impact of non-motorized transport and public transport infrastructure on travel behavior, energy consumption and CO₂ emissions – Delhi, Pune and Patna. *Sustainable Cities and Society*, 22, pp.1-10.
- Jonietz D., Schuster W. and Timpf S. (2013). Modelling the Suitability of Urban Networks for Pedestrians: An Affordance-Based Framework. In: Vandenbroucke D., Bucher B., Crompvoets J. (eds) *Geographic Information Science at the Heart of Europe*. Lecture Notes in Geoinformation and Cartography. Springer, Cham.
- Jonietz, D. and Timpf, S. (2013). An Affordance-Based Simulation Framework for Assessing Spatial Suitability. In: Tenbrink T., Stell J., Galton A., Wood Z. (eds) *Spatial Information Theory. COSIT 2013*. Lecture Notes in Computer Science, vol 8116. Springer, Cham.
- Kahila M. and Kytä M. (2009). *SoftGIS as a Bridge-Builder in Collaborative Urban Planning*. In: Geertman S., Stillwell J. (eds) *Planning Support Systems Best Practice and New Methods*. The GeoJournal Library, vol 95. Springer, Dordrecht.
- Key Statistics. (2015). HDB Annual Report 2014/2015. [online] Singapore: Housing & Development Board, pp.1-26. Available at: <http://www10.hdb.gov.sg/ebook/ar2015/html5/index.html?opf=tablet/Key%20Statistics.xml&launchpage=http://www10.hdb.gov.sg/ebook/ar2015/key-statistics.html> [Accessed 13 Mar. 2018].
- Koh, P. and Wong, Y. (2015). Walking and cycling as an urban transport option in Singapore. *Proceedings of the Institution of Civil Engineers - Municipal Engineer*, 168(2), pp.106-114.
- Koh, P. and Wong, Y. (2012). Balancing demand and supply for non-motorised transport in Singapore. *Cycling Research International*, 2, pp.91-103.

- Koh, P. and Wong, Y. (2013). Comparing pedestrians' needs and behaviours in different land use environments. *Journal of Transport Geography*, 26, pp.43-50.
- Koh, P. and Wong, Y. (2013). Influence of infrastructural compatibility factors on walking and cycling route choices. *Journal of Environmental Psychology*, 36, pp.202-213.
- Koh, P., Wong, Y. and Menon, G. (2014). Pedestrian archeology in Singapore: experiences from the past. *The IES Journal Part A: Civil & Structural Engineering*, 7(4), pp.297-305.
- Land Transport Authority, Singapore (2017). *Recommendations on rules and code of conduct for cycling and the use of personal mobility devices*. Singapore: Active Mobility Act.
- Lta.gov.sg. (2014). *More Companies to "Travel Smart" | Press Room | Land Transport Authority*. [online] Available at: <https://www.lta.gov.sg/apps/news/page.aspx?c=2&id=b89eb65a-f4ca-42de-8199-2ab7c50bd04f> [Accessed 20 Dec. 2016].
- Lta.gov.sg. (2016). *Intra-Town Cycling Networks | Cycling Infrastructure | Walk Cycle Ride | Land Transport Authority*. [online] Available at: <https://www.lta.gov.sg/content/ltaweb/en/walk-cycle-ride/integrating-cycling-with-public-transport/Intra-Town-Cycling-Networks.html> [Accessed 16 Nov. 2017].
- Li, Z. and Sinha, K. (2004). Methodology for multicriteria decision making in highway asset management. *Transportation Research Record: Journal of the Transportation Research Board*, 1885, pp.79-87.
- Mackie, P., Preston, J., 1998. Twenty-one sources of error and bias in transportation project appraisal. *Transportation Policy* 5, 1–7.
- Meng, M., Koh, P., P., Wong, Y., D., and Zhong, Y., H. (2014). Influences of urban characteristics on cycling: Experiences of four cities. *Sustainable Cities and Society*, 13, pp.78–88.
- Meng, M., Koh, P.P. and Wong, Y.D. (2016). Influence of socio-demography and operating streetscape on last-mile mode choice. *Journal of Public Transportation*, 19(2), pp.38-54.
- Meng, M., Zhang, J., Wong, Y.D. and Au, P.H. (2016). Effect of weather conditions and weather forecast on cycling travel behaviour in Singapore. *International Journal of Sustainable Transportation*, 10(9), pp.773-780.
- Molina-Garcia, J., Castillo, I., and Sallis, J., F. (2010). Psychosocial and environmental correlates of active commuting for university students. *Prev. Med.*, 51 (2), pp.136–138.
- Muslimana, R., Ariffinb, S., R., and Dinc, R. (2013). Assessing Students' Spatial Intelligence for Literacy and Numeracy Skills. *Procedia - Social and Behavioural Sciences*, 90, pp.695–701.

- MyTransport.SG. (2016). MyTransport.SG:Home. [online] Available at: <https://www.mytransport.sg/content/mytransport/home.html> [Accessed 20 Dec. 2016].
- Ng, S., W., Lau, F., Brown, E., Tam, M., Lao, & Booth, V. (2012). Walkable city, living streets. Hong Kong: Civic Exchange.
- Nguyen, P.N., Koh, P.P. and Wong, Y.D. (2015). Impacts of bicycle infrastructure: a case study in Singapore. *Proceedings of the Institution of Civil Engineers-Municipal Engineer*, 168(3), pp.186-198.
- Nijkamp, P., Rienstra, S. A., & Vleugel, J. M. (1998). *Transportation planning and the future*. Chichester: Wiley.
- Norton et al. (2015). Planning for cooler cities: A framework to prioritise green infrastructure to mitigate high temperatures in urban landscapes, *Landscape and Urban Planning*, 134, pp. 127-138.
- Pantha B.R., Yatabe R., Bhandary N.P. (2010). GIS-based highway maintenance prioritization model: an integrated approach for highway maintenance in Nepal mountains. *Journal of Transport Geography*, 18 (3), pp. 426-433.
- Parkin, J., Wardman, M., and Page, M. (2008). Estimation of the determinants of bicycle mode share for the journey to work using census data. *Transportation*, 35 (1), pp.93–109.
- Poyil, R. P., Misra, A. K. and Murugasan, R. (2014). Pedestrian safety modelling and analysis using GIS in Chennai. *International Journal of Remote Sensing Applications*, 4(2), pp.97-102.
- Public Housing – A Singapore Icon. (n.d.). Available at: <http://www.hdb.gov.sg/cs/infoweb/about-us/our-role/public-housing--a-singapore-icon> [Accessed 26 Oct. 2017].
- Quadros, S. G. R., and Nassi, C. D. (2015). An evaluation on the criteria to prioritize transportation infrastructure investments in Brazil, *Transport Policy*, 40, pp. 8-16.
- Rojas López, M. C., and Wong, Y. D. (2017). Attitudes towards active mobility in Singapore: A qualitative study. *Case Studies on Transport Policy*, In press.
- Rybarczyk, G., and Gallagher, L. (2014). Measuring the potential for bicycling and walking at a metropolitan commuter university. *Journal of Transport Geography*, 39, pp.1-10.
- Salonen, M., Broberg, A., Kytta, M., and Taivonen, T., (2014). Do suburban residents prefer the fastest or low-carbon travel modes? Combining public participation GIS and multimodal travel time analysis for daily mobility research. *Applied Geography*, 53, pp.438-448.

- Sanyal, S. (2013). Sharing and walking to cities of tomorrow. *AsiaOne*. Available at: <http://www.asiaone.com/singapore/sharing-and-walking-cities-tomorrow> [Accessed 10 Jul. 2017].
- Schaller, J., Gehrke, T., and Strout, N. (2009). *ArcGIS processing models for regional environmental planning in Bavaria*. In S. Geertman, & J. Stillwell (Eds.), *Planning Support Systems: Best Practices and New Methods* (pp. 243-264). New York: Springer.
- Shannon, T., Giles-Corti, B., Pikora, T., Bulsara, M., Shilton, T., & Bull, F. (2006). Active commuting in a university setting: assessing commuting habits and potential for modal change. *Transp. Policy*, 13 (3), pp.240-253.
- Tong, S. (2017). *Singapore Will Stop Increasing Car Numbers from February 2018*. Available at: <https://www.bloomberg.com/news/articles/2017-10-23/singapore-to-stop-adding-cars-on-itsroads-from-february-2018> [Accessed 30 Oct. 2017].
- Tsamboulas, D., A. (2007). A tool for prioritizing multinational transport infrastructure investments. *Transport Policy*, 14 (1), pp. 11-26.
- Victoria, G., Doron, B., Roby, C., Limor, H., and Fany, P. (2012). Characterization of pedestrian accidents and an examination of infrastructure measures to improve pedestrian safety in Israel, *Accident Analysis and Prevention*, 44, pp.63– 73.
- Yedla, S., and Shrestha, R. M. (2003). Multi-criteria approach for the selection of alternative options for environmentally sustainable transport system in Delhi, *Transportation Research Part A: Policy and Practice*, 37(8), pp.717-729.

Table 1. Statistics related to study area (Source: City Population; Housing & Development Board)

Sl. No.	Data	Sembawang	Yishun
1.	Total area (in km ²)	12.34	21.24
2.	Residential area (in km ²)	3.31	3.98
3.	Population	76,530	201,970
4.	Population density (per km ²)	6,200	9,500
5.	No. of dwelling units	20,311	56,698
6.	Projected no. of dwelling units	65,000	84,000

Table 2. Length of transport network in Sembawang and Yishun

Transport network	Total length (in m)
Road	158340
Footpath	195556
Cycling path	27477

Table 3. Characteristics of polygon layers

Serial No.	Type of buildings	Number of polygons	Minimum area (in sq. m)	Maximum area (in sq. m)	Total area (in sq. m)
1	Residential buildings	5518	0.9	30128	2480146
2	Community centres	156	2.2	15220	119786
3	Schools & hospitals	160	4.1	15497	221551
4	Recreation & sports centres	24	3	4598	19643
5	Economic zones	1289	2	40013	1273732
6	Transport hubs	3	6639	9765	23632

Figure captions

Figure 1. Selected features of NMT formal network

Figure 2. Selected features of NMT informal network

Figure 3. Study Area: Sembawang and Yishun townships

Figure 4. Study methodology flowchart

Figure 5. Details of ModelBuilder tool

Figure 6. Illustration of Euclidean distance analysis (ESRI, 2011)

Figure 7. Euclidean distance rasters – NMT movement in relation to specific spatial features
(Note: Please refer digital colour print of the article for better understanding)

Figure 8. NMT facilities in the study area

Figure 9. NMT prioritisation map (a) Existing & (b) Predicted (Note: Please refer digital
colour print of the article for better understanding)

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5_

Figure 6

Figure 7

Figure 8

Figure 9