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Demand-Based Model for Line Planning in Public Transport

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Abstract

A public transport network serves the society effectively if it evolves in time according to the changes in the population. Urban transportation problems of Thiruvananthapuram, a typical Indian city, is mainly due to the lack of evolution of the planned network adhering to the rapid urbanization and motorization. These issues are managed by constructing more infrastructure, which act as the catalyst to major urban problems, rather than addressing the cause. The purpose of this paper is to analyze the public transport operational characteristics of a typical Indian City (Thiruvananthapuram) emphasizing on link load on the selected route. In this paper, a methodology is proposed for line planning problem which includes optimization of public transport lines using operator costs, user costs and crowding on the bus. It also includes the determination of peak and off-peak frequencies of the existing network lines considering the critical demand.

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Keywords: public transport; line planning; critical demand

1. Introduction

In India, state-run public transport undertakings operate the majority of bus services in the public transport networks. But, the public transport system in India suffers from financial issues to inefficiency and unreliability. Low service frequency, increased travel time, overcrowding and poor service quality, are a few contributing factors of the decline of public transport. Very few cities have organized, planned, monitored and regulated public transport system. In the absence of adequate public transport services, private run modes like auto-rickshaws and other intermediate public transport have emerged in the cities, which have brought along problems of increased congestion, travel time and air pollution. Therefore, in the absence of any proper public transport system, the operational planning, regulation and management of public transport take place in an unplanned manner which further declines the patronage of public

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transport. In India, the bus is the most common mode of public transport accessible to a large section of society due to its wide-spread network and affordability. However, the major problem of the public bus transport is the degenerating service quality due to the unplanned operation of routes and arbitrary expansion of existing lines due to lack of appropriate planning strategies.

Line planning is one of the fundamental aspects of the planning of public transport. It is considered as an optimization problem of finding lines (selection of routes) and their corresponding frequencies in the public transport network based on the given travel demand. The bus frequency or headway indicates the timetable to be followed on the route which controls the link load capacity of the route. According to Schobel (2012), “A line l is a path in the public transportation network (PTN). The frequency f_l of a line l says how often service is offered along line l within a given time period T (e.g., an hour, a day). A line concept $(L; f)$ is a set of lines L together with their frequencies f_l for all $l \in L$”. Line planning problem can be considered as an optimization problem with two conflicting objectives: one is to minimize the operating cost of the lines or routes, and the other is to maximize the user comfort or service quality. In the following paragraphs, the literature on a few line planning models including modelling aspects and solution approaches are reviewed.

Amoroso et al. (2010) develop a demand-based methodology for the bus network design problem of a small and medium town. A multi-agent objective function is used to evaluate the performance based on different stakeholders: operator and user (car and bus). A two-step heuristic method for allocation of buses to regional transit bus routes was introduced by Kalaga et al. (2001). In order to handle peak demand on each route, base frequencies were calculated. The frequencies were worked out with the need to satisfy the demand on the critically (peak) loaded links on each route. A certain degree of overcrowding of buses on the critical links was allowed. An objective function was formulated to allocate more buses to the over-crowded link on availability of surplus buses to minimize passenger discomfort. Ceder & Israeli (1998) proposed a methodology for the construction of improved bus network routes considering the inter-modality factor. The objective functions for the bus-network-design problem were developed by taking into account the interests of passengers, operators and community. The solution to bus network design formulation was achieved in two stages. In the first stage, construction of skeleton feasible route networks to meet maximum travel time and length constraints reduced the problem dimension, wherein the network was the basis for optimization determining the shortest direct as well as indirect paths between each pair of nodes. The second stage considers optimization processes to derive the minimum value of the objective function. Borndörfer et al. (2007) proposed a new multi-commodity flow model for line planning which had two objectives: minimization of operating cost by transport companies and minimization of travel times of the passengers.

Cipriani et al. (2012) proposed a methodology for solving the bus network design problems and its subsequent application in a large urban area which are characterized by complex road network topology, a multimodal public transport system (rapid rail transit system, buses and tramway lines) and many-to-many transit demand. Ibeas et al. (2013) proposed an optimization model for bus headway determination and the size of the buses plying on the public transport network by minimizing the operator and user cost. The model allows different sizes of buses to be assigned on the network based on the demand. An integrated schedule based intercity bus line planning was studied by Steiner and Irnich (2016). Potential stations and best operating times are determined simultaneously using a branch-and-cut optimization solution method.

Line planning models have two contradicting objectives- the user’s perspective and the operator’s perspective. On the one hand, the line concept suitable for the passengers is expensive for the operator, while, on the other hand, the line concept which is economical for the operator usually lacks the service quality expected by the passengers. Therefore, it is a promising method to combine these two contradicting objectives in a single line planning optimization problem. Moreover, most of the studies regarding line planning have been done using a static demand. The proposed methodology includes optimization of lines taking operator costs, user costs and factors such as congestion. It also includes the determination of peak and off-peak frequencies of the existing network lines considering the critical demand.

2. Development of Line Planning Model

The main aim of line planning is to find the peak and off-peak frequencies along an existing line of the public transport network. A model is developed to minimize the generalized cost based on the critical demand on the maximum loaded link.

2.1. Formulation of the optimization problem

A mathematical model is developed with the objective of optimizing the frequency along a route taking user cost into consideration. The objective is to minimize the generalized cost for the user. To account for the operator perspective, the operating cost of the public transport line is taken as a constraint in the optimization problem. The generalized cost model is as below.

$$Minimize\ \ GC = VOT(\alpha.WT_1 + \beta.WT_2 + IVTT + \alpha.WT_3) + Fare \tag{1}$$

Subjected to,
Budget constraint,

$$c * L * n \leq B \tag{2}$$

Demand constraint,

$$s * n \geq D \tag{3}$$

Where,
GC is the generalized cost;
VOT is the value of time;
WT_1 is the walking time from the place of origin to the bus stop;
IVTT is the minimum in-vehicle travel time;
WT_2 is the waiting time at the bus stop;
WT_3 is the walking time from the bus stop to the point of interest;
α is the time weighting factor for walking time from origin to bus stop and bus stop to the point of interest;
β is the time weighting factor for waiting time at the bus stop;
c is the cost per km (cpkm);
L is the length of the trip;
n is the number of buses;
B is the budget allocated;
s is capacity of the bus;
D is demand in the critical link.

The values of α and β are taken as 1.5 and 2 as recommended by AASHTO.

3. Application of Model to Trivandrum City as a Case Study

The methodology starts with the selection of the study area and collection of primary and secondary data followed by data preparation. Data preparation includes the development of network topology, generation of the origin-destination matrix, sorting the fleet size, link length, speed, accessibility and data regarding operating cost. The flow chart in Fig. 1 gives a brief idea about the various steps involved in the methodology adopted for the study.

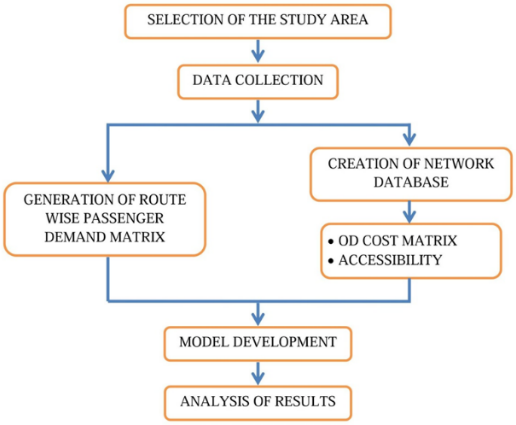

Fig. 1. Methodology Adopted for Line Planning

3.1. Data Collection

The data used in the study is a set of fare transactions in the Kerala State Road Transport Corporation (KSRTC) six city depots for the year 2013 in the form of Electronic Ticketing Machine (ETM) Data (Cyril, 2017). Other sources of data include the bus schedule data of the depots under consideration and the fare-stage data.

3.2. Data Extraction

A single ETM data file represents all the trips made by a single bus in a day (Cyril, 2017). The ETM data in text format are converted into Microsoft Excel format. Further, the excel files are then recompiled based on the date. The recompiled files are then split into different sheets based on the route code to get the data for each route. The route wise data can be combined again for the level of aggregation required. Extraction of data and conversion of ETM data into data used for analysis is done using codes developed in MATLAB.

3.3. Generation of OD Matrix

The data obtained from the data extraction process is on the basis of the route code. This data gives the passenger demand for each route. The following steps are used to obtain the route-wise OD matrix.

(i) The data is first categorized into seasonal and off-seasonal data.

(ii) Pivot tables are created with the origin, destination and the total tickets (inclusive of the full ticket, half ticket and physically handicapped) in Microsoft Excel.

(iii) The same route-wise OD matrices are added up for the formation of the final OD matrix that includes the demand along the selected route of the intra-city bus services operated by the depots of Trivandrum city.

3.4. Development of Network Database

The intra-city bus services of Trivandrum city cover an area of 214.9 km^2. The network database (network topology) includes the road network, bus stops, bus depots and intersections. It also includes the details of travel time, demand between the OD pairs, speed, and distance. The steps taken for the development of the public transport network of the study area are as follows.

(i) The boarding and alighting stops obtained from the ETM data were pinned in Google Earth as .kml files and then converted to shapefiles using ArcGIS 10.3.

(ii) The geo-referenced data of wards and road network were downloaded from Open StreetMap and re-projected in ArcGIS 10.3.

(iii) The cost matrix and accessibility matrix for the fare-stage wise stops were created in ArcGIS 10.3 using the shortest path algorithm.

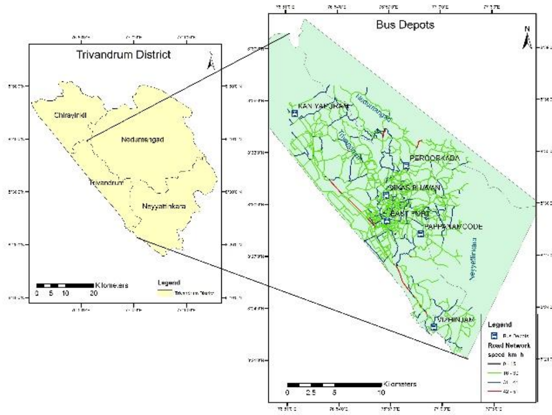

Fig. 2. Trivandrum City Depots and Route Network

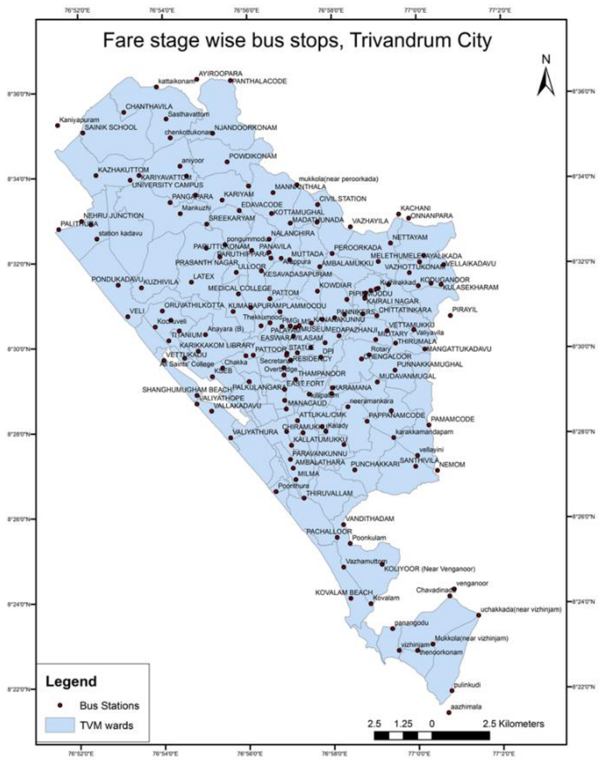

Fig. 3. Fare stage-wise Bus stations

Fig. 2 shows the Trivandrum city depots and route network and Fig. 3 depicts the fare-stage wise bus stops. Trivandrum city area is clipped using ArcGIS 10.3, and the roads are classified based on the speeds on the route network. Speed data, which is fed as attribute information in ArcGIS, was collected from NATPAC as secondary data.

3.5. Application of Line Planning Model

The main aim of line planning is to find the peak and off-peak frequencies along an existing line of the public transport network. The procedure for the achievement of the frequency along the individual routes is as discussed below. The trip-wise demand is used to check the loads across all stops. The loads are plotted to determine the passenger load profile with respect to distance travelled from departure stop to end of the route as depicted in Fig. 4. The values of unused seat kilometres show that about 40% of the seats are unoccupied during the entire trip of a bus.

Table 1. Load profile with occupied and empty seat kilometre

Start time from the origin point			10:55
Link	Distance (km)	Load	Occupied seat km
1	3.51	53	186.03
2	1.60	49	78.4
3	2.94	43	126.42
4	1.70	28	47.6
5	2.10	19	39.9
Total	11.85		478.35
Empty seat km			232.65
Available seat km			711
% of seat km occupied			**67.28**

Source: Cyril, 2018

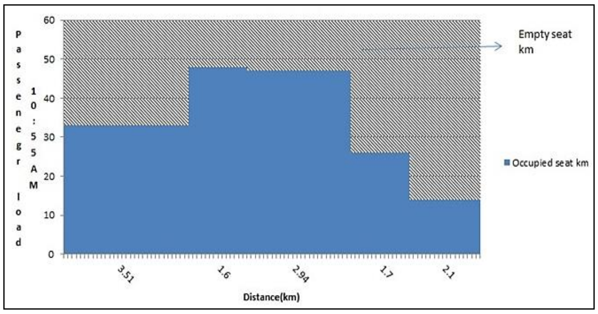

Fig. 4. Load profile with occupied & empty seat km (Source: Cyril 2018)

The route-wise OD matrix gives the number of passengers boarding and alighting from the bus at various stops along the trip. The load profile, i.e., a number of passengers onboard the bus is found out. Frequencies for three-time intervals, i.e. the morning peak, the evening peak and off-peak are to be determined. The OD matrix along the route is divided into three categories based on the time slots. Thus, three critical link demands are obtained. The demand in the critical link is used for the determination of frequency. The OD matrix along the route is divided into three categories: morning peak-8:00 to 10:30 am (Table 2), evening peak-4:00 to 6:30 pm (Table 3) and off peak-rest of the time is considered as off-peak (Table 4).

Table 2. OD Demand During Morning Peak (8:00-10:30)

Origin\ Destination	1	2	3	4	5	6	Load
1	0	14	52	31	38	14	197
2	3	0	0	12	10	2	**351**
3	25	1	0	3	2	0	303
4	17	46	1	0	1	1	253
5	17	45	17	0	0	0	93
6	14	20	14	0	0	0	0

Table 3. OD Demand During Evening Peak (16:00-18:30)

Origin\ Destination	1	2	3	4	5	6	Load
1	0	11	18	18	70	10	165
2	24	0	1	19	50	21	281

3	39	2	0	2	29	7	**365**
4	36	29	3	0	6	1	351
5	13	12	11	0	0	0	171
6	20	6	9	3	0	0	0

Table 4. OD Demand During Off-Peak Hours

Origin\ Destination	1	2	3	4	5	6	Load
1	0	29	76	79	144	27	472
2	53	0	12	83	91	33	785
3	40	1	0	10	56	15	**895**
4	48	73	6	0	10	4	728
5	64	31	28	0	0	2	359
6	73	18	16	10	0	0	0

The mathematical model proposed for line planning in this study is a passenger oriented model given in equation 1, taking budget (equation 2) and demand (equation 3) as constraints. In the budget constraint, length of trip (L) refers to the distance covered by the bus from the point of origin to the last stop. Since the financial data related to the operation of bus schedules are not available, budget allocation (B) along the routes is taken from the revenue collection obtained along the routes. Budget allocation is one of the crucial factors in finding the optimal frequency. The subsidies received from the government are not taken into consideration. For demand constraint, seating capacity (s) is considered. The seating capacity of city services operating in Trivandrum is 48. Since the buses operate within city limits, an average of 20% standees is considered as reported in the annual performance report of Kerala SRTU. Hence, the total capacity of the bus is taken as 60.

The model is converted to a non-linear optimization problem and solved using the fmincon (interior point) algorithm in MATLAB. The route-wise optimum number of buses during peak and off-peak hours based on dynamic demand are calculated and is listed in Table 5. The table also includes the number of buses plying on the routes under consideration for the year 2013.

Table 5. Number of Buses during Peak and Off-Peak hours

Route	Number of Buses during Peak Hours		Number of Buses during Off-Peak Hours	
	Recommended	Available	Recommended	Available
Route 1	6	8	13	14
Route 2	2	3	4	7
Route 3	12	12	18	20
Route 4	3	4	3	5
Route 5	4	4	9	12
Route 6	2	3	4	4

In route 1, the number of buses available during peak hour (one and a half hour each in morning and evening) and off-peak hours () are 8 and 14 respectively. However, the number of buses (n) obtained using the model for route 1 during peak hour and off-peak hours are six and 13 respectively. In route 2, it can be seen that three buses currently operate during peak hours while there are seven buses during off-peak hours. But, two buses are found to be optimal during peak hour and four during off-peak hours. The optimal number of buses during peak and off-peak hours for route 3 is 12 and 18 respectively. However, it is to be noted that the available number of buses is 12 and 20 for peak and off-peak hours respectively. In the case of route 4, the optimal number of buses for peak and the off-peak hour is three as against 4 and 5 (available number of the bus) respectively. It can be noted that both the recommended and operated buses are four during peak hours for route 5 while recommended is nine and available is 12 during off-peak hours. Also, in route 6, the optimal recommended number of buses are two as against three during peak hours while both the recommended and operated buses are four during off-peak hours.

The results indicate that only 25% of the schedules operated currently are having an optimal number of buses in contrast to 75% of the frequency of buses being on a higher side. Therefore, the number of buses can be decreased and hence rescheduling is required. The results listed in Table 5 shows that the number of buses for route 3 and route 5 during peak hours and route 6 during off-peak hours are optimal and hence there is no need of curtailment of the services. The number of buses operating for all the routes having values greater than the optimal recommended value given in Table 5 can be curtailed as there is more number of services than required.

4. Conclusion

The public transport operational characteristics of a typical Indian City (Thiruvananthapuram) was analyzed emphasizing on the link load of the selected routes. The frequency and the load occupancies of the Trivandrum city bus services were examined in the initial analysis. Improper scheduling of buses on the public transport network was found to be the major setback in the development of the public transport industry (KSRTC). This ad hoc allocation of buses on the network adversely affected the passenger occupancy levels in the bus, thus incurring heavy loss. The evaluation consisting of occupied seat kilometres and empty seat kilometres shows that rescheduling of buses is necessary to reduce the operating cost. This study proposed a methodology for line planning problem which includes optimization of public transport lines using operator costs, user costs and crowding on the bus. It also includes the determination of peak and off-peak frequencies of the existing network lines considering the critical demand. The values of unused seat kilometres show that a considerable number of the seats are unoccupied during the entire trip of a bus. The demand along the route is quite less for a significant length of the route, and hence line planning is needed. The results indicate that only 25% of the schedules operated currently are having an optimal number of buses in contrast to 75% of the frequency of buses being on a higher side. To ensure the operating costs are within the available budget and at the same time minimizes the generalized cost of user, the following recommendations are specified.

- The number of buses operating on the routes having values greater than the optimal recommended value can be curtailed as there is more number of services than required.
- The routes having overlapping lines can be merged. The frequency along these public transport lines can be maintained by combining the services passing along the same lines but different corridors.
- The routes can be modified to short routes or long routes in terms of curtailment of route length or extension of the route length based on the passenger demand pattern.

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