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Integrated Multimodal Transit Route Network Design with Feeder Systems

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Abstract

The rapid introduction of mass transit systems in cities around the world to counter traffic congestion and population growth has brought up the need of feeder systems which bridges the accessibility gap between the mass transit system and the users. This study aims to provide a way to reorganise the existing public transit system once a new system gets introduced in a city. This allows the existing and the new system to run in complement rather than in competition thus preventing losses to the existing system. The methodology is divided into two main components, generating a set of plausible routes and then finding the best route set along with associated frequencies using Genetic Algorithm. A cost objective function comprising of user costs and operator costs is minimized for finding the most feasible solution. A new methodology for public transit assignment is introduced and the solution route set satisfies both feeder and non-feeder demand. The methodology is tested for a large sized network with upcoming metro network namely, Mumbai Metropolitan Region, Maharashtra, India. The network design characteristics and routing is presented in this study.

Keywords: Transit Route Network Design, Rerouting, Multimodal, Existing system, Genetic Algorithm, Feeder Systems

1. Introduction

Urbanization and explosion in population has put acute pressure on existing transportation facilities in cities all over the world. As the city boundaries grow and the people start to settle in the fringes, the number of trips to and fro the city center increase exponentially. To address this need of increased trips, mass public transit systems are planned in the city to augment the existing public transit infrastructure. Usually the rapid mass transit systems

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(Metro, Mono, BRTS etc) have exclusive right of way and thus high ingress and egress costs. Thus it is necessary to provide services to make them accessible to the public. This is done by providing a feeder system for the mass transit line which encourages full capacity utilization of the system. As a new mode of transportation is introduced in the city, it is expected that the modal share of the existing lower capacity system will decrease as passengers shift to the new system. Thus, instead of dedicating resources for an exclusive feeder system for the new mass transit system, it is more prudent to redesign the existing system such that it runs in complement to the newly introduced system. In this scenario, the existing system runs as a feeder to the new system along with serving areas untouched by the new system. This prevents losses to the existing operator and ensures better public transit network integration for the user.

This study aims to propose a methodology to redesign an existing transit system in coordination with a newly introduced mass transit system. The reorganizing ensures that both systems run in complement to each other rather than being in competition thus improving the network performance. The existing routes are redesigned and their frequencies are adjusted using a meta heuristic algorithm. The next section reviews the existing literature in the field while the subsequent sections discuss the proposed methodology, the study area and the results obtained on implementing the proposed methodology on a large scale network. The conclusion and future scope of work is discussed in the final section.

2. Literature Review

Vehicle routing and transit route design problems have been around since a long time, but feeder systems have recently been gaining attention within the research community. Meta heuristics like Generic Algorithm (Tom and Mohan, 2003), Simulated Annealing (Kuan et al., 2004), Ant Colony optimization (Kuan et al., 2006) etc have been routinely used for solving such complex problems which are non convex in nature. Feeder systems can be modelled as a transit route design problem with extra constraints. Pattnaik et al. (1998) developed a two stage methodology for transit route network design using Genetic Algorithm with the fitness function being calculated on a methodology developed by Baaj and Mahmassani (1991) which is the basis of multiple feeder design research. Kuan et al. (2006) used genetic algorithm and ant colony optimization for the route design. Verma and Dhingra (2005) developed feeder systems in a mass transit framework with coordination with trains. A methodology for coordinated bus schedules with trains was developed by Shrivastava and O'Mahony (2007). Jiaqing et al. (2013) used two objective functions for maximizing the passenger density per unit time and minimizing the collection of feeder bus lines for solving the feeder network design problem. Mohaymany and Gholami (2010) developed a multimode feeder network for a multimodal system with bus route location and bus frequencies as the decision variables. Shrivastava and O'Mohany (2009) worked on development of coordinated schedules of multiple modes. The k-path algorithm was used by them for generating the routes and constraints on Load Factor, Fleet Size and Demand were used.

Most of the studies in feeder systems focus on designing it as an exclusive service aimed at feeding commuters to a mass transit line (Metro or suburban). The reorganization of the existing public transit network such that it serves the network demand as well as a feeder to a new mass transit system has not been explored much by researchers. This can be because reorganizing the existing system might lead to backlash from the public due to changes in routes and discontinuation of services. But to prevent the existing system from going into losses once a new system comes up, this is an essential task and this study aims to provide a methodology for the same.

3. Methodology

The network design consists of a two-step methodology. The first step entails generating a set of plausible routes while the second step consists of finding the best combination of routes and their associated frequencies for the network. The best combination of routes is found using a meta-heuristic technique for optimization namely, Genetic

Algorithm. Genetic Algorithm is chosen because of the non-convexity of the solution and large size of the search space.

3.1. Candidate Route Set Generation

The first step involves a candidate route set generation algorithm where a pool of plausible routes is generated. These routes are the potential routes on which the bus shall run. These routes are then used as input for the second step and a combination of routes is chosen as the final solution for the network. The inputs for route generation are – Terminal node pairs, OD demand matrix and Network file (with node and links data). The routes are generated between the terminal node pairs which are chosen on the basis of the demand between nodes. Areas with high residential and commercial density are chosen as terminal node pairs. Direct shortest routes are generated for each terminal node pair using Djikstra's algorithm. The OD demand satisfied by each of the route is recorded and this is used later in sorting the routes. If the routes satisfy the maximum length criteria they are added to the candidate pool of routes. To generate a wide variety of routes, alternate routes other than the shortest path are also generated. This is done by removing some links from the existing shortest routes and then again finding the new shortest path for the same OD pair. The alternate routes are expected to satisfy the maximum route length, maximum overlap, maximum allowed detour and route duplication criteria. This prevents very similar routes from becoming a part of the candidate route set. The route set generation is explained in detail in Patnaik et al. 1998.

Two kinds of routes are identified in this step. The feeder route set consists of routes that always begin or end at a mass transit station. These routes are primarily meant to cater transfer/feeder demand while also catering to the non-feeder demand. These routes are shorter in length. The identification of these routes encourages the plan of an integrated network design. These routes are added to the candidate route set to serve as the route pool.

3.2. Route Set Optimisation

This step involves finding the best set of routes from the candidate route set (CRS). The finding of the best route is fashioned into an optimisation problem where the sum of user and operator costs is minimized subject to constraints regarding minimum and maximum frequency and load factor. In this objective function (Eq 1), the first term is the user cost which is comprised of total travel time (including in vehicle travel time, waiting time and transfer time). This is computed by summing the product of demand (d) and total travel time (TT) over all the chosen routes in the network. The second term representing the operator cost is comprised of total time travelled by the bus in a single journey (T_k) multiplied with the frequency of the bus (λ_k). The objective function used to calculate the user and operator costs is represented in Equation 2.

$$Min\ Z = C_1\left[\sum_{i,j=1}^{n} d_{ij}\, TT_{ij}\right] + \ C_2\left[\sum_{k=R} \lambda_k T_k\right] \qquad 1$$

$$Z = \frac{\left(Tt + (D_{un} * Des_{Dur}) + bus_{pty}\right) * U_c + \ bus_{km} * O_c}{T_{dem}} \qquad 2$$

Where Z is the objective function, Tt is the total travel time and D_{un} is the unsatisfied demand. Des_{Dur} is the desired duration of the trip, *Bus_pty* and *bus_km* signify the bus penalty and total number of kilometers the buses have to traverse. Only the bus kilometres are considered in the operator part of the objective function as the distance travelled by the new mass transit lines is fixed and is a constant value. As this is a constant value, it does not affect the objective function variation and thus can be neglected in the objective function. U_c and O_c are the factors for equivalent user cost and operator cost while T_{dem} is the total demand.

To find the values of user and operator costs, trip assignment is done for the network. Multiple paths are identified for each OD pair and trip assignment is done according to frequency share rules on few selected paths. Contrary to the methodology used for transit route design, this study uses an integrated approach for trip assignment. The conventional approach of trip assignment for transit route prefers direct routes over transfer routes. This is in line with the behavior of the user who does not like transfers in his/her journey. For trip assignment, a one transfer route is identified only when a direct route does not exist while a two transfer route is identified only when both direct and one transfer routes do not exist. This approach is appropriate for route design in a scenario with only one mode but is inadequate when a mass rapid transit system is introduced in the network. A new approach is used in this study which is more realistic and is appropriate for networks with mass transit systems.

Numerous direct, 1 transfer and 2 transfer paths are identified for each OD pair in this approach. These paths can comprise of one or more transit systems. This is important because for a network with mass transit system, a two transfer path with metro and buses might be much faster than a direct path with only bus as the mode of transit. Though this approach of simultaneously identifying all direct, one transfer and two transfer routes increases the computation time manifold, it is vital for all such routes to be identified for the best path to be chosen for assignment. These paths are ranked according to travel time and the paths with travel time at most β times the fastest travel time are chosen for demand assignment on the routes. The trip assignment is done using frequency share rules, where the demand is divided according to frequency proportions for the chosen paths for assignment. Paths with higher frequencies satisfy more demand. This is in accordance with the fact that for almost equally fast routes, the passengers will be willing to take a path where the first bus arrives. The total travel time consists of in vehicle travel time, waiting time at the journey beginning and transfer, and transfer penalties. The penalty is representative of the time taken to change the modes and the discomfort of the passenger in shifting to another mode.

Genetic algorithm (Holland, 1992) is used for minimizing this function and finding the best route set as the solution. A population of frequencies linked with each route in CRS is generated randomly in the beginning. Any route with frequency violating the minimum and maximum frequency criterion is not taken in the solution set. The trip assignment is done for this solution route set. The mass transit lines (MTL) are also modeled as candidate routes but with fixed frequencies and distinct properties (higher link speed). The speed and frequency of the MTL is chosen as per standard data available. The mass transit lines are always included in the solution route set but are excluded from the genetic algorithm operators to prevent the MTL from getting eliminated in subsequent generations. The operators used are reproduction, crossover and mutation for creating the next generation. As this is a very computationally intensive program due to huge size of the candidate route set, the stopping criterion is chosen as number of generations as it might take huge amount of time and resources to reach convergence.

4. Study Area & Data Preparation

The study area chosen was a large size city network, namely Mumbai Metropolitan region, located in India. This area has been one of the fastest growing region with very high population in the city of Mumbai, located on west cpast of the region. The region is currently being served by an extensive suburban train network and multiple bus networks. The suburban trains have been the lifeline of the region with an average daily ridership of 7.6 million passengers. A metro system has been proposed for the region to ease the traffic and congestion woes. Currently, one route of this metro is operational while multiple are either in construction or tendering phase. The other modes of transport in the city are cars, taxis, two wheelers, walk and intermediate public transport (IPT).

The network data comprising of node and link information along with OD demand data has been taken from the CTS report (LEA Associates, 2008). A CUBE model was developed based on this study and the data has been extracted from it. In this study, the existing suburban train line and proposed metro lines have been considered as fixed lines i.e. they have set routes and frequencies. The route nodes data and the frequencies have also been extracted from the report. For the feeder route set (FRS), transfer OD demand data is required for the route creation in CRGA. This OD demand data is extracted using the trip assignment results in CUBE software. Once public transit assignment is done in CUBE, the paths enumerated and evaluated for each OD pair are extracted from CUBE. These paths also have transfer details, i.e. the transfer node and the mode chosen. Using this data the OD matrix for the transfer taken to or from metro is created. This OD is then used as input for developing the feeder routes.

5. Results and Discussions

The input parameters used for the study for both the candidate route set generation and route set optimization are illustrated in Table 1. The network and demand details are according to 2031 data. The candidate route set was generated comprising of both feeder and non feeder routes. 7049 node pairs were chosen as terminal node pairs and a candidate route set of 5271 routes was generated in the first step of the proposed methodology. Among the 5271 routes, 596 were feeder routes. This candidate pool is then used for the second step of the methodology where the route set optimization is undertaken.

The route set optimization is computationally very expensive and takes 52 hours to run 1000 generations on a 16 core Intel Xeon Processor. To achieve faster results, a population size of 16 was chosen as it was equal to the number of core available for processing. The objective function value over the generations is represented in Fig . As observed, the objective function value shows a decreasing trend indicating that genetic algorithm is progressing towards a global minima. The kink in between the graph can be representative of genetic algorithm trying to escape the local minima by exploring the non feasible search space. It also indicates that the weights for user and operator costs need to be such that there is a balance between the total values of operator and user cost thus preventing either of them from becoming dominant in the objective function. As seen in Figure 1. The total travel time of the user and the bus kilometres follow a decreasing trend thus reiterating the effectiveness of the algorithm in providing efficient network design for the region.

Table 1. Input Parameters for Route Set Optimization Program

Parameter	Value	Parameter	Value
Population Size	16	Bus Link speed (m/min)	250
Generations	1000	Metro Link speed (m/min)	450
Crossover Probability	.5	Suburban Link speed (m/min)	750
Mutation Probability	.0006	Bus Capacity (passengers)	80
No. of metro lines	22	Metro Capacity (passengers)	1800
No. of suburban lines	55	Suburban Capacity (passengers)	4500
Weight for user cost	.155	Weight for operator cost	4.49
Min freq for buses (in min)	60	One transfer penalty (min)	5
Max freq for buses (in min)	12	Two transfer penalty (min)	15
Max no. of 0T routes allowed	50	Size of FRS (no. of routes)	596
Max no. of 1T routes allowed	30	Size of CRS (no. of routes)	4675
Max no. of 2T routes allowed	15	Size of CRG (no. of routes)	5271
Total OD pairs for assignment	20,866	Total Demand for Assignment	5,31,207

The network parameters are presented in Table 2 for the best solution obtained in 1000 generations. The average In vehicle travel time obtained in 94.6 min per passenger per trip for the projected scenario by the proposed methodology. For the existing bus, metro, suburban and Intermediate Public Transport (IPT) routes in the city for 2031, the average IVTT obtained is 76.2 min per passenger per trip according to CUBE Voyager for the same demand matrix. This is 18% less than the value obtained by the proposed methodology. The difference in values can be attributed to multiple reasons. The primary reason is the presence of IPT routes in the CUBE Voyager model. These IPT routes have lower average travel time in peak periods and thus tend to lower the average IVTT. In far flung areas with low demand, IPT turns out to be a more economical service provider than buses for both users and operators. As for the network in the proposed methodology, the IPT network is also trying to be served by buses, the operator costs are much higher. Again, as the bus operating agencies in the MMR are government owned, it is possible for them to bear losses while providing services to the public. Currently the bus operators in MMR are running into huge losses representing very high operator costs. As the objective function for the proposed methodology comprises of both user and operator costs, it tries to find a balanced solution. This balanced solution ensures that neither the operator nor the user goes into losses. The minimum (60min) and maximum frequency (12min) obtained from the proposed methodology in Table is similar to current bus frequencies in the system. The total demand satisfied (70%) can be attributed to the infeasibility of running buses in areas with scant demand, In a city, such demand is usually served by IPT as it is much faster and demand responsive whereas buses run on fixed schedules.

Table 2 Network Characteristics for the Solution Route Set

Parameters	**Values**
No. Of Bus Routes	1109
Zero Transfer Demand (% of total)	5
One Transfer Demand (% of total)	29
Two Transfer Demand (% of total)	36
Waiting Time (min/pax)	20.6
In vehicle travel time (min/pax)	94.6
Total travel time (min/pax)	135.93
Bus kms	2,29,918
Fleet size required	4,933
Avg route length (km)	18.73
Avg_route frequency (min)	20
Number of routes chosen from FRS	134
Number of routes chosen from CRS	975

6. Conclusion

The results obtained from the proposed methodology for a possible rerouting of bus routes in a when a new mass transit route is introduced in the city (in this case, metro) have been presented in the previous section. As seen in the results, the methodology was successful in creating new routes and deciding their frequencies for the bus network. The credibility of the results obtained by the proposed methodology is established by comparing it with existing results even though the network conditions were not same in the data set for both conditions. Further it can be said that with appropriate network and more number of generations, this methodology will give much better results.

The size of the candidate route set has a substantial effect on the run time of the route set optimization. As the size of the candidate route set is dependent on the number of terminal node pairs and the route selection window for the node pair, it is important that the terminal node pairs are chosen with care. Too few terminal node pairs will not be able to cover the study area thus serving lower demand while too many of them will increase the computation time drastically. A minor study can also be done to find the optimum size of the candidate route set by utilizing the relationship between the percentage demand satisfied and the size of the candidate route set. For an effective solution, the terminal node pairs can be chosen as existing bus depots. The population size plays a vital role in the achievement of convergence by Genetic Algorithm. The current population size was chosen because of computational limitations. Convergence was not observed in the current solution and could have been achieved with higher population size and higher number of generations. Similarly, as represented by the trend of average In Vehicle Travel Time and bus kilometres, it is evident that a minima is yet to be achieved. The value of in vehicle travel time can be brought down further with network improvements, such as introduction of IPT lines in the network. The current study uses time as the sole factor for trip assignment. The fares of each mode also play a vital role in the choice of mode by the users. Thus, a generalized cost function with travel time and fare should be used as the constituent of user costs.

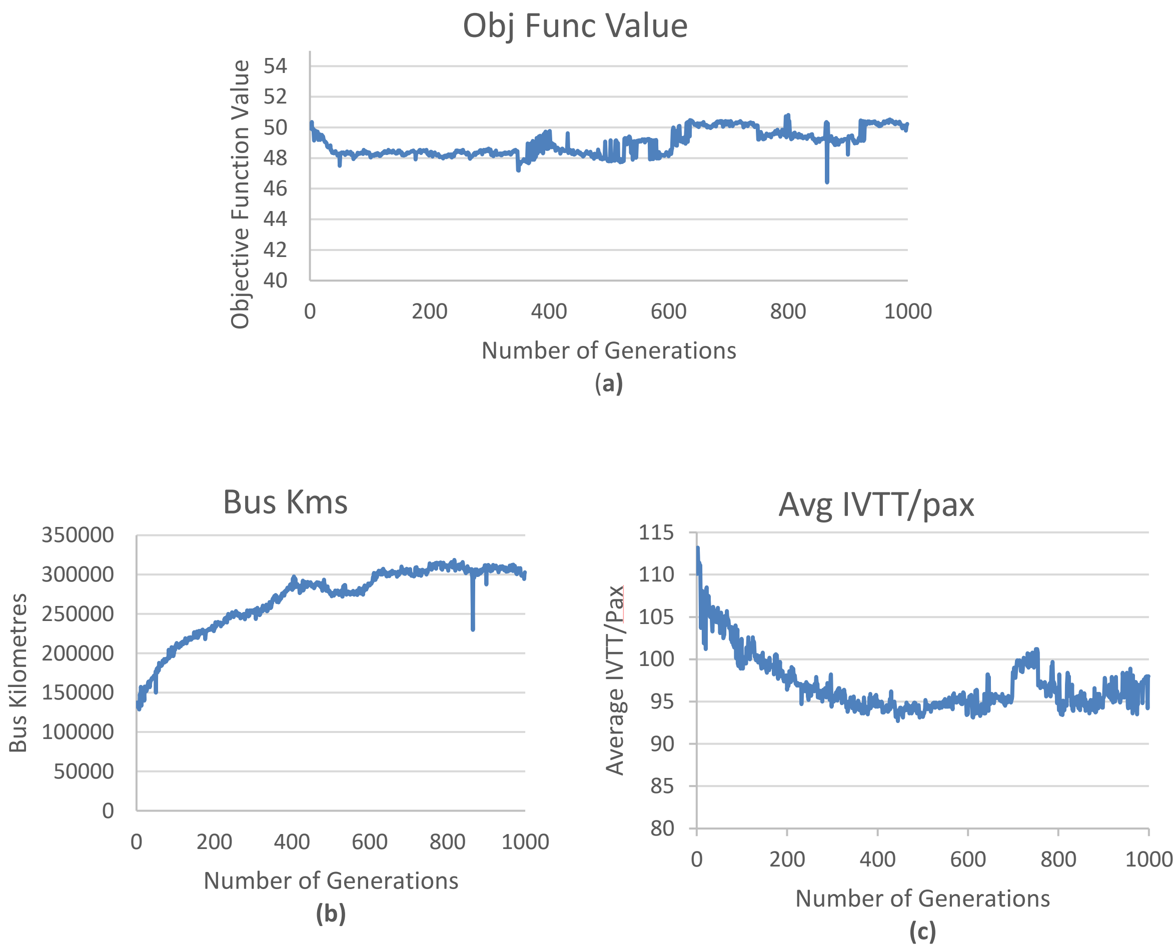

Figure 1 (a) Objective Function Variation over Number of Generations, (b) Bus Kilometres over Number of Generations, (c) Average In Vehicle Travel Time per Passenger over Number of Generations

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