Network Route Design of Public Transport System with Network Evolution

Takahiro Majima
Center for Logistics Research
National Maritime Research Institute
Email: majy@nmri.go.jp

Keiki Takadama
Faculty of Electro-Communications
University of Electro-Communications
Email: keiki@hc.uec.ac.jp

Daisuke Watanabe
Center for Logistics Research
National Maritime Research Institute
Email: watanabe@nmri.go.jp

Mitujiro Katuhara
Hokkaido Intellect Tank
Email: fwht4182@nifty.com

Abstract

Characteristics of network in the real world have attracted a number of scientists and engineers. Various findings are given from recent studies on the real world network, sometimes called complex network. The network evolution to produce complex network is also investigated actively and a number of models are proposed. Some model succeeded to produce public transport networks in the real world. We make active use of the network evolution for generating public transport network. In our model, the network of the bus lines evolves with a local evaluation value defined by the OD (Origin-Destination) demand multiplied with the required time including riding time and waiting time. Since the algorithm with network evolution is simple, our method is able to provide bus line network immediately. It is advantage to generate bus line network especially when a transport operation is required urgently under disaster circumstances.

Keywords: Complex Network, Network Evolution, Public Transportation, Route Generation, Local Optimization, Weighted Graph

1. Introduction

Characteristics of network in the real world have attracted a number of scientists and engineers. Various findings are given from recent studies on the real world network, sometimes called complex network. The complex networks, such as small world network [1] or scale free network [2], lie between two extremes, i.e., random network and regularly connected network like lattice. Many complex networks in real world have interesting characteristics found in both random and regular networks simultaneously.

The properties on the complex network are revealed mainly by early studies focused on the un-weighted relational network [3], in which there is no weight on links or vertices, such as distance or traffic amount. Meanwhile, studies investigating weighted network has begun to appear in recent year. Some of the papers the weight denotes distance between vertices [4][5] or traffic amount [6].

Further more, the network evolution to produce complex network is also investigated actively after the proposal of BA (Barabási and Albert) model [2]. The model produces the scale free network and the rule of its network evolution is known as preferential attachment (Rich gets richer). A number of models regarding to the network evolution were proposed [7][8][9] and some of them utilize the distance in the Euclidean space as a measure determining which node should be connected from the new added node. In the case of transport network in the Euclidean space, Gastner proposed a model of network evolution using the distance among nodes scattering in the Euclidean space and thereby presented that it can produce the subway network in Boston with the set of given nodes (stations) [9].

Considering this background, the knowledge of complex network seems to provide us useful information to design and construct the public transport networks. Our final purpose is to find an algorithm providing effective and optimized public transportation system, such as waterbus or bus expected to reduce traffic congestions and increase redundancy of transport system under disaster circumstances. We make active use of the knowledge of the network evolution to apply them to the problem in public transportation.

The design of public transport system is composed of four components, Network Route Design, Setting Time Tables, Scheduling of Vehicles and Scheduling of Drivers [10]. Toward the goal, this paper is focused on the process of the Network Route Design mainly and proposes a model to generate network using the network evolution. The network route design is the process to design the bus lines defined as a sequential order of stations at which vehicles stop. The bus lines also forms network over the stations on physical infrastructure network such as roads or rivers. In our model, the network of the bus lines evolves with a local evaluation value defined by the OD (Origin-Destination) demand multiplied with the required time (traveling time and waiting time). Since the algorithm with network evolution is simple, this model is able to provide bus line network immediately. It is advantage to generate bus line network especially when a transport operation is required urgently under disaster circumstances.

2. Model

In this paper, the nodes represent bus stops or stations and one set of links connecting nodes represents one bus line. Vehicles shuttle along with the set of links representing the bus line. The model with network evolution for bus line network is described below. It separates two processes. One process is to determine which node should be connected newly added node (i.e. network evolution). The other process describes how to determine the number of buses to be engaged into a designed bus line.

In this paper, the destination is limited to one bus stop for brevity. However this situation is well observed around stations of commuter trains. The passengers travel from their residential area to the railway station by bus. Although, there are many bus stops in the residential area, the number of destination, station of commuter train, is limited.

2.1 Network Evolution

Our model is inspired by Gastner[9]. One node (bus stop) is added to the network at each evolution step and connected one of the existing nodes with one link composing a part of a bus line route. Fig.1 shows the process of the growing bus line network. The newly added node (Node 3 in Fig.1), defined as *target node* in this paper, is selected in the order of the distance between the destination and the target node. Then, one of the already existing nodes, defined as *connection node* in this paper, is selected with an evaluation function described below and one link connects the target node to the connection node. After the connection between target node and connection node, the links are created along with the existing links from the connection node to the destination and this set of links comprises one bus line. Therefore, at the first step of evolution, the node nearest to the destination is selected as target node and the destination node itself becomes connection node. Thus, the network connected to the destination spread outward from the destination and it has tree topology (no loop).

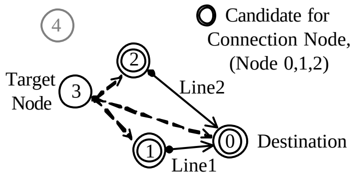
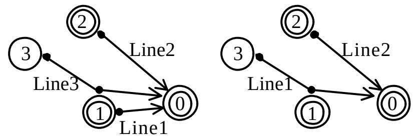


Fig.1 Schematic of Network Evolution

If selected connection node is terminal of the existing line, there are two types of connection as illustrated in Fig.2. One is *addition type*, the other is *subsumption type*. Number of bus lines is simply incremented by one for addition type. For subsumption type, the line, which one terminal is connection node, subsumes the new bus line and target node. The evaluation function is applied at each growing step and it determines the connection node and connection type.



(a) (b)

Fig.2 Two Types of Line Connection
(a) Addition Type (b) Subsumption Type

The evaluation function resembling in the following equation is applied frequently to the designed bus line network [11].

$$\min Z = Z_1 + Z_2 = \sum_i T_i D_i + w \sum_k B_k$$

Where, D_i is demand at bus stop i, T_i is required time for moving from bus stop i to destination composed of traveling time, Tm_i and waiting time, Tw_i, B_k is number of bus engaged into the bus line k, w is parameters controlling the balance of requirement between user and operator of vehicle. Users hope to reduce the first term, Z_1 and operators hope to reduce the second term, Z_2. Usually, this evaluation function is applied to the whole bus line network. However, we apply it for the selection of the connection node and connection type. Thus, i and k mean the set of nodes already connecting to the network and already existing bus lines respectively.

The expected waiting time of a bus stop at where more than one bus lines stop can be calculated by the following equation [12].

$$Tw_i = t_1\left[\frac{1}{2} + \sum_{r=1}^{N-1}\frac{(-1)^r t_1^{\,r}}{(r+1)(r+2)}\sum_{j_1=2}^{N-r+1}\sum_{j_2=j_1+1}^{N-r+2}\cdots\cdots\sum_{j_r=j_{r-1}+1}^{N}\frac{1}{t_{j_1}t_{j_2}\cdots t_{j_r}}\right]$$

Where, N is the number of bus lines running through the node i, t_1 is the smallest headway in the set of t_j representing headway of line j. Further more, the headway (frequency) is derived from the round trip time and bus number simply and the shortest path is found by Dijkstra's algorithm when considering the topology of the physical infrastructure network, such as road or rivers.

2.2 Determination of Vehicle Number

It should be satisfied that the transportation capacity is larger than the traffic amount. In the network evolution process, node is connected one by one and the bus line generated with addition type in Fig.2 is incremented by one at each evolution step. Thus, the number of vehicle assigned for a bus line can be calculated to satisfy the demand occurred at the target node and needless to consider the demand at nodes other than the target node.

Thus, the number of vehicle is calculated by the following equation simply.

$$B_k = \lceil Tr_k D_k / B_{capa} \rceil$$

Where, Tr is round trip time of target node k, and B_{capa} is capacity of one vehicle. We should consider another way for the case of subsumption type in Fig.2, because, the round trip time of existing line changes. There are several ways to determine the number of vehicles for subsumption type. In this paper, it is intended to determine the number of vehicle so that the headway of already existing line, which one terminal is the connection node, doesn't deteriorate. Thus, the following equation is employed.

$$B_k = \max\left(\lceil Tr_k D_k / B_{capa} \rceil, \lceil B_j Tr_k / Tr_j \rceil\right)$$

Where, subscript k and j represent target node and connection node respectively.

An example of network evolution is described in Fig.3. Although the number of nodes is only four, many possible network of bus line can be considered. It is easy to imagine that investigation for all patterns leads to combinatorial explosion when the number of nodes increases.

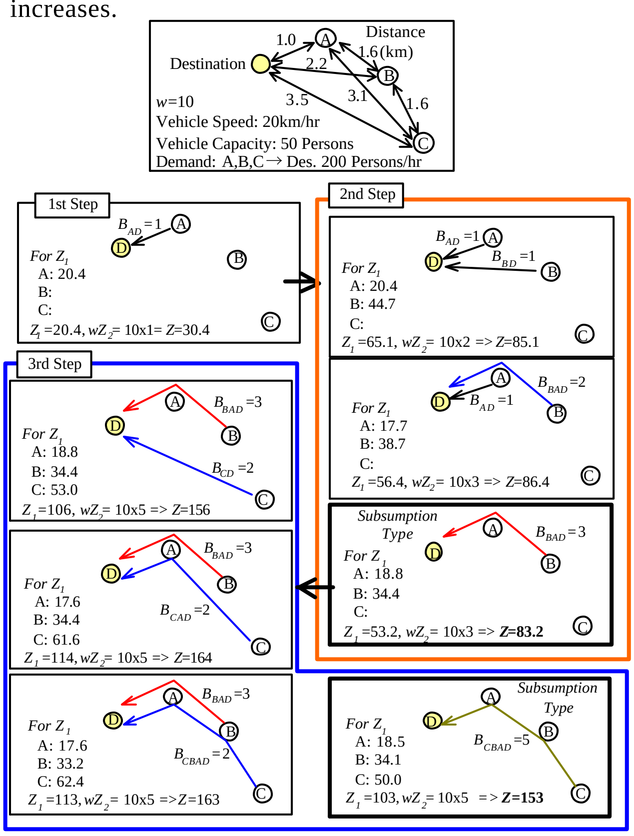


Fig.3 Example of process of network evolution

3. Application

In this section, the model described previous section is applied to two situations. One is simple physical infrastructure network and the other is waterbus line in the three rivers running through Tokyo metropolitan.

3.1 Simple Network

The arrangement of nodes is illustrated in Fig.4(a). Twenty nodes are positioned on the circle with diameter of 5 km. The capacity of vehicle, B_{capa} and speed, B_s set to 50 persons and 20km/hr respectively. The demand of each node is 200persons/hr and the road network is assumed to have the topology of complete graph with straight line. Fig.4(b) and (c) show the bus line network generated by the model with w=0 and w=25 respectively.

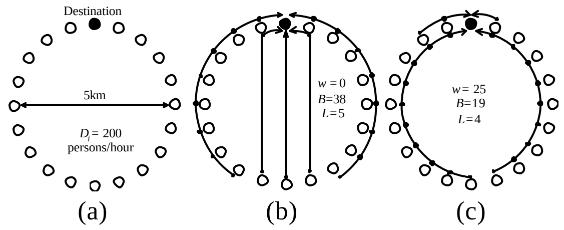


Fig.4 (a) Arrangement of nodes and problem to be solved. (b) Result of network evolution with w=0, (c) Result of network evolution with w=25, where L and B are total number of lines and vehicles respectively

As mentioned above, the model can analyze taking into account of the balance of requirement between user and operators with the control parameter, w. Fig.5 shows the relationship between total vehicle number and total required time, TD, normalized with riding time, Tm_{ideal}, calculated assuming that the all nodes are connected to the destination directly. The result varies by the controlling parameter, w. It is found the required time for traveling to the destination takes about 30% larger than that of the idealized bus line network for users. It is caused from the waiting time and the topology of not directly connected to the destination, even if w is set to 0 that is acceptable for users.

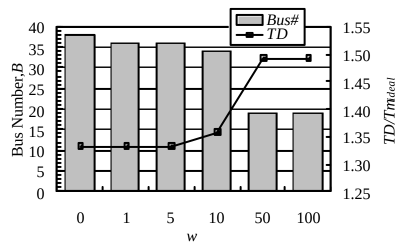


Fig.5 Relationship between bus number and total required time for the generated bus line

3.2 Application to waterbus line in the river system

The Tokyo metropolitan and around the region most populated area in Japan have been suffering from heavy traffic, congestions and commuter rushes on transport networks. Furthermore considering the fact that earthquakes occur frequently in Japan, road networks are collapsed when an earthquake causes massive destruction. The transport mode using rivers and ships that doesn't exist at this time is being expected to contribute to reducing traffic congestions or redundancy of logistics system under disaster circumstances. Fig.6 shows physical infrastructure network composed of three rivers running through Tokyo. There are 24 possible waterbus stations in the river system.

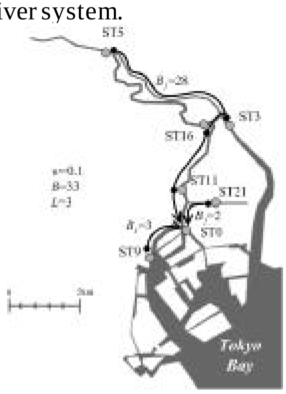


Fig.6 Rivers running through Tokyo, three solid lines connecting to ST0 represent generated waterbus lines.

For instance, making the Etchujima station represented by ST0 in Fig.6 to be destination, the model was applied. Table 1 shows the demand of six bus stops represented in Fig.6. The capacity of waterbus, B_{capa} and service speed, B_s set to 100 persons and 8 knot(15km/hr) respectively according to the ships operating for sight seeing around Tokyo bay area.

Table 1 Demand of Six Waterbus Stations (Destination: ST0)

Station No.	ST3	ST5	ST 9	ST11	ST16	ST21
Demand (Persons/hr)	34	3	358	607	119	287

Three waterbus lines generated with w=0.1 are drawn in Fig.6 by solid lines and Fig.7 shows relationship between the number of waterbus and normalized required time, as is shown in Fig.5. The generated bus lines network in Fig.6 seems rational and required time becomes about 30-40 larger than riding times of the network connected to destination directly.

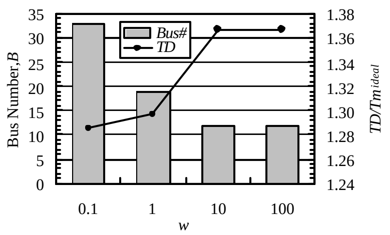


Fig.7 Relationship between waterbus number and total required time for the waterbus line

4. Discussion

Since our model generates bus line network with the evaluation function applied to the local network not to global network, it doesn't certify the completely optimized solution. However, the generated network and required time in this paper seem to be rational. Thus, advantage of our model is to produce the rational solution immediately. This advantage is considerably useful to engage a transport operation urgently such as disaster circumstance.

5. Conclusion

We proposed the model generating rational public transport network with network evolution. However, there are several subjects to be addressed for the practical use. For instance, the number of destination is limited to one station at this time. Furthermore, in the case of the waterbus, the congestion at bus stops should be considered, because the number of ships taking piers is limited.

Acknowledgement

This study is supported by the Ministry of Education, Culture, Sports, Science and Technology, Grand-in-Aid for Scientific Research (B), 17360424, 2005. We would also like to thank Kazue Honda for her support of programming.

References

[1] D.J. Watts, S.H. Strogatz, Collective Dynamics of 'Small-World' Networks, Nature, Vol.393, 1998, pp.440-442

[2] A.-L Barabási, R. Albert, Emergence of Scaling in Random Networks, Science, Vol.286, 1999, pp.509-512,

[3] S.H. Strogatz, Exploring Complex Networks, Nature, Vol.410, 2001, pp.268-276

[4] V. Latora, M. Marchiori, Efficient Behavior of Small-World Networks, Phys. Rev. lett. Vol.87, No.19, 2001

[5] T. Majima, M. Katuhara, K. Takadama, Analysis on Transport Networks of Railway, Subway and Waterbus in Japan, WEIN06 (Workshop on Emergent Intelligence on Networked Agents) Proceedings, May 2006, Hakodate, pp.152-166

[6] A. D. Montis, M. Barthélemy, A. Chessa, A. Vespignani, The Structure of Inter-Urban Traffic: A Weighted Network Analysis, arXiv:physics/0507106 v2, 2005

[7] M. Barthélemy, A. Flammini, Optimal Traffic Networks, arXiv:physics/0601203v2, 2006

[8] M. Kaiser, CC. Hilgetag, Spatial Growth of Real-World Networks, Phys. Rev. E Vol.69, 036103, 2004

[9] M.T. Gastner, M.E.J. Newman, Shape and Efficiency in Spatial Distribution Networks, arXiv:cond-mat/0409702, 2004

[10] A. Ceder, Methods for Creating Bus Time Tables, Transportation Research, Vol.21A, No.1, 1986, pp.59-83

[11] D. Dubois, G. Bel, M. Llibre, A set of Methods in Transportation Network Synthesis and Analysis, Journal of the Operational Research Society, Vol.30, No.9, 1979, pp.797-808

[12] W. Lampkin, P.D. Saalmans, The Design of Routes, Service Frequencies and Schedules for a Municipal Bus Undertaking: A case study, Operation Research Quarterly, No.18, 1967, pp.375-397