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Analysis and Modelling of the Multilevel Transport Network: The Metro and Railway System in Greater London

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Abstract

Transport development has become more and more important among all aspects of urban development in recent years. To accommodate the rising demand for daily travel and commutes, the public transport system, especially the rail system, is considered the better solution for sustainable mobility, instead of the road system for vehicles. Studies in urban morphology usually focus on the model of urban form without concerning the multi-dimensional network of public transport, whereas transport planning and engineering emphasise the capacity and travel demand within the road network, which disregards the spatial effect of the urban form. This research aims to bridge the gap between these two disciplines by developing an Integrated Urban Model (IUM), which combined various layers of urban information and dataset, including spatial network, land use and census. It seeks to identify the complex interrelationship between urban form networks and the socio-economic community by the synthetic analysis of the IUM. A multilevel multimodal network model has been built for the case of Greater London to combine the street network with the Metro/Rail network to investigate the network accessibility. In addition, this study applied space syntax theory and methodology as the primary approach to reveal the potential flow and movement pattern of the multilevel multimodal network. The result indicated that the multilevel network model with space syntax accessibility measurements could provide an interpretative overview of spatial distribution in both global and local scales. The IUM also allowed the spatial impact of public transport network to be uncovered through geodatabase modelling and spatial analysis.

Keyword: *Multilevel Multimodal Network, Geo-Spatial Modelling, Accessibility Analysis, Public Transport, Space Syntax.*

Introduction

People are making daily trips for various purposes via one or multiple transport modes. When planning the itinerary, travelling time is usually the most decisive factor when selecting the routes. According to Department of Transport UK (DfT, 2020), people made 18 trips per week on average in 2019. Although transport technology and engineering have improved over time to increase travel speed, people do not spend less time travelling. Travel time has remained constant at around one hour per day in most of the country. The most common trip purpose in England 2019 was for leisure (26%), following by shopping trips (19%) and commuting (15%). (Urry, 2007: P4)

All the activities to support social life would involve the combinations of proximity and travelling. People would commute in the states of physical and virtual travelling that link people together for obligation, desire and commitment without the limitation of the distance. Mobility is, therefore, the central concern of urban development to ensure the socio-spatial functionality of the towns and cities. (Urry, 2002;2007)

To enhance mobility is a matter of developing transport infrastructure and delivering efficient services. Thus, to overcome the social, economic, political and physical constraints of movement, a sustainable transport and urban mobility plan is required. It must coordinate policies across all sectors of transport, land use, environment, economy, social policy, health, safety, and energy, to provide an integrated development for the sustainable mobility solution. That being said, urban transport development should pay attention to bringing people and places together by creating an urban transport system that could enhance accessibility, rather than merely building more transport infrastructure or increasing the movement of people and goods. The goal of mobility plans should extend beyond gaining access to destinations, activities, services and goods, to focus on how people could reach opportunities for employment, education, leisure more easily and efficiently (UN-Habitat, 2013; Rupprecht Consult, 2019).

The strategy of improving mobility and accessibility requires a holistic and interdisciplinary approach to achieve. It has to establish the knowledge between urban form (in terms of shape, structure, function, demographics) and urban transportation system, which involves all forms of mobility, including walking, cycling, private vehicles and public transport. Cities and regions require an integrated urban transport system to decrease travel distance, increase frequency, and lower the environmental impact to alleviate the costs of energy and congestion. A well-integrated transport network will be able to encourage the modal share of public transport and non-motorised transport modes and reduce the usage of private motorised vehicles. Therefore, public transportation, particularly the high-capacity public transport system, plays a key role in the accessibility-based urban mobility plan.

In order to understand the impact of the public transport system and the multilevel multimodal network effect in the city, this study developed an Integrated Urban Model (IUM) to conduct the network accessibility analysis. By linking the urban dataset, including land use and census, IUM could uncover the microeconomic of the streets and identify whether the embeddedness of public transport systems could potentially increase mobility and facilitate connectivity in the specific territory of the city.

After describing the theoretical research background, this paper begins by introducing the Integrated Urban Model and the methodology of the spatial analysis. Continuing on applying IUM in the transport network of Greater London, this paper compares the accessibility between the street network and the multilevel network, which includes the Metro/Rail systems. Finally, this paper discusses the result of the multilevel network accessibility and the potential impact of the Metro/Rail systems on Greater London. This paper also highlights that the approach of IUM and spatial analysis can be used to understand the impact of transport development for any city or region in the world.

Background

Transport Study and Modelling

In transport research, the network analysis and modelling usually require travel information, including transfer time, speed and service frequency. Beyond the pure network topology and connectivity, this trend of study particularly considers journey price as the major determinant for travel patterns. In this regard, transport modelling such as MATsim, Urbansim, usually adopts Gravity Model (Masucci et al., 2013), Agent-Based Modelling (ABM) (Batty, 2013) and Cost-Benefit Analysis (CBA) (Hanley and Spash, 1993; Boardman, 2001) to investigate the network equilibrium at the prevailing costs to the users, where the system is a dynamic network (Bell and Iida, 1997; Daganzo, 1997). Nevertheless, the distribution of the trip frequency within the network is mainly determined by the journey price in the notion of economics. The result of simulation usually makes the characteristics of the topological and the geometric spatial effect difficult to be reflected. Even with the revolutionary technologies in the computational calculation which could apply Geographic Information System (GIS) in transport analysis (Haynes et al., 2004), most of the transport simulation could only be executed with the analysis in regional scale instead of the multiscalar network. The network accessibility of spatial effect in the local scale is typically absent from the transport network simulation.

Urban Study and Space Syntax

On the other end of the spectrum, urban morphology studies and analyses focus on the tangible characteristics of the cities, towns, and villages by examining the geometric arrangement or layout of the components, usually the streets or plots, based on the size, shape, and density. The spatial patterns of the urban tissue could inform the urban function of the city and settlement, as well as the social-spatial activities taking place inside the urban areas. As a set of theories and methodologies for investigating the relationships between urban characteristics and the social, economic and environmental effects, space syntax theory and measurements have been successfully applied to examine the spatial connectivity of the urban network by 'axial map' analysis (Hillier and Hanson, 1984; Hillier, 1996) and 'segment map' analysis (Turner, 2001; Hillier and Iida, 2005). The simplified physical components with the constant time spent and equal weight segments between all space to all other space are the features for the geometric network analysis in space syntax (Law et al., 2012). The result could present the relative accessibility or closeness for the location within the urban network. Space syntax studies have proved that the flow of pedestrian and vehicles are strongly correlated with the configurational effect of the urban form (Penn et al., 1998) but is limited to the street-based model without concerning the sense of the geographic properties for the non-street transport network between places (Jiang, 1999; Batty 2004). Therefore, space syntax analysis could only partially capture the flow of people and vehicles in the city by the geometric composition of street network and somehow lose the sense of the public transport network, which has been heavily relied on for travelling in the cities.

Integrated Urban Model

There is clear a gap between transport study and urban study. Transport study needs to involve the spatial effect of urban form while urban form analysis requires attention on movement pattern to inspect the influence of multilevel multimodal network. It requires the approach and concept which could access the multidisciplinary study and provides an advanced tool to combine the geometric urban analysis with the geographic analysis of transport accessibility model. Therefore, this study developed a synthesis methodology to assess the spatial interaction of the multilevel network in the cities by applying space syntax accessibility measurement. An Integrated Urban Model (IUM), which is based on the concepts and methodologies from multimodal network and advanced space syntax modelling literature (Law et al., 2012; Gil, 2016; Karimi et al., 2015; Acharya et al., 2017), is created to test the network phenomenon. IUM, which adopted the multilevel network system, allows the study to link space and movement patterns with the urban functions in terms of land use, and at the same time, uncovers the impact of the public transport network on the city in both global and local scales.

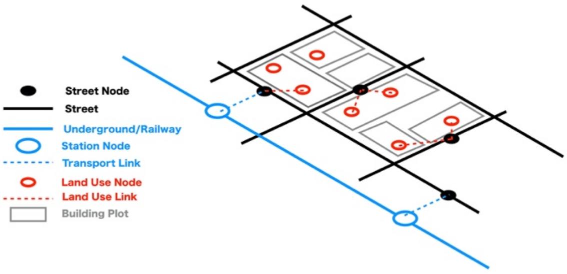
Methodology

Introduction of Integrated Urban Model

The development of the IUM started by joining two major networks, namely Road-Centre Line (street network) (Turner, 2005) and Transport API GTFS (public transport network), via the station nodes, as the primary multilevel multimodal model. IUM then allows land use and other demographic datasets to be joined with the network model through the links between street and building plots. It created a platform not only could perform the spatial analysis in terms of network accessibility measurements (space syntax) and land use catchment analysis, but also could link the result of accessibility variables with land use distribution and density together for statistical evaluation. A series of spatial query function based on SQL (Structured Query Language), has been applied in the development of the IUM. The method and scripts could be easily applied for different cities and regions with compatible datasets.

Spatial Modelling and Dataset

The dataset includes geographic, land use, demographic and census datasets, which have been imported and transformed into geodatabase for the quantitative description, analysis and visualisation. PostGIS is the primary programme for processing geospatial datasets. Every dataset will be loaded into the PostGIS database for cleaning, simplifying, attribute modifying, and further aggregating in the network model. PostGIS spatial database and the database management system – PostgreSQL are the powerful opensource platform in dealing with large number and size of dataset, and running spatial queries for the attributes and tables geographically. The IUM will link the selected dataset that is capable of providing a description of urban form in the cities and regions based on the components of the land use type and transport mode. Figure 1 and 2 introduce the structure of the IUM and PostGIS database. Also, a table of dataset which has been processed in this study is provided below.



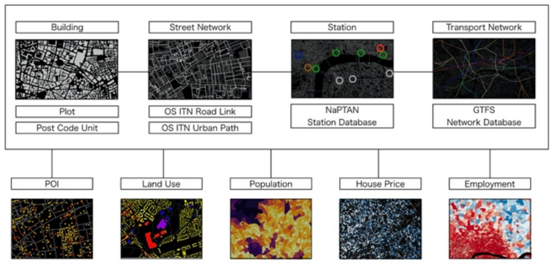


Figure 1. *(Left) Diagram of IUM structure.* ***Figure 2.*** *(Right) The dataset and structure of PostGIS database.*

Table 1. Datasets.

Dataset	Modelling Representation	Geometry Type	Data Source
Road-Centre Line	Street Network	Polylines	OpenStreetMap (OSM)
Transport API GTFS	Tube/Rail Network	Vector Lines	Department of Transport (DfT)
OS AddressBase Point	Land Use	Points	Ordnance Survey
NaPTAN	Station Node	Points	Department of Transport (DfT)

Spatial Network Analysis

Two main accessibility measurements of space syntax have been adopted in this study to uncover the topologic and geometric network connectivity in the city. *Integration* (Closeness Centrality) measures the 'to-movement' potential of a street segment. It examines the 'closeness' from all space to all other space within the defining system (Hillier and Hanson, 1984). Choice (Betweenness Centrality) measures the 'through-movement' on how likely a street segment is to be passed through on all shortest routes from all spaces to all other spaces in the defining system (Hillier et al., 1987).

The TfL metro system and National Rail services in Grater London have been selected for the case study. The multilevel model within London M25 motorway has been built to process the analysis and evaluate the accessibility in this region.

Results and Discussions

A study has been designed to examine the network effect with and without public transport network in Greater London. The accessibility network analysis of space syntax has been processed to reveal the global impact of the Metro and Rail services on the network centrality in four designed scenarios (Figure 3): 1. Street-Only Network, 2. Street + Metro Network (TfL Tube Services), 3. Street + Metro + Rail Network (Within M25), and 4. Street + Metro + Rail + Crossrail (Open in 2022) Network.

In scenario 1, the result of space syntax integration (Closeness Centrality) indicated that most of the highly accessible places are located in north of the River Thames. In scenario 2, the graph result suggested that the metro service increases the network centrality mainly in the North but rarely extends to the South. The value of accessibility measurements in Table 2 also supports the result that the top 50% integration is decreased proportionally in the South when considering only the metro service. The result of scenario 3 indicates that the Rail services enhance the network centrality enormously in the South from 13% to 70% of the area. In scenario 4, the result demonstrates that network centrality is boosted in most of the fringe areas with all types of public transport services, including Crossrail, which will begin its service in the coming years.

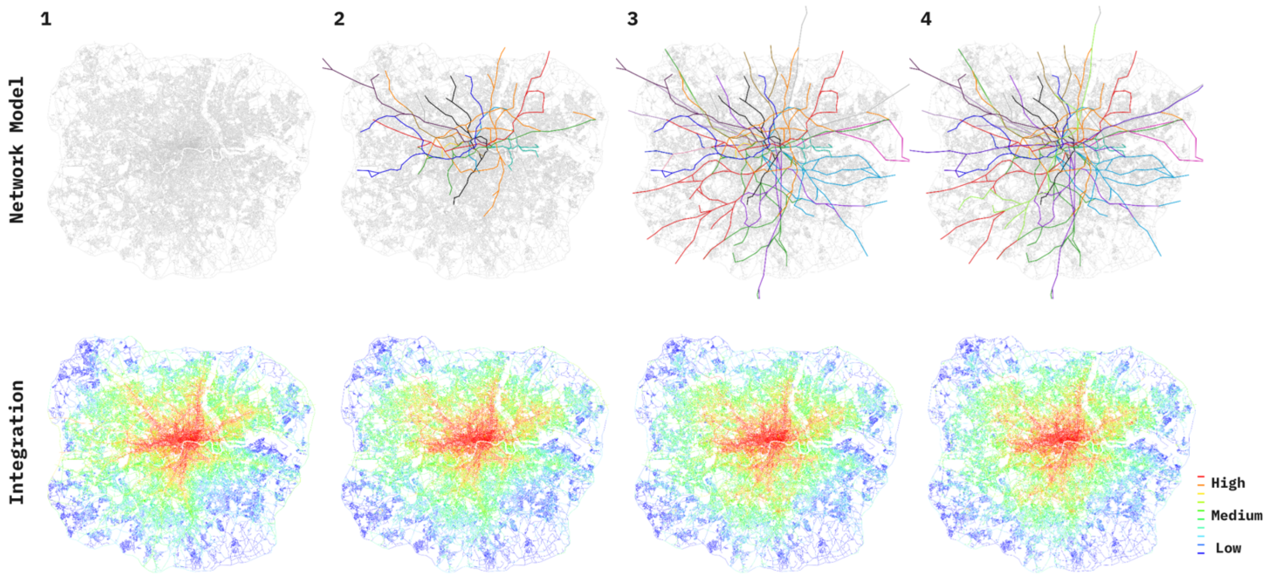


Figure 3. *Scenarios and Integration (Closeness Centrality) global measure result*.

It is more clear to present the change of accessibility within the London M25 by comparing the degree of centrality between street only network and multilevel network. Figure 4 is the graph of the integration increase in percentage between street only network and multilevel multimodal network of Metro service. The graph demonstrates that the Metro service enhanced the accessibility in the west, east fringes, and partially the south London. In Figure 5, the integration increase in the multilevel network with both Metro and Rail services, which indicates that the accessibility enhanced significantly in the South where the Rail system is the major public transport service. This result could suggest that people who live in the South might rely on Railway service more than Metro or other public transport services for daily commute between Central London and the South suburban area.

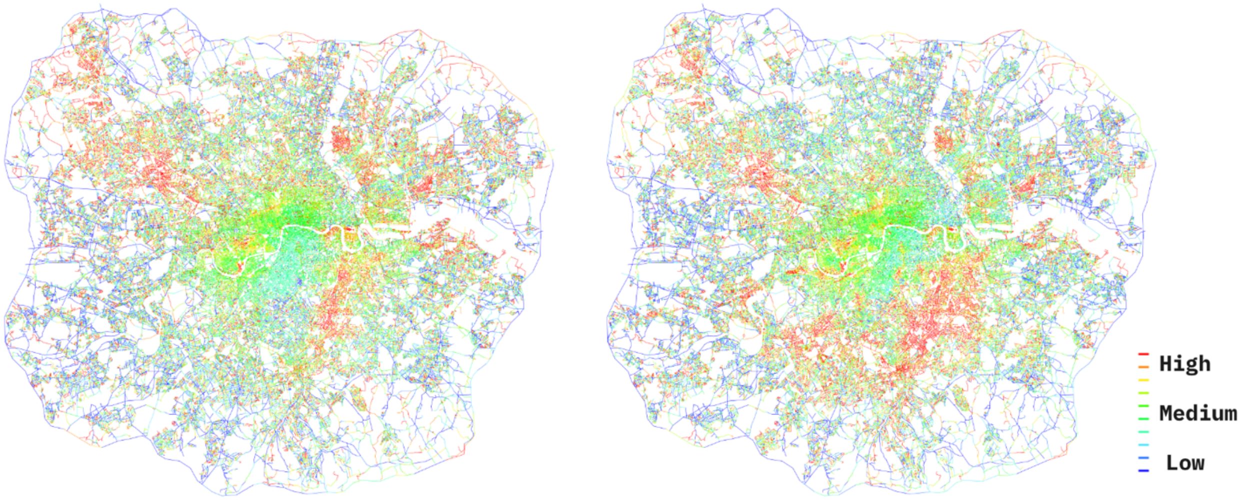


Figure 4. *(Left) Integration Increase Percentage between scenario 1 and 2.* ***Figure 5.*** *(Right) Integration Increase Percentage between scenario 1 and 3.*

Table 2. Multilevel Integration in 4 Scenarios.

Scenarios	**Top 50% Integration**			**Integration Increase Over 20% (Compare with street network)**		
Area	Greater London	South	North	Greater London	South	North
Street	46%	31%	58%	-	-	-
Street+Metro	45%	28%	59%	17%	13%	20%
Street+Metro+Rail	46%	36%	54%	67%	70%	64%
Street+Metro+Rail+Crossrail	46%	35%	54%	76%	77%	76%

The study then examined the correlation between land use distribution and the integration (closeness) in station neighbourhoods for both street only network and multilevel multimodal network. Three major land use types - retail, residence and office, have been examined broadly with the network model. A strong correlation could be found in retail density versus integration.

The result suggested that there is a strong positive correlation between the retail distribution with space syntax integration (closeness). It particularly indicated that network accessibility dominates the retail distribution within 400m catchment of the rail stations. Table 3 is the Pearson Correlation examination of the retail density and integration between both street only network and multilevel network, including Metro and Rail network. This result suggested that multilevel model correlates better with retail distribution than street only network model.

Table 3. Pearson Correlation Retail Density vs Integration in Street Network and Multilevel Network.

400m Catchment	Integration						
Analysis Radii	**400m**	**800m**	**1200m**	**1600m**	**2km**	**5km**	**10km**
Retail Density (Street Network)	0.640	0.749*	0.775*	0.742*	0.722*	0.669	0.681
Sig. (2-tailed)	0.087	0.033	0.024	0.035	0.043	0.07	0.063
Retail Density (Multilevel Network)	0.907**	0.908**	0.876**	0.888**	0.893**	0.870**	0.779*
Sig. (2-tailed)	0.002	0.002	0.004	0.003	0.003	0.005	0.023

Conclusions

The aim of this study was to investigate the influence of public transport network, particularly the metro and rail networks in the cities and regions. The approach this study took is to examine the multilevel multimodal network by building an Integrated Urban Model, which could assess the network connectivity as well as the urban dataset for the understanding of the network centrality and its relation with the land use distribution. By comparing the street-only model with the multilevel model, the spatial analysis of integration (closeness) demonstrates that the global influence of the public transport network might change the accessibility patterns significantly. The city fringes where were thought to be spatially segregated from the city centre, became closer to the rest of the region in terms of network accessibility with the services of metro and railway. These areas benefit from the public transport with enhanced network connectivity, but the street only network model might not be able to fully capture the phenomenon. The results indicated that the multilevel network proved to be a better model applied for the spatial analysis in the study of public transport not only for understanding the shift of global centrality but also could validate the local land use distribution influenced by the stations. Base on the findings, this study suggests that space syntax could be a useful tool and methodology to investigate the network effect of the city. In addition, employing multilevel multimodal network analysis could bridge the gap between transport and urban study with the functionality to decrypt the urban form and potential movement within the network. Since this study only applied the metric distance for the network analysis of multilevel network, future works are required to reveal the travel patterns by applying travel time as the unified cost to eliminate the speed difference in different modes of transport for the analysis of network connectivity. Furthermore, a correlation validation between the network centrality and transport usage in terms of the daily passenger numbers for each services and station entry/exits numbers is needed to strengthen the understanding of the multilevel network phenomenon.

In summary, the approach of the multilevel network analysis and IUM could be an asset for transport and urban study to provide a better understanding of the urban form phenomenon. The methodology could also become the assessment tool for future transport and urban development projects for cities and regions.

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