A Heuristic Method for Bus Rapid Transit Planning Based on the Maximum Trip Service

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Abstract

Bus rapid transit (BRT) is characterized by higher speed, higher comfort and bigger capacity compared to conventional public transportation service. Although more and more cities choose BRT in recent years worldwide, there is an absence of scientific and quantitative approach for BRT network planning. The problem of BRT planning in a given network is very complex considering the constraints of road geometrics, regulations, right of way, travel demand, vehicle operations and so on. This paper focuses on developing an optimization model for BRT network planning, where the authors establish a mathematical model with the objective of maximizing the number of trips served by the network, subjected to a number of constraints including distance between stations, expense of construction, road geometrics, etc. In addition, the nonlinear coefficient of the BRT route is taken as a constraint, which is an important indicator but widely ignored in previous studies. A heuristic method is applied to generate optimal solutions to the integer programming model with respect to all constraints. A case study is conducted in Luoyang, China and the numerical results indicate that the method is effective therefore can be applied to improve BRT network planning.

Keyword: Transportation Planning; BRT; Transit; Network Planning; OD; Heuristic Method
1. INTRODUCTION

The rising private car ownership has caused remarkable travel demand increase as well as traffic congestion, green gas emission, road accidents and energy consumption. To address these problems, developing efficient public transportation systems are extremely important. Various public transportation systems such as subway, light rail, conventional bus service, and BRT have been developed to compete with private cars. Among these public transportation systems, rail transit has the highest capacity and efficiency but needs large capital investment and a long implementation period. In addition, the rail transit only allows railroad car operations on fixed tracks and is lack of service flexibility. BRT, on the other hand, provides an option of high capacity, comfort, flexibility, quick implementation, and relatively low cost. It is defined as “a flexible, rubber-tired form of rapid transit that combines stations, vehicles, services, running ways and information technologies into an integrated system with strong identity”(1).

BRT possesses the advantages of both conventional bus service and rail transit in capacity and flexibility. It is considered one of those systems that can bridge the gap between the demand and supply of transportation. In the past decade, it has been embraced by a number of major and medium-sized cities in the world (2,3,4). To ensure the success of its implementation and to make full use of the limited financial and road capacity resource, the BRT network and station locations must be carefully planned.

The literature relating to transit network design has continuously grown over time. Magnanti et al. reviewed some of the applications of integer programming methods for transit network design, and introduced several continuous and discrete choice models and algorithms (5). Guihaire and Hao presented a global review of the design and scheduling of the transit network (6). Laporte et al. reviewed some indices for the quality of a rapid transit network, as well as mathematical models and heuristics that can be used to solve the network design problem (7). Farahani et al. presented a comprehensive review of the definitions, classifications, objectives, constraints, network topology decision variables, and solution approaches for the public transportation network design problems (8).

It has been widely recognized that operational research methods can help to determine the alignments and station sites of a transit network (9). Gutiérrez-Jarpa et al. proposed a tractable model in which travel cost was minimized and traffic capture maximized (10). The branch-and-cut method was used to solve the problem in the CPLEX framework. Besides, heuristic methods were often used to solve similar problems. Bruno et al. presented a mathematical model to maximize the total population covered by the rapid transit alignment, and a two-phase heuristic was used to generate a rapid transit alignment in an urban setting (11). However, the objective function in this study was only subjected to interstation spacing constraint, which was rather simplistic to reflect the reality. Nikolić and Teodorović developed a model to optimize the number of satisfied passengers, the total number of transfers and the total travel time of all served passengers (12). The problem was solved using the Bee Colony Optimization (BCO) meta-heuristics. For the same problem in Nikolic and Teodorović’s study, Nayeem et al. developed a Genetic Algorithm (GA) to solve it (13).

Beside the studies focusing on the model and the algorithm, some researchers have proposed methods to analyze and compare transit networks in forms of star, cartwheel,
triangle, grid and so on. Laporte et al. suggested that in grid cities, the modified grid and half-grid configurations were the best in terms of passenger-network effectiveness but inferior to grid configurations with respect to passenger-plane effectiveness (9). Hosapujari and Verma proposed an approach to develop a hub and spoke model for bus transit network services (14).

Due to its relatively short history and limited implementations in the developed countries, BRT has attracted little attention and the literature in BRT network design is limited. In practice, the planning of BRT route or network often depends on planners’ experience instead of a scientific approach with solid quantitative analysis. Taking the aforementioned studies in transit network design as a foundation, the authors aim to put the BRT planning problem in a mathematical framework and solve it. The remainder of this paper is structured as follows: In Section 2, the BRT planning problem is introduced and assumptions described; In Section 3, the mathematical model is established; In Section 4, a heuristic method is given to solve the problem step by step; Section 5 introduces an application to real case scenarios; The summary and future studies are presented in Section 6.

2. PROBLEM DEFINITION

2.1 The Right of Way for BRT

BRT differs from conventional public transportation modes in many aspects. It often requires dedicated right of way and special stations. Thus, it is a unique urban surface public transportation system. Some countries have planning guidelines and design standards for bus-only or BRT right of way settings. For example, according to “The setting for bus lanes (2004)” (15) of China, bus-only lanes, including BRT lanes, should be set up when the street links meet all of the following conditions:

a) The number of motor lanes in one direction should not be less than 3, or the total width of all motor lanes in one direction should not be less than 11 meters;

b) The number of bus passengers in one direction should not be less than 6,000 during peak hours, or the bus volume should not be less than 150 per hour per direction during peak hours;

c) The average traffic volume should be more than 500 vehicles per lane during peak hours.

BRT can be implemented on the roads that meet the conditions above. When developing the optimization model, these design standards or planning guidelines should be incorporated into the constraint set to reflect the regulation requirements, or we can first make a scan of the roads in the planning area and then search for feasible BRT routes on the candidate links. The scan criteria can be expressed mathematically as follows:

\[
\begin{align*}
LN_{ij} & \geq 3 \\
Q_{i,j} & \geq 150 \text{ veh/h} \\
Q_{ij,ave} & \geq 500 \text{ veh/h}
\end{align*}
\] (1)

Where \(i\) and \(j\) denote the serial number of intersections in the planning area and \(i \neq j\); \(LN_{ij}\) is
the number of lanes from intersection $i$ to intersection $j$; $Q_{n_{ij}}$ is the bus volume on the link from intersection $i$ to intersection $j$ during peak hours; $Q_{d_{ave}}$ is the average traffic volume on the lane from intersection $i$ to intersection $j$ during peak hours.

Eq. (1) is the first constraint for the model, which is considered as geometric and regulation constraints. Only two-way roads are considered in this study, and the BRT route is assumed to be on a link in both directions.

2.2 Trips Served by the BRT Network

In general, the OD matrices are established based on traffic analysis zone (TAZ) data such as land use, population, employment, etc. In this study, it is assumed the ODs in the planning area are known by modes of transportation and are presented in OD matrices. Since the centroids of TAZs, where trips start and end, are usually not station sites, the OD matrix based on TAZ centroids needs to be further converted into OD matrix based on potential stations. To simplify the problem, the induced travel demand is not considered when a BRT network is constructed.

In the form of piecewise function, an attraction function (16) is introduced as $\beta_{ki}$, that depends on the Euclidean metric distance $d_{ki}$ between the passenger location $k$ and the potential station $i$. The passenger locations are concentrated at the centroids of TAZs. The attraction function is then assumed as follows:

$$\beta_{ki} = \begin{cases} 1, & (d_{ki} \leq 100) \\ 0.75, & (100 < d_{ki} \leq 300) \\ 0.5, & (300 < d_{ki} \leq 500) \\ 0.25, & (500 < d_{ki} \leq 650) \\ 0, & (d_{ki} > 650) \end{cases}$$

Before calculating $t_{ij}$, which is the OD from $i$ to $j$, it must be known whether $\beta_{k1i}$ and $\beta_{k2j}$ equal to 0. If both $\beta_{k1i}$ and $\beta_{k2j}$ are not 0, then $(\beta_{k1i} + \beta_{k2j})*\frac{(BOD_{k1k2} + BOD_{k2k1})}{2}$ composes of the OD from $i$ to $j$, where $BOD_{k1k2}$ is BRT OD from zone $k1$ to zone $k2$. If multiple stations are selected to serve the passengers from a TAZ, then the passengers will be allocated to these stations proportionally based on their distances to the centroid.

In this study, it is assumed the amount of ODs served by the BRT network contains two portions: direct trips and trips with a transfer. To simplify the problem, it is assumed that trips with more than one transfers are at a low level. Also, there are transfers between BRT and the conventional public transportation. To obtain this portion of transfer trips, the conventional public transportation network in the planning area must be known well. A significant amount of work needs to be done to address these issues, which will be considered in future studies. Figure 1-a gives a simple example of a BRT route and the gray cells in Figure 1-b represent the direct trips served by the route. Figure 2-a shows two individual BRT routes: $a-c-e-g-h-m-p$ and $d-f-l-m-o-q-t$. Passengers make transfers at station $m$ when necessary. Figure 2-b presents the trips with a transfer served by the network.
FIGURE 1  Direct trips served by BRT.

FIGURE 2  Trips with a transfer served by BRT.

Then the serving trips of a BRT network can be calculated through Equation (3):

$$
\sum_{i:j<i} (t_{ij} + t_{ji}) \times v_{ij} + \sum_{i,m:i \neq m} (t_{im} + t_{mj}) \times v_{im} \times v_{mj}'
$$

Where \( t_{ij} \) is the amount of OD from \( i \) to \( j \), \( v_{ij}' \) is a 0-1 variable indicating whether \( i \) and \( j \) are on the same route \( l \) and the trips from \( i \) to \( j \) are directly served trips, so are \( v_{im}' \) and \( v_{mj}' \).

2.3 The Potential Stations and Connections

To simplify the problem, it is assumed the BRT stations can be set in the intersection areas. All intersection areas that are on the qualified road links can be potential BRT station sites. The stations will then be automatically searched and selected for the BRT route according to the model established in the following sections.

Using geographic information data, the distance \( \omega_{ij} \) between each pair of adjacent intersections can be obtained. For those intersections not adjacent to each other, their distances are set to be infinite. Based on \( \omega_{ij} \), the Floyd Algorithm is employed to calculate the distances between any two potential stations with the assumption of intersection-potential
station overlap. The distance matrix and the shortest paths between each pair of potential
stations are then generated. The procedure of the Floyd Algorithm is described as follows
(I7):
Step 0: Let \( k = 0 \), and every potential stations are given a serial number \( u_1, u_2, \cdots u_n \).
Create a matrix \( D^0 \), in which the elements is \( d_{ij}^0 = \begin{cases} \omega _{ij} & i \neq j \\ 0, & i = j \end{cases} \) and a matrix \( P^0 \), whose elements
\( p_{ij}^0 \) is \( i \).
Step 1: \( k = k + 1 \), derive matrix \( D^k \) from matrix \( D^{k-1} \), and derive matrix \( P^k \) from matrix
\( P^{k-1} \). For all \( u_i \) and \( u_j \), \( d_{ij}^k = \min (d_{ij}^{k-1}, d_{ij}^k, d_{ij}^{k-1}) \) and
\( p_{ij}^k = \begin{cases} p_{ij}^{k-1} & \text{if } d_{ij}^k = d_{ij}^{k-1} \\ p_{ij}^{k-1} & \text{if } d_{ij}^k = d_{ij}^{k-1} + d_{ij}^{k-1} \end{cases} \)
Step 2: If \( k = n \), stop; else, go to Step 1.

3. THE MATHEMATICAL MODEL
After a scan of qualified roads in the planning area according to eq. (1), we will further find
BRT routes and stations to establish the BRT network. It is defined that \( x_{ij} \) is whether the
link from \( i \) to \( j \) is chosen by BRT route \( l \); if \( x_{ij} = 1 \), then the link from \( i \) to \( j \) is chosen; if \( x_{ij} = 0 \),
then the link from \( i \) to \( j \) is not chosen. \( y_{ij} \) is whether the potential station \( i \) is chosen by BRT
route \( l \); if \( y_{ij} = 1 \), then a station is set at intersection \( i \); if \( y_{ij} = 0 \), then a station is not set at
intersection \( i \).

The objective of the model is to pursue the maximum number of trips served by the
BRT network. As shown in Eq. (3), the number of trips served is calculated as:

\[
T(i,j) = \sum_{i,j:<j} (t_{ij} + t_{ji}) \times v_{ij}^l + \sum_{i,m;i<m} (t_{im} + t_{mi}) \times v_{im}^l \times v_{mj}^l
\]  

(4)

Thus, the mathematical model for this problem can be formulated as:

\[
\text{max } T(i,j)
\]  

(5)

subject to:

\[
x_{ij} = 1, \text{when } d_{\min} \leq d_{ij} \leq d_{\max}
\]  

(6)

\[
\sum_l \sum_i E_i \times x_{ij} + \sum_i e_i \times y_{ij} < E_{\max}
\]  

(7)

\[
\sum_{(i,j) \in D} y_{ij} = \sum_{i \in N} y_{ij} - 1; \text{If } x_{ij} = 1, \text{ then } y_{ij} = 1, \text{ } y_{ji} = 1
\]  

(8)

\[
(\sum d_{ij} \times x_{ij} + d_{ij}^l) / d_{ij}^l \leq C_N
\]  

(9)

\[
v_{ij}^l \leq y_{ij}^l; \text{ } v_{ij}^l \leq y_{ij}^l; \text{ } v_{im}^l \leq y_{ij}^l; \text{ } v_{im}^l \leq y_{ij}^l
\]  

(10)

Where \( e_i \) is the construction expenditure of station \( i \); \( E \) is the construction expenditure to
implement BRT right of way on the link from \( i \) to \( j \); \( d_{\min} \) and \( d_{\max} \) are the minimum and the
maximum distances between two adjacent stations, respectively; \( C_N \) is a constant, i.e. the
threshold of nonlinear coefficient.

Constraint (6) is the station spacing constraint that ensures the distance between any two adjacent stations falls into a certain range. Constraint (7) is the cost constraint that ensures the expenditure of the BRT network is within the budget. Constraint (8) prevents a route from passing a station more than once and ensures the route is consecutive. Constraint (9) is the nonlinear coefficient constraint that ensures the overall layout of the route maintain a certain level of straightness. The nonlinear coefficient is the ratio between the Manhattan and the Euclidean distance from the start point to the end point of a route. In some countries regulations require that the nonlinear coefficient of a transit route should be under a threshold such as 1.4(18). Constraint (10) is to match the OD pairs with the chosen stations.

4. THE PROCESS OF HEURISTIC METHOD

Based on the model proposed above, there will be two stages to solve the problem: 1) obtain single route solutions, and 2) compose the routes into a network. The procedure of this heuristic can be found in Figure 3.

\begin{itemize}
  \item Determine planning area, obtain road network and travel demand
  \item Construction expenditure of every potential station
  \item Geometric and regulation constraints (eq.1)
  \item Potential stations sites
  \item Candidate BRT links
  \item Construction expenditure matrix for links from i to j
  \item Station spacing and consecution constraints (eq.6&eq.8)
  \item Feasible solution set I
  \item Expenditure constraint (eq.7)
  \item Feasible solution set II
  \item Nonlinear coefficient constraint (eq.9)
  \item Feasible solution set III
  \item Calculate served trips
  \item Top-ranked feasible solutions
  \item Identify key stations
  \item Determine the BRT network configuration and identify the optimal solution
\end{itemize}

FIGURE 3 Solving process of the model.
Step 0: As described in section 2.3, the distance matrix and the paths between each pair of potential stations are calculated using the Floyd Algorithm.

Step 1: If a path goes from \( i \) to \( j \) via \( M \) links, then the \( E_{ij} \) can be calculated according to Eq. (11). The expenditure matrix will then be established. The value of \( c_m \), which represents the cost per unit length of right of way construction, can be determined according to lane number, length, width, even breadth of the road.

\[
E_{ij} = \sum_{m=1}^{M} d_m \times c_m
\]  

(11)

Step 2: A new matrix with values in 1 or 0 is introduced, which indicates whether two stations can be selected consecutively on a route. The values of the matrix are determined by whether the distance \( d_{ij} \) of any two potential stations meets the station spacing constraint Eq (6).

Step 3: Starting from each potential station, a feasible solution set I is obtained, which contains the routes whose stations can be derived through the 0-1 matrix established in step 2. If a station has already been selected by a route, it will not be selected or passed through again. This ensures that BRT routes meet the route consecution constraint Eq (8).

Step 4: Examine the feasible routes generated from Step 3 with respect to cost constraint Eq (7). The feasible solution set II is then obtained, which contains those routes meet station spacing, consecution, and cost constraints.

Step 5: Calculate each route’s length and the Euclidean distance between the start station and the end station, and then calculate each route’s nonlinear coefficient. Eliminate the routes whose nonlinear coefficients exceed the threshold, as shown in Eq (9), and obtain the feasible solution set III meeting all constraints.

Step 6: Calculate and rank the quantity of direct trips for each feasible route.

Step 7: Identify the key stations that frequently appear on the top-ranked feasible routes.

Step 8: On the basis of key stations, compose the BRT network configuration by making combinations of the top-ranked routes. Calculate the trips with a transfer, then calculate \( T(i,j) \), and finally find the best combination as the optimal solution to the problem.

5. THE CASE STUDY AND NUMERICAL RESULTS
To validate the model and algorithm proposed in this study, Luobei District in the City of Luoyang, China (seeing Figure 4) was chosen for a case study. The road network and travel demand data were obtained from local planning agencies. The data of population, traffic analysis zones and transport network used in this study came from an established travel demand forecast model, which was last updated in 2014.
First, the geometric and regulation constraints are employed to identify the candidate links where BRT right of way can be implemented. Intersections on the candidate links are then numbered as the potential station sites, seeing Figure 5. As shown in the figure, the road network contains 96 links and 65 intersections.

In the case study, it is assumed $l_{\min} = 550\text{m}$, $l_{\max} = 1,800\text{m}$, and $C_N = 1.6$. $E_{\max}$ are assumed to be a certain budget value according to the number of stations and the total length of a BRT route. The average construction expenditure of a station is assumed to be 1 million CNY.

Following the steps described in Section 4, more than 100,000 feasible solutions are found till Step 6. In Step 7, station 38, 48, 49 are identified as the key stations because they
are the most frequently selected ones among the top-ranked feasible solution set. As pointed out by Laporte et al. (9), there are several basic configurations for a transit network including star, cartwheel, triangle, grid and modified configurations. Based on the recommendations and distribution of the key stations, the modified grid configuration is selected for the case study area in order to achieve the best in terms of passenger-network effectiveness.

Table 1 and 2 depict the detailed information of the network solution and routes included. Four network options, from a through d, are presented, each having three BRT routes. As shown in Table 1, each route will serve 31,758-35,537 trips directly with length varying from 2,308 to 3,095 meters. The transfer trips are added and shown in Table 2. The expenditure of each route is provided in Table 1 while the total expenditure of each network option is given in Table 2, which indicate the budget constraint $E_{max}$ is effective. The nonlinear coefficients are under the constraint of 1.6. However, from Figure 6 it can be seen that the alignment of the selected route zigzags in the planning area with the value ranging from 1.49 to 1.58. To improve this, the threshold value of the nonlinear coefficient constraint can be set lower according to the size of the planning area and the number of stations on the BRT route.

**TABLE 1** Summary of the Solutions and Selected Routes

<table>
<thead>
<tr>
<th>Option</th>
<th>Route No.</th>
<th>Route alignment</th>
<th>Served OD</th>
<th>Length (m)</th>
<th>Expenditure (10^4 CNY)</th>
<th>Nonlinear coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2</td>
<td>5-6-15-16-17-50-49-48</td>
<td>33,429</td>
<td>2,308</td>
<td>5,404</td>
<td>1.49</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>42-43-36-22-23-24-49-48</td>
<td>31,758</td>
<td>2,739</td>
<td>6,786</td>
<td>1.55</td>
</tr>
<tr>
<td>b</td>
<td>1</td>
<td>18-27-25-23-38-49-49-57</td>
<td>33,660</td>
<td>3,095</td>
<td>8,041</td>
<td>1.54</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>5-6-15-16-17-50-49-48</td>
<td>33,429</td>
<td>2,308</td>
<td>5,404</td>
<td>1.49</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>42-43-36-22-23-24-49-48</td>
<td>31,758</td>
<td>2,739</td>
<td>6,786</td>
<td>1.55</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>60-59-58-48-49-24-23-22</td>
<td>34,703</td>
<td>2,718</td>
<td>6,449</td>
<td>1.55</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>5-6-15-16-17-50-49-48</td>
<td>33,429</td>
<td>2,308</td>
<td>5,404</td>
<td>1.49</td>
</tr>
<tr>
<td>d</td>
<td>1</td>
<td>18-27-25-23-38-49-49-57</td>
<td>33,660</td>
<td>3,095</td>
<td>8,041</td>
<td>1.54</td>
</tr>
<tr>
<td></td>
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<td>1.55</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>5-6-15-16-17-50-49-48</td>
<td>33,429</td>
<td>2,308</td>
<td>5,404</td>
<td>1.49</td>
</tr>
</tbody>
</table>

**TABLE 2** Summary and Comparison of the Solutions

<table>
<thead>
<tr>
<th>Option</th>
<th>Directly-served OD</th>
<th>OD with Transfer</th>
<th>Objective Function Value</th>
<th>Total Length (m)</th>
<th>Expenditure (10^4 CNY)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>100,723</td>
<td>37,462</td>
<td>138,185</td>
<td>8,062</td>
<td>20,078</td>
</tr>
<tr>
<td>b</td>
<td>98,847</td>
<td>36,862</td>
<td>134,709</td>
<td>8,143</td>
<td>20,231</td>
</tr>
<tr>
<td>c</td>
<td>103,668</td>
<td>47,814</td>
<td>151,482</td>
<td>8,041</td>
<td>19,741</td>
</tr>
<tr>
<td>d</td>
<td>101,792</td>
<td>46,702</td>
<td>148,494</td>
<td>8,122</td>
<td>19,894</td>
</tr>
</tbody>
</table>
FIGURE 6  Layout of the network solutions.

From Table 2 it can be seen Option c is better than others in all aspects including the objective function value, the directly-served trips, served trips with transfers, total length and network expenditures. It is then considered the best solution for the case study area with respect to all the constraints. This BRT network option, containing 3 routes, will serve a total of 151,482 direct and one-transfer BRT trips per day in the case study area. It proves that the proposed method is capable of finding the BRT network that will serve the maximum number of OD trips while satisfying the constraints of budget, nonlinear coefficient, minimum and maximum stop distances, and road geometrics.

6. CONCLUSIONS AND OUTLOOK

Considering the factors including distance between stations, expense of construction, road geometrics and so on, the authors proposed a mathematical model for the BRT network planning problem, followed by a heuristic algorithm and a case study in Luoyang, China.

The objective function of the model is to maximize the total trips served by a BRT network, subjected to a number of geometric, regulation, station spacing, expenditure, and consecution constraints. Also, nonlinear coefficient is introduced in the mathematical model to measure the straightness of the BRT route alignment. A heuristic method is applied to solve the problem and to generate a BRT network solution. Although the algorithm has relatively low efficiency, it is effective to find the optimal solution of BRT network including routes and stations, and it is easy to understand and implement.

This study makes a contribution to improve the scientific and quantitative analysis in BRT planning. Since the planning practice is often influenced by politics and the subjectivity of decision makers, the quantitative results from applying this method can be presented as decision support materials. In the future it is possible to improve the algorithm
efficiency. The research effort can be further extended to investigate the most efficient
network configuration regarding the star, cartwheel, triangle, grid and modified
configurations. Also, trips with multiple transfers and the transfer trips between BRT and
conventional public transportation system can also be included for calculation to make it
close to the real situation.

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