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Improving the efficiency of public transportation in India using operations research

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ABSTRACT

The analysis shows that no single model or theory, such as Queuing Theory, Transportation Problem, Vehicle Routing problem, Hubs and Spoke Model etc., aim at increasing the efficiency of public transportation by addressing a particular segment of the problem are enough to solve the problem holistically. In this paper, we touch upon the shortcomings of the existing models and algorithms and suggest that a model should be developed which encompasses all these factors and provide an all in all solution to the problem.

Keywords— *Queueing Theory, Transportation Problem, Vehicle Routing Problem, Probability, Hub and Spoke Model, Holistic Development, Human Intelligence*

1. INTRODUCTION AND OVERVIEW

Public transport is one of the most essential means of transport in Indian metropolitan cities, for example, Delhi where roads make up over 20% of the land which is the highest for any city in the world (Bhatia & Jain, 2009). Although it is evident that public transport helps in combating air pollution and traffic congestion, the usage of Buses in India has been on a downward spiral while the overall travel demand has increased simultaneously. A lot of researchers have tried to solve this problem by focussing on some specific elements like reducing overcrowding discomfort or optimising routes. Hamed et al. (2017) have stated that along with providing economies of scale, the subsidized bus transit serves the interests of a sector of the population who cannot afford any other means of transport which is a factor that the government cannot ignore (Hamed et al., 2017). The demand for modern transport in an urban area is dynamic and multi-dimensional having dimensions like physical, technological and mass demand management. This has occurred due to the rapid growth of population in metropolitan cities like Mumbai and Delhi caused due to the migration of lower-income personnel who cannot afford private transport like cars and bikes. Metropolitan cities are usually thickly populated, making efficient and effective public transportation necessary to have in a modern and well-functioning city. Therefore, the transportation system in Metropolitan cities is typically massive and very complex. This is accompanied by some problems, especially in the transport system. The most frequent display of the urban transport problem is congestion and traffic which increases vehicle operating costs and environmental pollution. These solutions form the basis of a transport policy, which can be planned and implemented for a country, a city or even a town. Therefore, the focus must be on the improvement of the efficiency and upkeep of the existing buses, the methods of which have been discussed in this research paper.

2. LITERATURE REVIEW

Braekers et al. (2016) talks about Capacitated VRP (CVRP) and explains how classical VRP got extended in many divisions with varying capacities (Braekers et al., 2016). It also throws light on the ‘Milk Run’ concept, which is derived from the success of the Vehicle Routing Problem with Backhauls (VRPB). Eksioglu et al. (2009) focuses on VRP with multiple depots and provides an analysis of single and multiple objective programmes (Eksioglu et al., 2009). (Dixit & Kumar Tiwari, 2021). Liong (2008) focus on (PS-VRP) Model where the production and distribution system are taken into account (Liong, 2008). It has explained all characteristics involved like the production, inventory and distribution and how each contributes for the model to function properly. It has made an analysis of CVRP focussing on the number of trips, visits to customers and the transport data and following the assumptions trips per vehicle is limited to one during each vehicle. Royo et al. (2016) discusses the Hub and Spoke model in light of VRP's limitation of not focusing on long-distance problems, as well as how the Hub and Spoke model has distinct advantages (Royo et al., 2016).

Many papers have studied the concept and relevance of Queuing Theory in daily life, such as, (Patidar, 2015), (Berry, n.d.), etc. These papers have tried to define the building blocks and derive some basic queuing models. Shanmugasundaram & Umarani (2015) have studied the use of Queuing Theory in various sectors such as a sequence of computer programming, network building, medical sector, banking, etc (Shanmugasundaram & Umarani, 2015). There are quite a few papers that have studied the application of Queuing Theory in transportation. One such paper is (Varghese & Chandran, n.d.), which has studied its application in the sectors such as material transportation system, in the governance of traffic intensity, for the efficiency analysis of toll plaza, to minimize accidents due to traffic, at Signalized Intersection etc. The paper has concluded that Queuing Theory can be most effectively used in material transportation. There is a very limited study on the use of Queuing Theory in improving Public Transportation. JiaoPeng-peng et al. (2015) has used the Theory to increase customer satisfaction. The authors of this paper have created an algorithm for the same and have solved it using MATLAB Software. (JiaoPeng-peng et al., 2015) However, none of these papers has used the Queuing theory to determine the number of buses on the various routes based on the average number of passengers travelling on them. According to Jaramillo-Álvarez et al., (2013), the system and transit should be adequately planned to optimise their performance for the benefit of users and the city to create incentives to use public transportation and offset the negative consequences connected with the system's operation (Jaramillo-Álvarez et al., 2013). The suggested model improves on previous models by including additional aspects such as minimising transfers. Agrawal et al. (2020) aims to enhance the attractiveness of public bus transport by reducing the overcrowding in buses (Agrawal et al., 2020). One non-linear and two linear have been developed by the authors to determine the optimum frequency of buses and apply them over a vast network of bus routes. Mastorakis (2008) presents an analysis of characteristics of a transportation system and introduces a concept that is suitable to both Macroscopic and Microscopic models of control and management of transportation systems (Mastorakis, 2008). Illés et al. uses an object-oriented logical approach to analyse and optimise the public transit network (Illés et al., n.d.).

One of the major aspects to improve public transportation in India is by reducing the issue of overcrowding. Many research papers and articles have tried to improve public transportation by using various methods but they have not considered Overcrowding as an issue. The paper (Tirachini et al., 2006) tried to minimize overcrowding using Multinomial Logit (MNL) and Error Components models, they depicted some alternative assumptions concerning overcrowding that affects the value of travel time (VTTS). Papers like (Pathak et al., 2020) used one non-linear and two linear models of heuristic as well as meta-heuristic approaches to fix the problem. So, future work can put more emphasis on modelling more accurately. In (Pathak et al., 2020) this paper, the authors created a mathematical model that includes an exponential function multiplier with load factor and then uses it to find the cost of crowding discomfort. The authors concluded that their paper can be extended by adding the constraints of electric vehicles and estimating a suitable mix of both EVs as well as non-EVs transport vehicles, which is an important factor for the future.

3. METHODOLOGY

The Transportation Problem is formulated based on the characteristics of the transportation system, wherein, various bus routes in place of 'Origin' and various bus stops in place of 'Destinations' have been taken into consideration. The assumption has been set, such that there is a particular origin from where passengers are going to travel to 3 different bus stops (destinations), using 3 different bus routes. These routes connect to all three bus stops. The numbers mentioned in the example are hypothetical which have been used to simplify the process of understanding and implementation of the same.

Queuing Theory uses the model based on Kendall's notations. The questions have been taken into account based on relevance to our area of study to fulfil our objective behind the same. The steps of the procedure for allotting buses to various bus stops have been structured based on primary research, and the formulae have been used from existing papers.

4. ANALYSIS

4.1 Queuing theory

Queuing theory is widely used to solve problems relating to queues using mathematical formulae. It was introduced by Agner Krarup Erlang, a Danish mathematician, statistician, and engineer.

There are various models of Queuing Theory based on various parameters, such as, the pattern in which customers arrive, the pattern in which they are served, the number of customers allowed in the system, the number of servers, etc. Some of the basic models are:

- D/M/1 = Deterministic (known) input, one exponential server, one unlimited FIFO or unspecified queue, unlimited customer population.
- M/G/3/20 = Poisson input, three servers with any distribution, maximum number of customers 20, unlimited customer population.
- M/M/m/∞ = m servers, infinite number of waiting positions
- M/M/m/m = m servers, loss system, no waiting
- M/M/1/K = single server, queue with K-1 waiting positions
- M/M/1/∞ = Queue with Discouraged Arrivals

Queueing Theory is used to identify the requirement of additional buses at any given bus stop. We have selected the model, (M/M/S): (infinity (∞)/ FCFS) as it fulfils all the requirements needed for bus transportation. In this particular model, the number of occupied channels determines the length of the waiting line.

The various attributes of this model based on Kendall's Notation (a/b/c): (d/ e) are as follows:

- **a** = M i.e., the arrival of the customers follows a Markovian Distribution
- **b** = M i.e., the service time follows a Markovian Distribution.
- **c** = S i.e., there are a finite number of servers available.
- **d** = ∞ i.e., there are infinite customers allowed in the system.
- **e** = FCFS i.e., the customers are served on a "First Come First Serve" basis.

Here,
Server represents the number of buses.
Customers represent the passengers waiting in the queue.
System represents the whole process of waiting in the queue and travelling in the bus to reach the destination.

We will mainly focus on the following questions to identify the need for the introduction of an additional bus at any given bus stop:

1. Probability that all the servers (buses) are busy –
$$E(W_q) = \frac{\rho P_S}{\lambda(1-\rho)^2}$$
2. Expected (or average) number of customers in the system.
$$E(L_S) = \frac{\rho P_S}{(1-\rho)^2} + S\rho$$
3. Expected waiting time in the queue.
$$E(W_q) = \frac{\rho P_S}{\lambda(1-\rho)^2}$$
4. Expected queue length (average number of customers in the queue).
$$E(L_q) = \frac{\rho P_S}{(1-\rho)^2}$$

Where,

$$\rho = \frac{\lambda}{\mu s}$$

λ = average arrival per unit time
μ = service per unit of time
n = number of customers
S = number of servers
If n < S, then there will be no passengers waiting in the queue.
If n = S, then all the buses will be busy.
If n > S, then all the buses will be busy, and (n-S) passengers will still be waiting in the queue.

Assuming that there are 'x' number of extra buses available in the transportation system which are to be allotted for a given number of bus stops based on their requirement.

The following steps should be followed to determine the allocation of buses:

a) Calculate the "Probability that all the servers are busy" for each candidate bus stop.
b) Arrange them in descending order.
c) Allot a bus to the bus stop with the highest probability.
d) Again, calculate the probability for the stop to which the additional bus is allotted.
e) If the probability is still higher than the other stops, allot another bus to it, otherwise, allot a bus to the stop with the next highest probability.
f) Continue this process until all the additional buses are allotted.

Similarly, questions 2, 3 or 4 can also be answered instead of 1, based on the priorities of the transportation system. The problem with this model is that the values of λ and μ would be different for different bus stops. These values can vary depending upon the season, or the day of the week. Therefore, defining a single fixed value of these variables would be inappropriate.

4.2 Time Minimization using TP

The problem with using TP in Public Transportation is that here we're transporting people, and people have a fixed destination in their mind when they are travelling. If the cost or time for travelling to a particular destination is low, we cannot send them to that destination, if they want to go to a different one. However, we can use various routes for reaching a destination and try to choose the routes in such a way as to minimize the time taken to reach the destined bus routes. Hence, we have assumed that there is a particular origin from where passengers are going to travel to 3 different bus stops (destinations), using 3 different routes. Therefore, in place of origin, we have taken various routes, while changing destinations to the various bus stops that the passengers are willing to travel to. We have taken a hypothetical situation and some hypothetical numbers for proposing the model. Say, there are three bus stops that the passengers are willing to travel to from a particular origin. And the number of busses travelling to these stops, S_1, S_2 and S_3 are 28, 18, and 30 respectively. Also, three routes connect to all three bus stops. Let's say that there are constraints concerning the number of busses that can travel on a particular route. If the number of busses exceeds the given constraints, it would reduce the efficiency of the route (given the pre-existing high traffic in Delhi). So, the number of busses that can travel on R_1, R_2 and R_3 are 20, 32, and 24 respectively. The time is taken by a bus travelling on route R_j to destination S_i is given in the table for each cell.

Table 1

	S_1	S_2	S_3	Max. no. of Buses
R_1	2	0.6	2.4	20
R_2	0.6	1.4	1.6	32
R_3	1.2	1.4	0.8	24
Passengers	28	18	30	

(Source: The Authors)

Solving the TP using Vogel's Approximation Method (VAM), we'll get the IBFS giving us the most optimal solution to the problem. The limitation with the Time minimization TP model that we have created has some quite unrealistic assumptions. Firstly, we have assumed that each one of the three routes passes through each one of the three stops. This may not be necessarily true in the practical sense. Secondly, we have created a constraint for the number of buses that can travel on a particular route, assuming that the efficiency of the route would reduce if the number of buses exceeds the given number. Practically trying to find such a number would give very vague results.

There is yet another limitation with the model. If we were to apply this model in the real world, we would have to take many more bus stops than what we have taken in the model. This would make it way more complicated and confusing. This makes it more of a theoretical model which would need a lot of improvements to make it apt for the real world.

4.3 Hub and Spoke Model

A large number of bus routes result from the destination design methodology. Many sections of networks are formed, overlapping each other on corridors as the routes are connected node to node. This is a limitation of destination-oriented bus routes, which leads to an inconsistent distribution of headways at route stops, making the transit network inefficient and complex. To minimise this limitation, a different approach is designed and the best-suited design is Hub and Spoke Model. It is a combination of traditional destination-oriented bus routes along with a direction-oriented approach.

The distinct advantage of the Hub and Spoke model is that the number of routes and operation costs will go down due to centralised Hubs. Before if one wanted to travel from point A to point B in the city, he/she will take a bus from point A and will reach point B but now in Hub and Spoke model there are many 'Centralised Hubs' in the busier or more important routes. Feeder routes, which operate as "spokes," connect each of the non-hub nodes to one of these central hubs. As a result, the path from point A to point B now points A –> Hub 1 –> Hub 2 –> point B, with Hubs 1 and 2 acting as primary hubs for points A and B, respectively.

This approach will involve discovering possible hubs, determining optimal hub locations, and assigning non-hub nodes to a hub node, resulting in optimal inter hub and feeder pathways for each hub area. Individual passengers benefit from decreased fares and waiting times, as well as the reduction of bus bunching and increased service quality.

The limitation in this model is that as it is centralised it becomes relatively inflexible and makes it difficult to handle an occasional period of high demand by passengers. It also causes delay as the bus takes some halts between two destinations.

4.4 Human Factor

One critical factor which all papers ignore is the human factor. The majority of control tasks like controlling the vehicles are based on a human operator. Human intelligence must be included and presented algorithmically in any transportation system model. Human knowledge and experience need to be an essential component of model algorithms. These existing models are macroscopic and ignore the microscopic elements. But macroscopic and microscopic characteristics go hand in hand. Ex. A macroscopic model might help you in planning and optimizing the timetable of the transit. Still, to do so efficiently, accurate travel time is necessary, which can be estimated using the microscopic model.

The existing models have been developed based on ideal situations and thus are not very useful when applied in real-life scenarios. Also, the current models that aim to optimize timetables and reduce waiting time might be highly applicable and valuable in railways but fall short of solving this problem for public buses.

1. Railway vehicles are bound to the tracks; thus, they follow a predefined direction, and their position can easily be determined. The vehicle control is one dimensional, i.e. only acceleration or deceleration along the tracks, and maximum allowed speed is also predefined, thus making it easier for the researchers to run various algorithms as the trains are running more or less in the same manner. At the same time, the road vehicles are not bound to their tracks and can move freely on the road. The buses can move in any trajectory. Therefore, it becomes challenging to apply these models as the application of these models on one bus might not accurately represent the movement of all the buses in the system.
2. Another crucial factor that needs to be considered in the models is the mental capacity of the Human Drivers who has control over the speed profile of the buses. This problem is relatively easy in railways where speed profile is controlled by speed limits along the tracks and predefined travel times. Also, the trains cannot overtake each other, and each train is permitted to move ahead separately by external signalling equipment. Vehicles on the road have much more freedom in their behaviour. The driver has to take decisions on an individual level concerning the characteristics of the vehicle, existing road conditions, weather conditions, etc. He needs to react to traffic situations, solve traffic conflicts according to traffic rules, and then decide accordingly. Therefore, it is challenging to include the driver's intelligence in these models.

To summarise, excluding human factors in such models might give us the solution to an ideal situation. Still, to make them useful in the real world, the mathematical models and algorithms need to consider the various aspects of human behaviour as well.

5. FINDINGS AND CONCLUSION

India is a developing country and with a huge population, public transportation is a lifeline for middle- and lower-income groups. It helps them travel at minimal costs and reach on time. The government has been trying to improvise the system's efficiency. In our paper we have addressed the research gap which existed in the earlier papers using models like Queuing Theory, Transportation Problem, Hub and Spoke model, that is each of these papers addresses a particular segment of problem in public transport. They gave inconsistent solutions with the usual wishes of the decision-makers, who may prefer more expensive trips in time or length but do fewer transfers.

6. LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

As discussed above, there are certain limitations to every model:

- It has been observed that while Queuing Theory achieves the goal of identifying the need for additional buses, people do not prefer to wait in long lines.
- Transportation Problem is used to reduce costs, but many unrealistic assumptions must be made to prove the theory because demand and supply cannot meet at all times.
- Vehicle Routing Problem focuses on small clusters rather than long-distance travel
- Hub and Spoke Model achieves most of the goals, such as optimizing route numbers, reducing bus numbers, and meeting passenger demand all at once, it has the disadvantage of being inflexible and causing delays

We recommend building a model which covers all the limitations stated and hence for those who want to further build upon this model, we would recommend them to try and solve the above-mentioned limitations. They could also try to align it with other models that have the same objectives and create a wholistically synthesized model of their own.

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