Modeling and Evaluation of a City Logistics System with Freight Buses

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Abstract: Freight bus is a new public transportation means for city logistics, and each freight bus can deliver and pick up goods at each customer/supplier location it passes. In this paper, we study the route planning problem of freight buses in an urban distribution system. Since each freight bus makes a tour visiting a set of pickup/delivery locations once at every given time interval in each day following a fixed route, the route planning problem can be considered a new variant of periodic vehicle routing problem with pickup and delivery. In order to solve the problem, a Mixed-Integer Linear Programming (MILP) model is formulated. Based on the model, we compare a distribution system with freight buses with that without freight bus. Preliminary numerical results on randomly generated instances show that the system with freight buses can significantly reduce transportation costs compared with the system without freight buses.

1 INTRODUCTION

The rapid development of e-commerce has been making urban logistics flows more and more intensive. Driven by market demand, more and more city freighters operated by different private third-party logistics companies were born and circulate in the centers of cities. This has caused serious traffic congestion and environmental pollution problems in large cities. To reduce traffic congestions and improve the efficiency and time accuracy of delivery, collaboration among third-party logistics companies (carriers) in urban logistics is needed.

In 1973, Japanese scholar Shize (1973) first put forward the joint distribution which has been proved to be an effective way for city logistics. Joint distribution promotes enterprises with similar functions to use common facilities and equipment such as warehouses, logistics platforms, and vehicles, through which small orders of goods for delivery can be consolidated into a large-volume order to achieve the economics of scale in transportation and other related logistics services. Gill and Allerheiligen (1996) pointed out that members of a distribution channel should cooperate with each other through joint distribution, and illustrated the effectiveness of joint distribution, and proposed several principles for implementing it. Hao and Su (2014) discussed the basic concepts and operation models of joint distribution in city logistics. Xu and Yang (2017) proposed a model for cost sharing among small companies implementing joint distribution.

Motivated by joint distribution, in our previous work (Chang and Chen. 2017), we put forward the concept of freight bus, which is a new public transportation means for city logistics that can replace city freighters belonging to different private third-party logistics companies in the center of a city. Freight bus has some advantages compared with city freighter. Firstly, freight bus can realize joint distribution of different third-party logistics companies, and can thus save city logistics costs and reduce the air pollution; Secondly, because of having a regular schedule, freight bus can improve the timeliness and accuracy of logistics services; Thirdly, replacing private city freighters by freight buses can facilitate the traffic control in a city and reduce the traffic congestion. Finally, freight bus can improve the utilization rate of special lanes reserved for buses. In that article, we did not consider both pickup and delivery of goods at each customer/supplier location when a freight bus passes it. However, in practice, as a new public transportation means for city logistics, freight buses should perform both pickup and delivery of goods at every customer/supplier location they visit.

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The periodic vehicle routing problem (PVRP) was first introduced by Beltrami and Bodin (1974) in vehicle routing for municipal waste collection. This is the first time that the periodicity of customer deliveries was specifically addressed in combination with the consideration of vehicle routing costs. Russell and Igo (1979) named the periodic routing problem as the assignment routing problem. Christofides and Beasley (1984), which is well cited by periodic routing papers, named the problem as a period routing problem and provided the first mathematical formulation of the problem. The first article that uses the term "periodic vehicle routing" appears to be Gaudioso and Paletta (1992). In the paper entitled "Forty Years of Periodic Vehicle Routing", Ann and Jill (2014) discussed a wide range of circumstances and settings in which the PVRP has been applied and reviewed models and solution methods developed for the PVRP, including both exact and heuristic methods.

In this paper, we study the route planning problem of freight buses with both pickup and delivery in an urban distribution system. In this system, each freight bus makes a tour visiting a set of pickup/delivery locations once at every given time interval in each day following a fixed route in a city, and the route planning problem can be considered a new variant of periodic vehicle routing problem with pickup and delivery. To the best of our knowledge, this problem was rarely studied in the literature. In order to solve the problem, a Mixed-Integer Linear Programming (MILP) mathematical model is formulated. Based on the model, we compare a distribution system with freight buses and that without freight bus. Preliminary numerical results on randomly generated instances show that the system with freight buses can significantly reduce transportation costs compared with the system without freight buses.

2 FREIGHT BUS IN CITY LOGISTICS

With the increase of freight distribution in urban transportation, more and more private city freighters were born in the city. Motivated by joint distribution, in this paper, consider an urban distribution system with freight buses, which is a new public transport means that can replace city freighters belonging to different private logistics companies in the center of a city. The following two figures compare city freighters and freight buses in an urban distribution system. We can see in Fig. 1, there are city freighters from two companies A and B, which separately deliver their customers' demands from a distribution center to multiple depots. However, in Fig. 2, freight buses are used to deliver all the demands from the distribution center to the depots.

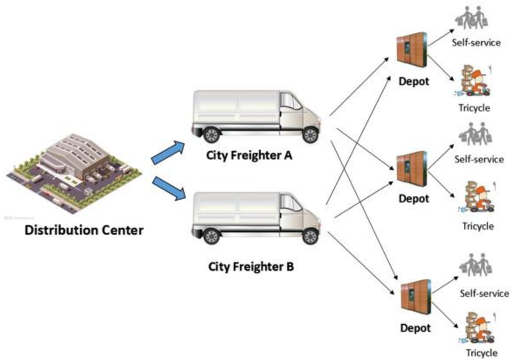

Figure 1: City freighters in urban distribution system.

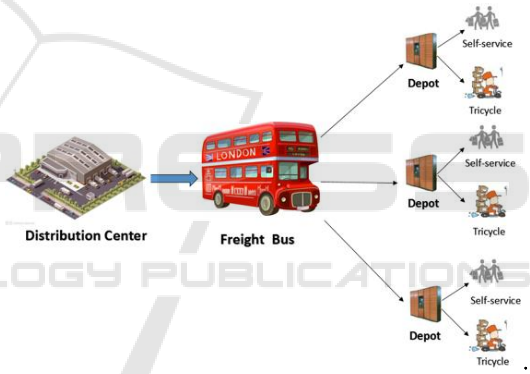

Figure 2: Freight buses in urban distribution system.

As a public service for third-party logistics companies and customers, the use of freight buses can achieve joint distribution. One important feature of freight buses is that they are standardized vehicles and have fixed time schedules. With the fixed schedules, both shippers and customers can well arrange their order delivery and delivery times. As we can see from Fig. 2, each depot in such distribution system is a freight bus station, which has a smart cabinet (depot) for temporary storage of goods. According to the schedules, customers can pick up their ordered products by self-service at the freight bus stations (depots), or ask the last-mile delivery men to deliver the goods from a freight bus station to their homes (Dayarian, Crainic, Gendreau, & Rei. 2015). The following figure 3 illustrates freight bus lines, where each freight bus station is visited and served by a freight bus line periodically.

In each run (period), each freight bus starts from a distribution center, delivers and pick up goods at multiple depots, and finally returns back to the distribution center, according to a predefined route and time schedule. Moreover, as a public transportation means, freight buses can also enjoy the policy of bus priority and use special lanes reserved for buses, which can improve the timeliness and accuracy of logistics services (Trentini, Campi, Malhene & Boscacci, 2011).

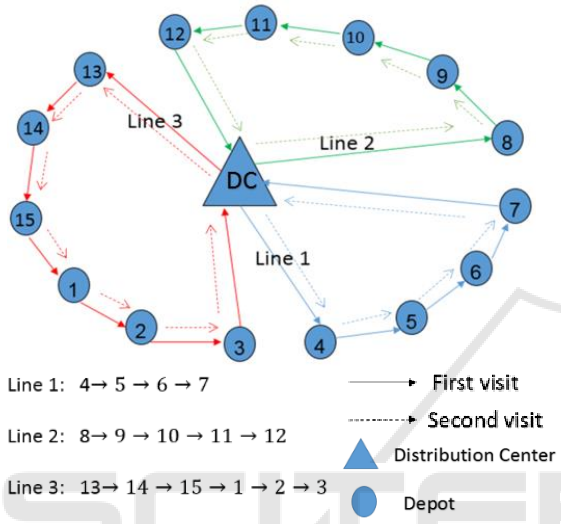

Figure 3: An example of freight bus lines.

Freight bus has some advantages compared with city freighter. Firstly, freight bus can realize joint distribution of different third-party logistics companies, and can thus save city logistics costs and reduce the air pollution; Secondly, because of having a regular schedule, freight bus can improve the timeliness and accuracy of logistics services; Thirdly, replacing private city freighters by freight buses can facilitate the traffic control in a city and reduce the traffic congestion. Finally, freight bus can improve the utilization rate of special lanes reserved for buses. Just like the birth of passenger buses, we believe that in cities with high freight demands, freight buses are very likely to be born in the near future.

3 MATHEMATIC MODEL FOR FREIGHT BUS ROUTING

In this section, we establish a mathematical model for the vehicle routing problem of freight bus.
Each freight bus is operated (run) between a distribution center and multiple depots. Compared with the capacitated vehicle routing problem, the vehicle routing problem of freight bus has the following new characteristics: 1、Each freight bus makes a tour visiting a set of pickup/delivery locations once at every given time interval (period) in each day. 2、Each freight bus has a fixed vehicle route in these periods. 3、Both delivery and pick up can be operated at each depot (customer/supplier location). 4、delivery and pickup of goods can be delayed but with penalties.

Therefore, the freight bus routing problem considered in this paper is a multi-period vehicle routing problem with pickup and delivery, fixed routes, and late pickup/delivery penalties. To the best of our knowledge, this problem was rarely studied in the literature. In order to solve the problem, in this section we first formulate a Mixed-Integer Linear Programming (MILP) model for the route planning problem of freight buses.

3.1 Problem Description

In the model, each freight bus runs between a Distribution Center and a set of depots. For simplicity, we don't consider the interactions of the freight buses with the electro-tricycles which perform last-mile deliveries from depots to customers. Key features of the model are first introduced in the following.

(1)Multiple periods: We consider a time horizon (e.g. one day) that is divided into M periods (M > 1) and assume that each freight bus visits its served depots once in each period, and the demand of delivery and pickup of goods to each depot in each period is known.

(2)Fixed routes: As passenger buses，we assume that each freight bus has a fixed route in the time horizon, and every depot must be served by one freight bus in each period.

(3)Both delivery and pick up: Each freight bus can perform pickup and deliver goods at each depot (customer/supplier location). The freight bus arrives at each customer/supplier location (station), unload goods first and load goods later. During the whole tour, the total amount of goods in the freight bus should not exceed its capacity. So it is possible that the delivery or the pickup demand of a depot in a period is only partially met in this period because of the capacity limitation of a freight bus, in this case, the unmet demand of the period can be only met in later periods. In other words, the goods loaded or unloaded by the freight bus must be the pickup or delivery demand of this period or the previous periods that were not met due to the limitation of vehicle capacity.

(4)Penalty of delivery/pickup delay. Delivery and pickup of goods at a customer/supplier location can be delayed but with penalties. There are two types of penalty introduced in this model. One is the penalty caused by the delay in the time horizon (e.g. one day) of M periods, which linearly depending on the quantity of the late delivery or pickup demands and the number of periods delayed, with the penalty per period and per unit of demand given by a coefficient α (In this paper, we assume late pickup and delivery have the same penalty coefficient). The other is the penalty for all unmet demands at the end of the time horizon (e.g. one day) of M periods, which linearly depending on the quantity of the late delivery or pickup demands, with the penalty per unit of demand given by another coefficient β.

What's more, Because of these two types of penalty, we can assume that the operation of the freight bus has two characteristics: 1,When the freight bus arrives at a depot, it unloads/delivers first and then loads/pickup the goods. (In order to free up more capacity for pickup). 2, For delivery, the freight bus will give priority to meeting the needs of the previous visiting depots according to the order of visiting; for pickup, the freight bus will try its best to meet the loading needs of the depots according to its maximum remaining capacity (Because late pickup and delivery have the same penalty coefficient).

The main parameters of the model are defined as follows:

- o The distribution center where each freight bus leaves from and returns to.
- V Set of freight buses.
- G Set of depots.
- U The capacity of each freight bus.
- C_{ij} The operating cost for a freight bus when it travels from node i to node j ($i, j \epsilon \{o\} \cup G$).
- M The number of time periods we consider in the route planning problem.
- $d_i(k)$ The demand of delivery of depot i in the k-th period, $i \in G$, $k \in \{1,2 \ldots M\}$.
- $p_i(k)$ The demand of pickup of depot i in the k-th period, $i \in G$, $k \in \{1,2 \ldots M\}$.
- α The per period and per unit late delivery/pickup penalty cost for goods delivered/picked up in the time horizon of M periods.
- β The per unit late delivery/pickup penalty cost for goods delivered/picked up beyound the time horizon.

We assume that the Distribution Center o serves all depots G in the distribution system considered. The distance between node i and node j is denoted by D_{ij}. The operating cost of a freight bus from node i to node j is calculated as $C_{ij} = \gamma * D_{ij}$, where γ is the unit distance operating cost of each freight bus. There are N (N is an integer) freight buses operated for the Distribution Center o, and the capacity of each freight bus is U.

In each period, each freight bus leaves from the Distribution Center o, visits its served depots and returns to the Distribution Center. What's more, for one freight bus, every period, all goods loaded at the DC must be unloaded at its served depots before it returns to the Distribution Center; and all goods loaded at its served depots must be unloaded at the Distribution Center when it returns to the DC . It is assumed that the demand $d_i(k)$ and $p_i(k)$ of each depot i in each period $k \in \{1,2 \ldots M\}$ is known.

We need to plan the vehicle route for each freight bus v, and the delivery and pickup quantity of each freight bus at each depot in each period. The objective is to minimize the operating costs of all freight buses plus the late delivery and pickup penalty costs.

We need to plan the vehicle route for each freight bus v, and the delivery quantity of every freight bus at each depot in each period. Our objective is to minimize the operating costs of all the freight buses in the M periods.

3.2 Mathematic Model

In this subsection, we propose a mathematic model for freight buses. With this mathematic model, we can calculate the whole operating costs of the system with freight bus in the planning horizon. At the same time, we can also get the optimal routes of freight buses. In this subsection, we propose a mathematic model for the route planning of freight buses by considering its all characteristics. With this mathematic model, we can optimize the total cost of freight buses composed of their operating costs and penalty costs for the late delivery and pickup of goods in the planning horizon. At the same time, we can also get the optimal routes of freight buses by solving the model.

The detailed mathematical model for the route planning of freight buses is given as follows:

Decision Variables

- x_{ij}^{v} A binary variable which is equal to 1 if the freight bus v ϵV goes from node i to j (i, $j \epsilon \{o\} \cup G$); 0 otherwise.
- y_i^{v} A binary variable which is equal to 1 if and only if the depot i ϵG is served by the freighter

bus v ϵV ; 0 otherwise.

- $d_i^v(k)$ The unloaded quantity of the freighter bus v ϵV at the depot i ϵG in the k-th visit k$\in$ $\{1,2 \ldots m\}$; 0 otherwise.
- $p_i^v(k)$ The loaded quantity of the freighter bus v ϵV at the depot i ϵG in the k-th visit k$\in$ $\{1,2 \ldots m\}$; 0 otherwise.
- $Q_i^v(k)$ The quantity of all goods remaining to deliver in the freighter bus v ϵV when it just arrives at node i $\epsilon\{o\} \cup$ G during the k-th visit, k$\in$ $\{1,2 \ldots M\}$.
- $W_i^v(k)$ The quantity of all goods picked up by the freighter bus v ϵV when it just arrives at node i $\epsilon\{o\} \cup$ G during the k-th visit, k$\in$ $\{1,2 \ldots M\}$.

Objective Function

The objective is to minimize the sum of all costs including the operating costs of the freighter buses and the penalty costs for the late delivery and pickup of goods in the planning time horizon of *M* periods.

$$\text{Minimize Z} = M * \sum_{i\in\{o\}\cup G}\sum_{j\in\{0\}\cup G}\sum_{v\in V} c_{ij}x_{ij}^v + \alpha * \sum_{i\in G}\sum_{n=1}^{M-1}\sum_{k=1}^{n}(d_i(k) - \sum_{v\epsilon V} d_i^v(k)) + \beta * \sum_{i\in G}\sum_{k=1}^{M}(d_i(k) - \sum_{v\epsilon V} d_i^v(k)) + \alpha * \sum_{i\in G}\sum_{n=1}^{M-1}\sum_{k=1}^{n}(p_i(k) - \sum_{v\epsilon V} p_i^v(k)) + \beta * \sum_{i\in G}\sum_{k=1}^{M}(p_i(k) - \sum_{v\epsilon V} p_i^v(k)) \quad (0)$$

Constraints

$$\sum_{j\in G} x_{oj}^v = \sum_{j\in G} x_{jo}^v \quad \forall v \in V \quad (1)$$

$$\sum_{i\in\{0\}\cup G} x_{ij}^v = \sum_{i\in\{0\}\cup G} x_{ji}^v \quad \forall j \in G, \forall v \quad (2)$$

$$\sum_{i\in\{0\}\cup G} x_{ij}^v = y_j^v \quad \forall j \in G,\ \forall v \quad (3)$$

$$\sum_{v\in V} y_j^v = 1 \quad \forall j \in G \quad (4)$$

$$Q_j^v(k) <= Q_i^v(k) - d_i^v(k) + U(1-x_{ij}^v) \quad (5)$$
$$\forall i \in G, \forall j \in \{o\}\cup G, \forall v \in V,\ \forall k\in \{1,2 \ldots M\}$$

$$Q_o^v(k) = 0 \quad \forall v \in V,\ \forall k\in \{1,2 \ldots M\}$$

$$W_j^v(k) >= W_i^v(k) + p_i^v(k) - U(1-x_{ij}^v) \quad (6)$$
$$\forall i \in G, \forall j \in \{o\}\cup G, \forall v \in V, \forall k\in \{1,2 \ldots M\} \quad (7)$$

$$W_o^v(k) = \sum_{i\in G} p_i^v(k)$$
$$\forall v \in V,\ \forall k\in \{1,2 \ldots M\} \quad (8)$$

$$0 <= Q_i^v(k) + W_i^v(k) <= U$$
$$i \in \{0\}\cup G, \forall v \in V \quad (9)$$

$$\sum_{k=1}^{n} d_i^v(k) <= \sum_{k=1}^{n} d_i(k) * y_i^v$$
$$\forall i \in G, \forall v \in V, \forall n\in \{1,2 \ldots M\} \quad (10)$$

$$\sum_{k=1}^{n} p_i^v(k) <= \sum_{k=1}^{n} p_i(k) * y_i^v$$
$$\forall i \in G, \forall v \in V, \forall n\in \{1,2 \ldots M\} \quad (11)$$

$$x_{ij}^v \in \{0,1\} \quad y_i^v \in \{0,1\}$$
$$d_i^v(k) >= 0;\ p_i(k) >= 0;\ Q_i^v(k) >= 0;\ W_i^v(k) >= 0$$
$$\forall i \in \{o\}\cup G,\ \forall j \in \{o\}\cup G, \forall v \in V \quad (12)$$

Constraints (1) indicate that each freight bus leaves from and returns to the DC. Constraints (2) ensure that each freight bus arriving at a depot has to leave it. Constraints (3) and (4) guarantee that all depots must be served and each depot is served by at most one freight bus. Constraints (5) (6) and (7) (8) (9) formulate vehicle capacity constraints. Constraints (10) (11) indicate that in each period, the delivery and pickup of freight bus *v* at each depot *i* can only be the demand of that period or earlier periods but cannot be the demand of later periods. Finally, constraints (12) define the domains of all decision variables.

4 IMPACT OF THE JOINT DISTRIBUTION REALIZED BY FREIGHT BUSES

4.1 The Distribution System without Freight Bus

In order to evaluate the impact of the joint distribution realized by freight buses, we compare our proposed distribution system with freight buses with that without freight bus.

In the system without freight bus, it is assumed that there are city freighters operated by two private third party logistics companies A and B, which separately deliver and pickup their customers' demands from a distribution center to multiple depots. Each city freighter of company *A* or *B* also visits its served depots once during each period k$\in$ $\{1,2 \cdots$ M$\}$, and the demand of each company's customers at each depot *i* in each period must be served by its own city freighters. In each period, each city freighter also begins and ends its travel at the distribution center. What's more, and it is possible that part of the demand of a depot in a period is served in later periods because of the limited capacity of a city freighter, and we also consider two types of penalty costs for late deliveries and pickups.

To simplify the comparison of the two distribution systems, we assume that all city freighters operated by company A and company B have the same capacity U, the same unit distance operating cost γ, the same penalty coefficient α and β, and the same number of periods M in the planning time horizon as those of the freight buses, and all the city freighters also have fixed vehicle routes. The objective of each city freighter company is to minimize its total cost which includes the operating costs and the penalty costs of its own city freighters. With this assumption, we can use the MILP proposed in this paper to optimize the vehicle routes of the city freighters of each company and get its total cost. The total cost of the distribution system without freight bus is thus the sum of the total costs of company A and B.

4.2 Experimental Results

In order to verify the freight bus routing model proposed in section III and evaluate the impact of joint distribution realized by freight buses, we need to generate instances which are representative for both the distribution system with freight buses and the distribution system without freight bus.

The freight bus routing problem considered in this paper is related to the vehicle routing problem with pickup and delivery. So when generating the instances, we use some data from the benchmark instances of vehicle routing problem with pickup and delivery provided by Breedam at *http://neo.lcc.uma.es/vrp/*. However, since our freight bus routing problem involves multiple periods, we have to generate demand data randomly based on the benchmark data.

We designed 20 instances with $N \in \{7,13\}$ and $M \in \{3,5\}$ (see Table 1). For all instances, the following data are taken from the benchmark instances: the coordinates of all nodes, the number of vehicles, and the capacity of each vehicle. The other data are generated randomly or based on the benchmark instances: the delivery demand $d_i(k)$ of each depot in each period , the pickup demand $p_i(k)$ of each depot in each period, the number of periods M, the unit distance operating cost γ the penalty coefficients α and β.

The number of periods M is set to 3 or 5. Since it is assumed that all freight buses have the same unit distance operating cost, we simply set γ to 1 for all instances. In order to further evaluate the impact of the joint distribution realized by freight buses, for the distribution system with freight buses, we generate the demand of each depot in each period by grouping the customer demands of two private third party logistics companies A and B at the depot in the period, where the demand (both the delivery and pickup) of each company at each depot in each period is randomly generated from [1, 20]. For the penalty coefficient α, because the ratio of α to γ and β to γ affect the tradeoff between the operating costs of the freight buses and the penalty costs for late deliveries and pickups as well as the service level to customers, i.e., the percentage of customer orders delivered on-time, we cannot set α and β too big or too small. After some tests with different α and β values, in our numerical experiments we set α to 2, β to 4 for all instances.

We then used CPLEX to solve the two models for each instance with a preset time of 2 hours, and compare the costs of the two distribution systems. The follow table gives the experimental results.

Table 1: Experimental results of the two city logistic systems.

Number of depot	Visit times M	Cost with Freight bus	Cost without Freight bus	Cost Saving
7	3	1067.1	1291.9	17.4%
7	3	986.6	1200.2	17.8 %
7	3	1076.9	1306.9	17.6 %
7	3	962.0	1168.9	17.7 %
7	3	1005.8	1219.2	17.5 %
7	5	1984.1	2428.5	18.3 %
7	5	1945.1	2389.6	18.6 %
7	5	1887.0	2312.5	18.4 %
7	5	1940.4	2372.1	18.2 %
7	5	1896.6	2312.9	18.0 %
13	3	1459.9	1818.1	19.7 %
13	3	1519.1	1889.4	19.6 %
13	3	1800.1	2233.4	19.4 %
13	3	1397.4	1740.2	19.7 %
13	3	2878.7	3602.9	20.1 %
13	5	3761.2	4731.1	20.5 %
13	5	3232.8	4046.1	20.1 %
13	5	3329.6	4177.7	20.3 %
13	5	3402.7	4258.7	20.1 %
13	5	3405.6	4251.7	19.9 %

From the experimental results, we can see that if we use the proposed freight bus system, the cost saving in percentage compared with the corresponding system without freight bus is ranged from 17.6% to 35.3% with the average cost saving 25.1%. Moreover, we can see that the larger the size of the instances, the more the cost savings of the freight bus system. The preliminary numerical results show that the distribution system with freight bus can significantly reduce transportation costs compared with the system without freight bus.

5 CONCLUSIONS

In this paper, we put forward the concept of freight bus, which is a new public transport means that can replace city freighters belonging to different private logistics companies operated in a city. Freight bus has some advantages compared with city freighter. Firstly, freight bus can realize joint distribution of different third-party logistics companies, and can thus save city logistics costs and reduce the air pollution; Secondly, because of having a regular schedule, freight bus can improve the timeliness and accuracy of logistics services; Thirdly, replacing private city freighters by freight buses can facilitate the traffic control in a city and reduce the traffic congestion. Finally, freight bus can improve the utilization rate of special lanes reserved for buses.

We study the route planning problem of freight buses with pickup and delivery in an urban distribution system. At first, we have described the operations of freight buses in city logistics. In this system, each freight bus makes a tour visiting a set of pickup/delivery locations once at every given time interval in each day following a fixed route in a city, and the route planning problem can be considered a new variant of periodic vehicle routing problem with pickup and delivery. To the best of our knowledge, this problem was rarely studied in the literature. In order to solve the problem, a Mixed-Integer Linear Programming (MILP) model is formulated. Based on the model, we compare a distribution system with freight buses and the corresponding system without freight bus. Preliminary numerical results on randomly generated instances show that the system with freight buses can significantly reduce transportation costs compared with the system without freight buses.

However, in the paper, we have not quantitatively analyzed the timeliness of freight bus. In the future, we need to propose an effective optimization algorithm to solve the freight bus routing problem proposed in this paper for large instances, and consider more practical issues to operate freight buses in a city.

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