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Optimization of Electric Bus Scheduling for Mixed Passenger and Freight Flow in an Urban-Rural Transit System

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***Abstract*— Transport accessibility and urban-rural connectivity are seen as critical aspects of rural economic development. In the transit network, passenger flow between urban-rural corridors demonstrates directional imbalances and low utilization of scarce resources. Freight transportation, on the other hand, lags due to poor geography, high operating costs, and scattered demand. This paper proposes a new mode of public transit that integrates passenger and freight transport, providing a carrier for logistics while compensating for the low utilization of passenger transport. In this mode, each timetabled round trip is divided into one dedicated passenger trip with high demand and one mixed-flow trip with on-demand requests. A space-time-state network is constructed considering the picking-up time window, loading/unloading service time, and electric bus energy replenishment. A mixed-integer linear programming model is developed to optimize the bus schedule that covers the travel demands and the charging requests with minimized travel costs. A Lagrangian relaxation framework with a dynamic programming algorithm and sub-gradient method is presented for problem-solving. The real-life rural-urban transport instance and a simulated network demonstrate the operation of the new mode and validate the efficiency of the proposed method. The innovative concept and the optimization framework are expected to serve as a reference for public administration to alleviate passenger and freight transportation bottlenecks in the urban-rural context.**

***Index Terms*— Urban-rural transport, mixed flow transport, mixed freight and passenger flow, electric bus scheduling, space-time-state network, Lagrangian relaxation.**

I. Introduction

SUCCESSFUL rural development strategies remain elusive in both the developed and underdeveloped world, despite attempts at the development of education, health, housing, and transport [1], [2], [3]. Structural transformation is required to mitigate the long-term decline in rural communities, including non-agricultural development and urbanization [4]. It is reported that rural growth rates are generally determined by physical transportation that serves people and goods [5], [6]. Therefore, the urban-rural integration process supported by transport accessibility has been presented as one of the transitions that allow rural communities to capture beneficial spatial spillovers from urban-based economic growth [7].

Commuting is the way of urban-rural passenger flow. It allows workers to link their work to their residence, which eases housing costs in urban areas while reducing demographic pressure on existing urban infrastructure [8]. However, the public transit that provides urban-rural commuting has an asymmetric passenger flow [9]. Traffic is considerably heavier toward than away from the urban district during the morning peak, and this phenomenon is reversed during the afternoon peak. This results in a high directional disequilibrium factor, which poses a challenge for traffic planning [10]. Due to such a typical uneven flow of passengers, corresponding strategies were presented to improve operational efficiency. Flexible transportation systems, such as a combination of scheduled and on-demand public transit, provide a potential method to reduce the number of empty trips and unnecessary stop times [11]. Further enhancements are made by incorporating intelligent systems, such as mobile applications that collect curb-to-curb booking information in advance to schedule buses accurately. Besides, communication facilities that release real-time vehicle location information assist passengers with temporary needs [12], [13]. But even if operational efficiency can be improved, the nature of commuting is doomed to imbalances. The high urban-rural operating costs, along with low and moderate bus fares, place a significant strain on bus revenue.

The urban-rural flow of goods is primarily focused on two aspects. One is the industrial and consumer freight movement from urban to rural areas via wholesale marketplaces or logistical distribution hubs. The other is agricultural product logistics, which involves moving agricultural products from farmers or agricultural operators to end-users in urban areas. This flow is conducive to rationally allocating urban and rural resources and maximizing the supportive role of urban-rural logistics in the regional economy [14]. However, road networks and consolidation and distribution centers are primarily concentrated in urban regions. Rural logistics growth, on the other hand, is lagging due to the poor topography and dispersed population [5]. For daily operations, freight carriers may face greater expenses and hence provide restricted service, exacerbating the areas' isolation [15].

The integration of passengers and goods transport appears to be a breakthrough in addressing the issue of efficient

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and un-even transport [16]. The mobility and logistics across urban-rural regions confront comparable challenges: limited transportation resources and sparse demand. Bus networks connect numerous stations in rural regions to metropolitan hubs while presenting extreme asymmetry in passenger flow. If the spare capacity of public transit is implemented to carry freight for short-haul operations, the loss of empty trips can be offset by the profitability of transporting goods. For logistics, this approach promotes the accessibility and robustness of shipments. Not only does it reach remote rural areas, but it also rationalizes the parcel delivery time through the bus schedule, which dramatically improves the service level. There are three alternatives for mixed transport using public transit: Physical bundling of freight and passenger flows: vehicle modification or redesign and interior space planning [17]; Bus re-scheduling: proposing customized scheduling or time windows for resource sharing (e.g., vehicles and lanes) [18]; Bus re-routing: adjusting existing bus routes (e.g., close to the distribution center or loading/unloading point) [19]. However, the majority of existing commercialized operating instances just use idle time windows on city roads/tracks or retired vehicle resources, while more integrated transportation still depends on the systematic schedule design and the cooperation between authorities [20].

Mixed passenger and freight transport services are still in their infancy. Currently, this service is on an ad-hoc basis in various countries, including modifying luggage racks for partial mail storage and delivery, which can relieve the pressure of urban-rural logistics to some extent, but the effect is very limited, and the subsidy to public transportation is also small [21]. The normalization of this business mode also raises the issue of fairness regarding the timeliness and safety of passengers. Thus, the design of such a system would need to address three issues: when to allow mixed passenger and freight transport, how to flexibly adjust existing bus routes for cargo loading/unloading while ensuring passenger service punctuality, and how to efficiently schedule EB operations and charging activities?

We answer three questions and provide a practical business mode for mixed passenger and freight flow based on the current public transit network. First, we look at when mixed traffic is permitted. For public transportation, a hybrid of planned and on-demand techniques is recommended, with scheduled timetables in high-traffic directions and on-demand services in low-traffic ones. We define that only low-traffic direction is assumed to be utilized for parcel delivery. To flexibly schedule the bus, we re-route the bus once it has completed one scheduled trip. The bus is allowed to deadhead to the cargo distribution center for loading before returning to the origin to service the pre-booked passengers. Based on such a novel transportation mode, we further provide a reliable scheduling method to optimize the electric bus schedules and charging plans with minimized operational costs while avoiding transportation interruptions due to energy shortages.

In this paper, we make the following contributions:

1) To standardize and normalize the mixed flow transportation service in the urban-rural transit system, a practical business model is provided. The innovative combination of three operational strategies makes this complex transport system feasible and alleviates the scarcity of logistics resources while increasing the public transit revenue.
2) The multi-dimensional network embedded in a set of hard constraints enables a concise optimization model with very few side constraints to efficiently schedule the fleet of electric buses and prepare for the charging operations. It works for various scheduling strategies and charging technologies.
3) A customized dynamic programming algorithm under the Lagrangian relaxation (LR) framework is proposed for problem solving with low time and computational burdens compared to off-the-shelf solvers.
4) Two application scenarios, including a real-world urban-rural operational case and a network-scale simulation, are designed to verify the effectiveness of the proposed approach.

The rest of this paper is organized as follows: Section II reviews the related project and prior research in this domain; Section III formulates the mixed transportation network and provides the mathematical model for optimizing bus schedules and charging schedules. Section IV introduces the solution algorithm. A real-world case study is presented in Section V. Section VI concludes the paper and discusses future expansions.

II. Related Work

The combination of passenger and cargo flow means close cooperation between logistics and transportation systems. It depends on the policy and regulation of the public administration, and the collaboration between transport participants and providers [22]. Typically, collaborative transportation systems can be divided into vertical and horizontal. For vertical collaboration, transportation is organized uniformly by service operators according to different modes. For example, the first leg of intra-city transport may be carried out by conventional trucks, while the last mile to the end-user may be carried out by emission-free urban freighters or freight bikes. In horizontal cooperation, multiple providers cooperate in the same transportation chain, for example, by sharing transportation demands and infrastructure [23].

The idea of passenger-fright collaboration has lasted for decades by means of outsourcing a portion of the transportation service in long-distance air and rail operations [24]. The European Commission first hinted at a transition toward shared passenger and freight urban transportation networks in 2007. It was suggested that urban freight distribution might be more effectively integrated into local policy-making and institutional systems [25]. Driven by this, the use of overcapacity in public transportation to convey freight for short-haul operations is receiving increasing attention but remains scarce in the literature. We summarize the application of passenger and freight integration in public transportation systems in urban and rural areas, respectively.

In the city context, considering vertical collaboration, Trentini et al [26] proposed a mathematical model and an adaptive large neighborhood search to solve a two-tiered transportation problem. They use city buses to transport goods from consolidation and distribution centers to bus stops, but that is not the focus of their research. Route planning for the last-mile delivery of the urban freight fleet was the goal, with these freighters handing off rolling containers with buses at bus stops. By implementing bus re-scheduling, Fatnassi et al. [18] jointly optimize personal rapid transit and freight rapid transit with consideration of horizontal collaboration. They introduce time windows for a single day, each exclusively providing heterogenous passenger or freight service. They attempt to reduce total energy usage and waiting time for transportation requests while taking into account the restricted battery capacity. To address and evaluate the optimization issue, a dynamic matching method and a fixed vehicle number technique are presented. A similar time slot insertion method for dedicated freight trains is proposed by Lu et al. [27] without considering physical bundling. However, none of these studies indicate the operational details such as the optimal allocation of resources, passengers, and goods. To our knowledge, Ghilas et al. [24] constructed the first bus scheduling model with mixed passenger and freight traffic. They introduced dedicated pick-up and delivery vehicles to transfer passengers or goods between bus terminals. A mixed-integer linear formulation is presented and was solved by the commercial solver CPLEX. Their case study indicates that this integration reduced the operational cost by 27% and the CO2 emission by 70%. They did, however, make two assumptions that are not realistic in real-world operations. First, they presume that parcels can be retained at the terminal until the planned departure time. Second, they anticipate that some passengers may have to wait for an extended period of time at the station hub while freight is loaded and unloaded.

Some analyzed the possibility and sustainability of integrated transportation through operational data in the urban area. Mazzarino and Rubini [19] explored the practicality of a combined passenger and freight transit system for the Venice Lagoon by developing a novel scenario-building methodology framework. According to the findings, the whole present urban transport capacity can sustain urban freight movements on the Lagoon's main links. The reduction in spare public transportation capacity and the number of circulating freight boats illustrate the positive impacts on urban sustainability in various scenarios. Cochrane et al. [28] outlined the findings of a three-round Delphi research to examine the prospects and limitations of freight on transit and to assess future operations in Toronto. They conclude that institutional hurdles may be more difficult to overcome than technological obstacles. While the existing public transit system in Toronto does not have the capacity to support any additional movements, there may be feasible opportunities to include freight service in future projects as a way to offset operating costs and lessen the effects of goods movements. This discovery motivated us to concentrate on rural-urban commuter bus lines since they had enough idle capacity outside of peak hours.

The literature on rural programs is fairly limited. Van Duin et al. [29] assessed the critical social and environmental advantages, as well as the viability of a cargo hitch business model of a rural pilot project built in the Netherlands' east. Their findings revealed that cargo hitching

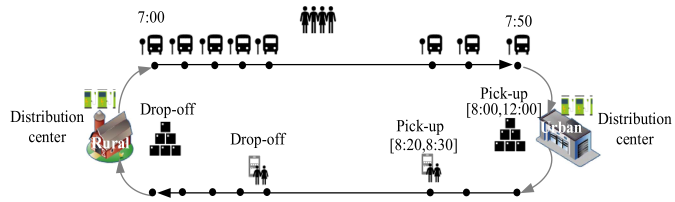


Fig. 1. Graphical representation of the MFURT system.

solutions are feasible and deliver significant environmental benefits in terms of CO2 reductions. In comparison to urban implementations, the mixed transportation mode in rural areas has been proven to have a greater influence on travel behavior and bus operations as local transit operators uncover incentives to increase public transportation utilization [17].

An emerging editorial identifies the importance of an urban-rural bus transit system with a mixed passenger-freight flow. Two challenges are raised as the main handers for mature mixed fleet transportation. One is that the rural freight market, which has traditionally belonged to logistics service providers, will be shared by transit operators and may be opposed by logistics service providers. The second is that coordination of public transportation operations and logistics services may be an obstacle. However, the authors suggest that both challenges can be easily overcome if there are many logistics service providers enrolled in the rural freight market. To illustrate the operation mode, they construct a simple framework and decide whether or not a bus carries cargo and the number of cargos. The authors conclude that the operation and planning of mixed passenger and freight urban-rural bus systems will be a focus of future research [21].

In response to the above research gaps, we attempt to advance the research frontier by designing an innovative urban-rural transportation mode for mixed passenger and freight flows. This study is expected to serve as a reference for operators to make informed decisions for integrated passenger and freight flow in the urban-rural corridor from a cost-benefit perspective.

III. Problem Formulation

In this section, we define the mixed-flow rural-urban transit (MFURT) problem. Specifically, section A states the problem, and section B illustrates the construction of a space-time-state network. Following that, the mathematical formulation is presented in section C. A reformulation under the LR framework is presented in section D to further simplify the model. Notations mentioned in this section are summarized in Table I.

A. Problem Statement

We define the MFURT problem at the operational level and propose to optimize EB scheduling and charging schedules. In this problem, bus timetables, bus fleet size, charger deployment, and passenger and cargo demand are the input conditions [30]. Fig. 1 presents an exemplary MFURT service. We consider an MFURT network of two distribution centers

TABLE I

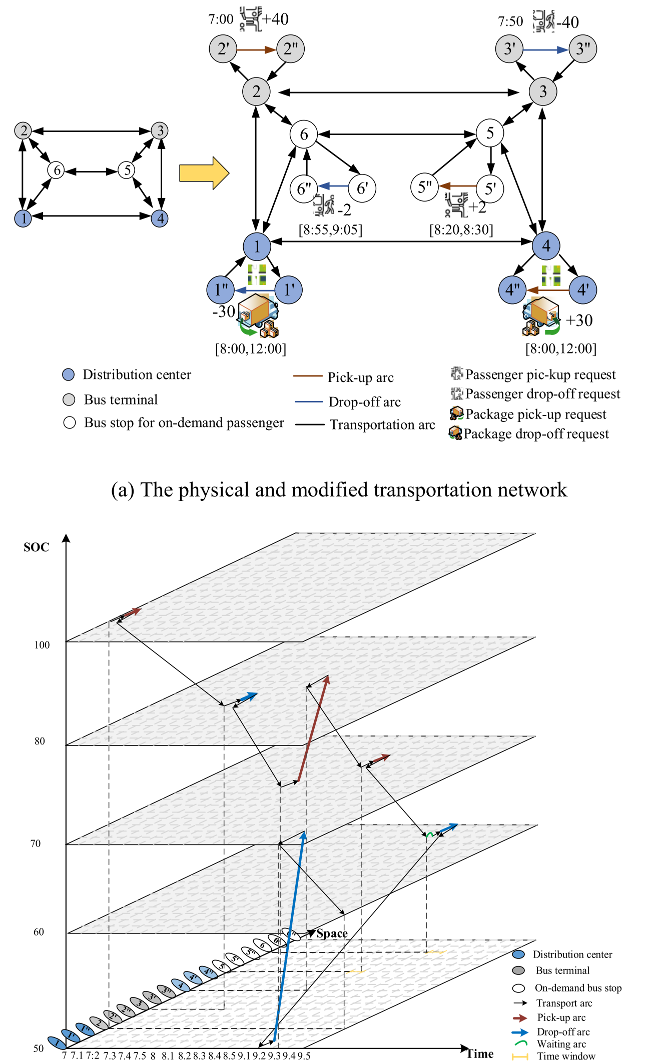
LIST OF NOTATIONS

Notation	Definition
Sets and Indices	
$\bar{V}, V$	Set of nodes, $i, i', i'', j, o_k, d_k \in \bar{V}$, $(i,t,s), (j,t,s') \in V$
$\bar{A}, A$	Set of arcs, $(i,j) \in \bar{A}$, $(i,j,t,t',s,s') \in A$, $a \in A$
P_r, D_r	Ser of picking up or dropping off arcs of request r
T	Set of time steps $t, t', t_o^k, t_d^k \in T$
S	Set of state-of-charge status $s, s', s_o^k, SOC_{min}, SOC_{max} \in S$
K	Set of electric buses $k, k^* \in K$
R	Ser of requests r
Decision variables	
$x_{i,j,t,t',s,s'}^k$	Whether bus k travels on arc $(i,j,t,t',s,s') \in A$
Parameters and other variables	
$e(i,j,t)$	Time-dependent arc energy consumption or replenishment
$TT(i,j,t)$	Time-dependent arc travel time
$c_{i,j,t,t',s,s'}^k$	Arc $(i,j,t,t',s,s') \in A$ travel cost of bus $k \in K$
$\tilde{c}_a^k$	Lagrangian relaxation-based arc $a \in A$ travel cost of bus $k \in K$
$d_{i,j,t,t',s,s'}^r$	Demand of request r on the arc $(i,j,t,t',s,s') \in \{P_r \cup D_r\}$
V_k	Capacity of bus $k \in K$
$\lambda_{k,r}$, $\bar{\lambda}_r$	Lagrangian multipliers
Z	Total travel cost of Lagrangian dual problem

with several charging piles, one bus route, and a collection of passengers and goods. EBs in this system offer passengers a scheduled service with predefined departure and arrival times (e.g., 7:00 and 7:50) during peak hours in one direction and on-demand service in the other due to passenger flow asymmetry. We are targeting low-frequency bus routes with departure intervals of up to one hour. Freight transport is only allowed to use vehicle resources in that direction where passengers are scarce. Before being transferred (e.g., from the urban to the rural area), we assume that all progressing products are gathered and stored at the distribution center. When the EB has completed a scheduled timetable trip, it might deadhead to the nearest distribution center to load multiple palettes or sets of parcels, and the time window for cargo picking up is relatively generous (e.g., 8:00-12:00). Although only on-demand service is available for passengers on the return journey, the bus still follows the original bus route while eliminating unnecessary stops. Passengers' requests, therefore, need to set up pick-up and drop-off sites along the bus route, as well as the expected time range. When the passenger service has finished, the EB may deadhead from the terminal to the nearest distribution center for unloading. During the loading/unloading process, EBs have access to chargers to refill their energy consumption. When the unloading is complete, the bus returns to the terminal to serve the next scheduled trip.

B. Illustration of the Extended Space-Time-State Network

Consider a one-dimensional physical transportation network $D = (\bar{V}, \bar{A})$ that has a number of potential bus stops $\bar{V}$ and a finite number of available arcs $\bar{A}$, where nodes $i, j \in \bar{V}$ and directed link $(i, j) \in \bar{A}$. Under planning time horizon T and restricted battery energy level S, a space-time-state network $G = (V, A)$ with several space-time-state vertices V and a set of space-time-state arcs A may extend the transportation network D. In a space-time-space context, each vertex



(a) The physical and modified transportation network

(b) Illustrative bus schedule for a round trip

Fig. 2. A toy example of the time-space-state network.

$(i, t, s) \in V$ represents both time, location, and battery state-of-charge; each arc $(i, j, t, t', s, s') \in A$ represents a directed journey from physical node i to node j departing at time t and arriving at a time t' with battery state-of-charge (SOC) changing from s to s'. In this way, the SOC dimension can describe the process of charging and discharging.

The six-node physical network is first constructed in Figure 2(a). For the on-scheduled timetable trip, only the terminals (node 1 and node 2) remain, and the demand is concentrated on terminals, as the travel times and stop patterns are fixed in this mode of operation. The network is further extended, where each requesting node for pick-up or delivery is expanded to include three nodes. The main node i stands for the physical node. Similar to [31], two dummy nodes i and i are introduced to denote the starting and ending of each service, respectively. The time duration for each service is denoted by the link between dummy nodes i and i. For distribution centers (nodes 3 and 4), the bus charging time is predefined and is included in this service duration time. When a bus is planned to cover the request, the arc between i and i must be visited for both pick-up and drop-off.

A standard time-discretized space-time network can be constructed through the procedure proposed in the papers with a minimum feasible space-time prism [31], [32], [33]. Fig. 2(b) shows the corresponding spatial and temporal variations in battery state-of-charge to demonstrate both the state transition and bus route in the space-time-state network for a round trip. The bus, according to the timetable, travels from the starting point at 7:00 and picks up 40 people via the arc $(2', 2'')$ with a fully charged battery. It arrives at the last stop after 50 minutes and passes through $(3', 3'')$ for passenger alighting. The bus then deadheads to the urban distribution center with a SOC of 70% and is loaded and recharged for 15 minutes by an arc $(4', 4)$. The bus left station 4 with SOC at 80%. Based on the on-demand passenger request and their preferred time window, the bus arrives at the passenger pick-up point 5 at 8:30 and takes these two passengers to drop-off point 6 at 8:55 after waiting for 2 mins. To finish the unloading operation, the bus arrives at the rural distribution center at 9:20 and completes 15-minute unloading and charging activities through arcs $(1', 1'')$, with the SOC climbing from 50% to 70% before returning to station 2.

In the space-time-state network, there are three types of mutually exclusive multi-dimensional arcs:

(1) Transportation arcs $(i, j, t, t + TT(i, j, t), s, s' = s - e(i, j, t))$, with travel time $(t' - t)$, energy consumption $(s' - s)$, and the time-dependent travel cost $c^k_{i,j,t,t',s,s'}$ for each bus $k \in (K \cup K^*)$. If a dummy bus $k \in K^*$ is used to serve the request, the travel cost $c^k_{i,j,t,t',s,s'}$ would be much larger. It is assumed that the travel time $TT(i, j, t)$ and energy consumption $e(i, j, t)$ are time-dependent.

(2) Service arcs $\left(i', i'', t, t', s, s' = s + e(i, j, t)\right)$ including pick-up and drop-off arcs, with a utility such as a negative travel cost for dropping off. i' and i'' belong to the same physical node i. $e(i, j, t)$ describes the amount of energy charged during the dwell time. It is assumed that the bus starts charging as soon as it reaches the starting point i'. When the charging process is assumed as linear, $e(i, j, t) = \left(t' - t\right) \cdot PowerRate$. Also, a non-linear charging process can be used, which usually depends on s, $\left(t' - t\right)$ and the charging power. we include the possible state transition in the set $\{P_r \cup D_r\}$, where $\{P_r \cup D_r\}$ denotes the r-th request for pick-up and drop-off. A positive volume d is associated with the pick-up arc, while a negative one is for the drop-off request.

(3) Waiting arcs $\left(i, i, t, t + 1, s, s' = s\right)$ with a unit waiting cost at physical node i. When buses are waiting at the depot before or after a whole day of service, the cost is defined as zero.

Bus scheduling, unlike social vehicle routing [34], has a tight time constraint based on timetables. In addition, after completing one task, the state transitions in three dimensions are highly limited by bus capacity, energy consumption, and service time windows. These restrictions computationally reduce the solution space and improve search efficiency. We believe that the rapid growth of computer technology may provide more memory and faster computing speed to meet the high number of state search decisions.

C. Model Construction

Before presenting the model, it should be noted that the space-time-state network must be pre-built, including the location of each node, the trip time or travel cost of each arc, the attribute of each arc, and the feasible SOC state transitions in the three-dimension network. Furthermore, we propose two depot nodes to indicate the flow beginning and terminating, each with its own space, time, and SOC information.

Based on these prerequisites, we now present our optimization model for the MFURT network, which aims to optimize bus schedules, ensure passenger and cargo services, and arrange the charging events for the electric bus fleet so as to minimize the total operational cost.

Primal problem:

Objective function,

$$\text{minimize} \sum_{k \in (K \cup K^*)} \sum_{(i,j,t,t',s,s') \in A} c^k_{i,j,t,t',s,s'} x^k_{i,j,t,t',s,s'} \quad (1)$$

subject to,

(1) Flow balance constraint for each bus k:

$$\sum_{(o_k, j, t^k_o, t', s^k_o, s') \in A} x^k_{i,j,t,t',s,s'} = 1, \quad \forall k \in (K \cup K^*) \quad (2)$$

$$\sum_{(i, d_k, t, t^k_d, s, s^k_o) \in A} x^k_{i,j,t,t',s,s'} = 1, \quad \forall k \in (K \cup K^*) \quad (3)$$

$$\sum_{i,t,s:(i,j,t,t',s,s') \in A} x^k_{i,j,t,t',s,s'} = \sum_{i,t,s:(i,j,t,t',s,s') \in A} x^k_{j,i,t',t,s',s}$$
$$\forall k \in (K \cup K^*), \quad \forall \left(j, t, s'\right) \notin \left\{\left(o_k, t^k_o, s^k_o\right), \left(d_k, t^k_d, s^k_o\right)\right\} \quad (4)$$

(2) Pick-up and delivery coupling constraint for each bus k and each request r:

$$\sum_{(i,j,t,t',s,s') \in P_r} x^k_{i,j,t,t',s,s'} = \sum_{(i,j,t,t',s,s') \in D_r} x^k_{i,j,t,t',s,s'}$$
$$\forall k \in \left(K \cup K^*\right), \quad \forall r \in R \quad (5)$$

(3) Mandatory visiting constraint for pick-up of request r:

$$\sum_{k \in (K \cup K^*)} \sum_{(i,j,t,t',s,s') \in P_r} x^k_{i,j,t,t',s,s'} = 1, \quad \forall r \in R \quad (6)$$

(4) Capacity limitation for each bus:

$$\sum_{r \in R} \sum_{(i,j,t,t',s,s') \in \{P_r \cup D_r\}} d^r_{i,j,t,t',s,s'} \cdot x^k_{i,j,t,t',s,s'} \leq V_k$$
$$\forall k \in \left(K \cup K^*\right) \quad (7)$$

(5) Binary decision variable:

$$x^k_{i,j,t,t',s,s'} \in \{0, 1\} \quad (8)$$

The objective function in Eq. (1) is designed to minimize the total costs of all types of selected arcs, including travel costs, waiting expenses, and service revenue. Eqs (2-4) are the standard vehicle-based traffic balance constraints with a given initial departure state (o_k, t^k_o, s^k_o) and end-of-service state (d_k, t^k_d, s^k_o) for each vehicle. The possible traveling arcs are enumerated in the space-time-state arc sets A with proper SOC limitation and specification of the flow direction.

Eq. (5) ensures that each demand r containing both pick-up and delivery needs to be served by the same vehicle within a given time window. Eq. (6) indicates that the pick-up and delivery arcs for each demand should be visited by exactly one bus. Eq. (7) ensures that the capacity limitation is respected. The decision variable $x^k_{i,j,t,t',s,s'}$ defined in Eq. (8) is a binary variable indicating whether the arc (i, j, t, t', s, s') is selected in the 3D route of bus k. Finally, our proposed model is a 0-1 integer linear programming model, which can be solved directly in a commercial solver.

D. LR Framework

The 3D structure of the decision variable would raise the computational complexity, which should be properly addressed by dedicated procedures and innovative solution frameworks.

In this section, we relax the model introduced by relaxing Eqs (5-7) with two lagrangian multipliers $\lambda_{k,r}$ and $\bar{\lambda}_r$ in the objective function to reduce the number of constraints in the primal problem. Let parameter a represents the link $\left(i, j, t, t', s, s'\right)$. The dualized Lagrangian function is shown in Eq. (9).

$$Z = \sum_{k\in(K\cup K^*)} \sum_{a\in A} c^k_a x^k_a + \sum_{k\in(K\cup K^*)} \sum_{r\in R} \lambda_{k,r}\cdot\left(\sum_{a\in P_r} x^k_a - \sum_{a\in D_r} x^k_a\right) + \sum_{r\in R} \bar{\lambda}_r \cdot \left(\sum_{k\in(K\cup K^*)} \sum_{a\in P_r} x^k_s - 1\right) \tag{9}$$

We aggerate all x^k_a related cost in parameter $\tilde{c}^k_a$. The problem can be formulated as follows.

Lagrangian dual problem:

Objective function,

$$Z = \sum_{k\in(K\cup K^*)} \sum_{a\in A} \tilde{c}^k_a x^k_a - \sum_{r\in R} \bar{\lambda}_r \tag{10}$$

where,

$$\tilde{c}^k_a = \begin{cases} c^k_a + \lambda_{k,r} + \bar{\lambda}_r, & \left(i, j, t, t', s, s'\right) \in P_r \\ c^k_a - \lambda_{k,r}, & \left(i, j, t, t', s, s'\right) \in D_r \\ c^k_a, & \text{otherwise} \end{cases}$$

Subject to,

Eq. (2)−Eq. (4) and Eq. (7)

IV. Solution Framework

In the LR framework, the MFURT problem is transformed into a time- and state-dependent constrained shortest path problem. We introduce an LR process to obtain the optimal solution to the primal problem based on a dynamic programming algorithm. Table II lists the notations for the symbols required for the LR-based algorithm.

TABLE II
Notations Used in LR Algorithm

Symbol	Definition
$L(i,t,s)$	Label cost of 3D vertex (i,t,s)
d_k	Accumulated load of bus k
v	Iteration number
$\bar{\lambda}_r{}^v$	LR multiplier represents the request r 's pick-up constraint at iteration v
$\lambda_{k,r}{}^v$	LR multiplier represents the pairing constraint of request r and bus k at iteration v
UB^*	Best global upper bound for the prime problem
LB^*	Best global lower bound for the prime problem
UB^v	Global upper bound for the primal problem at iteration v
LB^v	Global lower bound for the primal problem at iteration v
$\bar{\theta}^v_r, \theta^v_{k,r}$	Parameter of updating LR multipliers
$\nabla L^v_{\lambda_{k,r}}, \nabla L^v_{\bar{\lambda}_r}$	The change of LR multipliers at iteration v

A. Dynamic Programming for Constrained Shortest Path

In this section, we use the dynamic programming (DP) algorithm to solve the constrained shortest path problem obtained in Section III. DP is an efficient algorithm that is widely used for problem solving [35]. Mahmoudi and Zhou [36], for the first time, implemented DP, the three-dimensional shortest path problem, and they claimed that the 3D structure ensures the advanced time and status of the network.

Algorithm 1 described below uses dynamic programming, in which a label correction algorithm is coded to manipulate unprocessed and useful paths.

Algorithm 1 Time- and State- Dependent Forward Dynamic Programming Algorithm

For each bus $k \in \left(K \cup K^*\right)$ **Do**
// Initialization
  Label cost $L\,(.,.,.) := +\infty$;
  Node predecessor of vertex $(.,.,.) := -1$;
  Space predecessor of vertex $(.,.,.) := -1$;
  State predecessor of vertex $(.,.,.) := -1$;
  Set load d_k for bus $k \in \left(K \cup K^*\right)$ to 0;
  // Bus k starts from depot with $L\left(o_v, t^v_o, s^v_o\right) = 0$
  For the entire operating period $t \in (t^v_o, t^v_d)$ **Do**
    Foreach link (i, j) **Do**
      Foreach state s **Do**
        derive downstream state $s' = s \pm e(i, j, t)$;
        derive arrival time $t' = t + TT(i, j, t)$;
          If $d_k + d_{i,j,t,t',s,s'} \leq V_k$ **and** $L\,(i, t, s) + \tilde{c}^k_{i,j,t,t',s,s'} < L\left(j, t', s'\right)$ **and** $s' \in [SOC_{min}, SOC_{max}]$ **Then**
            $d_k = d_k + d_{i,j,t,t',s,s'}$ //load update
            $L\left(j, t', s'\right) = L\,(i, t, s) + \tilde{c}^k_{i,j,t,t',s,s'}$ //label update
            Node predecessor of vertex $\left(j, t', s'\right) := i$;
            Node predecessor of vertex $\left(j, t', s'\right) := t$;
            State predecessor of vertex $\left(j, t', s'\right) := s$;
        End If;
      End For;
    End For;
  End For;
End For;

Output: state–time path for each vehicle

B. Solution Algorithm Under LR Process

The LR-based Algorithm 2 is presented in this section. The optimum value generated by the Lagrangian dual problem can

Algorithm 2 LR Procedure

// Initialization
Ser iteration number $\upsilon = 0$;
Ser LR multipliers $\lambda_{k,r}$, $\bar{\lambda}_r$ to base value;
Initialize upper and lower bound solutions $\{x^0_{UB}\}$, $\{x^0_{LB}\}$;
Initialize upper bound $UB^* = +\infty$, lower bound $LB^* = -\infty$;
Define a termination condition, a gap between UB^* and LB^*
While termination condition is false, for each iteration υ
Do
Reset the visit count for each arc $a \in \{P_r \cup D_r$ to 0;
// Step 1. Calculate LB^υ
Initialize $LB^\upsilon = 0$
For each bus $k \in (K \cup K^*)$
Do
//input: $\tilde{c}^k_a$
Call Algorithm 1 based on arc cost $\tilde{c}^k_a$;
Update the visit count for each arc $a \in \{P_r \cup D_r$;
//Output LB^υ
End For
// Update LB^*
Substituting solution vector LB^υ in Eq. (10);
Update $LB^* = \max(LB^*, LB^\upsilon)$ and x^*;
// Step 2. Update LR multipliers
Calculate the visit of each request arc in P_r:
$\sum_{k \in (K \cup K^*)} \sum_{a \in P_r} x^k_a$
//Update arc multipliers $\bar{\lambda}^{\upsilon+1}_r$ and sub-gradient $\nabla L^\upsilon_{\bar{\lambda}_r}$ for each request with the following equations:
$\nabla L^\upsilon_{\bar{\lambda}_r} = \sum_{k \in (K \cup K^*)} \sum_{a \in P_r} x^k_a - 1$,
LR multiplier: $\bar{\lambda}^{\upsilon+1}_r = \bar{\lambda}^\upsilon_r + \bar{\theta}^\upsilon_r \cdot \nabla L^\upsilon_{\bar{\lambda}_r}$,
Step size: $\bar{\theta}^\upsilon_r = \frac{\bar{\theta}^0_r}{\upsilon+1}$
Checking the pairing between bus k and request r:
$\sum_{a \in P_r} x^k_a$
$\sum_{a \in D_r} x^k_a$
Update arc multipliers $\lambda^{\upsilon+1}_{k,r}$ and sub-gradient $\nabla L^\upsilon_{\lambda_{k,r}}$ for each bus and each request with the following equations:
$\nabla L^\upsilon_{\lambda_{k,r}} = \sum_{a \in P_r} x^k_a - \sum_{a \in D_r} x^k_a$
LR multiplier: $\lambda^{\upsilon+1}_{k,r} = \lambda^\upsilon_{k,r} + \theta^\upsilon_r \cdot \nabla L^\upsilon_{\lambda_{k,r}}$
Step size: $\theta^\upsilon_{k,r} = \frac{\theta^0_{k,r}}{\upsilon+1}$
Update the arc cost for $a \in \{P_r \cup D_r$
$\tilde{c}^k_a = \begin{cases} c^k_a + \lambda^{\upsilon+1}_{k,r} + \bar{\lambda}^{\upsilon+1}_r, a \in P_r \\ c^k_a - \lambda^{\upsilon+1}_{k,r}, a \in D_r \end{cases}$
// Step 3. Generate UB^υ
Find a feasible solution for the primal problem with the result in Step 1.
For each request r:
Ifthe pick-up requests are being served by more than one EB, then designate one of the EBs for the request.
Ifboth the pick-up and drop-off requests are not being served by any EB, then assign a backup EB for both requests.
Ifthe pick-up and drop-off requests are partially served, then designate the original EB and assign a backup EB for both requests.
End For
Calculate the upper bound UB^υ based on the feasible solution $\{x^\upsilon_{UB}$
Update the upper bound $UB^* = \min\left\{UB^*, UB^{(k)}\right\}$
//Step 4: Evaluate the solution quality
Calculate the relative gap percentage by $\frac{UB^* - LB^*}{UB^*} \times 100\%$
$\upsilon = \upsilon + 1$
End while

be seen as the lower bound to the primal problem. This strategy calls algorithm A and updates the arc cost $\tilde{c}^k_a$. By calculating the path cost for each vehicle, the solution is generated. If the optimal solution of the Lagrangian dual problem is feasible for the primal problem, we have certainly got the optimal solution for the primal problem. If this is not the case, we use a heuristic to determine an upper bound for the primal solution based on the solution of the lower bound. In the heuristic, the demand satisfaction would be checked, and virtual EBs would be dispatched to provide services for requests not accessed by physical EBs.

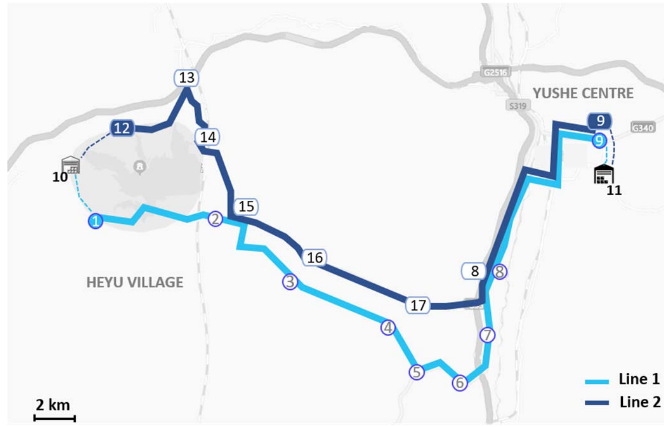


Fig. 3. Urban-rural bus routes.

C. Computational Complexity Analysis

First, we define the length of each set, $|K|$ for buses, $|T|$ for time stamps, $|A|$ for possible connections, $|S|$ for SOC status. The worst case of DP is traversing every element in the four-level loop, and the complexity becomes $|K| \cdot |T| \cdot |A| \cdot |S|$. It should be noted that the SOC state is uniquely determined by the preceding state and the associated link (i, j), depending on its service type: pick-up and delivery, transport, or waiting. Furthermore, in the transport network, the feasible links are much smaller than their counterparts in the complete graph, which is determined by the time window and direction, i.e., $|A|$ is much smaller than $|V| \cdot |V|$. For the time dimension, the bus timetable trips have strict departure times, while on-demand passengers have a small window of time to be picked up. Although the time window for container loading is relatively soft, it will not cover the entire timestamp.

V. Case Study

In order to verify the optimality and computational efficiency of the proposed algorithm, two scenarios are formulated to validify the efficiency of the proposed method. The algorithm is coded in Python and executed on a Windows computer equipped with Intel(R) CPU(TM) i7 -8650U CPU, 1.90 GHz, and 16 GB RAM.

A. Real-World Scenario

Two urban-rural bus routes in Shanxi Province, China, are used as an example to show how to integrate passenger and freight transport. Both the rural and urban terminals are close to a distribution center, at distances of 3 km and 2 km, respectively. Energy replenishment is planned at the distribution center with a charging power of 450 kW and a charging efficiency of 0.95. We are targeting two bus lines with lengths of 40.2 km and 37.3 km, as shown in Fig. 3. They share the same city terminal and cover 8 and 7 rural stations, respectively. The one-way operating time is 70 minutes for

TABLE III
BUS LINE INFORMATION OF THE URBAN-RURAL BUS ROUTES

Bus line 1			Bus line 2		
From	**To**	**Distance (km)**	**From**	**To**	**Distance (km)**
10	1	3	10	12	3
1	2	6.12	12	13	3.63
2	3	6.58	13	14	3.19
3	4	4.9	14	15	4.4
4	5	2.16	15	16	3.49
5	6	3.6	16	17	5.83
6	7	2.6	17	8	4.51
7	8	2	8	9	12.28
8	9	12.28	9	11	2
9	11	2			

TABLE IV
TIMETABLE AND ON-DEMAND REQUEST

Bus line 1			Bus line 2		
Morning trip from node 1 to node 9			Morning trip from node 12 to node 9		
No.	Departure	Arrival	No.	Departure	Arrival
1	6:00	7:10	7	6:10	7:15
2	7:30	8:40	8	8:10	9:15
3	9:00	10:10	9	10:10	11:15
Afternoon trip from node 9 to node 1			Afternoon trip from node 9 to node 12		
4	15:00	16:10	10	15:10	16:15
5	16:30	17:40	11	17:10	18:15
6	18:00	19:10	12	19:10	20:15
On-demand request for passenger (P) and cargo (C)					
No.	From	To	Pickup time window		Load (P/C)
13	9	3	[7:40, 7:50]		2 P
14	9	8	[9:00,9:10]		4 P
15	9	15	[9:10,9:40]		3 P
16	4	8	[15:20,15:30]		2 P
17	12	9	[16:10,16:20]		6 P
18	1	9	[17:00,17:10]		8 P
19	12	8	[18:30,18:40]		5 P
20	8	2	[9:30,9:40]		5 P
21	11	10	[7:00,12:00]		20 C
22	11	10	[7:00,12:00]		20 C
23	10	11	[10:00,15:00]		20 C
24	10	11	[14:00,19:00]		20 C
25	10	11	[17:00,19:00]		20 C

line 1 and 65 minutes for line 2. The distance between stations is shown in Table III.

In China, urban-rural buses run at intervals of over an hour, typically three round trips in the morning, a long break during off-peak hours, and three round trips in the afternoon. Due to the extreme asymmetry in passenger flow, only the trips in the direction of high demand are retained as scheduled trips, while trips in the opposite direction are changed to on-demand requests. These on-demand requests can further include the need to transport goods from one distribution center to another by re-routing the EBs. We summarize the adjusted schedules and on-demand requests in Table IV. Referring to Mahmoudi and Zhou [36], the operational cost of a transportation arc traversed by a physical bus is assumed to be \$22/h, while the expenses for a virtual one is \$50/h. Besides, the waiting cost of a physical bus is \$15/h, while waiting at depots is assumed to cost \$0/h. The revenue of passenger service is assumed to be \$10. Because the transit system focuses primarily on passenger service, the service allowance for goods is set at half the passenger rate. The initial value for LR multipliers is 2.

TABLE V
OPTIMIZED SCHEDULE FOR EACH EB

Bus	Bus route	SOC (%) profile
1	1-(21&13)-9-4-18-12	76-100-76-53-29-6
2	2-(14&15)-23-10-17-6	76-53-100-77-54-30
3	7-22-3-5-(25&19)	77-100-75-52-100
4	8-20-(24&16)-11	77-52-100-77

* Each SOC value represents the energy left after finishing serving a single trip. All buses depart from a virtual depot with 100% SOC. When the bus serves a request for goods, it can get charged at both the origin and destination. Thus, the SOC could reach 100% after unloading the goods.

TABLE VI
CHARGING STRATEGY FOR EACH EB

Bus	Charging location	Charging start time	Charging duration (min)	From SOC (%)	To SOC (%)
1	11	7:16	11	75	100
	10	9:06	12	73	100
2	10	10:21	20	52	100
	11	11:52	9	77	100
3	11	7:28	9	77	100
	10	8:41	9	77	100
	10	17:46	21	50	100
	11	19:41	11	75	100
4	10	10:56	20	52	100
	11	16:06	11	75	100

For mixed passenger and cargo journeys, we specify the number of passengers or cargo per requirement and ensure that the load on board is less than the capacity (for example, 20 passengers and 20 containers). Four EBs are available for daily operation, each with a 300-kWh battery capacity. A unit consumption of 1.8 kWh/km is assumed for the EB fleet. We assume that it takes 10 minutes to load and unload 20 containers and less than 1 minute to board and alight passengers. During the container loading/unloading time, the energy replenishment would achieve 7.125 kWh per minute under the linear charging procedure. We offer a variety of charging time (dwell time) options on the virtual arcs (e.g., $(10', 10'')$ and $(11', 11'')$) to ensure that the goods can be loaded while having enough power to support subsequent journeys.

The optimized result is shown in Table V. It indicates that all passenger and cargo demands can be met within the time window and that there are three sets of passenger demands combined with cargo movements. Furthermore, we discovered that no EBs were operating on empty. Suppose the EB is unable to pick up a passenger within the time window after performing the scheduled trip. In that case, it will choose to carry the cargo exclusively to improve transport efficiency.

Due to the long rural-urban bus routes, each EB is charged at least twice, while bus 3 has four charges. We assume that the EB does not have the opportunity to be charged during the midday break. The specific charging schedule, charging duration, charging start times, and SOC fluctuations are shown in Table VI. Thanks to the high-power charger, the EB can be

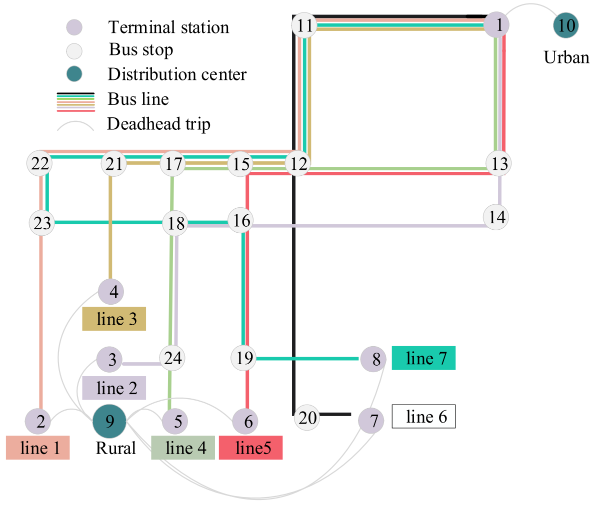


Fig. 4. Simulated urban-rural bus network.

TABLE VII
FIXED SCHEDULE FOR BUSES

	Request ID	Departure	Arrival	Energy consumption
Line 1 (node 1 to node 2)	1	15:00	16:50	30 kWh
	2	17:00	18:50	30 kWh
Line 2 (node 1 to node 3)	3	15:30	17:00	25 kWh
	4	17:30	19:00	25 kWh
Line 3 (node 1 to node 4)	5	16:30	18:00	25 kWh
Line 4 (node 1 to node 5)	6	15:10	16:40	25 kWh
	7	17:10	18:40	25 kWh
Line 5 (node 1 to node 6)	8	16:50	18:20	25 kWh
Line 6 (node 1 to node 7)	9	16:40	17:50	19 kWh
Line 7 (node 1 to node 8)	10	17:20	20:00	44 kWh

replenished with 50% of its energy in 21 minutes, making a full charge the ideal alternative while loading and unloading freight.

The results show that the LR algorithm can converge in fourth iterations and achieve the upper bound solution without a gap. This is due to the fact that our upper bound is derived from the lower bound solution, which is consistent with Ref. [37]. We modify the solution of the lower bound in three cases: (1) If the pick-up requests are being served by more than one EB; (2) If both the pick-up and drop-off requests are not being served; (3) If the pick-up and drop-off requests are partially served.

B. Network-Scale Simulation

In this section, we extend the urban-rural bus network in [21], as shown in Fig. 4. Similar to [36], four scenarios are randomly generated in the transportation networks, while the schedules of the seven bus lines in the high-traffic direction are fixed and are shown in the Table VII. We only address bus operations in the afternoon hours, where buses departing from the city and arriving in the countryside run on the schedule, while the reverse is booked in advance. The on-demand passengers and cargoes only determine the origin and destination and the corresponding time windows, without specifying a specific bus line. Cargoes are allowed to be loaded from the rural distribution center 9 and unloaded at the urban distribution center 10. The EB battery and charging post configurations are the same as in the preceding section. Table VIII shows the optimal results.

TABLE VIII
RESULT OF NETWORK-SCALE SIMULATION

Case No.	**Demand**	**Gap**	**Number of run-overed requests**	**CPU run time (sec)**
1	20P + 20C	0.00%	0	12.54
2	40P + 40C	0.00%	0	36.20
3	100P+100C	3.28%	4P	217.69
4	60P + 200C	2.63%	20C	282.15

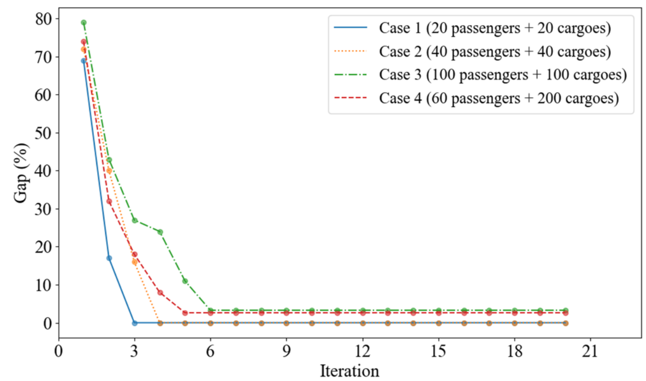


Fig. 5. Gap percentage along 20 iterations in four scenarios.

The proportion of gaps in 20 iterations is shown in Fig. 5, which is consistent with the results in [36] that the proposed method converges after a limited number of iterations. In the simulated network, the sub-gradient method often converges to a tiny gap (less than 4%). Additionally, we solved the four cases in which the optimal gap was set at 5% using the off-the-shelf solver in order to confirm the model's efficacy. We find that cases 1 and 2 can be solved by GAMS with a gap of 0.00% and CPU run times of 94.33s and 167.09s, respectively. However, as the demand increases, cases 3 and 4 cannot find the optimal solution with a gap of less than 5% in one hour. We can infer from the performance that the Lagrangian multiplier, which is consistent with the results in [33], is used to dynamically regulate the cost of passenger/cargo pick-up and drop-off, resulting in better computational efficiency and accuracy of our proposed algorithm for network-scale applications.

VI. CONCLUSION

MFURT services offer an innovative and cost-effective solution for public transportation providers, logistics providers, and authorities to improve the coverage of logistics services and balance the directional transportation demands. In places with scattered freight demand, the use of buses for freight transport has the potential to enhance on-time performance by displacing the usage of logistics transport vehicles. Focusing on minimizing operational costs, this paper describes the MFURT design problem within a space-time framework. The work described provides systematic technical direction and has important methodological implications.

Technical direction for standardized MFURT services is first provided, which helps construct innovative transportation solutions. Three strategies are raised for efficient operation: physical bundling, re-scheduling, and re-routing. Physical bundling enables passengers and freight to use the same transport resource at the same time with physical separations in between, but only in the off-peak direction. Re-scheduling splits the original round-trip into a scheduled trip and an on-demand request to allow flexible adjustment of EB schedules while ensuring the service level for passengers. Re-routing allows EBs to travel from the terminal to the nearest distribution center for cargo loading/unloading and recharging, where chargers are available for energy replenishment.

At the methodological level, the problem is first formulated in a space-time-state network with pairing and capacity constraints in the pick-up and delivery context. The multi-dimensional structure embedded in a set of hard constraints enables a concise model with very few side constraints. The computational complexity caused by the extended dimension is reduced by forming the feasible arc sets to narrow the search region and reformulating the model under the LR framework to tackle the constraints. The dualized Lagrangian model can be easily solved by resource-constrained shortest path algorithms, while the sub-gradient-based pricing method ensures the pairing of picking up and dropping off requests. The proposed optimization model and solution algorithms are systematically tested on a real-world urban-rural transportation system in Shanxi province, China, and a simulated large network. The results demonstrate the capacity of the proposed model to efficiently perform logistics transportation while ensuring passenger demands are met. These findings offer preliminary insight into the MFURT benefits, but more experiments employing different city logistics contexts are required to generalize them.

The design of the MFURT service has the potential to be integrated into the existing multimodal transportation system, extend the rural freight delivery market, and solve the problem of rural logistics backward development and restrictive infrastructure. However, logistics service providers must share the cargo transportation market with public transit operators at the management level, and cooperation between the two parties may constitute a hurdle to large-scale deployment. According to Qu et al. [21], if the rural freight market has numerous logistics service providers, both sharing and coordination concerns may be resolved; however, if there is a monopoly or oligopoly market, a sizable government and industry effort will be required to address the challenges.

In future research, the impact of pricing of transportation for both passenger and cargo can be further evaluated when on-demand passenger and cargo transport conflict, priority design, or price regulation become new challenges. Since the value of the Lagrangian multiplier for each request can be interpreted as the real-time price of service for a single trip, we will concentrate on the design of the updating rules for the multiplier to reflect the new regulations so as to better approach the final global optimal scheduling solution. Besides, more work will go into analyzing algorithm efficiency, and the suggested approach will be enhanced using parallel computing techniques for real-world large-scale scenarios.

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