Determining the Regional Job-House Balance Ratio Based on Congestion Factor and Centrality

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Abstract—**It is accepted in urban and regional planning that a proper distribution of land use zoning will be able to optimize the Vehicle Miles Travelled (VMT) to reduce the transportation-related energy consumption and congestion. One of the strategic approaches of integrating transport and urban planning is introducing an optimized ratio for administrative level job-house combinations. The objective of this research is to develop a computer-aided mechanism to assist the determination of development zoning regulations based on the job-house combination in a regional context. The R programming platform is used to develop the automated tool. The data required for the analysis are road network details, trip generation and trip attraction details at each Traffic Analysis Zone (TAZ). The gravity model is used to carry out the trip distribution and it is assigned to the road network using the graph theory. The centrality values are used to estimate the potential trip attraction levels. The main assumption undertaken in the study is that the trip generation occurred by a group of population in a particular TAZ is considered as work based trips. The result of the method for Colombo district, Sri Lanka indicated that the job-house ratio varies from 0.1 to 9.2 resulting in an average trip length of 23 km from houses to work locations. Finally, the method suggested a minimum and maximum value of 0.5 and 4, which reduced the VMT from 46% and average fuel consumption by 22%**.

Index Terms—**Centrality, Job-house ratio, Land use – transport simulation model, R programming, Route assignment**

I. Introduction

This research study focuses on examining the possibility of applying centrality and route assignment techniques to determine the development zoning regulations for a regional area. To perform the mentioned task a few widely adopted concepts are interrelatedly considered. In the literature review, the concepts of centrality, four step modeling and job-house ratio are deeply studied on their correlation possibilities. The analysis and tool development stage is consisted of the GIS application for data preparation and interpretation and R programming platform for generation of output result. The test application is carried out focusing the Colombo District in Sri Lanka, however the continuation of the road network is considered to capture the inter district trip distribution form the study area.

II. Relationship between Land Use Planning and Transportation

Under the present rate of urbanization in the world it is identified that 54% of the world's population is living in urban areas since 2014. The urban population has been growing rapidly since 1950 up to 3.9 billion [1]. The variation in income levels with respect to the working areas has caused for an accelerated between-place and within-place energy consumption. In Sri Lanka, "The main reason for congestion was poor city planning, inappropriate public transport facilities and insufficient traffic system, which leads to waste of time, fuel and wear and tear of vehicles," [2]. In this situation a systematic distribution of job-housing locations will create a proper structure for a city having the Vehicle Miles Travelled (VMT) properly configured to minimize the transportation related energy consumption and congestion. The research studies carried out in the University of Wisconsin, USA has identified, the Job-House ratio directly influences the VMT in a region and a planned ratio can directly manipulates the region's travel behavior. As a land use policy, balancing job-house ratio based on the region's travel behavior can mitigate road related congestion and environmental impacts [3]. Sri Lanka is losing 1.5% of its annual GDP due to traffic congestion. Not only the economic loss but also the loss in man hours due to the traffic congestion is higher in the urban context [4]. According to the Sri Lanka Labour Department, few cities consist of a higher number of employment and the periphery keeps growing since the communities are agglomerating around the zone (Ex: Colombo – 3,875,720 / Kandy – 511,341 / Gampaha – 144,938 / Kurunegala – 448,022)[5]. Colombo is developing as Sri Lanka's major commercial capital, currently there are 7.8 million motorized trips being generated within the Colombo metropolitan region (CMR) "Fig. 1".

Approximately 1.4 million trips are generated within the CMR towards the Colombo municipal council (CMC). The seven major transport corridors towards CMR carry 100,000 average trips daily for the city where in Galle corridor it is 250,000 and in Avissawella corridor, it is 200,000. All these traffic flow towards Colombo city is

Manuscript received October 23, 2018; revised June 10, 2019.

doi: 10.18178/ijscer.8.3.284-289

happening at an average speed of 17km/h [6]. The overall VMT within CMR is approximately 95 million km out of which 40% are served by the public transport modes. It is estimated that the values are growing by 10% per annum. Over 40% of the length of the road network in CMR has Level of Service below C which indicates they have reached capacity [7]. In the United States, it is considered as "compact, transit accessible, pedestrian oriented, mixed use development patterns and land reuse epitomize the application of the principles of smart growth" [8]. The Transit Oriented Developments (TOD) is a widely adopted strategy with higher density developments at the transit destinations where non-motorized trips are better served. The automobile utilization has been reduced by 20 – 25% following the TOD pattern [9]. The infrastructure and public services development costs are comparatively low in the compact development strategies due to the scale of economies [10]. In terms of energy efficiency high density multinuclear urban forms have been identified as better configurations [11]. The concept of centrality is another widely adopted method in estimating the accessibility levels in cities. It is identified that the centrality parameters are highly related to the traffic movement pattern and can be modeled to identify the quantities [12]. It is comprehensively applied based on the space syntax concept and the results of the study in Colombo, Sri Lanka has proved a thorough relationship (R2 > 0.75) between centrality measures and trip attraction [13]. Further, the models and frameworks consist of different hypotheses and assumptions. (I.e. concentric city and constant congestion levels in Two model analyses of the urban structure of minimal transportation energy consumption [14] and Six Settlement Patterns in Six Settlement Patterns Compared [15]). The studies have distinctly identified the requirement of reducing transport related energy consumption and integrated land use planning approaches. However, the method for reducing such energy consumption through land use planning is not comprehensively analyzed in the researches. The integrated approach of balancing job-house ratio based on transport planning will compile a comprehensive mechanism to shape the urbanization pattern using an integrated land use and transport system.

Figure 1. Colombo metropolitan region. [5]

III. Model Development Architecture

A. Methodology

The objective of this research is to develop a computer-aided mechanism to optimize the traffic volume in road network in the study area by introducing a balanced ratio of job-house combinations for each traffic analysis zones (TAZ). The job-housing balance rational refers to the geographic relationship between the amount of jobs and houses available within a considered spatial context. In 1994, the entropy index was used to identify the level of heterogeneity among land uses. The highly mobile employment locations and residential locations keeps the job-housing ratio balanced over time. [16]. The data required for the analysis are details of the road network and intersections including the road class and carrying capacity, trip generation and trip attraction amounts at each intersection based on its Traffic Analysis Zone (TAZ). The Zonal models "(1)", "(2)" are used to perform the trip generation and trip attraction values.

Zonal trip generation Model
Ln (Trips Produced) = 1.0229 x Ln (Population) (1)

Zonal trip attraction model
Ln (Trips Attraction) = 0.9384 x Ln (Employment) + 0.96 (2) [17]

The first stage of the process is defining the Traffic Analysis Zone (TAZ). The TAZ is considered as the micro feature for analyzing the travel demand modeling. In the study, the TAZ is defined using the Theissen Polygon tool in Geographic Information System (GIS) software. The Theissen Polygons are constructed based on the Delaunay triangulation network theory. The base of constructing the TAZs is the nodes, which are placed, based on the transportation network intersections. Network Analysis Tool in GIS was used to perform the task. The basis of the formulating TAZs is to demarcate the geographical clusters of population and employment locations based on their proximity to the road centroids.

The gravity model "(3)" is used to perform the trip distribution and the result is gained through several iterations and generalized with a K-factor. The model assumes that the trips being transferred among zones in an area is dependent based on the relative attraction and the geographic distance between them. The spatial distance adjusts the relative attraction of zones for its capacity.

$T_{i-j} = K\ P_i\ A_j /\ d_{ij}^n$ (3)

T_{i-j} = Trips between zone i and j

P_i = Trips produced in zone i

A_j = Trips produced in zone j

d_{ij}^n = Distance between zone i and zone j

K = Constant independent of i

n = an exponential constant (varies 1 - 3) [18]

Using the graph theory, shortest paths are identified where, a minimum amount of intersections are passed between two given intersections after weighted by the segment length. In transport planning the Graph theory is used for routing analysis and network analysis. In this study the application of minimum cost flow solution is used to identify the shortest possible paths among the intersections [19]. The trip distribution is assigned to the road network based on the identified shortest paths which is known as "Route Assignment" "Fig. 2,".

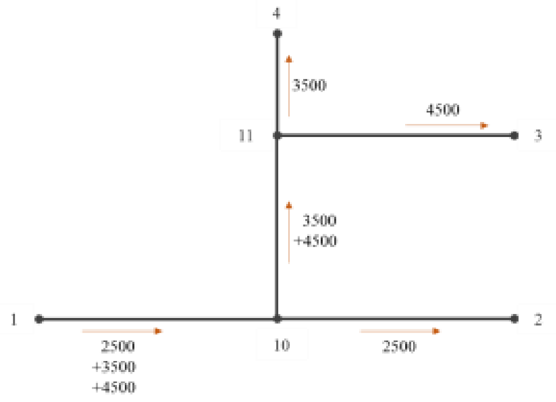

Figure 2. Road network and traffic volume

According to the standards of level of service (LoS) in the road network, the congestion levels are optimized and according to the optimized values, new combination of trip generation and trip attraction values are calculated. In summary, the traffic condition in the road network is reduced to its capacity in level of service and the job-house combinations are redefined to achieve the mentioned condition. For a given road, the design capacity is considered as fixed, but the actual flow rate varies based on the commuting population of the area. The quality of the traffic is divided into six categories ranging from level A to Level F. The main criteria considered in the LoS estimation are speed and travel time, density, and delay. In planning practices, the Volume to Capacity ratio (V/C) is used to characterize the result of LoS. In V/C ratio, volume (demand) is compared to the estimated capacity of each road link during the peak period. The VMT is calculated by multiplying the amount of trip generation by their respective length of the shortest paths.

Based on the V/C value the roads are categorized and identified in order of their quality of traffic level. Further it is identified the levels where the quality needs to be improved or can be maintained. Accordingly, for each segment a moderated value for V/C is identified (Level C) based on its percentage contribution for overall traffic congestion. Based on the moderated V/C ratio in the roads, the trip distribution is redefined and a new number of trips for each segment is calculated. The attributes of centrality application were used to estimate the potential trip attraction amounts for the identified TAZs.

$$\mathrm{Exp(TAD)} = 18.33 + 1.87 * Exp(C^{GI}) + 0.98 * Exp(C^{C}) \quad (4)$$

[20]

TAD – Trip attraction density
C^{GI} – Global integration
C^{C} – Connectivity

TABLE I. CONGESTION FACTORS IN LEVEL OF SERVICE

LOS main roads	Volume	Capacity	Travel speed	V/C	State of quality
A	2100	6000	65	0.35	Good
B	3300	6000	60	0.55	To be maintained
C	4620	6000	55	0.77	To be maintained
D	5520	6000	50	0.92	To be Improved
E	6000	6000	40	1.0	To be Improved
F	>6000	6000	20	> 1.0	To be Improved

[21]

The output of the above calculation provides the potential amount of trip attraction for each TAZ. Once it is identified the trip attraction, the values can be matched with the trip generation requirement and identify the labour force participation in a particular area. Using the following formula, the values can be concluded to a ratio, which can be applied to the respective analysis zones in terms of mobilizing the population and employment to maintain a traffic congestion free road environment.

$$Job - House\ Ratio = \frac{Available\ Employment\ Opportunities}{Labour\ Force\ Population} \quad (5)$$

[22]

B. Programming Platform

The R programming platform is used to develop the automated tool for the process. The R is an open source programming language and software environment for statistical analysis, graphics representation and reporting [23]. R is an object-oriented language and platform where objects as a single number, data set, or model output, are stored within an R session/workspace. [24]

The igraph package is a powerful tool for neatwork analysis and graph model development. The graph theory is utilized based on the functions of the tool. In the tool development, the package was specifically used to identify the network links and length of the shortest paths. The data.table and RMySQL packages are used to access .csv and mysql databases. When the number of nodes are higher than 1000, it is time efficient to link the progamme into a database system. The main outputs of the R programmed tool consist of a table of the lengths of all shortest paths among the nodes, a table with the result of gravity model and route assignment, a table with congestion factors of each segment and required trip reduction for a unit trip and an Origin Destination matrix with the final trip distribution amounts. These outputs can be obtained in the form of .csv files or can be exported to SQL database based on the user requirement. The R programme will automate the entire process and produce the result within an approximate time of 40 minutes for 200 nodes. Several other automated platforms (python, visual basic macros) were tested for the same purpose and identified consuming more time than R platform.

IV. ANALYSIS AND RESULTS

The Colombo district "Fig. 3," as mentioned previously is liable for the highest agglomeration point of Sri Lanka.

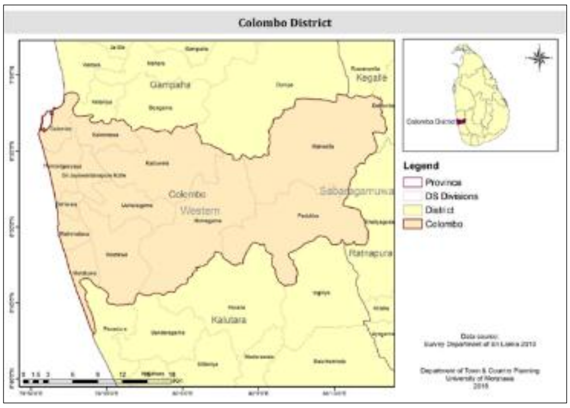

Figure 3. Study Area – Colombo district, Sri Lanka.

A. Population Density and Trip Generation

In values the population density at (Colombo Central Business Area) CBA is between 8,000 - 14,000 persons/sq.km (80 -140 p/Ha) and towards Hanwella DSD it drops down to around 2,000 p/sq.km (20 p/Ha). The condominium development and high rises within the CBA annually cause for a growth of 12.1% [25] in the floating population towards the CBA causing for an increased population density. As per the calculations, the trip generation rate is 20,000 average trips per day / 550 average trips per Ha in the red coloured areas in the map "Fig. 4.a,".This scenario is caused since the resident population is higher in the blue coloured zone, which cause for lengthier vehicle trips (VMT per capita 23 km)

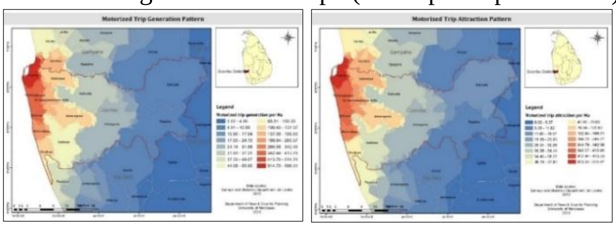

Figure 4. a. Motorized trip generation pattern, b. Motorized trip attraction pattern.

B. Employment Density and Trip Attraction

The Colombo district is consisted of a vast disparity in terms of the employment distribution. The annual growth rate in the employment availability is 9.4% in CBA and particular concentration is seen at the Fort, Pettah and adjacent DS divisions [26]. In particular, the employment density in the CBA varies between 20,000 - 30,000 employements/sq.km (200-300 per Ha) and the distant areas are occupied with a lower rate whereas 5,000 - 10,000 (50-100 per Ha) employments/sq.km. Since the density of employment opportunities is found high at the CBA, it attracts most of the trips generated from the TAZs "Fig. 4.b," (The Colombo Municipal Council attracts 26% of the total trips generated in the Colombo district).

C. Present Job – House Ratio in Colombo District

The red coloured areas mentioned in the map "Fig. 5.a," demonstrates where the job-house ratio is comparatively higher (Employment level is nine times more than the resident economically active population). The blue areas demonstrate a lower level of job-house ratio stating a high amount of resident population than the employment availability. Within the zone the job-house ratio varies between 0.5 – 9.3 demonstrating that the job-house balance is significantly uneven. As per the calculations the VMT per capita significantly depends on the Job-house ratio. (R2= 0.593) "Fig. 5.b," The relationship between the Job-house ratio and VMT per capita is demonstrated by the given equation (6).

$$Y = 0.01 * X^2 - 0.0698 * X + 9.1032 \qquad (6)$$

Y – Job-House ratio for a given TAZ
X – VMT per capita

Accordingly, TAZs with comparatively higher Job-house ratio and lower Job-house ratio are accountable for lengthier VMT per capita.

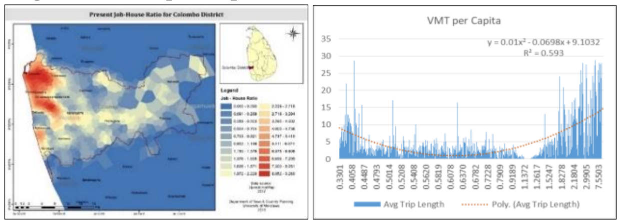

Figure 5. a. Present job-house ratio in Colombo district, b. Relationship between VMT per capita and job-house ratio.

As an average, trips of 30 – 50 km length occurs at a daily rate of 150,000 from the distant TAZs. Since the job availability is low in the distance areas from CBA a larger portion of population, (60%) tends to travel a distance of 30 – 50 km searching for better job opportunities in CBA. At an average speed of 20km/h, a vehicle consumes 140 ml (approx.) per 1km. It is twice as the amount in a standard situation [27].

D. Route Assignment and Congestion Levels

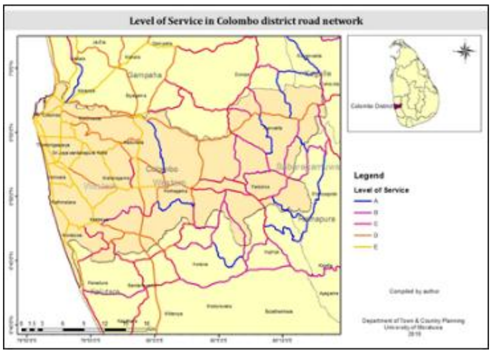

Figure 6. Level of service in Colombo district main roads (A & B class).

The above map "Fig. 6," demonstrates that the LoS of the road links connecting hinterland and CBA is much more congested (more than 60% of its design capacity) than the roads distributed in hinterland. The LoS of the roads near CBA demonstrates E – F values which represent the V/C is one and above. The speed varies between 17 – 20 km/h. Many of the A class, B class, Expressways and minor roads are destined at the Colombo district causing for 10 million passenger trips towards the zone. The design capacities of the Colombo district roads can bear only an amount of 3.8 million PCU under the design speed and zero congestion level. However, there is an exceeded amount of 4.7 million traffic inside the Colombo district causing to overdue the road holding capacities and congestion levels.

E. Road Capacity and Proportionate Trip Balance

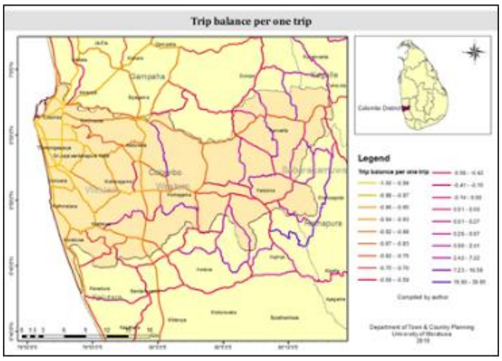

Figure 7. Proportionate trip balance per a unit trip.

Considering the LoS of the road links and based on the level of congestion the each segment generates, a new combination of trip generation and trip attraction is calculated for each TAZ to reduce the congestion and to improve the LoS in each segment. It is considered while calculations to maintain the LoS in roads segments in C & D levels, which makes a convenient environment for road users. The number of trips along each shortest path are proportionately balanced to achieve the mentioned LoS “Fig. 7,”.

As mentioned in the equation (4) the potential overall trip attraction values are calculated based on the global integration and connectivity values, which obtained based on the closeness centrality analysis. The “Fig. 8.a,” demonstrates the assigned values for each centroid based on the closeness centrality analysis. The connectivity measures are demonstrated in the “Fig. 8.b,”.

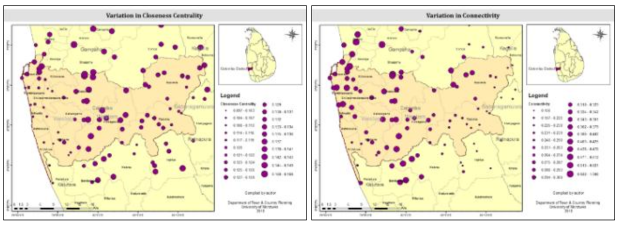

Figure 8. a. Variation in closeness centrality, b. Variation in connectivity.

Based on the demonstrated trip distribution and potential trip attraction the trip generation for each TAZ is characterized. The employment density is limited to 400 employments per hectare (40,000 per sq.km) having a dissolved distribution. The maximum proposed population density is 200 persons per hectare (20,000 per sq.km) and it is distributed over the district. Within the Colombo district, the proposed maximum job-house ratio becomes 3.8 and these maximum locations are distributed at seven distant locations “Fig. 9.a,”. Further, there are several minor level spots that can be identified for job concentrations.

F. Proposed Employment Clusters Based on Job-house Ratio

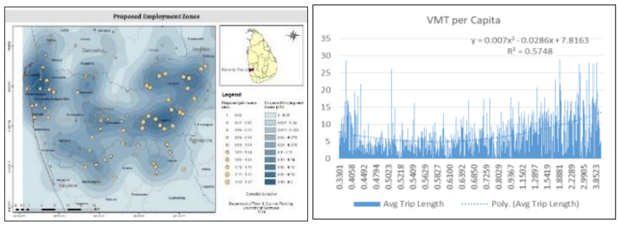

Figure 9. a. Proportionate employment zones, b. Relationship between new VMT per capita and job-house ratio.

This scenario demonstrates the traffic volume on any road link stays below the proposed design capacities of the roads (LoS A, B or C). With the new proposed job-housing scenario, it is clearly demonstrated that the passenger travel distances are significantly reduced. In the previous scenario, the total VMT was recorded as 8,318,764 km and with the proposed context, it has reduced to 3,609,670 km. It is a reduction of 43% of the total VMT in the city and VMT per capita is reduced to 13.9 km from 23 km “Fig. 9.b,”. It also reduces the average fuel consumption by 22%.

V. Conclusion and Recommendations

The proposed job-house balance ratio is derived based on the zero congestion levels in the road network. The centrality analysis for the study area is used to identify the potential trip attraction amounts in each TAZ. The main assumption made in the study is that the trips generated by a group of population in a particular area is merely for the occupation and office purposes. Therefore, the trips considered in the model is not based on activities but based on home location and employment location. The main limitation confronted in the study was identifying a method to quantify the requirement of land use and transport integration.

The ultimate recommendation of the research study is the job-house balancing strategy and the automated tool shall be utilized in demarcating the development zones and guide plans. Even though the model provides a scientific input to balance the job house locations, the existing situation can be very much deviated from the result. The research study can be further carried out to incorporate the capacities at the road junctions.

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