

# Evaluating a Proposed Urban Transportation System Using Advance Transport and Land-Use Modelling Framework

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## ABSTRACT

The effect of traffic congestion, emission, and road accident on cities that depend solely on motor vehicles make them unsustainable. Increased mobility from rapid urbanization has placed great demand on the transport system of such cities. To meet the increasing demand, modelling travel demand based on the transport network has become a necessity for sustainable urban development. In this study, an advanced transport and land-use modelling framework was developed to evaluate a transport system of a proposed new city. Furthermore, transport (road) network connectivity indices were used to measure the level of connectivity of the transport network. The findings show that the proposed transport system may not support the sustainable urban development of the new city due to the low level of network connectivity. The result further revealed that about 52% of the residents will depend on auto modes of transportation making the new city car-dependent rather than transit-dependent. Specifically, all corridor road links showed a high level of traffic congestion problem. The alternative of building more rails or a bus rapid transit (BRT) system connecting the main and a new city is worth considering when proposing an urban transport system. The advanced transport and land-use modelling framework developed in this study to evaluate the performance of the transportation system could serve as a decision-support system (DSS) towards sustainable planning and development of both old and new cities.

**Keywords:** network performance, proposed transport system, connectivity measure, modelling framework.

## INTRODUCTION

The negative impact of the interaction between land-use activities and the transportation systems affects the sustainable development of cities. In recent years, the continuous migration of people from rural (villages) to urban (cities) areas has resulted in rapid urbanization. This has increased transportation demand due to increased mobility and the need to access job opportunities. For this reason, (high travel demand from rapid urbanization) most urban road networks in most cities are unable to meet the high travel demand [1]. In most cities, transport network improvement strategies and optimization methods

are proposed and implemented toward improving existing transport systems and achieving sustainable targets [2]. However, the problem of traffic congestion, emission, and other factors from the transport system that affect the sustainable economic development of cities still exist. The development of the suburban areas is the only alternative for most cities undergoing rapid urbanization to help reduce urban sprawl. As indicated by Kumar et al [3], the transport network parameters (vehicle speed, road capacity, etc.) are influenced by increased socio-economic factors and population densities resulting in delays in the transport network. Therefore, some developed and developing countries including China are redeveloping

their suburban areas to meet the growing demand of rapid urbanization. It is documented in the literature that car-dependent cities are unsustainable, therefore, cities are moving towards a multimodal transport system that focuses on enhancing transit development. According to Kumar et al [4], the multimodal transportation system, in general, are convenient, efficient, and safe for the movement of people. For urban cities where multimodal transportation systems are present, economic growth, public health, accessibility, environmental protection, social cohesion, safety, and security are enhanced. It helps in ensuring successful mixed land-use development and also helps in improving traffic congestion.

The transport network is key to ensuring the quality of life and residents' prosperity therefore, building a resilient transport network should be the goal of urban planners [5]. However, no matter the transportation system developed for cities, evaluating the performance of the transport system is still required. Prior to the development of integrated land-use interacting models (ILUIM), most urban planners relied heavily on traditional methods proposed by researchers for evaluating the performance of the transportation system of cities [3]. The most common methods were the use of connectivity measures or indices. These indices allow researchers and planners to determine the connectivity pattern of the transport network, especially the urban road networks. [6] argued that although the transport network (road) plays an important role in the development of regions, there is a limited number of theoretical research as far as evaluation of the transport network is concerned. Some also believed that in evaluating the performance of the transport system of a city, a holistic approach should be used where the interaction between connectivity, accessibility, and mobility is considered [7]. However, both mobility and accessibility are influenced by the connectivity of the transport network, and where there is unavailability of appropriate data, the inclusion of accessibility measures in any transport network performance model could influence the overall model results negatively.

The major disadvantage of the use of only transport network connectivity measures or indices such as Alpha, Gamma, Beta, Eta, etc. as used in the work of [6,8] is that they do not capture the land-use which affects the performance of the transport network. To overcome this drawback, travel demand models (TDMs) were developed.

These TDMs (based on a four-step process) were used to assess the supply and demand side of land use and transportation system. In a typical conventional transportation planning process, land-use (origin and destination of trips), travel (demand), and road capacity are considered where the TDMs are used for the evaluation of the transport system. Although modeling travel demand is a challenging task, it is required for rational planning and evaluation of transportation systems [9,10]. The TDMs for the fact that they include the land-use component of evaluating the transportation system, does not make them an ideal model for evaluating all land-use and transportation system projects. The TDMs has also been criticized by several researchers for many disadvantages [11, 12]. According to Zhong, et al, [13], the conventional TDMs do not consider changes in the transport system of cities undergoing rapid urbanization. Integrated land-use transport interaction models (ILUTIM) were developed to overcome this drawback. However, most ILUTIMs developers still use the four-step travel demand model in their integrated models [14]

To reduce the negative externalities from land-use and the transportation system interactions, city authorities are emphasizing evaluating land-use and transportation projects. To this effect, integrated land-use and transport models have become the necessary tool for evaluating land-use and transport projects in most developed and some developing countries [13].

In this study, we evaluated the transport system of a proposed city (Yangtze River New City of the City of Wuhan) using an advanced transport and land-use modeling framework. Prior to the development of the modeling framework, we first evaluated the road transport network using connectivity indices. This enabled us to thoroughly evaluate the transport network by considering the transport network with and without the land-use effect. The use of the advanced modelling framework enabled us to focus on the major corridor roads of the transport network connecting the proposed new city and the main city which cannot be revealed by the use of the connectivity indices. Furthermore, this approach revealed whether the new city is auto-dependent or planned to achieve transit-oriented development. To the best of our knowledge, this is the first study that considers both network connectivity measures and the land-use/transport modelling approach in evaluating the performance of a transport system of a proposed city.

## METHODS AND STUDY DATA

This study uses the land-use transport interaction modelling framework developed by [14]. The modelling framework (PECAS, which stands for Production, Exchange, and Consumption Allocation System), was first developed by Parsons Brinckerhoff Ohio, in 1999. According to Hunt and Abraham [15], PECAS provides a generalized approach for simulating spatial economic systems where land use activities and the transport system interact. To effectively evaluate the proposed transportation system which is the main objective of this paper, a multimodal transport model was developed using Cube Voyager software licensed to Wuhan university of technology. Wuhan PECAS model developed by Zhong et al [13], was first modified to include the proposed new city. The Wuhan PECAS model was then used to simulate and forecast land-use activities for the proposed new city and these activities were then converted into socioeconomic activities as an input to the transport model.

As shown in Figure 1, the conceptualized modelling framework for the study includes two major components (the land-use and the transport model). The development procedure for these two models are briefly explain below.

### The land-use model

Starting with the land-use model, the activity allocation (AA) module which is among the four modules of the PECAS model was modified to

simulate and forecast activities for both the main city and the proposed new city. The AA module represents how activities are allocated within the space provided by developers and how these activities interact with each other at a given point in time. Activity totals for each type of the activities were calculated. The base year (2019) of the AA module has to be constrained at the traffic analysis zone (TAZ) level so that the module will not allocate activities beyond the observed. Since the land-use model is developed to simulate the spatial economic system of land-use activities of the entire city, TAZs of both the main city and the proposed new city were integrated. The forecasted land-use activities from the PECAS model include: households (Urban and Rural), agriculture, industrial, transport utilities and commercial services. Applying socioeconomic factors, these activities were converted to socioeconomic activities (Population and employment) for the transport model.

The activity totals for the proposed new city were calculated using the stages of urban development method proposed by Liu [16] based on the proposed population and the employment data provided by the new city planners. The logistic function or the S-curve method was used to calculate activity totals (Figure 2) for the period of twenty years when the proposed new city is expected to be fully developed. It is worth mentioning that the total quantities of all the activity totals are expressed in monetary terms (Ren Min Bi which is the official currency of Chinese people abbreviated-RMB). The land-use model is

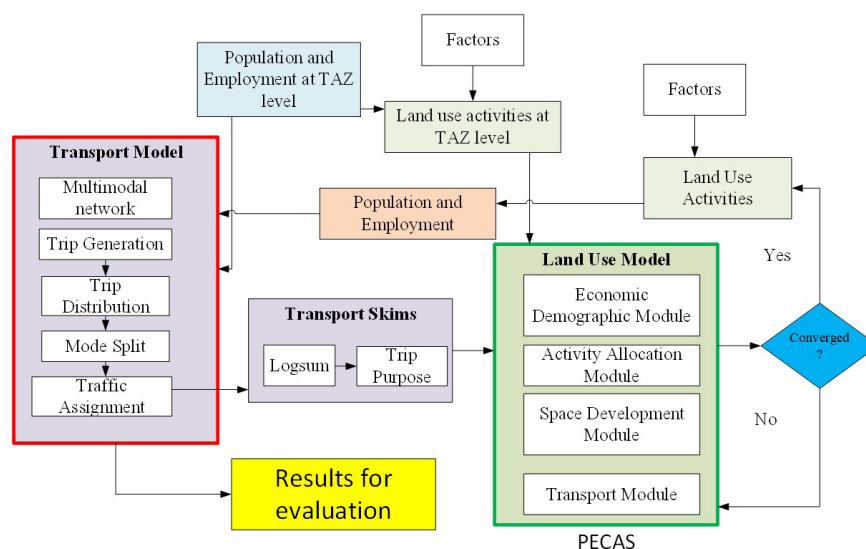


Fig 1. Advance transport and land-use modelling framework

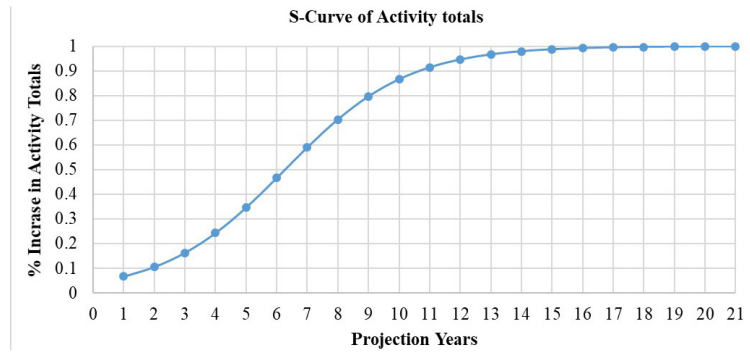


Fig 2. Logistic function (S-curve) for estimating land-use activities

calibrated using both buying /selling dispersion parameters and floor space quantity (match prices with new demand elasticity).

### Transport model

A four-step travel demand model was developed using Cube Voyager software (Figure 3) and this section discusses the four-step process and the various modules adopted in developing the transport model. The section covers network development, trip generation, trip distribution, mode choice and trip assignment chronologically. It should be noted that the model is developed with a feedback loop system. The reason for the feedback loop is to enable us to obtain a composite utility based on the congestion on the transport network. In this way, the results of the model represent the real-world scenario where traffic

situation on the transport network affect mode choice behavior of commuters.

To develop the transport model used for the evaluation of the proposed transport system of the new city, the transport networks (road network and transit networks) and zones containing socio-economic data were obtained from the planning institute of the City. The road networks and the transit network (Metro and regular Bus) on the traffic analysis zones (TAZs) as shown in Figure 4 a, b and c respectively, were integrated as a single multimodal transport network file using ArcGIS tool. To ensure the various networks prepared for the study were free from geographical errors, Esri's ArcMap was used to remove any dangling and unconnected links and nodes. The attributes of the transport network are presented in Table 1. The attributes include the total number of road links and lengths, the total number and length of

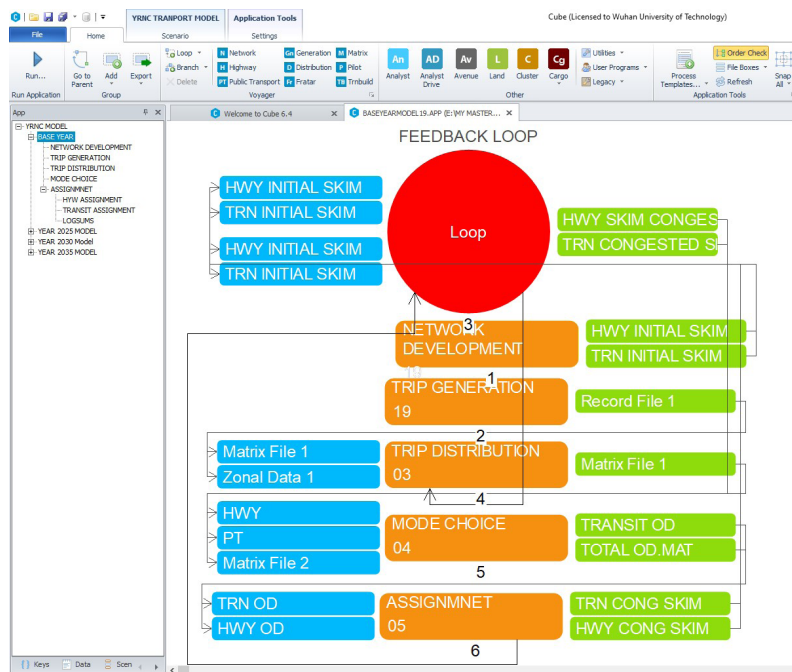
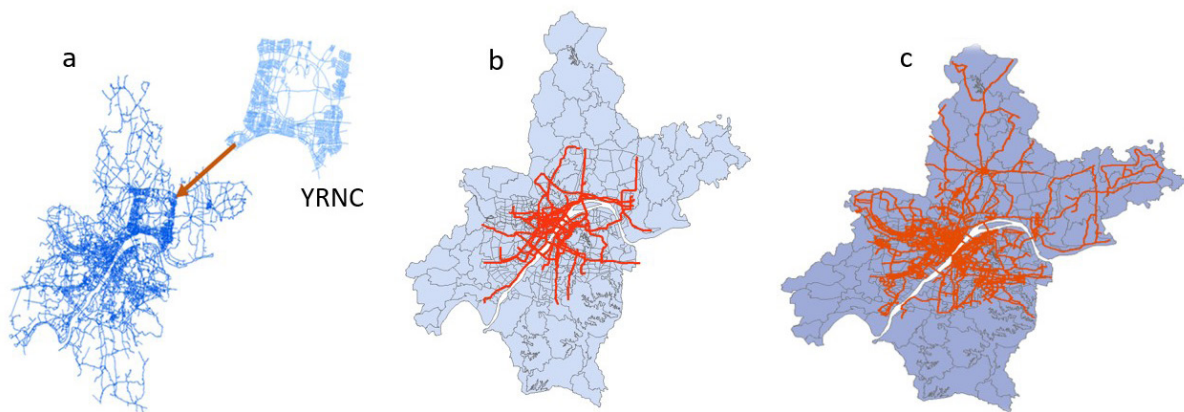


Fig 3. Multimodal transport model (Cube Voyager software)





**Fig. 4** Road network (a) Metro lines on TAZs (b) Bus lines on TAZs (c)

metro and bus routes. It must be noted that there were no available future plans regarding the extension of bus routes.

The transport model was developed using synthesized calibrated socioeconomic data set and transport network (road, metro, and bus) for the year 2019 as the base year model. Using a forecasted socioeconomic data from the Wuhan PECAS model, a multimodal transport model is developed to predict the transport demand for the year 2035 (Known as YRNC scenario year). In this case, we were able to evaluate the transport system of the proposed new city.

#### The four-step process of the developed transport model

The trip generation module accounts for the production and attraction of trips from zone to zone in a study area. Socioeconomic data is required for trip generation. This study uses population and employment data for the production and attraction of trips by a trip purpose: Home-Base Work (HBW), Home-Base Others (HBO), and Non-Home Base (NHB) trips at the TAZ level. The trip generation module has different methods for producing and attracting trips. In this study, a cross-classification method was used to calculate

trip production rates whilst the linear regression model was used to calculate trip attraction rates. The travel survey data of the study area revealed that urban and rural zones make trips at different rates. For this reason, the trips were generated for urban and rural zones separately. The two were later combined and a script was written to produce a single aggregate production-attraction (PA) trips as an input to the trip distribution module explain in the next paragraph. As indicated earlier, a linear regression model was used for trip attraction forecasting. Employment data used for the trip attraction were classified into three main categories (Basic, Service, and Other) for trip attraction module.

In the trip distribution module, the generated trips (PA Trips from the trip generation module) were distributed from zone to zone based on travel impedances (time or distance). Usually, a composite time impedance of auto and transit based on the transport networks is desirable to produce a real-world scenario result. This study uses a composite time impedance calculated from the highway (road network) and transit networks as an input to a gravity model used to distribute the trips. Due to the data limitation, the socioeconomic adjustment factor for interchanges was assumed to be equal to 1 which is the default setting in Cube Voyager. Synthesized friction factors were calibrated using mobile phone signal data and smoothed using the gamma distribution function for the trip distribution.

The mode choice or split module is developed to distribute or split the PA trips to each zone from the trip distribution model to available modes of travel by trip purposes based on transport utilities. The most commonly used model for mode split is the nested logit model. The initial highway and

**Table 1.** Transport network attribute (lengths are in km)

Attributes	Base year	YRNC Scenario year
Total length road links	54922	59227
Total length of Metro lines	1425.33	1801.84
Total length of Bus routes	16327.04	16327.04
Number of Metro lines	9	20
Number of Bus routes	527	527

PT skims were computed as an input to the nested logit model together with other transport coefficients for calculating transport (dis)utilities. The output from the nested logit model is a matrix file containing trips by modes and trip purpose. An average occupancy rate were applied to convert person trips by modes to vehicle and metro trips.

In the final step, the user-equilibrium assignment method was adopted for assigning trips on both the highway and transit networks using the Bureau of Public Road (BPR) function. This method was selected among other trip assignment methods because of its ability to produce results that represent the actual behavior of travelers [9] on the transport network in a real-world scenario.

### Model calibration and validation

Transport models require several sources of primary data for its calibration and validation. These data sources according to Wegmann, & Everett, [17] are, TAZ household characteristics and employment information, an accurate representation of the base year highway and transit network, an accurate base year travel survey, and accurate base year ground counts. This study, therefore, relies on primary data sources such as travel surveys (2008), census (2010), and mobile phone signal data (2019) for calibrating and validating the transport model. Furthermore, the Federal Highway Authority of the United States of

America's (FHWA) standard benchmark values were used to validate model parameters where deem appropriate.

Table 2, 3 and 4 show the calibration and validation results for trip generation, trip distribution and mode choice modules from the developed four-step transport model. The calibration is usually done for the base year model to replicate the observed values which is then used to forecast the future years. As shown in Table 2, the estimated values from the developed model for both urban and rural areas were the same as the observed values except HWO trips for rural. The trip distribution module calibration and validation result (Table 3) shows that for all the trip purposes, the trip length estimated were below the observed values but falls within the benchmark value of [18]) except for NHB trips but below that of the observed value. Meanwhile, the results from the mode choice module (Table 4) show that the model estimated an accurate percentage of trips by mode when the standard error of percentage (preferable +/- 2% and acceptable +/- 5%) were taken into consideration.

### Evaluation method

The evaluation was done using two main approaches. In the first approach, we conducted a network connectivity test were we analyze the connectivity of transport network using Gamma

**Table 2.** Trip generation calibrated results (%)

Trip purpose	Observed		Model estimated	
	Urban	Rural	Urban	Rural
HBW	23	20	23	20
HBO	49	52	49	51
NHB	28	28	28	29

**Table 3.** Trip generation calibration and validation results (minutes)

Average Trip by Purpose	Benchmarks		Observed	Model estimated
	Low	High	Travel survey	Base year
Average Trip length – HBW	12	35	27.6	19.8
Average trip length – HBO	8	28	26.2	26.7
Average trip length – NHB	6	19	23.2	20.4

**Table 4.** Mode choice calibrated results (%)

Standards		Percent trips by different modes						
Preferable	Acceptable	Validation	Car	Taxi	Metro	Bus	Bike	Walk
+/- 2	+/- 5	Observed	37.2	3.4	8.1	11.1	18.3	21.8
		Estimated	37.2	3.6	8.2	11.3	17.2	22.7

index, Alpha index, Sinuosity, Link-Node Ratio and Connected link node ratio. These initial tests were conducted using the urban form connectivity function in TransCAD software. The second approach includes visual inspection of the thematic results from the trip assignment module of the transport model developed. Furthermore, we focused on the major corridor road links connecting both the main and the new city. Finally, we analyzed the result from the mode choice module in order to draw conclusion on whether the new city will be car-dependent or will favor public transportation which is more sustainable means of transportation.

## RESULTS AND DISCUSSION

### Network connectivity

Table 5 shows the results of the various indices used to measure transport network connectivity. For easy interpretation and analysis, the values and the descriptions are presented. The results revealed that there were more dead routes in the transport network as the Sinuosity index is only 1.02, indicating the lowest value. The Link-Node Ratio is more favored with a median value of 1.61. The Gamma Index is 0.54 which means that the transport network is 54% connected, whilst the Alpha Index is 0.31 representing only 30% of connectivity. However, the connected Node Ratio of 0.83 is more favored due to the relatively few cul-de-sacs. From the results, especially those of Sinuosity, Gamma and Alpha indices, the proposed transport network may not favor certain modes of transport. For example, non-motorized modes such as walking and biking as routes from one zone to the other become longer. This implies that majority of residents of the new city will depend on motorized modes of transport which come with transport-related challenges (traffic congestion, emission and road crashes).

### Trip assignment

Figure 5 shows the estimated travel demand on the transport network. The thematic representation of the transport network would show links that are congested and those that are not depending on the vehicle volume to capacity (V/C) ratio. The assignment result revealed that the majority of the links in the YRNC were within the acceptable V/C ratio limit (1.0) implying that internally, the YRNC is free of traffic congestion. However, almost all the major roads that pass through the city and connect other districts of the main city were congested (higher V/C ratios). It has been found that major corridor roads were showing signs of high traffic congestion. This means that there were inadequate major roads in the proposed transport network to connect the new city and the main city or the transport plan does not capture a multimodal transportation system enough. A detailed analysis of the corridor roads is discussed in the next section. In general, the proposed transport system could support the corresponding land-use activities within the city.

### Corridor analysis

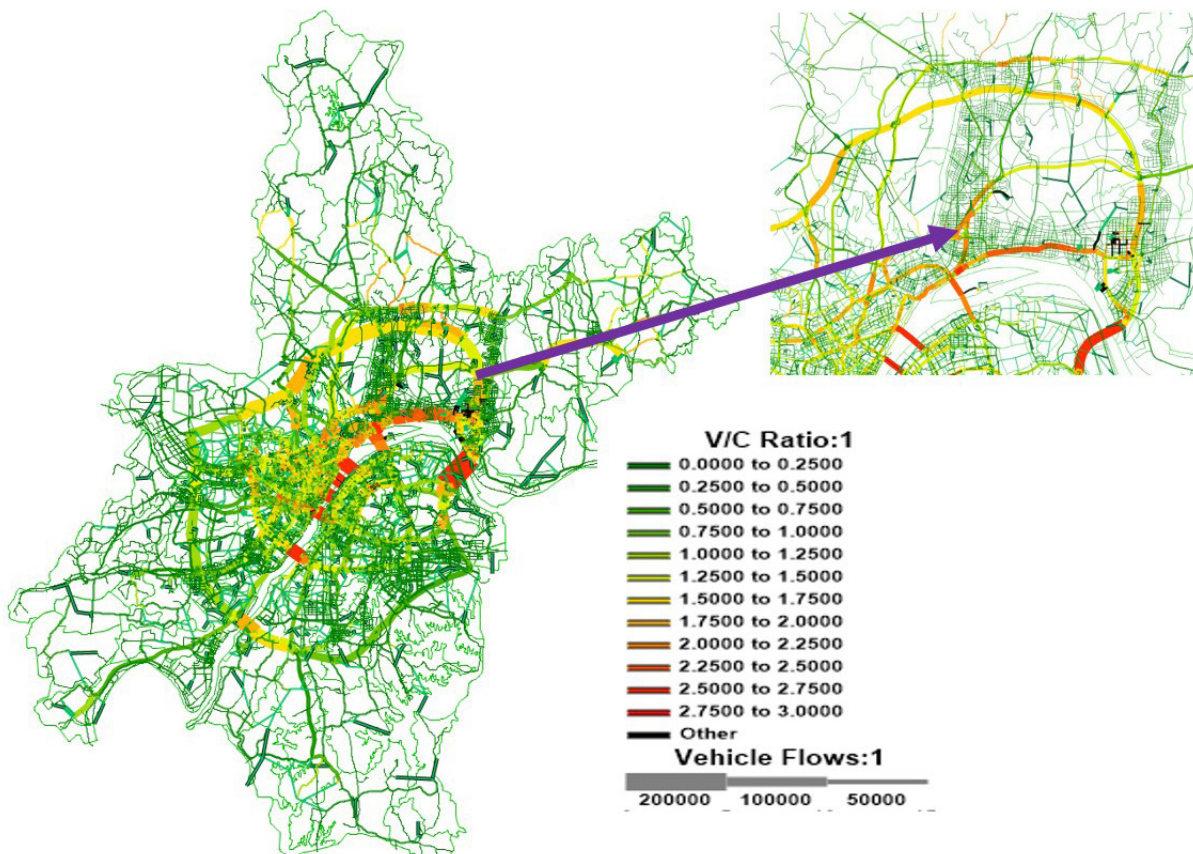
To identify the impact of the new development area on the main city, we assessed the traffic situations on the major corridor roads linking the two cities. The interaction of activities between the two cities, depending on the number of activities distributed will inevitably lead to a certain amount of transport-related challenges. The inflow and outflow of activities between the cities would depend on the attractiveness of the corridor roads connecting the two cities. Higher traffic congestion leads to increased travel time, emission and energy use [2].

Internally, the transport system may seem good to support land-use activities, however, failure to provide adequate road links that extend to the neighboring urban area to support

**Table 5.** Network connectivity indices

Measurement	Value	Description
Sinuosity	1.02	Values start from 1, with lower values representing more dead routes
Link-Node Ratio	1.61	Values range from 0 to 2.5, with values $\approx 1.4$ favored due to being a 'median' value
Gamma Index	0.54	Values range from 0 to 1, with higher values representing a more connected network
Alpha Index	0.31	Values range from 0 to 1, with higher values representing a more connected network
Connected Node Ratio	0.83	Values range from 0 to 1, with values $\geq 0.7$ favored due to relatively few cul-de-sacs





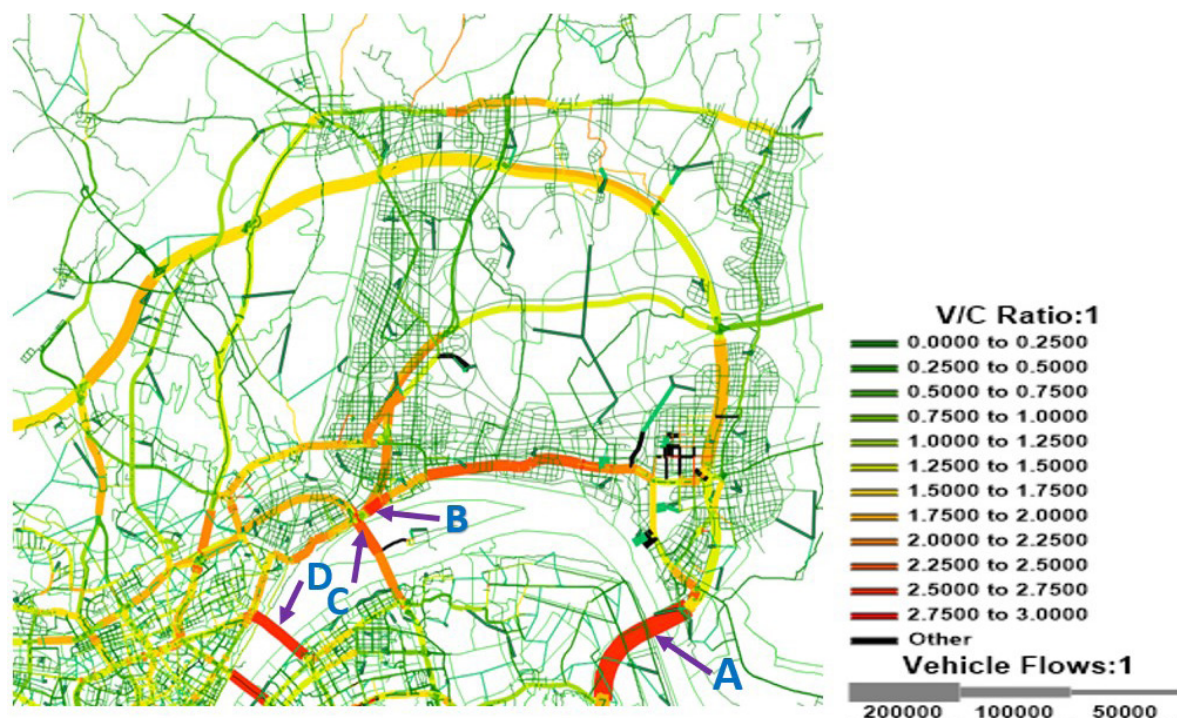
**Fig 5.** Estimated travel demand on the transport network

the inflow and outflow of activities could lead to economic, social, and environmental issues. For this reason, an analysis was conducted on major roads linking the YRNC and the main city. The trip assignment results revealed that the majority of the corridor road links are estimated to be congested. Thus, most of these road links are above 1.75 vehicle capacity to volume (V/C) ratio as compared to the acceptable ratio of 1.0. The details of the traffic situation of some of the selected major corridor road links, A, B, C, and D as shown in Figure 6 are analyzed (Table 6). The daily average congested speed, travel time and their corresponding V/C ratios are presented to support the previous argument that most of the corridor roads may not support the sustainable development of the proposed new city. The performance of the transport network is measured based on its efficiency and the efficiency of a transport network can be measured by its ability to transport people and goods within a reasonable time from their origin to destination [19]. Also, urban city that is well planned to achieve transit-oriented development deals with corridor (transit) and the influential areas [20].

### Mode choice

Table 7 shows the mode choice results conducted in the third stage of the four-step transport model developed. The results showed that in the base year scenario, there were 57% car trips, 1% taxi trips, 4% metro trips, 3% bus trips, 3% bike trips, and 31% walk trips (Table 7). However, the estimated mode choice for the YRNC scenario revealed some interesting results. Car trips significantly decreased from 57% to 49%, whilst there was an increase in the use of taxis (1% to 3%). In general, the aggregate auto trips (car and taxi) decreased in the YRNC scenario. For public transport modes, metro trips increased from 4% to 12% and bus trips from 3% to 7%. Meanwhile, for non-motorized modes, there was an increased in bike trips (3% to 8%) and a decreased in walk trips (31% to 21%). The results from the various indices used to evaluate the connectivity of the transport network revealed that the level of the connectivity of the proposed transport network does not support walking. This means that most people will prefer biking to walking hence the shift from walking mode. Doing the mathematics, the higher percentage





**Fig 6.** Traffic assignment result (Congested Corridor Roads)

**Table 6.** Congestion situation on selected major corridor road links

Links	Free flow Speed (km/h)	Free flow Time (minutes)	Link length (km)	V/C Ratio	Congested Speed (km/h)	Congested Time (minutes)
A	120	2.19	4.38	2.51	62.48	4.21
B	100	0.33	0.54	2.32	25.10	2.7
C	100	0.49	0.82	1.75	43.86	2.61
D	100	1.32	2.2	2.71	55.48	3.85

**Table 7.** Estimated percentage of trips by modes of YRNC (%)

Scenarios	Car	Taxi	Metro	Bus	Bike	Walk
Base year	57	1	4	3	3	31
YRNC year	49	3	12	7	8	21

(52%) of the estimated trips were by auto (car and taxi) modes as compared to public transport (19%) modes (metro and bus). Based on the available data and information used in conducting the mode choice module, the possibility of the majority of potential residents of the YRNC depending on private vehicles is high if the transport plans of the YRNC is not revisited and revised.

## CONCLUSIONS

In this study, we evaluated the transport system of a proposed new city using an advance transport and land-use modelling framework.

Furthermore, network connectivity indices were used to determine the level of connectivity of the road network. An integrated land-use transport model was developed using PECAS and Cube Voyager software to simulate and forecast the land-use and transport activities within the entire study area. This enabled us to evaluate the performance of the transportation system of the proposed new city by considering the effect of both land-use and transportation interaction. The results from the road network connectivity measure revealed that the road network is not highly connected to support non-motorized mode of transportation such as walking and biking. This is congruent with the mode choice result from the transport model as

52% of the residents will commute by auto (car and taxi) modes as compared to non-motorized modes (29%). The result from the transport model showed that internally, there were low level of traffic congestion problems within the new city. This means that both land-use and transport activities are evenly distributed to support each other.

In general, the transport system (arrangement and connection of road segments) of the entire city performs better and is spatially distributed. However, the corridor road analysis revealed a high level of inadequate major road links connecting the new and the main city. Enhancing the corridor roads using a more multimodal approach could support land-use activity distributions toward more sustainable urban development. The alternative of building more rails or a bus rapid transit (BRT) system is worth considering when proposing an urban transport system.

The transport and land-use modelling framework adopted in this study to evaluate the performance of the proposed transportation system of the new city could serve as a decision-support system (DSS) towards sustainable planning and development of new cities.

Future works can also consider the inclusion of accessibility measures to further enhance the evaluation method. Also, extending future works to consider other network connectivity measures that capture the topology of the network structure could further reveal more about the level of the connectivity of the transport network. Finally, the regional transferability of the developed evaluation framework could be tested by cities redeveloping their suburban areas into new cities.

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