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ORIGINAL RESEARCH ARTICLE

Transport-land use systems of sustainable London city

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ABSTRACT

Transportation and land use are interrelated and should be investigated simultaneously for sustainable urban. This paper investigates the interaction between transport and land-use systems using TRANUS model, to support the sustainable development of the London city, provide implicative information for London Mayor's Transport Strategy (MTS), and reduce transport energy use and CO_2 emissions. Three infrastructure improvements scenarios for 2025 for MTS are examined. Results show that the trips will increase from 2012 to 2025 by over 1 million. High-occupancy car, bike, rail and tube are still the main transit, and CrossRail will be increasingly recognized. The transport energy use in 2025 high scenario is the smallest compared to 2025 baseline and low scenario. The transport CO_2 emissions show difference for these three 2025 scenarios, with low and high scenarios having smaller transport CO_2 emissions than baseline. These have informative implications for UK national infrastructure plans, and suggest that accounting environmental benefits of infrastructures will contribute to reduce the underinvestment in infrastructure.

Keywords: energy; transport; urban sustainability; infrastructure; CO_2 emissions

1. Introduction

Human population demonstrates increasing growth and is projected to be 9 billion by 2050. Owing to increasing mitigation in urban areas, over 68% of the world's population will live in urban areas by 2050[1], and consequently, urban infrastructures face big challenges in accommodating the growing population. Transport and land use are top-tier infrastructures and are interrelated. As the most social and economic activities in urban areas take place at separate locations, the transport is needed to support the relevant movements of passengers and freight. On the other hand, these urban activities have the locational and international nature. It has been recognized that transport and land-use modelling play a key role in implementing urban sustainability[2], and is critical to create sustainable cities for future[3]. The transport and land use modelling also have direct relevance to the energy use in cities[4]. Only the transport sector will account for 30% of the growth in petroleum consumption between 2004 and 2030[5], and the UK is a key source of CO_2 emissions which accounts for 20% of total CO_2 emissions[6].

There are three families of methods which are mainly used to investigate transport-land use systems. The first is surveys and interviews with users. This is the ordinary method used to acquire the data. The

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disadvantage of this method is, however, about the reliability. Due to the subjectivity of answers, it cannot guarantee reliability. The second method is based on empirical observations of users' behaviour. This method can provide more reliable results for current situations than the first one. It, however, is incapable to deal with the future scenarios. The third method is based on mathematical simulation models of human behaviour. This method aims to develop the mathematical simulation models from data coming from observations of user's actual behaviour and empirical studies, and can simulate the future scenarios. The third method has been investigated continually[7–9], and two main theories have been constructed for the development of the mathematical simulation models for the coupled transport-land use systems. One is the theory of spatial interactions[10], and the second is the theory of entropy maximization[11] which is based on analogy with Newton's gravitational theory and physical principles of maximization of entropy. Zhou et al.[12] utilized an integrated transport-land use model to study the relationship between transport energy consumption and resident settlement morphology in the southeast coastal city of Xiamen. Kii et al.[13] provided a review of the integrated transport-land use models. Although a lot of integrated transport-land use models have been developed, the application of these models to the reality are still on the way because of data availability and model calibration[7,14], and still need further investigation.

London has experienced significant economic and population growth since the early 1980s, and it is projected that the substantial growth will be continue over the next 20 years. The population of London is projected to 8.3 million by 2025, increasing around 0.9 million compared to 7.4 million in 2004[15,16], and it is expected that there are up to 3 million more people living in London by 2050[17]. This, together with the climate change, throws big pressure to the London transport system and land use for urban sustainable development. The London government is looking for scientific evidences to make proper policy to tackle this issue[15,16,18,19]. This paper aims at this purpose.

In this paper, an integrated transport-land use model and the relevant data and scenarios will be introduced first. Then the paper provides the results and discussion. Finally, some conclusions are drawn.

2. Materials and methods

2.1. Methods

The TRANUS model is employed to examine the interaction between the transport and land-use systems. This model is an integrated transport and land-use model, and has been validated and applied to some real cases and research projects[20]. The model has two main components: land use and transport. The land use model estimates the activities for zones in which the study area has been divided, and equilibrates a property market. These activities will generate economic flows which will be transformed into travel demand for each origin-destination pair. The transport model will then assign the flows to the transport network, and calculates the generalised composite cost of transport which is then fed back to the land use model and influence the location and flows between activities in the next time. **Figure 1** depicts the procedure.

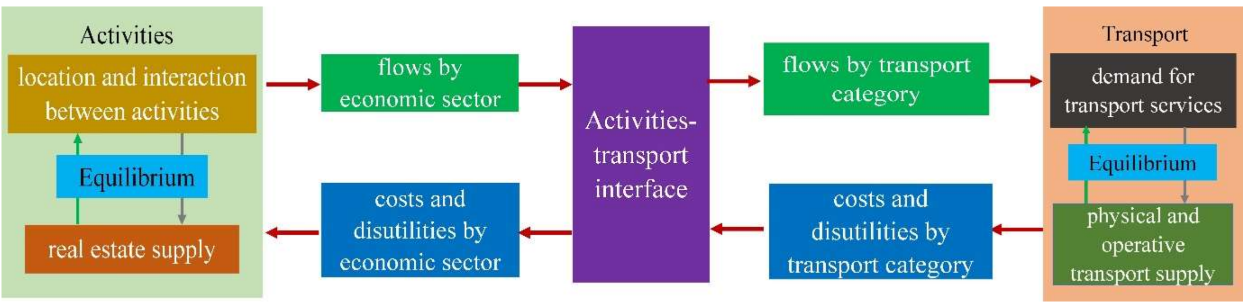

Figure 1. TRANUS structure[21].

If the exogenous production of sector *n* in zone *i* at time period *t* is $X_i^{*n,t}$, then the Equation (1) is held.

$$X_i^{*n,t} = X_i^{*n,t-1} + \Delta X^{*n,t} \rho_i^{*n,t} + \Delta X_i^{*n,t} \tag{1}$$

where $X_i^{*n,t-1}$ is the exogenous production of sector *n* in zone *i* for time period $t-1$. $\Delta X^{*n,t}$ is the global increment of exogenous production of sector *n* between $t-1$ and *t*. $\Delta X_i^{*n,t}$ is the given increment of exogenous production of sector *n* in zone *i* for time period *t*. $\rho_i^{*n,t}$ is the proportion of the increment of sector *n* allocated to zone *i* for period *t*.

The proportion of the global increment assigned to each zone is a function of the attraction function (Equation (2)).

$$\rho_i^{n,t} = \frac{\mathrm{A}_i^{n,t}}{\sum_i A_i^{n,t}} \tag{2}$$

where $A_i^{n,t}$ is the attractor of sector *n* in zone *i* for period *t*, and can be determined by Equation (3):

$$A_i^{n,t} = \sum_k b^{n,k} (\alpha^{n,k} \tilde{X}_i^{k,t-1} + \beta^{n,k} p_i^{k,t-1} + \chi^{n,k} Q_i^{k,t-1}) \tag{3}$$

where $b^{n,k}$ is the relative weight of sector *k* in the attraction function of sector *n*. $\tilde{X}_i^{k,t-1}$ is the total production (exogenous plus induced) of sector *k* in zone *i* at period $t-1$. $p_i^{k,t-1}$ is the price of sector *k* in zone *i* at period $t-1$. $Q_i^{k,t-1}$ is the excess capacity (maximum constraint − total production) of sector *k* in zone *i* at period $t-1$. $\alpha^{n,k}$, $\beta^{n,k}$ and $Q_i^{k,t-1}$ are the parameters indicating the relative importance of each element.

The activities for zones are then transformed into trips. An elastic demand curve is used to derive trips from activities, and is defined as Equation (4):

$$T_{ij}^s = F_{ij}^s [v_{\min}^s + (v_{\max}^s - v_{\max-\min}^s) e^{(-\eta^s \tilde{c}_{ij}^s)}] \tag{4}$$

where T_{ij}^s is the trips from zone *i* to zone *j*. F_{ij}^s is the flow by transport category *s* from zone *i* to zone *j*. $v_{\min}^s$ is the minimum number of trips per unit of flow made by category *s*. $v_{\max}^s$ is the maximum number of trips per unit of flow made by category *s*. η^s is the elasticity of category *s*. $\tilde{c}_{ij}^s$ is the composite disutility for category *s* traveling from zone *i* to zone *j*.

2.2. Materials

The city of London is the capital of the UK, and has been recognized as the heart of the world's leading financial, business and maritime centre. To support the sustainable development of the London city, it is of importance to understand the interaction between the transport and land-use systems at urban scale which will contribute to London city planning and Mayor's Transport Strategy (MTS). The London's resident population reaches 8.2 million according to the 2011 Census, and is projected to be 8.3 million by 2025 and 9.84 million by 2031, respectively. Population growth show spatial heterogeneity across Greater London. It has highest rate in East London, followed by South and West London. In order to support population and economic growth, the London's public transport system has been progressively developed. The average Londoner could access 989,450 jobs within a minute travel time by public transport in 2012[16]. By 2025 employment is projected to increase by 970,000 and the total travel is projected to increase by four million journeys every day[15]. In order to improve London's public transport system to accommodate the growth of employment, effectively manage the road network, reduce traffic congestion, and reduce transport energy use and CO_2 emissions, there is an urgent need to investigate the interaction between transport and land-use.

Mainly due to the data availability in land-use system, the city of London is zoned into 33 subarea called "borough" (**Figure 2**). In this study, the external zones are not specified explicitly and therefore the external trips are omitted. Due to large zones, the short trips, such as intra-zone trip, are omitted as well. Due to the data availability on bus lines and the considered road characteristics (which will be described in the following text), the bus trips are also omitted accordingly. In terms of the availability of data, the base year is set to 2012, which is used to calibrate model.

Figure 1. London borough map.

The number of sectors considered is 12, and is depicted by **Table 1**. Among these 12 sectors, the first eight sectors are economic sectors among which the first two sectors are exogenous sectors (exogenous parameters), and the rest are land types. According to their different transport behaviours, the households are further divided into three categories: higher income, medium income and lower income household. According to UK Office of National Statistics (ONS), the lower income household refers to those whose annual income is less than £25,000, medium income is from £25,000 to £49,999, and higher income is over £50,000. The land types are further distinguished into residential floorspace, commercial floorspace, and education and health floorspace as well, with respect to the characteristics of economic sectors. Each floorspace will be consumed by specific economic sectors and themselves consume land, as depicted by **Figure 3**.

Table 1. Sectors.

Name	Exogenous	Unit	Description
Industry and agriculture	yes	number of employment	
Government	yes	number of employment	
Service		number of employment	Induced by households
Health		number of employment	Induced by households
Education		number of employment	Induced by households
Lower income households		number of households	Induced by employment
Medium income households		number of households	Induced by employment
Higher income households		number of households	Induced by employment
Residential floorspace		m^2	consumed mainly by households
Commercial floorspace		m^2	consumed mainly by Government, Industry and agriculture, and Service
Education and health floorspace		m^2	characterised by zero cost, as these activities location is considered to be planned and not be the result of competition on land market with other uses
Land		m^2	consumed by floorspace

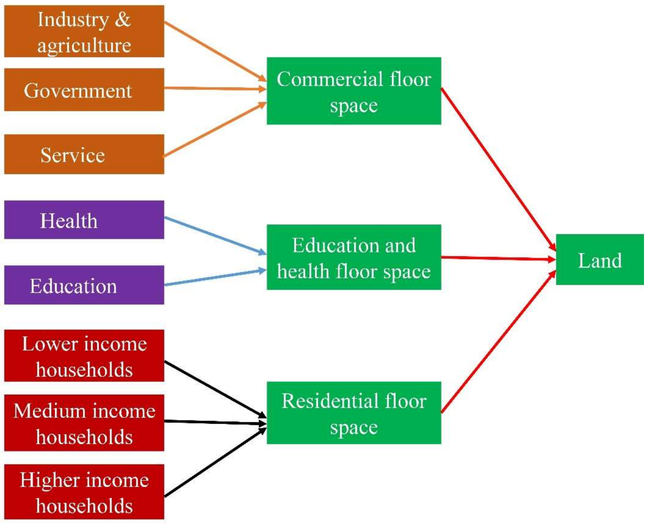

Figure 2. Relationship between activities and floorspace.

The household amount data is acquired from London Travel Demand Survey (LTDS), which commenced in 2005/06. The employment is obtained from Greater London Authority (GLA), which follows the SIC categorisations and thus allows GLA reports to be compared to future and past reports produced by others. The house prices (here rent) are also obtained from GLA. The floorspace used by each sector is obtained from National Land Use Database (NLUD) version 4.4.

The transport network is acquired from Ordnance Survey-Meridian and by digitising London tube map where tube network is not available. It includes three main road type-A Road, B Road, and Motorway-Rail Road, and London tube lines. Since the main road type has no connection with rail road and tube line, the nearest roads are constructed to connect the rail road and tube line using Geographical Information Systems (GIS) software. Totally, it has 3914 nodes and 6167 two-way links. The links are only for passage, therefore, the freight transport is not considered. The operators for links are shown **Table 2**. In **Table 2**, the normal type refers to operators that may move freely around the network, such as cars or trucks, and transit type is the one that may also move freely around the network, but charge fares and have a waiting time, such as a taxi. Transit-with-routes type operators are used to specify bus routes or metro. Non-motorized are used to represent walking and cycling.

Table 2. Operators.

Name	Description
Single-occupant car (SOV)	Normal
High-occupancy car (HOV)	Normal
Walk	Non-motorized
Bicycle	Non-motorized
Passenger rail	Transit with routes

In order to support London's future growth in a way that improves social inclusion, tackle climate change and enhances the environment, the Transport for London (TFL) designs the Transport 2025 (T2025) to feed into a future update of the Mayor's Transport Strategy. T2025 has three Infrastructure improvements scenarios described in **Table 3**. In these three scenarios, the marked component is CrossRail. CrossRail is a programme to construct a new East-West Heavy Rail link in London connecting Paddington to the Liverpool Street and Canary Wharf areas. This includes a new section of railway line in a tunnel beneath central London and improvements to existing lines either end of the tunnel to allow higher speeds and greater capacity[15]. These improvements are included in the network model by means of the new links and stations to reflect the new tunnel route and the increased speeds on the existing lines to reflect greater frequency and shorter travel times. The fare is assumed to be consistent with other rail travel. These three scenarios will be examined for the exploration of the behaviours of transport and interactions between transport and land-use system.

Table 3. Infrastructure improvements implemented in T2025 baseline, low and high investment scenarios[15].

T2025 Scenario	Road	Rail	Light rail
Baseline		Crossrail High Speed 1 Heathrow Express to Terminal 5	Heathrow Terminal 5 extension
Low	Thames Gateway Bridge	Reduce journey time by 4.5%	DLR extensions, Greenwich and East London transit systems
High	Silvertown Link Bridge National Road User-charging scheme	Crossrail 2, East London line extension (Overground).	Tramlink extensions, DLR extension to Dagenham Dock

3. Results

Table 4 shows the trips by operators. The trips by operators have big change from 2012 to 2025. Totally, the trips have increased from 2012 to 2025 by over 1 million. Given that the external trips and short trips are omitted, the value is to some extent consistent to the estimation of increase of four million trips by TFL[16].

Table 4. Trips by operators.

	SOV	HOV	Walk	Bike	Rail	Tube	CrossRail	Total
2012	219,275	1,557,018	621,690	1,630,670	1,514,172	1,176,486	0	6,719,311
2025B	244,356	1,756,951	739,933	1,928,328	1,772,011	1,412,691	0	78,542,70
2025L	242,742	1,761,024	734,306	1,913,907	1,758,405	1,399,139	0	7,809,524
2025H	243,879	1,755,892	736,666	1,926,469	1,766,235	1,402,888	80,558	7,912,587

The transit varies for three 2025 scenarios (**Figure 4**). In the 2025 baseline scenario, the main transit is by high-occupancy car (HOV), bike, rail and tube, accounting for 22.37%, 24.55%, 22.56% and 17.99%, respectively. The situation has no big change for 2025 low scenario when compared to 2025 baseline scenario. HOV, bike, rail and tube are still the main transit, accounting for 22.55%, 24.51%, 22.52% and 17.92%, respectively. HOV has slight increase in 2025 low scenario when compared to 2025 baseline scenario. The transit has relatively large change in 2025 high scenario relative to 2025 baseline scenario. The CrossRail now accounts for 1.02% of total transit. However, HOV, bike, rail and tube are still the main transit in 2025 high scenario, accounting for 22.19%, 24.35%, 22.32% and 17.73%, respectively.

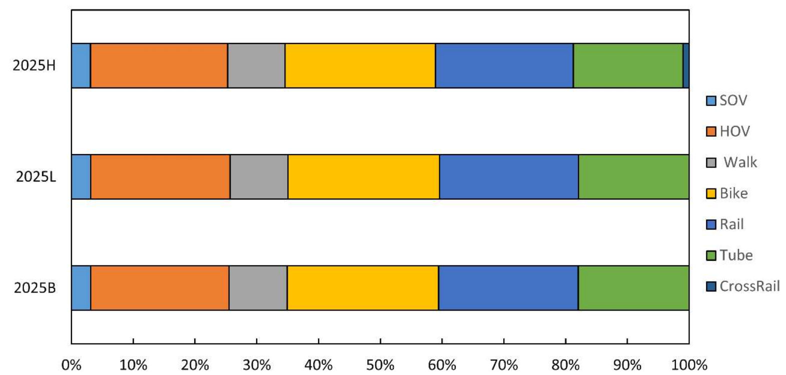

Figure 4. Proportions of trips by operators.

The trips by purpose also vary for these three 2025 scenarios (**Figure 5**). In 2025 baseline scenario, the trips are mainly generated for the purpose of service and home to work by low income households, accounting for 42.81% and 21.48% respectively. Similarly, in 2025 low scenario, the trips are mainly generated for the purpose of service and home to work by low income households. However, the sharing percentage for the purpose of service has increased by 0.07% when compared to 2025 baseline scenario. Compared to 2025 baseline scenario, the percentages of trips for service and for work from home by low income households have increased from 42.81% to 42.82% for the purpose of service and from 21.48% to 21.51% for work from home by low income households.

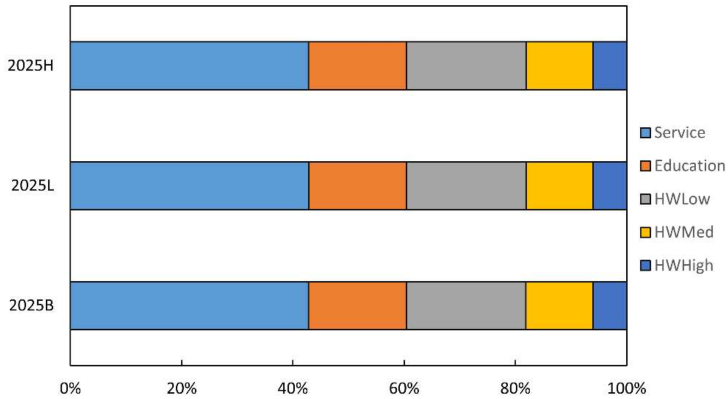

Figure 5. Proportions of trips by category.
Service and education mean trip to service and education, respectively. HWLow, HWMed and HWHigh mean trip from home to work by low income household, medium income household and high income household, respectively.

The transport energy use and CO_2 emissions increase from 2012 to 2025 (**Table 5**). The transport energy use has the largest increase for 2025 low scenario. The transport energy use in 2025 high scenario is the smallest when compared to 2025 baseline and low scenario. The CO_2 emissions increase by one order of magnitude in 2025 relative to 2012. This is due to the increase of population. Furthermore, the CO_2 emissions show difference for these three 2025 scenarios, with low and high scenarios having smaller CO_2 emissions than baseline.

Table 5. Energy use and CO_2 emissions; the factor of energy use (MJ/km) is from Potter[22] and the factor of CO_2 (CO_2-e/km) is from DEFRA[23].

	2012		**2025B**		**2025H**		**2025L**	
	Energy (MJ)	**CO_2-e (kg)**	**Energy (MJ)**	**CO_2-e (kg)**	**Energy (MJ)**	**CO_2-e (kg)**	**Energy (MJ)**	**CO_2-e (kg)**
SOV	2.42E + 06	3.73E + 05	2.69E + 06	4.16E + 05	2.68E + 06	4.13E + 05	2.67E + 09	4.11E + 05
HOV	1.17E + 08	3.95E + 06	1.33E + 08	4.47E + 06	1.33E + 08	4.46E + 06	1.33E + 08	4.47E + 06
Walk	0	0	0	0	0	0	0	0
Bike	0	0	0	0	0	0	0	0
Rail	4.04E + 09	7.05E + 08	4.70E + 09	8.19E + 08	4.64E + 09	8.09E + 08	4.66E + 09	8.13E + 08
Tube	1.47E + 09	1.52E + 08	1.86E + 09	1.92E + 08	1.81E + 09	1.86E + 08	1.84E + 09	1.90E + 08
CrossRail	0	0	0	0	3.27E + 07	1.42E + 07	0	0
Total	5.64E + 09	8.61E + 08	6.69E + 09	1.02E + 09	6.61E + 09	1.01E + 09	9.30E + 09	1.01E + 09

The spatial distributions of households have considerable change from 2012 to 2025 (**Figure 6**). The low-income households are projected to have large increase around North-East of London and have considerable increase around Western portions of London. However, they will decrease around the Southern portions of London. In contrast, the medium income households have large increase around the most part of London and have considerable increase around almost the rest of London. For high income households, they have large increase around the Eastern and Southern portions of London and have considerable increase for almost the rest of London.

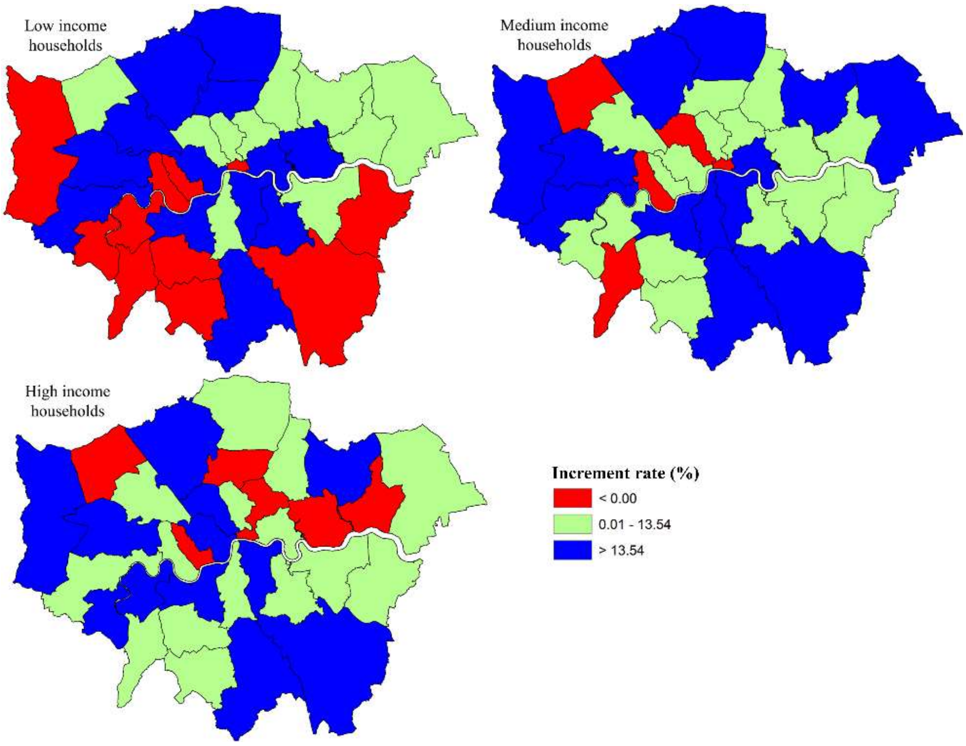

Figure 6. Increment rate for households from 2012 to 2025. The value of 13.54% is chosen as critical value because it is the average increment rate of job vacancy from 2012 to 2025.

4. Discussion

The 2025 high and low scenarios have lower CO_2 emissions than 2025 baseline, suggesting that the investment in transport infrastructures will reduce CO_2. Investment in the transport infrastructure is always expected having economic and social benefits, and its environmental benefits may be omitted, resulting in underinvestment in infrastructure. The UK Government initiated National Infrastructure Plans (NIP) recognise the undervaluing infrastructure's contribution to the environmental wellbeing, and call for a sophisticated analysis to target infrastructure investment which takes into account the value of environmental benefits of infrastructure[18].

Although 2025 high and low scenarios have the same CO_2 emissions, the transport energy use for the 2025 high scenario is lower than that for the low scenario, and also lower than that for the 2025 baseline scenario. This has something to do with the investment strategies and household distributions (**Figure 6**). It is pointed out that the cost-optimal transport strategy can favour sustainable transport[6]. Cairns et al.[24] concluded that the 'soft' measures like improved public transport information, car clubs, car sharing and teleworking can make travel behaviour towards more benign and efficient options, resulting in carbon emission reductions and energy savings.

In the 2025 baseline scenario, the CrossRail 1 does not have significant impact on transport, probably due to that the CrossRail 1 has rather overlay with tube lines, although it will have higher speeds and greater capacity (**Figure 7**). In the 2025 high scenario, the CrossRail lines have imposed impact on transport, accounting for 1.02% of total transit, and the total transport energy use is also reduced. This implies that the high infrastructure improvement strategy in 2025 may be a good option for Mayor's Transport Strategy, given the busy congestion for London and limited finance infrastructure investments due to the financial crisis commenced in 2008.

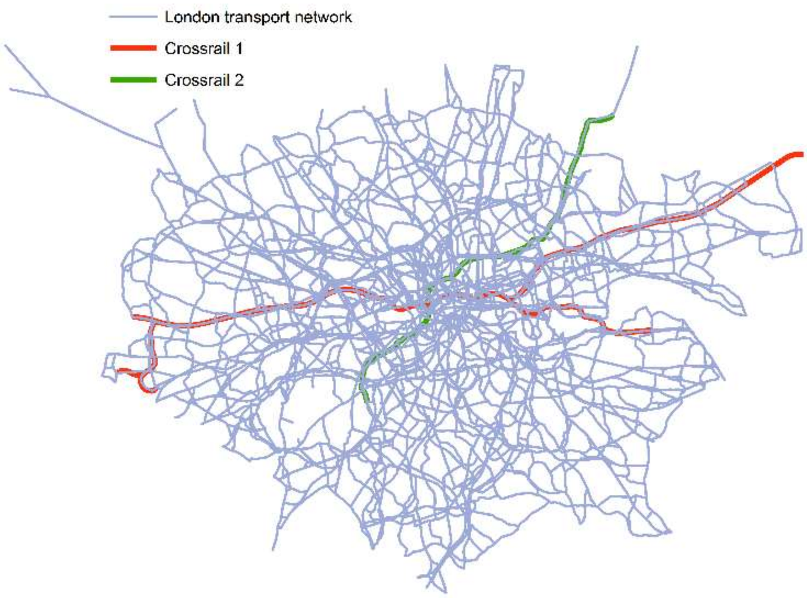

Figure 7. London transport network and CrossRail 1 and 2.

There is certain uncertainty in this study. Firstly, we don't consider the bus trips due to the data available. The bus has been one of London's transport success stories. In 2012, the bus (including tram) accounted for 21% of the daily journey[16]. When bus is taken into account, the story may be different. New efforts are thereby needed. Secondly, there is also uncertainty in data processing. For example, trips are assumed to start and end at zone centres which do not practically exist. This assumption requires the building of a number of virtue links from the zone centre to physical transport infrastructures and thus introduces uncertainty to the final results. Thirdly, there is uncertainty in the factors of transport energy use and CO_2 emissions. The factors of transport energy use vary with the energy efficiency of the vehicle, the load of the vehicle, the congestion and condition of the road, and other factors. The same argument can be applied to the factors influencing transport CO_2 emissions.

5. Conclusion

This paper investigates the interaction between transport and land-use systems using the TRANUS model to support the sustainable development of London, provide implicative information for London MTS, and reduce transport energy use and CO_2 emissions. Results show that the trips will increase from 2012 to 2025 by over 1 million. High-occupancy cars, bikes, rail, and tubes are still the main modes of transit, and CrossRail will be increasingly recognized. Transport energy use and CO_2 emissions increased from 2012 to 2025. The transport energy use in the 2025 high scenario is the smallest compared to the 2025 baseline and low scenarios. The CO_2 emissions show differences for these three 2025 scenarios, with low and high scenarios having smaller CO_2 emissions than baseline. These have informative implications for UK national infrastructure plans. Firstly, the investment in transport infrastructure will reduce CO_2. This will contribute to reducing the underinvestment in infrastructure when environmental benefits are considered. Secondly, effective investment strategies should take account of both transport energy use and CO_2 emissions simultaneously.

Author contributions

Conceptualization, SW; methodology, SW; software, HW; formal analysis, SW and SW; writing—original draft preparation, SW, SW and HW; writing—review and editing, SW and SW. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

The authors declare no conflict of interest.

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