A Decision Support System for the Design of Urban Inter-modal Public Transit Network

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ABSTRACT: This paper discusses a decision support system for the optimum design of an urban inter-modal public transit network. The system is a tool to provide useful reference for transport planners in carrying out service planning, routing, and scheduling in an inter-modal transit network. The development of this decision support tool (problem description, assumptions, and solution approach) is briefly introduced. A numerical example is used to illustrate its implementation, and sensitivity analysis results demonstrate that it is capable of providing reasonable solutions and is responsive to various changes in the planning environment.

1 INTRODUCTION

1.1 Problem identification

Great importance has been placed on urban public transportation due to population growth and expansion of urban areas. However, neither the conventional bus nor the rail transit service is sufficient to serve the increasing and diverse demand alone due to their respective limitations. The widely accepted solution now is an integrated public transit system combining rail and bus services to serve the demand either jointly or individually, and complement each other to achieve better operating performance and stimulate demand. However, irregular service area and unpredictable demand in reality make the design of such an integrated transit system a challenge, and call for the development of a decision support tool to provide planners useful reference for this complex task.

1.2 Historical development

Past research in the optimum design of conventional transit services can be reviewed with special attention to four aspects. Geometric layout of the transit service is the first one. Several studies stated that the geometric structure of a transit network has a considerable influence on its performance (Vuchic & Newell 1968, Dias 1972, Fawaz & Newell 1976).

The second one is about the two assumed demand patterns. One is a "many-to-one" type demand. Ghoneim & Wirasinghe (1987) studied the optimum zone configuration for urban commuter rail lines with one-to-many or many-to-one demand and concluded that the impact from the-value-of-time parameters in determining zone length is insignificant. The other pattern is a "many-to-many" type demand, which is an interest of more researchers. Several studies in bus transit service concerning optimum stop spacing and operating headway were conducted with this demand pattern (Holroyd 1967, Wirasinghe & Ghoneim 1981, Vaughan 1986).

Whether demand varies over time and space is another aspect. Inelastic demand was assumed in most analytical models previously developed to optimize an urban public transportation system (Vuchic & Newell 1968, Wirasinghe 1980, Ghoneim & Wirasinghe 1987). However, these studies are not capable of explaining whether and how the riders are attracted, and the assumption of inelastic demand may not be reasonable in reality when lots of riders have alternative transport modes. Hence, further studies were conducted to solve this problem with the introduction of elasticity in demand over time (Kocur & Hendrickson 1982, Oldfield & Bly 1988), over space (Wirasinghe & Ghoneim 1981), or both (Chang & Schonfeld 1989).

The last aspect is the selection of different sets of variables in optimization. For the optimization of an urban public transportation system, the most commonly used variables can be summarized into four groups: goal variables (user cost, operator cost, and user waiting time), policy variables (vehicle capacity, fleet size, headway, route, stop spacing, and stopping strategies), environmental variables (demand, capital cost of facilities, and the-value-of-time parameters for users and operators), and system characteristics (speed, street pattern, and service area).

Regarding the design of an integrated public transit network (typically a number of rail lines fed by conventional bus services), not many studies were found in the literature. Chien (1991) proposed a simple inter-modal transit corridor with a single rail line associated with a number of straight feeder-bus routes in a rectangular service region. A model was developed for jointly optimizing the characteristics of the rail transit route and feeder bus routes under the objective of minimizing the total cost. Chien (1995) extended his approach to solve a complex transportation optimization problem, involving inter-modal network design for coordinated rail and bus transit services in two-dimensional space. Two sub-models, for inter-modal transit network optimization and route coordination, were developed to determine the optimum network characteristics (rail line length and location, bus route and station locations) and decision variables (e.g., rail station spacing, bus route spacing, bus stop spacing, rail headway, and bus operating headways), which minimize the total system cost. Irregular "many-to-many" demand distribution, zonal variations in route costs, probabilistic vehicle arrival patterns at transfer stations and stopping at stops, vehicle size, and vehicle capacity constraints were considered in the optimization. Chowdhury (2000) studied the scheduling of vehicles in an inter-modal transit system based on the network proposed by Chien, with special attention on reducing user transfer time. He developed two models, one for the coordination of a general inter-modal system and another for dynamic dispatching of vehicles on coordinated transit routes. A major constraint in the applicability of these studies to the design of an inter-modal public transit network is their regular service regions and network structures, which were assumed in order to keep the problem geometrically simple enough to be analytically solvable, at the cost of losing practical applicability.

1.3 Outline

The rest of this paper is organized as follows. Section 2 introduces the integrated transit network and the relevant assumptions and definitions for each transit mode. Section 3 presents the approach used to solve the optimization problem. Section 4 provides a numerical example and sensitivity analysis results to demonstrate the applicability of the developed tool. Finally in Section 5, applications and contributions of this decision support system are concluded.

2 DESCRIPTIONS AND ASSUMPTIONS

2.1 The inter-modal public transit network

The inter-modal transit network has an irregular service area, which is divided into small independent zones of appropriate sizes based on differences in zonal characteristics (e.g. demand density, railway construction cost). Within this area a grid street pattern is assumed. Hence, the movements of buses and passengers are orthogonal and easy to be represented mathematically. In each zone, only one potential rail station/express bus stop is permitted for each run of the optimization, and each rail station/express bus stop is fed by one or more feeder bus services. Figure 1 presents an example of the assumed transit network with its service region divided into 10 zones.

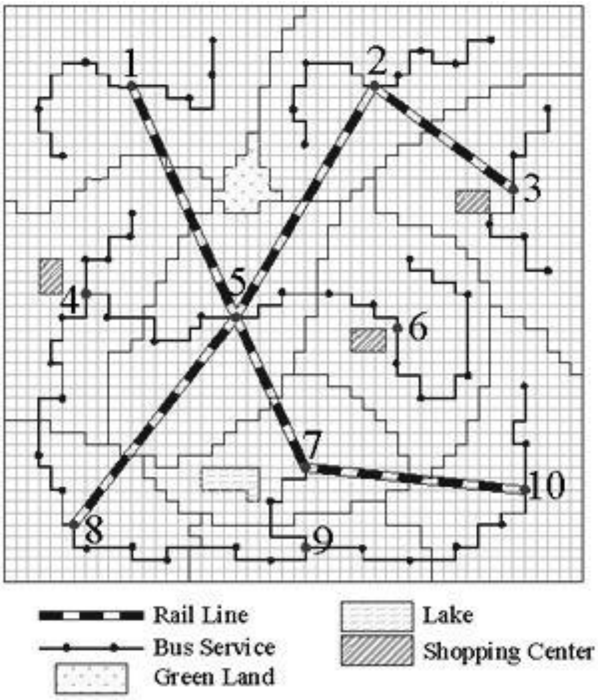

Figure 1. An example of the integrated transit network.

The peak period zonal passenger trips in the service area, which is a closed system, are grouped into Origin-Destination (OD) pairs from one zone to another. These OD pairs are stored into an OD matrix, which governs the design of the inter-modal public transit network. The travel demand is uniformly distributed over time during the peak period and over space in each zone. Thus, the demand in each zone is deterministic for each run of optimization. An iterative process can be performed in order to take into account the elasticity of demand over service quality.

The assumed inter-modal public transit network, which comprises a number of rail and express bus lines fed by feeder bus services, has a typical pattern of Trunk-Lines-with-Feeders. Each rail service is a high-speed trunk line with exclusive right-of-way mainly serving the high-volume OD pairs that are inappropriate for bus transit. Express bus service is another type of trunk line serving OD pairs with relatively lower demands. The two trunk services are used to bring passengers from one zone to another. The role of Feeder bus services is to provide access to and egress from the trunk service stops for passengers in each zone. Since it is economically infeasible to provide high quality service to all passengers in reality, a step-by-step optimization strategy is proposed to give higher priorities to the high-volume OD pairs in design to guarantee the benefits for the majority of users.

2.2 Rail service

In the design of the rail network, each potential rail station in a zone is called a node, which is specified by the planner based on urban land use and government policy considerations. A railway connecting any two nodes is called a rail segment, and one or more rail segments comprise a rail line, which is an individual rail service with its own fleet of trains and operating headway. The rail network includes a number of rail lines and different rail lines may share the same rail tracks.

Three parameters, operating headway (H_T), fleet size (F_T), and alignment of each rail line, govern the configuration of the rail network. Here H_T refers to the operating headway during the peak period. The design of the rail network is the determination of the optimum values of these three parameters for each rail line that lead to the minimal total system cost. The cost of a rail line (C_T) equals the sum of its operator cost (C_{OR}) and user cost (C_{UR}) as presented in Equation 1 below,

$$C_T = C_{OR} + C_{UR} \tag{1}$$

where C_{UR} is the sum of the cost for user waiting time (C_{WR}), cost for user in-vehicle time (C_{VR}), and cost for user access time (C_{XR}), while C_{OR} is the sum of cost for operating the rail fleet and its annualized capital cost (C_R), cost for maintaining rail tracks and their annualized capital cost (C_L), cost for maintaining rail stations and the annualized capital cost (C_{SR}).

Due to the increase in facility maintenance cost, the rail track cost (C_L) increases as the headway on it decreases, and so does the rail station cost (C_{SR}) as the number of passengers using a rail station increases.

2.3 Express bus service

Only one express bus stop in each zone is allowed, which is collocated with the rail station in the same zone. To promote integration, it is assumed that an express bus always stops at the rail station of a zone (if any part of the bus route lies in that zone) so as to simplify the transfer activities and enlarge the potential service area covered by the express bus services. When a bus travels from one stop to the next, it always follows the street pattern and selects the shortest path. An express bus line is an individual express bus service, which can be defined by three parameters: headway (H_B), fleet size (F_B), and route alignment. The cost of an express bus line (C_B) equals the sum of its operator cost (C_{OB}) and user cost (C_{UB}) as presented in Equation 2,

$$C_B = C_{UB} + C_{OB} \tag{2}$$

where C_{UB} is the sum of the cost for user waiting time (C_{WB}), cost for user in-vehicle time (C_{VB}), and cost for user access time (C_{XB}), while C_{OB} is the sum of cost for operating the bus fleet and its annualized capital cost (C_C), and cost for maintaining bus stops and their annualized capital cost (C_{SB}).

2.4 Feeder bus service

Feeder bus service acts as a supplement to the trunk services -- rail and express bus services. An individual feeder bus service is called a feeder bus line, which can be characterized by headway (H_F), stop spacing (S_F), fleet size (F_F), and route alignment. A feeder bus line only serves the passengers within the zone and its role is to bring passengers from their origins to the trunk service stop, or dissipate the alighted passengers from the trunk service stop to their ultimate destinations. Thus, the demand pattern is “many-to-one” or “one-to-many”. The cost of a feeder bus line (C_F) equals the sum of its operator cost (C_{OF}) and user cost (C_{UF}) as presented in Equation 3 below,

$$C_F = C_{OF} + C_{UF} \tag{3}$$

where C_{UF} is the sum of the cost for user waiting time (C_{WF}), cost for user in-vehicle time (C_{VF}), and cost for user access time (C_{XF}), while C_{OF} is the cost for vehicle operating and its annualized capital cost (C_D). The cost for feeder bus stops is ignored.

Accessibility to passengers and service coverage are the major considerations for the determination of a feeder bus route, which is different from the goal of shortest travel distance for an express bus service. An exhaustive search algorithm introduced by Chien and Yang (2000) is employed with appropriate adaptation for this task.

3 SOLUTION APPROACH

The solution approach used to solve this complex optimization problem is a combination of heuristic search algorithms and analytical derivation.

3.1 Step-by-step optimization strategy

As stated in Section 2.1, a step-by-step strategy is proposed to optimize the three modes of transit services (i.e. rail, express bus, and feeder bus) in separate stages, but under joint consideration. Thus, the two trunk line services, which compose the backbone of the integrated transit network, are optimized before feeder bus service. The first stage is the design of rail network due to its higher capacity and best service quality. Express bus network is optimized in the second stage based on the tentative optimum rail lines from the first stage, and these rail lines are also constantly updated in the design of express bus services to keep the total system cost minimal. The third stage is the design of feeder bus services, which has little influence on the operation of the first two based on the assumption regarding the role of feeder bus service.

3.2 Optimization algorithms

Rail network design is first based on high-volume OD pairs that are inappropriate for bus transit, to guarantee these passengers a high quality service. When a new OD pair enters the system, an optimization algorithm is employed to generate all possible network configurations based on the tentative optimum results from the previous run. The minimal value of the objective function for each of the possible new configurations is calculated. The configuration that leads to the minimal objective value is selected as the optimum one and becomes the updated rail network for the next run of optimization.

The rail optimization algorithm, as shown in Figure 2, is heuristic in nature, while the objective function used for selecting optimum candidates is analytical. In this stage, the meaning of the value of the objective function (see Equation 4) is the total system cost (C_N) calculated on the basis of individual rail lines and passenger transfer cost (C_P), the user cost for delay due to transfer activity, in this stage.

$$C_N = C_P + \sum_{i=1}^{k} C_{Ti} \tag{4}$$

$$= C_P + \sum_{i=1}^{k}\left(\frac{a_i}{H_{Ti}}\right) + \sum_{i=1}^{k}\left(H_{Ti} b_i\right) + \sum_{i=1}^{k} c_i$$

where k is the number of rail lines in the network, C_{Ti} is the cost of rail line i ($1 \le i \le k$) as shown in Equation 1, and terms a_i, b_i, and c_i are constant values for rail line i. The derivation of the terms in Equation 4 and all the following Equations can be found in Peng (2003).

The objective function in Equation 4 is a non-linear function of rail line operating headways, which can be analytically minimized in a range (from H_{Tmin} to H_{Tmax}) defined by the planner to determine their optimum values. Fleet sizes of rail lines can be obtained from operating headways directly, and the alignments of each rail line are already determined by the network configuration being optimized.

The design of express bus service in the next stage is based on the tentative optimum rail network obtained from the first stage. The optimization algorithms for rail and express bus services are basically the same except the latter has an extra consideration of rail transit before assigning a new OD pair to express bus service. The total system cost in this stage (C_N'), presented in Equation 5, is based on individual rail lines and express bus lines, and passenger transfer cost (C_P') in this stage.

$$C_N' = C_P' + \sum_{i=1}^{k} C_{Ti}' + \sum_{i=1}^{m} C_{Bi} \tag{5}$$

where m is the number of express bus lines in the network, and C_P' and C_{Ti}' are updated transfer cost and rail line cost in the second stage, respectively, due to changes in their demand levels.

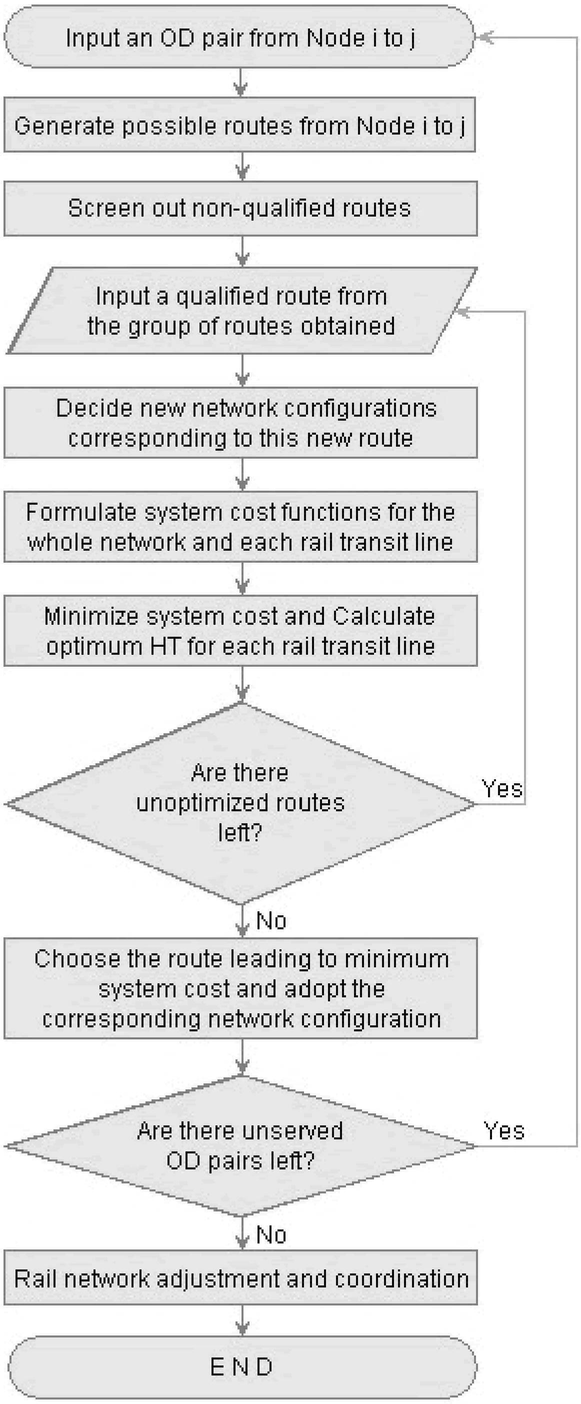

Figure 2. Flowchart for the rail network optimization algorithm.

Equation 5 is also a non-linear function of rail line operating headways and express bus operating headways. The optimum values of each H_{Ti} and H_{Bi}

can be analytically obtained in the ranges from H_{Tmin} to H_{Tmax} and from H_{Bmin} to H_{Bmax}.

The last stage, design of feeder bus services, has no influence on the cost and operation of the previous two networks because feeder bus services only operate within individual zones. The optimization principles, employment of a heuristic algorithm for candidate generation and an analytical objective function for determination of optimum state, are the same as those for the first two stages.

The total system cost for the last stage (C_N'') is given in Equation 6,

$$C_N'' = C_P'' + \sum_{i=1}^{k} C'_{Ti} + \sum_{i=1}^{m} C_{Bi} + \sum_{i=1}^{n} C_{Fi} \qquad (6)$$

where C_P'' is the passenger transfer cost in the last stage, and n is the number of feeder bus lines in the network.

4 NUMERICAL EXAMPLE AND SENSITIVITY ANALYSIS

Corresponding to the three stages in the optimization of the inter-modal public transit network, the decision support tool consists of three components, rail service module, express bus service module, and feeder bus service module. A computer program coded in Visual Basic including the first two modules has already been completed. Section 4.1 shows how this tool is applied to optimize an integrated rail and express bus network on an irregular urban area with 10 zones. Sections 4.2 and 4.3 give the sensitivity analysis of the selected decision variables with respect to some important parameters to demonstrate the applicability of the decision support system.

4.1 Test and results

A simple service area with 10 zones as shown in Figure 3 is assumed for this test.

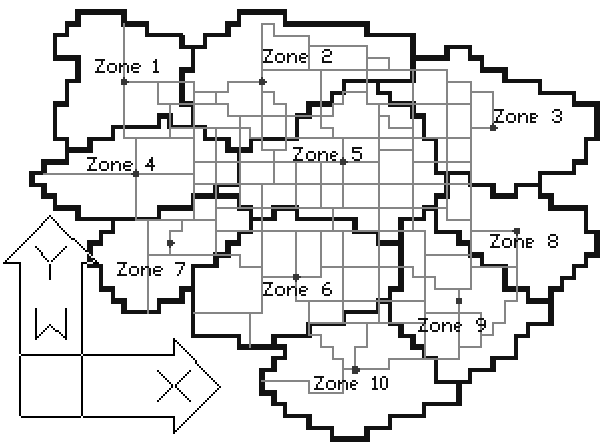

Figure 3. Configuration of the sample service area.

The thin lines in Figure 3 represent streets and the bold ones are zone boundaries. For illustration purpose, the centroid of each zone is selected as the potential rail station/express bus stop for that zone. An assumed peak hour OD matrix for the service area is given in Table 1.

Two threshold values for the adoption of rail and express bus services are set to be 1200 pax/hr for rail and 300 pax/hr for express bus service in this case study. Thus, any OD pair in Table 1 with demand greater than 1200 is recommended to be served by rail service, and only those with demand between 300 and 1200 may be served by the express bus service. These two values can be set and adjusted by the planner based on local demand and characteristics of transit modes selected. The default values used for some important system constants for rail and express bus service optimization are listed in Tables 2.

Table 1. A peak hour OD matrix (pax/hr).

O/D	1	2	3	4	5	6	7	8	9	10
1	0	207	139	79	363	240	700	360	227	54
2	145	0	410	1610	730	1120	590	2170	214	944
3	270	380	0	1237	120	1379	218	1537	120	789
4	113	54	1400	0	148	1850	1581	788	792	1745
5	2896	726	1183	1440	0	4223	380	3790	2057	2174
6	956	718	93	2905	1118	0	997	2221	4306	954
7	767	385	1685	275	111	329	0	249	641	245
8	243	1086	1977	86	440	1245	638	0	666	116
9	356	441	321	505	207	103	126	739	0	172
10	1841	310	194	1543	3914	1366	457	788	337	0

Table 2. Default values for the design of an integrated rail and express bus network.

Var	Unit	Description	Default values
H_{Tmax}	min	Maximum rail headway	7
H_{Tmin}	min	Minimum rail headway	1.5
H_{Bmax}	min	Maximum bus headway	20
H_{Bmin}	min	Minimum bus headway	1
n_b	pax/bus	Capacity per express bus	75
n_c	car/train	Number of cars per train	6
n_v	pax/car	Capacity per car	300
t_{d1}	min	Average dwell time at rail stop	0.35
t_{d2}	min	Average dwell time at bus stop	0.25
t_{dt1}	min	Average terminal time for rail	3
t_{dt2}	min	Average terminal time for bus	2
t_p	min	Penalty in time for transfer	2
u_I	$/hr/pax	Value of pax in-vehicle time	5
u_W	$/hr/pax	Value of pax waiting time	10
u_{Lk}	$/hr/km	Average rail track cost	284
u_r	$/hr/car	Train operating cost per car	100
u_b	$/hr/bus	Express bus operating cost	35
V_T	km/hr	Train cruise speed	50
V_B	km/hr	Express bus cruise speed	40

* Values for the other secondary system parameters are not given here.

In the optimization results, a total of 18 trunk services have been obtained, 11 for rail services and 7 for express bus services. The minimal total system cost is $130,206/hr, in which the total user and operator costs are $82,036/hr and $48,170/hr, respectively. Demand density of the assumed service area is 82,864 trips/hr. Thus, the average user, operator, and total costs are $0.99, $0.58, and $1.57/trip.

Figures 4 and 5 show each cost component and its corresponding percentage in the total system cost. The cost that passengers spent on waiting and transfer activities is 30.6% of the total cost and the proportion for passenger in-vehicle cost is 32.4%. Therefore, the average cost for user waiting and transfer activities is $0.48/trip. Similarly, the average user in-vehicle cost is $0.51/trip. The average travel time per trip is around 6.1 minutes.

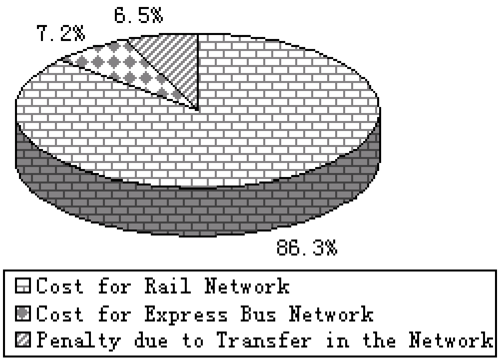

Figure 4. Proportions of the cost for each transit mode in the total system cost for the integrated rail and express bus network.

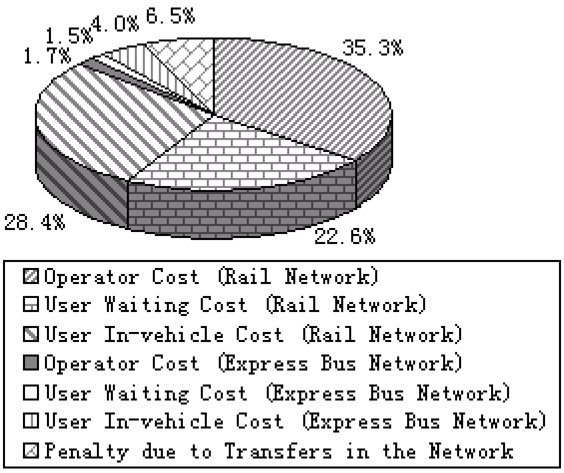

Figure 5. Detailed breakdown of each cost component in the total system cost for the integrated rail and express bus network.

Table 3 summarizes all the 11 rail segments in the rail network, their nodes, length, overall headway, and number of tracks. The rail track cost in the optimum result is around $340/hr/km, which is higher than the default rail track cost ($284/hr/km) in Table 2 as expected because the rail track maintenance cost increases when the number of vehicles running on it increases as stated in Section 2.2. The 11 rail lines and 7 express bus lines in the optimization results are listed in Tables 4 and 5, respectively.

Table 3. List of rail segments in the integrated network.

Segment	Node 1	Node 2	Length (km)	H (min)	Track Num
1	1	5	4.05	4.09	1
2	2	5	1.98	2.6	1
3	3	8	1.844	2.15	1
4	4	6	3.329	1.85	1
5	4	7	1.342	6.36	1
6	5	6	2.154	2.24	2
7	5	8	3.231	2.33	1
8	6	7	2.28	3.85	1
9	6	9	2.828	1.86	1
10	6	10	1.887	2.71	1
11	8	9	1.562	3.85	1

Table 4. List of optimized rail lines.

Line	Nodes Connected	Headway (min)	Total Cost ($/hr)
1	Nodes 6-9	3.60	8178
2	Nodes 5-6	3.12	7831
3	Nodes 10-6-5	2.71	16,067
4	Nodes 5-8	4.04	7767
5	Nodes 6-4	2.97	11,755
6	Nodes 5-1	4.09	10,263
7	Nodes 2-5-8	5.51	8419
8	Nodes 8-3	4.89	4387
9	Nodes 7-6-9-8-3	3.85	21,819
10	Nodes 2-5-6-4	4.93	12,659
11	Nodes 4-7	6.36	3251

Table 5. List of optimized express bus lines.

Line	Nodes Connected	Headway (min)	Total Cost ($/hr)
12	Nodes 3-5	1.68	1574
13	Nodes 10-9-8	2.54	1457
14	Nodes 7-4-1	1.72	1836
15	Nodes 2-4-7	2.71	1628
16	Nodes 9-5-2	4.26	1024
17	Nodes 2-3	3.35	986
18	Nodes 5-7	3.32	822

Figure 6 gives a simple illustration of how the rail optimization algorithm works. The number in the *x* axis represents each run of optimization when a new OD pair enters the network, and the system costs of all the candidates in each run are shown in vertical dotted lines. The bold line connects the costs of the candidates selected in the 25 runs of rail optimization. It is obvious that the algorithm succeeded in selecting the candidate leading to the minimal total system cost in each run. The same characteristic can also be observed in the optimization process for express bus network because it has a similar optimization algorithm to that for the rail service.

4.2 Analysis of a single transit line

The sensitivity analysis in this section focuses on the analysis of the relationships between some decision variables (mainly optimum operating headway) and system parameters for individual rail or express bus service, while the next section attempts to show how the entire optimum network would change if one or more parameters are revised.

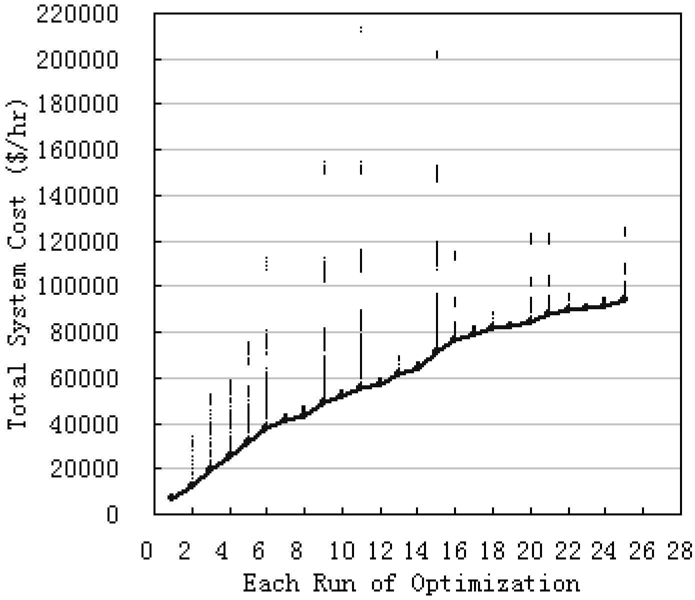

Figure 6. Illustration of the rail network optimization process.

Figure 7 shows the curves of rail line system cost, rail operating cost, and user waiting cost of rail line 9, respectively, as the operating headway varies from the minimum value to maximum value (1.5 min to 7 min). It can be observed that the developed objective function for a rail line is convex with respect to its operating headway.

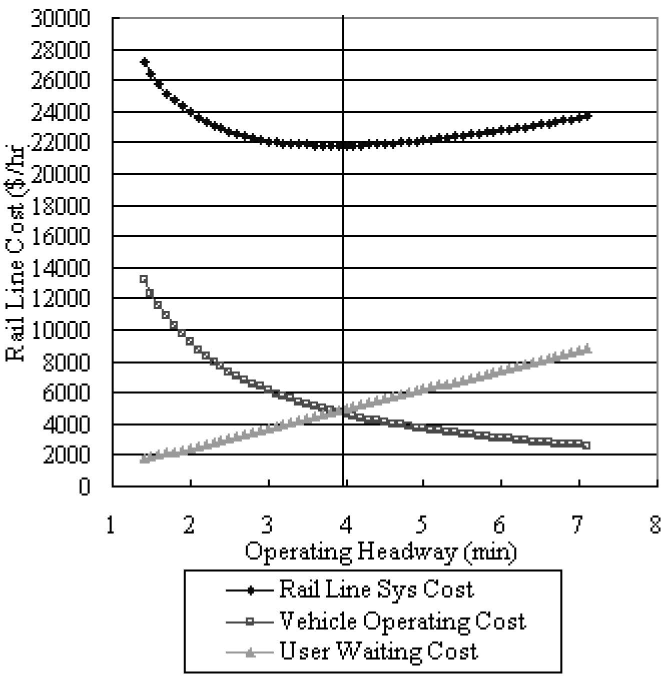

Figure 7. Costs vs. operating headway for rail line 9.

It is interesting to note that the rate of change for the system cost of rail line 9 is negligible when the operating headway is somewhere near its optimum value of 3.85 minutes. A variation in the operating headway of rail line 9 of about 20% on each side of the optimum value would result in only a 1% increase in its system cost. Studies of the other 17 transit lines also give similar results. It may be concluded that the system cost of a transit line is insensitive to changes in headway near its optimum value. This finding partially relaxes an assumption of this study that the arrival of vehicles strictly follows the preset schedules. Actually the headway of a transit system with bus services can hardly remain constant due to the influence from mixed traffic on the road. Since the system cost is insensitive to the headway near the optimum value, the solution from this tool can still remain valid even if strict adherence to the schedule cannot be achieved in operation.

A study of the optimum headway of a transit line with respect to the vehicle operating cost at different speeds shows that the optimum headway increases with the operating cost at a declining rate and approaches a maximum value beyond which the passenger waiting time would be unacceptable (set by the planner) or the service capacity cannot meet the demand. Also, it was found that vehicle speed only has a slight influence on the optimum headway when other parameters and variables remain constant.

Another study of the relationship between optimal headway and the value of user waiting time at different demand levels also yielded similar results for rail and express bus services. The optimum headway decreases as the value of waiting time increases at a declining rate (in order to reduce the user cost) until it reaches its minimum value (H_{Tmin} or H_{Bmin}) in this study.

Different results for rail and express bus services are obtained when investigating the variation of optimum headway with respect to the increase in bus/train capacity. The optimum headway of a rail line keeps increasing as the number of cars per train increases (in order to reduce the operator cost), while the optimum headway of express bus service only increases when the bus capacity is small (usually an unrealistic value). When the bus capacity passes 60 in this study, its optimum headway remains constant. The reason for the two different patterns of variation in headway is because the operating cost of a bus does not change with its capacity in this study. This characteristic may be true for large vehicles, which are commonly used for most express bus services. Thus, it can be concluded that for express bus services, increasing vehicle capacity may not reduce the operator cost since the optimum headway may not increase accordingly.

4.3 *Analysis of the total Network*

The express bus network can be easily changed in implementation if necessary. However, a physical change of the rail network is highly expensive due to the fixed facilities and expensive investment. Therefore, this section analyzes the impacts of some parameters to the entire integrated urban transport system but focuses on the optimum rail network.

A simple test is conducted to study the solutions obtained based on various demand levels in the rest of the day using a demand multiplier. Results revealed that when demand is 80% of its peak period value, only minor physical changes to the rail segments would occur. As demand decreases further, distinct changes in the optimum rail network appear. However, most of the segments in the solutions for these lower demand levels can still be found in that for the peak period demand. These distinct changes are mainly due to some rail segments in the solution for the peak period becoming unnecessary for lower demand levels. This finding indicates that the difference in investment for the rail network due to differences in demand is small, especially when the difference is no more than 20% lower than the peak period demand.

It is also likely that the peak period demand may exceed the planning value if the forecast is not accurate. No physical change of rail segments was observed in the optimum rail networks if demand increases up to 1.3 times of the peak hour demand used in this test. This finding is inspiring in that the optimum solution from the developed models is likely to remain valid even if the demand was underestimated.

The impacts from variations in vehicle operating cost and the value of user waiting time to the optimum rail network are also interesting issues. Numerical analysis of this assumed example indicated that for values in a small range of the two parameters near their planning values ($\pm 20\%$ for the rail operating cost and $\pm 30\%$ for the cost of passenger waiting time), the optimum rail networks obtained are the same or very similar. Thus, if there is no major physical change to rail segments, these two costs need not be determined accurately at the planning stage.

In the three analyses of the impacts of travel demand, values of rail operating cost and user waiting time, identical optimum rail networks can only be obtained for a small range of variation in the three parameters. Nevertheless, within the range of $\pm 20\%$ of the planning values used, most of the rail segments in the new optimum rail networks coincide with the original ones. That is, a great part in the solution from this decision support tool may remain valid if these system parameters do not change significantly in the future.

5 CONCLUSIONS

The decision support system disused in this paper is capable of providing useful reference in solving a complex public transportation optimization problem with sufficient accuracy under reasonable assumptions. Two major assumptions of past studies -- idealized service area and inflexible routing of transit services, are relaxed in this study. The introduction of elastic maintenance cost for transport facilities is also an advantage of this tool.

This decision support system contributes to the design of urban inter-modal public transit network from both the theoretical and practical points of view. From a theoretical perspective, an optimization framework and models for the integrated public transit system were developed. From a practical perspective, a decision support tool was developed, which can be used to help in the design of an integrated transit system with relatively complex factors, or adjust an existing system under specific objectives and constraints, search for the optimum operation strategy from a wide range of alternatives, and examine the mathematical relationships between important decision variables of a transit service and system parameters.

REFERENCE

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