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Systems Approach to Develop High Mobility Road Network Plan for Sri Lanka

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Abstract: Transportation between major commercial and socio economic hubs will play a vital role in the economy. Since existing road networks have developed based on historical and natural reasons and expressways also have come up with individual proposals with very little consideration on overall connectivity, a need for a systematic approach for future network development has become a necessity. This study focuses on developing a high mobility road network taking into account the possibility of upgrading existing roads as well.

Since Administrative Districts and their capitals have already established and developed, 25 District Capitals were selected as the primary centers to be connected and considered as main nodes in the high mobility road network. In addition, all expressway interchanges, other major A-Class road intersections and cities with major traffic attractions were considered as nodes when defining the initial road network.

During the analysis stage, development of minimum distance paths and minimum spanning tree were considered to identify bottlenecks, critical nodes and critical links. To identify the optimum network, two criteria, minimizing overall link length, maximizing network speed and achieving desired average speed levels, were considered. A methodology was developed to identify the links to be added or improved such that overall mobility level of the country is improved.

Keywords: Mobility, Minimum Distance Path, Minimum Spanning Tree, Nodes

1. Introduction

Since transportation systems directly affect the demand and supply level of an economy, it is essential to look forward to investing for establishment of transportation network among major socio economic centres. Transportation demand between critical nodes (regions or cities) has gradually increased over the last few decades. Therefore, the level of service of certain critical links has dropped due to the increase in traffic volume and density with respect to the constant capacity of considering links. Introduction of expressways, widening of the existing roads, increasing the sight distance, and surface re-layering can be considered as solutions provided by the authorities through policy decisions to improve mobility level. Several changes such as, travel time reduction, fuel consumption reduction and job creation have occurred in the transportation system as well as in the economy due to the introduction of expressways and other major road improvements.

Due to the high investment cost, time, space and labour for transportation based developments (especially roads), it is essential to look forward to evaluate the performance of the existing links & develop the entire road network in different perspectives such as sustainability of traffic behaviour, financial sustainability, environmental sustainability and social aspects (Sotiropoulos, 1978).

2. Goals & Objectives

Interpretation of a development plan of high mobility road network can be identified as the goal of the study. The basic objectives are recognition of bottlenecks and critical links and prioritization of necessary improvements to increase average network speed while maintaining minimum average speed between any node pair.

3. Literature Review

3.1 Network Optimization Methods in Other Studies

When considering similar studies in other regions, it was observed that shortest path analysis was considered frequently because of its wide range of Applications. (Winn, 2014.) The road network minimization algorithms were developed by incrementally determining cost, time or distance between source node and

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all other nodes. The values (time/distance/cost) from each source node to all other nodes were repeatedly compared and the least value option was determined. The model then proceeds to the next node until the destination is reached. (Alam et al., 2012) According to (Ahmed et al. 2017) and Winn, 2014), GIS was effectively used to identify the geometric behaviour and the relationships of the considering network.
Ghaffariyan (2010) proposed heuristic methods as well as liner programing methods for network optimization.

3.2 Gravity Model for Demand Analysis

In transportation studies, population and distance can be identified as the major influences of trip generation and trip attraction. Though many advanced demand modeling techniques have developed recently, basic approach was considered as it is less sensitive to any other developments and it is appropriate for early planning stage. Therefore, gravity models can be developed with respect to population density and distance parameters to identify the demand of traffic generation (Jung et al., 2008).

$$G = \frac{PD\ of\ Node1\ \times PD\ of\ Node\ 2}{1000x(Distance\ between\ Nodes)^2} \quad \ldots(1)$$

PD: Population Density
Populations of nodes were indicated as population density in terms of number of total heads in thousands per square kilometer. Population density was considered instead of population since the dispersion of population among entire district does not reflect actual impact on inter district transportation. Therefore, population density can be identified as a mean value which can be applicable for every district. (*Khan Academy*, no date) Distances between node pairs were indicated in kilometers. Since the results of the general calculation without having the constant had a range of 0.00 to 5000.00. Therefore, constant value was used to reduce the dispersion of the scale of the gravity formula from 0.00 to 5.00.

3.3 Minimum Spanning Tree

A tree is a subset of a network not containing loops. Minimum spanning tree is the tree which connects all nodes of the network with a minimum length/travel time of links (Effanga and Edeke, 2016). It gives the most feasible tree for an economy when considering cost of construction & maintenance (Kumar *et al.*, 2014). The Prims Algorithm was used to develop the minimum spanning tree.

3.4 Minimum Distance Path

The path which connects two nodes in a defined network with minimum length/travel time of links can be identified as the minimum distance path (Parsakhoo and Mostafa, 2016). Dijkstra's Algorithm was used to evaluate the minimum distance path between each node pair.

4. Methodology

4.1 Identification of Nodes

The following were considered as nodes for the analysis.

- Administrative district capitals
- Expressway Interchanges
- Major intersections of A-Class roads
- Other considerable nodes based on trip attraction

Since the entire economy was decentralized up to some extent towards district basis, Administrative, Commercial & Socio Economic activities of district capitals were increased. Therefore, district capitals were considered as primary nodes.
Expressway interchanges can be identified as coordinating gateways towards high mobility segment of inter district transportation.
Commercial activities of major intersections of National A-class roads were increased due to increase of through traffic of the junction.
Special nodes such as Katharagama (a religious place where people travel all year around in large numbers) were considered due to high socio economic activities and cultural behaviour.

4.2 Definition of Performance Indices of Nodes & Links

Key performance indices which create a baseline to evaluate overall performance of the network are as follows.

- Trip Generation/attraction level based on a Gravity model
- Average Acceptable Speed for Expressways & A Class roads
- Route Directness (distance of minimum time path/ minimum distance path)

4.3 Data Collection, Matrix Development & Application of Algorithms

Recently, Google traffic data have become the major traffic data source for the analysis when considering the reliability of data with respect to other sources (Vidanapathirana et al., 2020). Real time Google traffic data may vary due to time of the day and travelling season. Average value during office and school hours (0600hrs to 0900hrs and 1600hrs to 1800hr) were taken into consideration. Matrices were developed based on following considerations.

- Distance
- Travel Time
- Average Speed

Minimum spanning trees based on travel time and distances were developed. Minimum distance paths between each district capital node pairs were calculated. Other nodes, such as expressway interchanges, A-class road intersections and nodes with special trip attraction behavior, were also taken into consideration during calculations. But only district capitals were considered when developing resultant Origin Destination matrices since the objectives are more towards administrative districts. Nodes and links which occupy in each minimum distance path were recorded. Average speed of each link was calculated with respect to 25 main district nodes and average speed between all 25 district capitals were estimated. Average speed of expressways including proposed and under construction expressways were assumed as 80km/h based on previously developed driving cycles (Galgamuwa, et al., 2016).

4.4 Approximation of Demand Between District Capital Nodes Using Gravity Model

The matrix of gravity values with respect to 25 district capitals was developed as follows:

- Population density (heads per square kilometer) of Colombo: 3417
- Population density of Gampaha: 1711
- Distance Between Colombo & Gampaha: 34.4km

$$G\ (Gampaha\ \&\ Colombo) = \frac{3417\ \times 1711}{1000x\ (34.4)^2} \quad \ldots(2)$$

The gravity value obtained from calculation would reflect the attractiveness between each node pair. Attractiveness is directly proportional to the population density and it is inversely proportional to the distance between nodes. Therefore, demand between each node pair can be approximated with respect to the gravity value. The concept of gravity model was extracted from newton law of gravity which reflects the attractive force between nodes with respect to population density of nodes and the distance (Jung et al., 2008).

4.5 Identification and prioritizing of critical links /nodes

Critical links and nodes can be identified based on the following criteria:

- Links and nodes which have higher frequency of employing in minimum distance paths but having poor average speed (less than 40km/h)
- Links and nodes which relate to minimum spanning tree
- Links and nodes which have high Gravity level with a poor average speed (less than 40km/h)

Since some of the critical links have already developed up to acceptable level (e.g. Expressway links with average speed of 80km/h), links and nodes to be improved were identified and ranked with respect to importance to the entire network and performance.

Introduction of new links and evaluation of impacts to the overall performance of the network due to introduction should be considered after optimisation of existing network.

5. Summary of Results and Discussion

5.1 Critical Nodes and links which were identified through gravity model

Since Colombo, Gampaha & Kalutara have the higher population density among district capitals, such node pairs give the values of gravity which is more than 1.

Table 1 - Links with Highest Gravity

Rank	Link Description	Gravity Value
1	Colombo- Gampaha	4.94
2	Colombo- Kalutara	1.32

Node pairs which have gravity value of more than 0.1 but less than 1 were identified as node pairs with moderate gravity which have heavy potential to impact on traffic behaviour over the next decade.

Table 2 - Links with Moderate Gravity Level

Rank	Link Description	Gravity Value
3	Kalutara- Gampaha	0.30
4	Gampaha Kegalle	0.30
5	Kandy- Matale	0.28
6	Colombo- Kegalle	0.23

7	Kegalle- Kandy	0.23
8	Galle- Matara	0.19
9	Kurunagala- Kegalle	0.16
10	Colombo- Kandy	0.16
11	Colombo- Ratnapura	0.15
12	Gampaha- Kandy	0.15
13	Kandy- Kurunegala	0.13
14	Gampaha- Kurunegala	0.13
15	Colombo- Kurunegala	0.12
16	Colombo -Galle	0.11

Graphical representation was developed to identify the critical intermediate nodes and critical paths with respect to gravity level of node pairs.

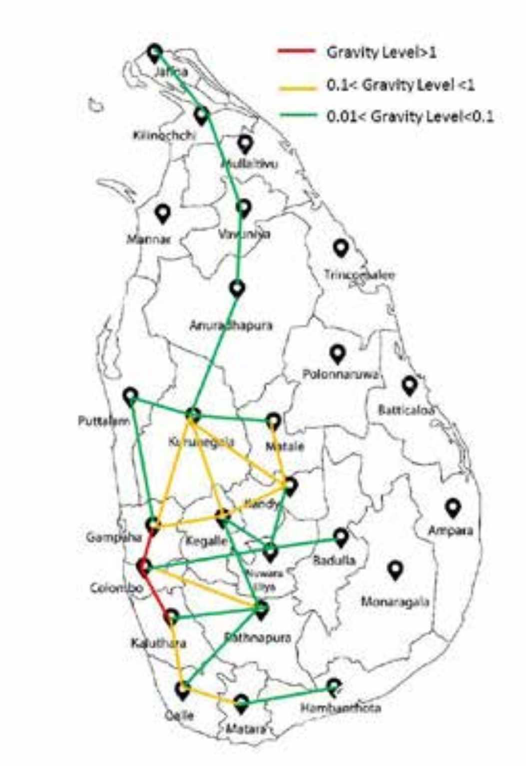

Figure 1- Gravity Model Observations

All the maps show the main 25 nodes at the exact geographical location (City centre of the District capital).

5.2 Development and Graphical Representation of Minimum Spanning Tree

After the implementation of the minimum spanning tree based on distance, it was observed that the following important links with relatively higher gravity were bypassed through other links by the minimum spanning tree algorithm.

- Kandy- Kurunagala
- Colombo- Ratnapura
- Gampaha- Puttalam
- Kurunagala- Matale
- Colombo- Nuwara Eliya
- Galle- Ratnapura

Since the above mentioned deviations were observed through the comparison of distance based minimum spanning tree and the gravity model; travel time based minimum spanning tree was developed to identify the existing network with the optimum level of service.

Figure 2 - Minimum Spanning Tree w.r.t Travel Time

Through the travel time optimized minimum spanning tree, it was observed that the following nodes are close to each other by distance but they are linked to each other by alternative paths due to geographical barriers. Level of service of the existing direct links of considering node pairs are relatively low.

- Kandy- Badulla
- Kandy- Nuwara Eliya
- Nuwara Eliya- Ratnapura
- Kegalle- Nuwara Eliya
- Kalutara- Ratnapura
- Matara- Ratnapura

Figure 3 - Geographical Barriers

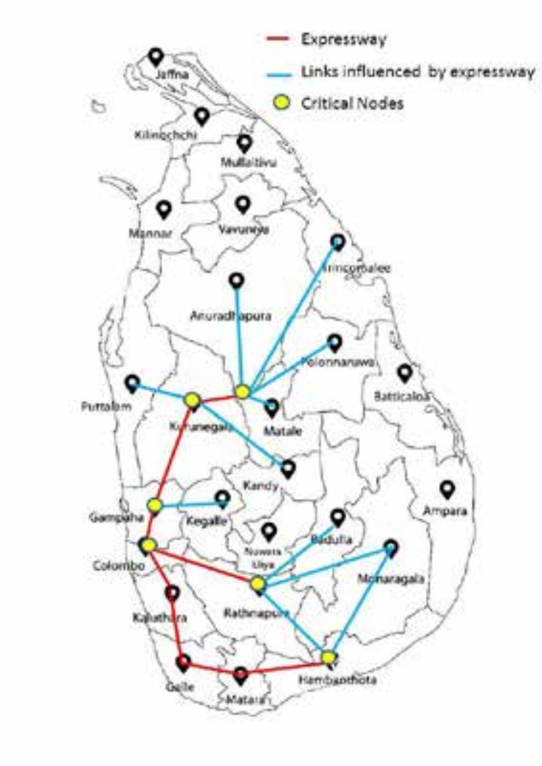

Figure 4 - Influence due to Expressway Network

5.3 Effect of Implementation of Expressway Network

Travel time between the nodes connected by expressway network were optimized up to the maximum level of service. Therefore, following nodes can be identified as the critical nodes when considering the travel time optimization of the network.

- Colombo
- Gampaha
- Kalutara
- Galle
- Matara
- Hambantota
- Kurunegala
- Dambulla
- Ratnapura

Following links can be identified as the links influenced by the expressway which require considerable performance improvement to maintain the mobility level between nodes through expressways.

- Gampaha- Kegalle (35km/h)
- Kurunegala- Puttalam (42km/h)
- Kurunegala- Kandy (30km/h)
- Dambulla- Matale (39km/h)
- Dambulla- Polonnaruwa (50km/h)
- Dambulla- Trincomalee (51km/h)
- Dambulla Anuradhapura (51km/h)
- Ratnapura- Beragala (36km/h)
- Ratnapura- Hambantota(42km/h)
- Hamabantota- Monaragala(48km/h)

5.4 Critical Nodes Identified through the Calculation of Minimum Distance Path of each District Capital Node Pairs

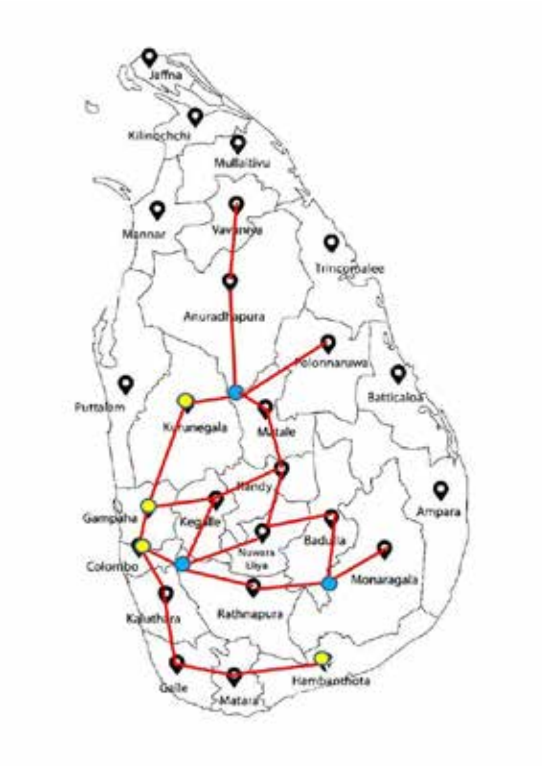

Figure 5 - Frequent Links in Minimum Distance path Calculation

The links which most frequently observed during minimum distance path calculation for node pairs are represented in Figure 5.
Some of the links can be identified as functioning or proposed expressway links. Therefore, they can be categorized as links with adequate mobility level.

5.5 Identification and Ranking of Improvement required links

Since the study provides different observations from different methods such as gravity level, minimum spanning tree & minimum distance path, it is necessary to implement a combined method to extract the most critical links to be improved. Therefore, the following ranking was implemented based on combined criteria.

Table 3 - Combined Ranking of Observed Links

Rank	Link Description	Average Speed
1	Kandy- Matale- Dambulla	25km/h
2	Gampaha- Kegalle	35km/h
3	Kegalle- Kandy	30km/h
4	Kurunegala- Kandy	30km/h
5	Kegalle- Kurunegala	34km/h
6	Kandy- Nuwara Eliya-Badulla	30km/h
7	Colombo- Avissawella-Nuwara Eliya	35km/h
8	Kurunagala- Matale	36km/h
9	Gampaha (Katunayake)-Puthtalam	37km/h
10	Ratnapura-Bearagala(Badulla & Monaragala)	36km/h

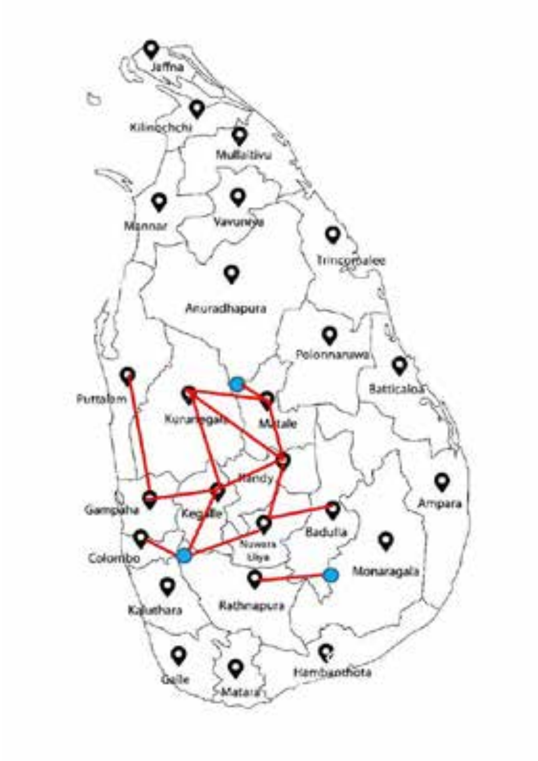

Figure 6 - Critical Nodes to be Improved

6. Conclusions

Links with low level of service and high demand for occupancy have been identified through a systematic approach. During the study, it was identified that population density plays a vital role with respect to transportation demand. Therefore, most of the links with considerable demand were located in the west and the central region of the country (Refer Figure 1). Minimum spanning tree with respect to travel time was developed to utilize the link improvements towards connecting all district capitals with minimum number of links. But node pairs with considerable attraction not connected by minimum spanning tree were observed. Therefore, minimum distance path was taken into consideration and frequently used links with low level of service was identified (Refer Figure 5).
Since expressway network and the proposed traces were confirmed through policy decision level and the strategic level of the economy, the

study focused towards effective utilization of existing expressway network to increase the overall network performance.

As an economical initiation, 10 links with poor level of service and high demand were obtained and ranked through the combined system approach (Refer Table 3 & Figure 6).

Most of the links which require improvements are located in the central region of the country. It reflects that the level of service dropped due to the geographical issues related with the considering links. Therefore, advanced engineering aspects towards landslide mitigation and slope stabilization should be considered effectively during improving of roadway infrastructure of existing traces.

Soil nailing, ground anchoring, shotcreting, construction of lightweight embankments, construction of drainage wells with horizontal perforated drilling and installation of anti-rockall nets can be identified as mitigation measures for ground improvement parallel to the existing roadway infrastructure development.

After implementing necessary improvements to the existing nodes and links, the strategy developed by the study could be applied towards the improved network to identify the necessity of introduction of new links to the network.

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