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A Matching Model for Door-to-Door Multimodal Transit by Integrating Taxi-Sharing and Subways

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Abstract: We present a sustainable multimodal transit system that integrates taxi-sharing with subways to alleviate traffic congestion and restore the cooperative relationship between taxis and subways. This study proposes a two-phase matching model based on optimization theory, in which pick-up/drop-off sequences for participants, as well as their motivation to shift to a TSS service, were considered. For the transportation system, achieving a reduction in vehicle miles is considered to be the matching objective. We tested the matching model using empirical taxi global positioning system (GPS) data for a typical morning rush hour in Beijing. The optimization model performs well for large-scale data and the optimal solution can be calculated quickly, which is ideal in a dynamic system. Furthermore, several sensitive analysis experiments were conducted to evaluate the performance of the TSS system. We found that approximately 23.13% of taxi users can be served by TSS transit, total taxi mileage can be reduced by 20.17%, and carbon dioxide emissions may be reduced by 15.16%. The proposed model and findings demonstrate that the TSS service considered here is a feasible multimodal transit mode, with the advantages of flexibility and sustainability, and has great potential for improving social benefits.

Keywords: taxi-sharing; subway; multimodal; matching model; MaaS service

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1. Introduction

Public transport is regarded as one of the most effective methods to mitigate serious road congestion and air pollution [1,2]. Traditional public transportation modes in urban areas include subways, buses, trams, and taxis. The various transportation modes have different responsibilities in interdependent public transit networks to achieve high-efficiency and energy-saving targets. In densely populated cities, subway services are frequently the dominant mode of public transportation because they are sustainable and have high passenger capacities. Taxis, which provide a car-like service with low capacity, are designed to provide a feeder service to subways or buses and serve as a substitute in areas that are inaccessible via other public transportation modes [3]. Connecting a subway via a taxi can reduce car ownership and attract more passengers to the subway because such practices extend the accessibility of fixed subway lines. In some cities, taxis have become competitors to subways within city centers, where most taxi trips can be served by the subway; in such cases, the primary usage of taxis (i.e., to extend the subway system) only accounts for a small proportion of actual use [4,5]. This problem has been neglected by most scholars and the taxi mode has been omitted in most transportation mobility and multimodal connection studies [6]. Consequently, it is necessary to study how to resolve the competition and restore the cooperative relationship between taxis and subways.

Taxis may waste road resources when driving without passengers or waiting for passengers. This waste may even occur when traveling with passengers, as the seats in the taxi may not always be fully occupied [7,8]. To overcome these issues, taxi ridesharing may be considered an environmentally friendly and sustainable mobility service. Ridesharing is a transportation mode whereby travelers can travel together. This is not a new concept and can be traced back to World War II [9]. With the development of mobile technology and global positioning systems (GPSs), ridesharing has become a convenient and popular on-demand service in recent years. Ridesharing is a joint trip of at least two participants with similar itineraries and time schedules that share a vehicle [9,10]. Taxi ridesharing is a similar service to typical ridesharing, except that passengers share rides in taxis instead of private cars [11,12]. Herein, we refer to such practices as taxi-sharing, which means that passengers with similar itineraries and schedules can share their rides in the same taxi. Unlike a conventional taxi service, taxi-sharing is an app-based service. Passengers can obtain a taxi-sharing service by providing trip information from their mobile phones instead of finding a taxi at the roadside. Moreover, passengers have opportunities to enjoy lower fares due to this sharing behavior; the disadvantage is that they may also need to tolerate additional detour costs induced by other riders, which are not involved in a conventional taxi service. From the perspective of passengers, taxi-sharing can be regarded as a special type of demand-responsive transport (DRT). DRT has become another popular concept in recent years, providing flexible routes and timetables based on travel demand [13]. Generally, the travel demand of all participants in a DRT service will be satisfied by selecting an appropriate route [14,15]; however, this is not the case for taxi-sharing. Taxi-sharing may not provide service to a rider if his or her trip is far away from the others. From an operational perspective, a DRT service is only launched when there is travel demand [16], whereas taxis always operate, despite a lack of transit requests.

The combination of taxi-sharing and subway (TSS) transit modes can form a novel transit mode that is more sustainable than a traditional multimodal taxi and subway service. Few studies have analyzed TSS integration. This may be due to the complexity of the matching mechanism for multimodal transit.

Herein, a data-driven multimodal TSS transit model is regarded as an encapsulated service that differs from the first-mile problem encountered by taxi-sharing and follows the concept of "mobility as a service" (MaaS) [17]. Passengers purchase packaged shared services, including TSSs, according to their travel demand, rather than only the feeder service. From a practical perspective, the additional operating cost is limited because taxi and subway services are two commonly used transit modes. From the user perspective, the MaaS scheme is more convenient and can provide support for seamless multimodal journey plans and multiple corresponding transit services for all trips. We propose a two-phase matching model for taxi users, which is the core of TSS services. The TSS service was examined using actual taxi trip data obtained from Beijing; a sensitivity analysis with various factors was performed to evaluate its performance. Some policies have been proposed to promote TSS performance. The results obtained here can provide valuable insights into the development of practical TSS matching systems.

The remainder of this paper is organized as follows. In Section 2, we present a literature review related to shared mobility and the integration of a shared multimodal transit scheme. In Section 3, we describe strategies of TSS service. In Section 4, we introduce the methodology of the model-matching scheme in the TSS multimodal service. In Section 5, we investigate the TSS performance and sensitivity analysis, using Beijing as a practical case study. Finally, Section 6 summarizes the main conclusions and discusses future work.

2. Literature Review

2.1. Taxi-Sharing and Subway Multimodal Transit Service

Shared mobility has become popular in theoretical research and practice owing to the development of information and communication technologies in recent years. It is defined as a short-term access to shared vehicles according to the passenger's needs and convenience that does not require vehicle ownership [18–20]. Shared mobility includes many services, such as carsharing, bike-sharing, and ridesharing. Ridesharing is one of the most commonly shared transportation modes worldwide, where travelers and drivers send their requests to a ridesharing platform via mobile phones and then receive the matched trip plan. The principle of ridesharing is that, in a shared group, the itineraries and scheduled times of travelers are similar. This shows that ridesharing services can improve the utilization of available seats in vehicles and effectively reduce the number of automobiles on the road. According to the number of participants in a shared trip, there are four basic ridesharing schemes: single-driver–single-rider strategy, single-driver–multiple-rider strategy, multiple-driver–single-rider strategy, and multiple-driver–multiple rider strategy [12]. The first operating scheme is prevalent in today's market [21]. In ridesharing services, drivers are private car owners who have their own itineraries and share rides to split travel costs. Taxi ridesharing is analogous to ridesharing except that the taxi drivers are employed and transport passengers via taxis for profit [11].

As the shared mobility service presents advantages for travelers, operators, and social systems, integrating shared mobility into public transportation has become a new focus of research interest. Public transportation agencies in many cities are designing multimodal integration of shared mobility services—such as bike-sharing and car-sharing—with public transit [22]. Some ridesharing intermodal modes have been explored in different studies, such as research on connecting public transit with ridesharing, ride-splitting, and shared autonomous vehicles [23–25]; however, few studies have focused on taxi-sharing, which can also be a part of multimodal transit. Ma et al. [26] reported that there is a significant potential for taxi-sharing at airports. Most studies have simply regarded shared mobility as a feeder service, which is a solution to the first/last mile problem of public transit. Few studies have analyzed the integration of multimodal services from all trips that belong to the MaaS service scheme. To the best of our knowledge, the study by Ma et al. [27] was the first to consider ridesharing and public transit multimodal services as integrated door-to-door services.

2.2. Matching Model of Shared Multimodal Transit

The key problem in ridesharing is determining how to group travelers according to their travel plans [28]. In taxi ridesharing, at least two passengers will be served. Therefore, in addition to determining the shared group, another key problem in taxi-sharing is the pick-up and delivery problem. Moreover, intermodal transfer between taxi-sharing and the subway is another challenge in the TSS integrated service.

In ridesharing, an effective approach for solving the matching problem is the mathematical programming method. The objectives of the optimal matching model are designed from two perspectives, i.e., the viewpoint of the operator, where earning a profit is the goal of the ridesharing matching scheme, and social benefits, where the ultimate goal is to reduce road congestion and air pollution. These goals can be achieved simultaneously by developing specific objective functions, such as minimizing the number of vehicle miles in the system, minimizing the travel time in the system, and maximizing the number of participants [21,29–31]. In some studies, the attractiveness of ridesharing is guaranteed and considered in the matching model via the constraint of participants saving travel costs [10,21,29,32]. Models in most of the aforementioned studies can only be solved via heuristic algorithms; moreover, they are not tested in large-scale instances. In practice, it is better to reduce computational complexity when applying the optimization model to real-life instances. A limited number of studies have focused on developing an integer linear programming model or obtained an optimal solution based on large-scale instances [32,33].

Compared with ridesharing, passengers in taxi-sharing have an additional problem: the sequencing of pick-up and drop-off. Qian et al. [11] avoided this issue by presetting meeting places for passengers who have similar travel plans. Lin et al. [34] proposed an optimization model of a vehicle route that aims to minimize the total operation cost and maximize passenger satisfaction. In this model, all passengers must be served and the similarity of the trips is neglected; however, transporting similar itineraries is the core concept of taxi ridesharing. Similar issues have also been reported in several studies [35–37]. In their research, they only focused on optimally matching requests to vehicles and the vehicle routing problem was extensively analyzed; however, the similarity principle was not considered. Passengers whose travel plans are dissimilar to others cannot be put into the shared system because this may result in additional wastage of resources. In addition, the travel cost savings of participants were not considered in the aforementioned models; thus, it was unknown whether taxi-sharing could attract passengers.

In TSS multimodal transit, determining the transfer location is a significant issue in addition to the taxi ridesharing problem. When taxi-sharing is only regarded as a feeder service for the first/last mile of public transit, the tap-in and tap-out stations are known in advance; this is simpler than the shared multimodal transit considered in this study. In some multimodal studies, the mode transfer stations were nearest to the origin or destination [38,39] and were also determined according to the minimal travel time [40] and travel cost [41]. Note that the cost of intermodal transfer should be calculated because transferring is a major deterrent for passengers [42].

2.3. Gaps and Contributions

To the best of our knowledge, few studies have focused on TSS integrating services and few studies have analyzed this shared multimodal transit as a MaaS scheme. There is no optimization research to match integrated, shared, and multimodal trips; moreover, there are no studies that report its potential to solve large-scale real-world problems.

The contributions of this study can be summarized as follows:

(1) We propose a new share mobility strategy that integrates TSS transit to provide a door-to-door service.
(2) An optimal matching model involving route planning and mode attraction was designed for a TSS multimodal system.
(3) The matching model can determine the optimal solution and performs well in large-scale real-world instances.
(4) The potential benefits of TSS services were quantified based on massive empirical data in Beijing; extensive experiments were conducted to determine the performance of the TSS system.

3. Strategies for Taxi-Sharing and Subway Integrating Service

In this study, we designed a new demand-responsive transportation service by integrating taxi-sharing and subway systems. The TSS multimodal transportation is a door-to-door share service that can plan a sharing route with mode transfers from the origin to the destination of each participant. In the TSS intermodal transportation platform, passengers are asked to provide their origins, destinations, scheduled departure times, and the number of partners in advance. After a short time, they receive information regarding the allocated driver, travel information of partners, a route plan containing tap-in and tap-out transfer stations, and the estimated times at each node, including the origin, destination, and transfer stations.

According to the features of the TSS service, passengers' trips are divided into three segments by two transit modes: access to the subway, subway, and egress from the subway. Depending on the access or egress distance, the TSS multimodal transit has three subtypes: taxishare-to-subway-to-taxishare (TST), taxishare-to-subway-to-walk (TSW), and walk-to-subway-to-taxishare (WST), as shown in Figure 1. Note that walking is not regarded as a transit mode.

In this service, there can be more than one passenger in each request and we assumed that the TSS system will only match two requests. More requests in a match group will increase the computation complexity rapidly and a greater time is required to obtain the optimal matching result. In this case, passengers have to wait longer to receive matching information, which lowers the service level of the TSS transit. The multimodal system may lose some passengers as the travel information returns later than the scheduled departure time. In addition, achieving more requests in a match group may cause more detours, travel delays, and inconvenience.

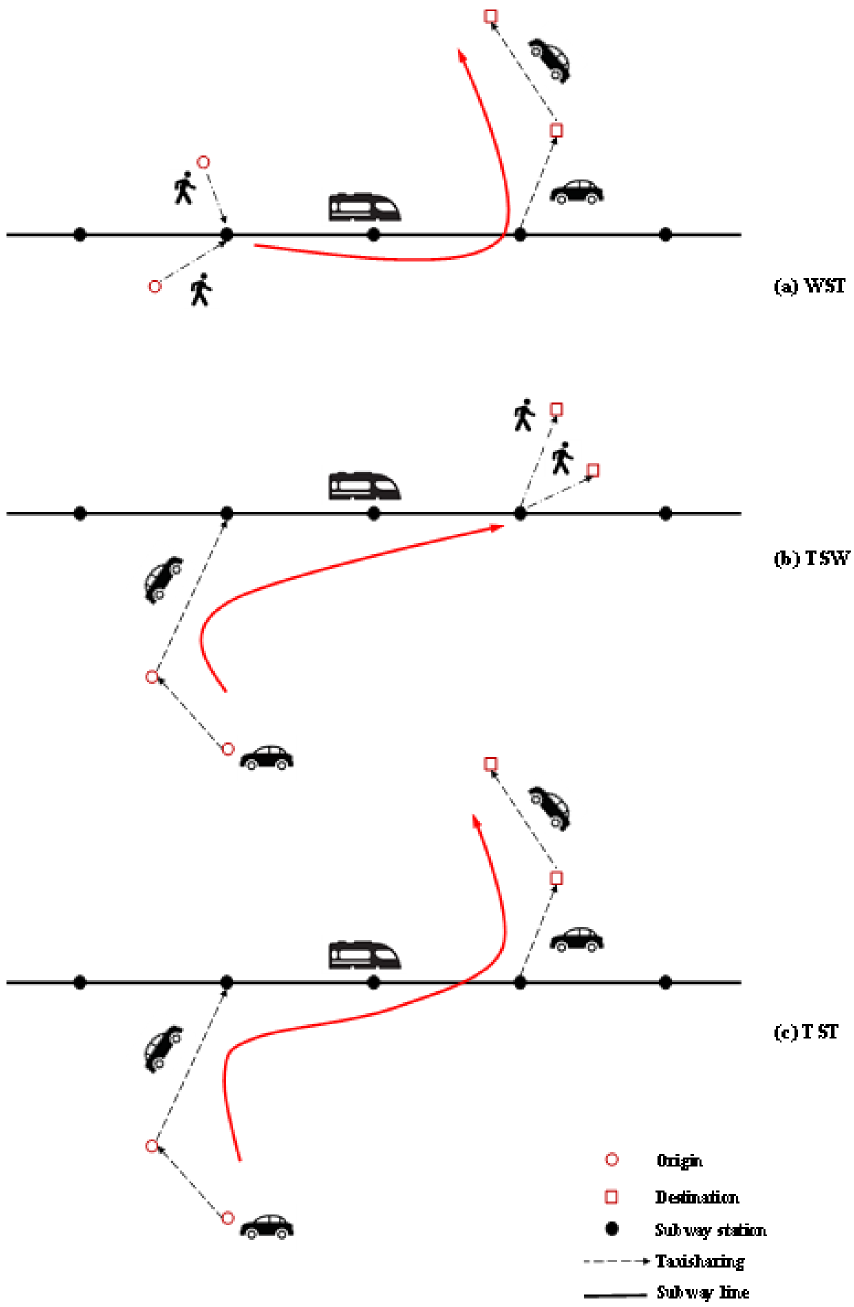


Figure 1. Illustration of three subtypes of taxi-sharing and subway multimodal transportation including (**a**) WST (**b**) TSW and (**c**) TST.

In the TSS multimodal transit, we also assumed that there is no change in passengers in a matching group, which means that, if matched, two passengers will travel together in both taxi-shared and subway trip chains. In general, the idea of traveling with strangers deters users from adopting sharing services [43,44] because passengers experience a loss of independence and privacy during the itinerary [45,46]. For a participant, changing carpoolers during his or her trip will result in greater psychological loss, which is not beneficial to developing the ridesharing service.

To achieve multimodal trips, two core phases were launched in the TSS system. First, the mode transfer stations in the subway system were determined according to the passengers' itineraries. Second, we optimized the matching mechanism for all trips with a certain objective. In multimodal trips, passengers who need to transfer between the TSS and mode transfer stations are chosen before matching riders because, in practice, they can shorten the response time and are workable for large-scale instances in dynamic systems. Some basic assumptions considered while designing the model are as follows:

1. Travelers are rational and prefer to choose the mode or route with the minimum travel cost.
2. The taxi-sharing fare scheme is based on the traveled distance and the coefficient is constant, which represents the unit fare.
3. Passenger pick-up and drop-off sequences are determined according to the travel distance. The system chooses a sequence that results in a shorter total vehicle distance.

The notations adopted throughout this paper are listed in Table 1.

Table 1. Notations for indices and parameters.

Notations	Descriptions
w, t, s, ts, tss	Modes of walking, taxi, subway, taxi-sharing, and TSS multimodal transit.
i	Index of passenger requests. For simplicity, we assume only one passenger in a request; i is also the index of the passenger.
o, d, v_o, v_d, so, sd, v_{so}, v_{sd}	Origin, destination, projective subway station of origin, projective subway station of destination, access mode transfer station, egress mode transfer station, node of access transfer station, node of egress transfer station.
t_o, t_d, $t_o{}'$, $t_d{}'$	Scheduled departure and arrival times; actual departure and arrival times in TSS.
α, μ, θ, γ, λ	Unit costs of in-vehicle time of taxi, taxi-sharing, subway, walking, and intermodal transfer, respectively, (CNY/min).
β	Unit fare of taxi-sharing, (CNY/km).
$\eta = \{\eta^+, \eta^-\}$	Unit cost of departure time deviation = {Depart earlier, Depart later}, (CNY/min).
$\zeta = \{\zeta^+, \zeta^-\}$	Unit cost of arrival time deviation = {Arrive earlier, Arrive later}, (CNY/min).
C, T, F, D	General cost, travel time, fare, and travel distance.
$\Omega, \Omega_a, \Omega_e, \Omega_b$	Sets of potential participants including TSS, TSW, WST, and TST.
$\Psi, \Psi_a, \Psi_e, \Psi_b$	Feasible sets of TSS, TSW, WST, and TST.

4. Methodology

4.1. Locations of Intermodal Transfer Stations

This algorithm first finds an alternative subway path for each participant according to the OD information and then determines a pair of subway stations from the alternative path, which can minimize the cost of the multimodal taxi and subway service. The pairs of stations were intermodal transfer stations.

4.1.1. Alternative Path in Subway Networks

In this study, the subway network is represented by a directed graph G = (V,E), where V is a set of nodes representing stations and E is the set of edges representing the links between adjacent stations. A path between two stations is represented by a sequence of nodes, for example, P = (v_1, v_2 … v_m).

Definition 1. (**Projective subway station**): *For a given location, the nearest subway station chosen by the Euclidean distance to the location is the projective subway station. Only one projective subway station can be assigned to a specific location.*

Therefore, in a taxi trip, the origin and destination pair can be mapped onto a subway network by an exclusive projective subway station pair, such as $(\mathrm{o}, \mathrm{d}) \rightarrow (v_o, v_d)$.

Definition 2. (**Alternative subway path**): *For a given taxi trip, the alternative subway path is the shortest path between two projective subway stations of origin and destination. The path is represented by AP =* $\{v_o \ldots v_d\}$.

There may be a special case in which the same projective stations are allocated for the origin and destination of a trip. Then, the alternative subway path is a null set (AP $= \varnothing$).

The shortest path in a subway network is calculated by the Dijkstra algorithm based on the generalized distance—including the physical distance and transfer penalty distance—because transfers between subway lines significantly influence the choice of route. The penalty is calculated using the average subway speed and perceived time [47]. Note that all subway times involved in this study adopt the perceived time by considering the transfer penalty in the subway network.

The alternative path defined in this paper may not be a subway path that can replace the taxi for a certain trip; it is only the theoretical shortest path on a subway network. We use an illustrative example to better understand this difference. For subway lines and even networks, there is a given coverage area, as not all residents in urban areas can be served by subways. The taxi trip in Figure 2 is outside the metro coverage area, which means that it cannot be completed using only the subway. For this trip, the subway is not the substitute mode; however, the shortest path can be found based on projective stations on the network and is represented by the red line in the example. The shortest path is regarded as an alternative subway path for this taxi trip. Obviously, there is always only one alternative subway path for any trip.

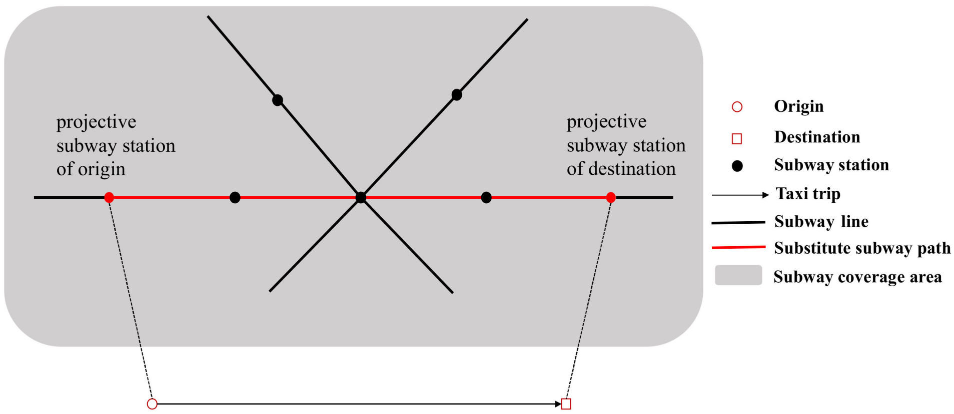


Figure 2. Illustration of alternative subway path.

4.1.2. Optimal Transfer Subway Station

To obtain the intermodal transfer stations, we utilized multimodal travel costs without sharing behavior. We assume that a rational traveler always prefers to choose the route with the minimum generalized cost. For each passenger, nodes on the subway network with the lowest generalized cost are the optimal transfer stations in a multimodal trip, as expressed in Equation (1). Variables v_{so} and v_{sd} are the nodes of the access and egress transfer stations in the subway graph G. The generalized cost consists of five main components in Equation (2): (a) travel time cost on subway, (b) fare cost of subway, (c) in-vehicle time cost on access and egress segment, (d) fare cost of taxi-sharing, and (e) cost of mode transfer penalty.

$$\begin{gathered} \mathrm{argmin} C(v_{so}, v_{sd}) \\ v_{so} \neq v_{sd} \\ v_{so}, v_{sd} \in AP \end{gathered} \tag{1}$$

$$\begin{aligned} C(v_{so}, v_{sd}) = \underset{(a)}{\theta T_s(so, sd)} + \underset{(b)}{F_s(so, sd)} + \underbrace{\alpha T_t^{ac}(o, so) + \alpha T_t^{eg}(d, sd)}_{(c)} \\ + \underbrace{F_{ts}^{ac}(o, so) + F_{ts}^{eg}(d, sd)}_{(d)} + \underset{(e)}{\lambda T_{tr}} \end{aligned} \tag{2}$$

where o and d are the origin and destination of the multimodal trip, respectively, and sd are the transfer stations. The aforementioned locations are represented by the longitude and latitude. Parameters α and θ are the unit costs of the in-vehicle time of the subway and taxi, respectively, and λ is the unit penalty cost of the mode transfer. The subscript "*tr*" denotes mode transfer. The superscript "*ac*" denotes the access segment to the subway and "*eg*" denotes the egress segment from the subway. The variables and parameters of each equation are summarized in Table 1. Note that the fare scheme on the taxi segment adopts a taxi-sharing fare scheme based on travel distance.

After determining the intermodal transfer station, the access and egress distances were computed. In TSS multimodal, taxi-sharing is not allowed for very short distances, which are walkable. The distance threshold is represented by $D_{threshold}$. Therefore, the set of total TSS trips (Ω) contains three subsets, TSW, WST, and TST, which are represented as Ω_a, Ω_e, and Ω_b, respectively. The sets are defined as follows:

$$\Omega_a = \{i | D_i(o, so) > D_{threshold}, D_i(d, sd) \le D_{threshold}\} \tag{3}$$

$$\Omega_e = \{i | D_i(o, so) \le D_{threshold}, D_i(d, sd)\rangle > D_{threshold}\} \tag{4}$$

$$\Omega_b = \{i | D_i(o, so) > D_{threshold}, D_i(d, sd) > D_{threshold}\} \tag{5}$$

$$\Omega = \Omega_a \cup \Omega_e \cup \Omega_b \tag{6}$$

4.2. Optimization Model for TSS Trips

4.2.1. Generalized Travel Cost

Before giving the generalized cost function of the TSS multimodal system, we first define several basic cost functions of various single modes, including walking, subway, taxi, and taxi-sharing. We only consider travel time and fare, which are two of the most commonly used factors in the basic travel cost function. From nodes a to b, the basic generalized cost of the aforementioned modes is expressed as follows:

$$\mathrm{C_w(a, b)} = \gamma T_w(a, b) \tag{7}$$

$$C_s(a, b) = \theta T_s(a, b) + F_s(a, b) \tag{8}$$

$$C_t(a, b) = \alpha T_t(a, b) + F_t(a, b) \tag{9}$$

$$C_{ts}(a, b) = \mu T_{ts}(a, b) + \beta D_{ts}(a, b) \tag{10}$$

In Equation (7), only the travel time is considered when calculating the basic cost of walking. γ is the unit cost of time. Travel time and fare are considered simultaneously to determine the travel costs of other transit modes. The parameters differed according to the different modes. In Equations (8)–(10), θ, α, and μ represent the unit costs of the in-vehicle time of subway, taxi, and taxi-sharing, respectively. For taxi-sharing, the fare is a function of travel distance, where β is the unit fare.

In TSS multimodal transport, participants are guaranteed to realize generalized cost savings relative to the previous transit mode. This criterion satisfies the principle of utility maximization where passengers make choices when presented with multiple transportation modes. For potential TSS users in this study, the previous transit mode is a taxi and we assume that taxi users travel alone. The generalized cost of a taxi trip with OD points comprises the (1) in-vehicle time cost and (2) taxi fare cost. This function is expressed by Equation (11).

$$C_t(o, d) = \alpha T_t(o, d) + F_t(o, d) \tag{11}$$

In TSS multimodal transport, the generalized cost is more complicated due to the combination of various modes and sharing behavior. In this study, we consider five components to compute the TSS generalized cost: (1) access cost from the origin to the mode transfer station, (2) egress cost from the mode transfer station to the destination, (3) subway cost between mode transfer stations, (4) mode transfer penalty cost, and (5) time deviation penalty cost. This function is expressed by Equation (12):

$$C_{tss}(o,d) = C(o,so) + C(d,sd) + C_s(so,sd) + C_{tr}(o,d) + C_{td}(o,d) \tag{12}$$

Referring to Equation (8), the travel cost of the subway part can be easily formulated via Equation (13).

$$C_s(so,sd) = \theta T_s(so,sd) + F_s(so,sd) \tag{13}$$

Transfers between different transit modes will result in additional costs for passengers, which cannot be overlooked in multimodal transit [42]. The penalty for the mode transfer is formulated in Equation (14) based on the transfer time and penalty coefficient. T_{tr} represents the time required for a single transfer. In TST multimodal trips, passengers will transfer twice between taxi-sharing and the subway.

$$C_{tr}(o,d) = \lambda T_{tr} \tag{14}$$

The cost of the access segment has different expressions because passengers may travel to subway stations by walking or taxi-sharing. The access cost by walking is formulated in Equation (15) by referring to Equation (7). The access cost by taxi-sharing is calculated in different ways, depending on the pick-up sequence. The first picked-up rider travels alone until the second rider is picked up and then shares rides with the second passenger to the transfer station. The access costs of the first and second passengers are described in Equations (16) and (17), respectively.

$$\mathrm{C(o,so)} = C_w(o,so) = T_w(o,so) \tag{15}$$

$$\mathrm{C(o,so)} = C_{ts}(o_1,so_1) = \alpha(T_{ts}(o_1,o_2) + T_{ts}(o_2,so_1)) + \beta(D_{ts}(o_1,o_2) + D_{ts}(o_2,so_1)) \tag{16}$$

$$\mathrm{C(o,so)} = C_{ts}(o_2,so_2) = \alpha T_{ts}(o_2,so_2) + \beta D_{ts}(o_2,so_2) \tag{17}$$

The calculation of the egress cost is similar to that of the access segment. Two transit modes, walking and taxi-sharing, were considered. Equation (18) represents the egress cost of walking: in a taxi-sharing trip, passengers share the ride from the transfer station to the destination of the first passenger; the second passenger subsequently travels alone to finish their trip. The egress costs of the first and second passengers are formulated in Equations (19) and (20), respectively.

$$\mathrm{C(d,sd)} = C_w(d,sd) = \gamma T_w(d,sd) \tag{18}$$

$$\mathrm{C(d,sd)} = C_{ts}(d_1,sd_1) = \alpha T_{ts}(d_1,sd_1) + \beta D_{ts}(d_1,sd_1) \tag{19}$$

$$\begin{aligned}\mathrm{C(d,sd)} = C_{ts}(d_2,\ & sd_2) \\ & = \alpha(T_{ts}(d_1,sd_2) + T_{ts}(d_1,d_2)) + \beta(D_{ts}(sd_2,d_1) \\ & + D_{ts}(d_1,d_2))\end{aligned} \tag{20}$$

The time deviation cost is incurred by departures and arrivals that are earlier or later than the scheduled time. It is expressed in Equations (21)–(23), where ΔT_o and ΔT_d denote the time deviation at the origin and destination, respectively; t_o and t_d are the scheduled times of departure and arrival, respectively; and $t_o{}'$ and $t_d{}'$ are the actual times. Parameters η^+, η^-, ζ^+ and ζ^- denote the unit cost of departing early, departing late, arriving early, and arriving late, respectively. Generally, for passengers, a late arrival generates a greater penalty and the coefficient is the largest [48,49].

$$C_{td}(o,d) = \eta\Delta T_o + \zeta\Delta T_d \tag{21}$$

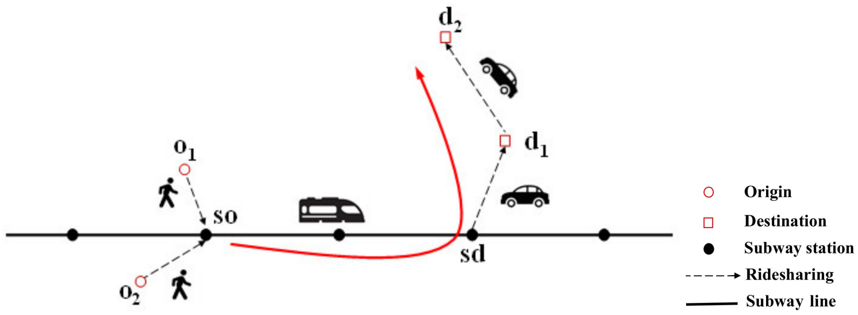
$$\eta\Delta T_o = \eta^{+}\max\{(t_o - t'_o),0\} + \eta^{-}\max\{(t'_o - t_o),0\} \tag{22}$$

$$\zeta\Delta T_d = \zeta^{+}\max\{(t_d - t'_d),0\} + \zeta^{-}\max\{(t'_d - t_d),0\} \tag{23}$$

To date, each part of the generalized travel cost of the TSS participants has been described in the aforementioned formulations.

In a match group, the generalized cost of each passenger is not only decided by the subtype (TSW, WST, and TST) but also the pick-up and drop-off sequences. We present the travel cost of each rider in the matching group in Equations (24)–(35) in Tables 2–4.

Table 2. Generalized cost of WST multimodal trips.

Sketch map	
The first drop-off rider	$C^1_{tss}(o_1,d_1) = C_w(o_1,so) + C_{ts}(d_1,sd) + C_s(so,sd) + C_{td}(o_1,d_1) + C_{tr}(o_1,d_1)$ (24) $C^1_{tss} = \gamma T_w(o_1,so) + \alpha T_{ts}(sd,d_1) + \beta D_{ts}(sd,d_1) + \theta T_s(so,sd) + F_s(so,sd) + \zeta^{+}\max\{(t_{d1} - t'_{d1}),0\} + \zeta^{-}\max\{(t'_{d1} - t_{d1}),0\} + \lambda T_{tr}$ (25)
The second drop-off rider	$C^2_{tss}(o_2,d_2) = C_w(o_2,so) + C_{ts}(d_2,sd) + C_s(so,sd) + C_{td}(o_2,d_2) + C_{tr}(o_2,d_2)$ (26) $C^2_{tss} = \gamma T_w(o_2,so) + \alpha(T_{ts}(sd,d_1) + T_{ts}(d_1,d_2)) + \beta(D_{ts}(sd,d_1) + D_{ts}(d_1,d_2)) + \theta T_s(so,sd) + F_s(so,sd) + \zeta^{+}\max\{(t_{d2} - t'_{d2}),0\} + \zeta^{-}\max\{(t'_{d2} - t_{d2}),0\} + \lambda T_{tr}$ (27)

4.2.2. Feasible Match TSS Trips

To facilitate the matching of similar itineraries, taxi trips were first extracted and grouped according to spatiotemporal conditions. We define passengers who have the same transfer station pairs as similar in the space dimension and those whose departure time difference is within the threshold as similar in the time dimension. Passengers with similar spatial and temporal itineraries belong to the initial feasible set. For WST trips, the temporal condition is adjusted slightly such that the time difference is computed by the departure time from subway stations.

The prerequisite for riders shifting from taxis to TSS multimodal transit is that they can benefit from new transportation. Trips are then filtered further from the initial feasible set according to the generalized cost constraint. In a match group, regardless of the pick-up and drop-off sequences, each passenger should realize generalized cost savings.

Table 3. Generalized cost of TSW multimodal trips.

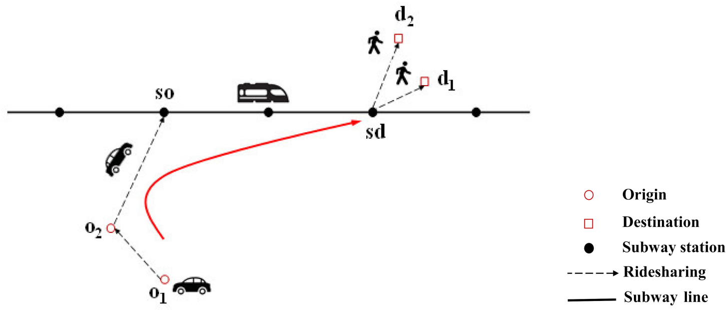
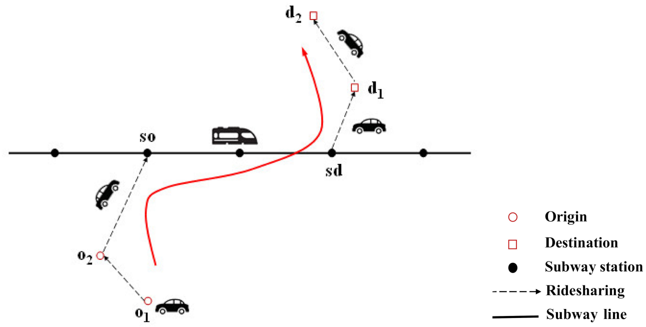
Sketch map	
The first pick-up rider	$C^1_{tss}(o_1,d_1) = C_{ts}(o_1,so) + C_w(d_1,sd) + C_s(so,sd) + C_{td}(o_1,d_1) + C_{tr}(o_1,d_1) \quad (28)$ $C^1_{tss} = \alpha(T_{ts}(o_1,o_2) + T_{ts}(o_2,so)) + \beta(D_{ts}(o_1,o_2) + D_{ts}(o_2,so))$ $+\gamma T_w(d_1,sd)$ $+\theta T_s(so,sd) + F_s(so,sd) \quad (29)$ $+0 + \zeta^+\max\{(t_{d1} - t'_{d1}),0\} + \zeta^-\max\{(t'_{d1} - t_{d1}),0\}$ $+\lambda T_{tr}$
The second pick-up rider	$C^2_{tss}(o_2,d_2) = C_{ts}(o_2,so) + C_w(d_2,sd) + C_s(so,sd) + C_{td}(o_2,d_2) + C_{tr}(o_2,d_2) \quad (30)$ $C^2_{tss} = \alpha T_{ts}(o_2,so) + \beta D_{ts}(o_2,so)$ $+\gamma T_w(sd,d_2)$ $+\theta T_s(so,sd) + F_s(so,sd) \quad (31)$ $+\eta^+\max\{(t_{o2} - t'_{o2}),0\} + \eta^-\max\{(t'_{o2} - t_{o2}),0\}$ $+\zeta^+\max\{(t_{d2} - t'_{d2}),0\} + \zeta^-\max\{(t^{2\prime}_{d2} - t_{d2}),0\}$ $+\lambda T_{tr}$

Table 4. Generalized cost of TST multimodal trips.

Sketch map	
The first pick-up and drop-off rider	$C^1_{tss}(o_1,d_1) = C_{ts}(o_1,so) + C_{ts}(d_1,sd) + C_s(so,sd) + C_{td}(o_1,d_1) + C_{tr}(o_1,d_1) \quad (32)$ $C^1_{tss} = \alpha(T_{ts}(o_1,o_2) + T_{ts}(o_2,so)) + \beta(D_{ts}(o_1,o_2) + D_{ts}(o_2,so))$ $+\alpha T_{ts}(sd,d_1) + \beta D_{ts}(sd,d_1)$ $+\theta T_s(so,sd) + F_s(so,sd) \quad (33)$ $+0 + \zeta^+\max\{(t_{d1} - t'_{d1}),0\} + \zeta^-\max\{(t'_{d1} - t_{d1}),0\}$ $+2 \times \lambda T_{tr}$
The second pick-up and drop-off rider	$C^2_{tss}(o_2,d_2) = C_{ts}(o_2,so) + C_{ts}(d_2,sd) + C_s(so,sd) + C_{td}(o_2,d_2) + C_{tr}(o_2,d_2) \quad (34)$ $C^2_{tss} = \alpha T_{ts}(o_2,so) + \beta D_{ts}(o_2,so)$ $+\alpha(T_{ts}(sd,d_1) + T_{ts}(d_1,d_2)) + \beta(D_{ts}(sd,d_1) + D_{ts}(d_1,d_2))$ $+\theta T_s(so,sd) + F_s(so,sd) \quad (35)$ $+\eta^+\max\{(t_{o2} - t'_{o2}),0\} + \eta^-\max\{(t'_{o2} - t_{o2}),0\}$ $+\zeta^+\max\{(t_{d2} - t'_{d2}),0\} + \zeta^-\max\{(t^{2\prime}_{d2} - t_{d2}),0\}$ $+2 \times \lambda T_{tr}$

Let Ψ_a,Ψ_e and Ψ_b denote feasible TSW trips, feasible WST trips, and feasible TST trips, respectively. Depending on the spatiotemporal similarity and generalized cost-saving conditions, three feasible sets for subtypes of transit trips are depicted as follows: In Equations (36)–(40), (*i*,*j*) indicates the matched passengers in a group; it does not represent the boarding or alighting sequence. Let Ψ be the total number of passengers in feasible sets, R represents the total number of passengers in feasible pairs, and $|R| \leq 2 \times |\Psi|$.

$$\Psi_a = \{(i,j)|\ so_i = so_j, \left|t_o^i - t_o^j\right| \leq t_{threshold}, C_{tss}^i \leq C_t^i, C_{tss}^j \leq C_t^j, i \neq j, \forall i,j \in \Omega_a\} \quad (36)$$

$$\Psi_e = \{(i,j)|\ so_i = so_j, \left|t_{so}^i - t_{so}^j\right| \leq t_{threshold}, C_{tss}^i \leq C_t^i, C_{tss}^j \leq C_t^j, i \neq j, \forall i,j \in \Omega_e\} \quad (37)$$

$$\Psi_b = \{(i,j)|\ so_i = so_j, \left|t_o^i - t_o^j\right| \leq t_{threshold}, C_{tss}^i \leq C_t^i, C_{tss}^j \leq C_t^j, i \neq j, \forall i,j \in \Omega_b\} \quad (38)$$

$$\Psi = \Psi_a \cup \Psi_e \cup \Psi_b \quad (39)$$

$$R = \{i | \exists i \in \Omega \text{ such that } (i,j) \in \Psi\} \quad (40)$$

For two given riders, the pick-up and drop-off sequences have four arrangements, as shown in Figure 3. The sequence affects the generalized cost of each passenger in a matching combination. Once the feasible match is determined, the pick-up and drop-off sequences are determined, i.e., the route of the driver is assigned synchronously while determining a feasible match.

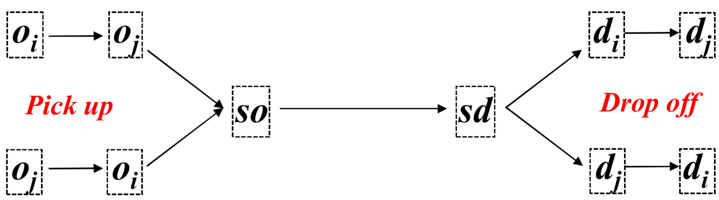


Figure 3. Pick-up and drop-off sequences.

4.2.3. Match Model

The TSS integrating service should benefit the traffic system and the individual simultaneously. Each passenger in a feasible set can save the generalized cost using the TSS multimodal transit. Therefore, the objective of the matching model was designed from the perspective of the social system. Based on the set of feasible TSS trips, the matching model is formulated as an integer linear programming (ILP) problem, given as follows:

$$\max \sum_{(i,j)\in\Psi} c_{ij} x_{ij} \quad (41)$$

Subject to

$$\sum_{i \in R, (i,j) \in \Psi} x_{ij} \leq 1\ , \forall j \in R \quad (42)$$

$$x_{ij} = \{0,1\}\ \forall (i,j) \in \Psi \quad (43)$$

The objective in Equation (41) maximizes the taxi distance savings realized in the TSS multimodal system. The weight coefficient c_{ij} was calculated using Equation (44). Constraint (42) guarantees that each passenger is matched only once in the system. Constraint (43) is a binary decision variable: x_{ij} is equal to 1 if passengers *i* and *j* can be matched in a group, and 0 otherwise.

$$\begin{aligned} c_{ij} &= D_t(o_i, d_i) + D_t(o_j, d_j) \\ &-(D_{ts}(o_i, o_j) + \min(D_{ts}(o_i, so_i), D_{ts}(o_j, so_j) + \min(D_{ts}(d_i, sd_i), D_{ts}(d_j, sd_j)) + D_{ts}(d_i, d_j)) \end{aligned} \quad (44)$$

To evaluate the performance of the TSS multimodal service, we designed three indicators with respect to the number of matched passengers, taxi distance saved for the system, and generalized cost savings for participants. More specifically, indicator *MR* (45) is the match rate formulated as the percentage of total potential TSS riders (Γ), DR (46) is the taxi distance saving rate, and CR (47) is the travel cost-saving rate.

$$MR = \frac{2 \times \sum_{(i,j)\in\Psi} x_{ij}^*}{|\Gamma|} \times 100\% \quad (45)$$

$$DR = \frac{\sum_{(i,j)\in\Psi} c_{ij} x_{ij}^*}{\sum_{m}^{|\Gamma|} D_t(o_m, d_m)} \times 100\% \quad (46)$$

$$CR = \frac{\sum_{i,j\in R,(i,j)\in\Psi} (\Delta C(o_i, d_i) + \Delta C(o_j, d_j)) \cdot x_{ij}^*}{\sum_{m}^{|\Gamma|} C_t(o_m, d_m)} \times 100\% \quad (47)$$

$$\Delta C(o_i, d_i) = \max\{0, C_t(o_i, d_i) - C_{ts}(o_i, d_i)\} \quad (48)$$

5. Case Study

5.1. Data

In this section, we illustrate the designed multimodal mechanism by considering Beijing as a case study. In 2014, the spatial distribution of the residential population in Beijing was nonuniform [50]. More than 75% of the total population lived and worked within the 6th Ring Road [51]. To relieve road pressure, subway networks have been continuously expanded to provide more travel options for passengers. There were 17 subway lines and 233 stations located in the central area of Beijing in June 2014; however, road congestion and air pollution caused by traffic systems remain serious. The TSS shared multimodal transit, which can shift passengers from the taxi service (car-like service) to the subway system, is a new approach to alleviate these problems.

In this case, the existing subway network and operating taxis provide services to the TSS system. The coordinates of the subway stations were recorded using a geographic information system. On June 18, 2014, the total number of taxi trips made between 7:00 and 9:00 is the potential trip in the TSS multimodal system. We extracted OD information from the taxi GPS trajectory dataset as the travel demand in the TSS multimodal system. Trip information includes the pick-up/drop-off time and location. The longitude and latitude were recorded to determine the location. After filtering out the basic erroneous records, there were a total of 19,156 trips. The subway network layout and the origins of the total potential taxi trips are shown in Figure 4. For all potential TSS trips, the TSW, WST, and TST subtypes are distinguished according to the distance threshold, which is 1 km. Passengers walk between intermodal transfers and origin/destination if the distance is less than 1 km.

5.2. Input Setting

Referring to the results of previous studies [48,51–54], the parameters of the travel cost functions are listed in Table 5. We took the same values of in-vehicle time (IVT) of taxi and taxi-sharing because the services are similar. Compared with the taxi, the value of IVT in the subway is greater than that in a taxi (taxi-sharing). In TSS multimodal transit, the transfer between the subway and taxi generates a penalty cost for passengers because the unit cost of the mode transfer has a larger value. Moreover, the arrival time deviation increases the cost. The unit cost of the late arrival time was three times greater than the unit cost of the taxi-sharing IVT.

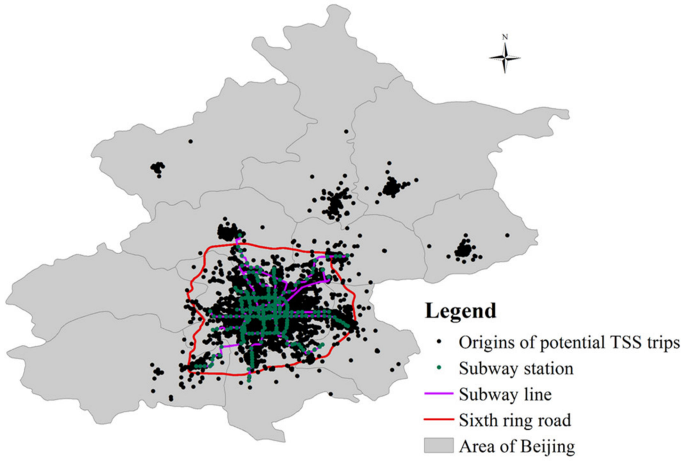


Figure 4. Study area and origins of potential TSS trips.

Table 5. Parameter values.

Parameter	Value (CNY/min)
α,μ	1.03
λ	1.75
θ	1.23
γ	1.75
η^+	0.34
η^-	0.44
ζ^+	0.95
ζ^-	3.01

In the generalized cost function, travel time is one of the most important components. For each potential TSS trip, the previous travel time by taxi $T_i(o_i,d_i)$ was obtained from the boarding and alighting time records in the GPS dataset. In the TSS multimodal system, between the origin/destination and mode transfer stations, travel times obtained by taxi-sharing ($T_{ts}(o_i,so_i)$ and $T_{ts}(d_i,sd_i)$) are estimated using the road distance and average taxi speed (27 km/h, as calculated from taxi GPS data), whereas travel times by walking ($T_w(o_i,so_i)$ and $T_w(d_i,sd_i)$) are estimated by the distance and average walk speed (4.8 km/h, referring to [55]). In the subway segment, the travel time is estimated based on the distance of the shortest path with the transfer penalty [47] and the minimum subway speed in the network (30 km/h, referring to [56]). The pick-up and drop-off times in the GPS dataset are regarded as scheduled times and the actual departure and arrival times are computed based on the estimated travel times of each segment. The time deviation cost was then determined for each potential TSS trip.

In addition to travel time, the fare is another important factor to be considered in travel cost functions. As the taxi fare is not recorded in the GPS dataset, it is estimated according to the taxi fare scheme in Beijing. The taxi fare comprises three main parts (http://fgw.beijing.gov.cn/fgwzwgk/zcgk/bwqtwj/201912/t20191226_1506265.htm.2013/60/06, accessed on 29 June 2021). The first is the fare based on distance. The flag-down fare was CNY 13 for the first 3 km, CNY 2.3 for each additional kilometer beyond 3 km; the fare then increased by 50% for each additional kilometer beyond 15 km. The second part comprises waiting and congestion fares. During peak hours (7:00–9:00 and 17:00–19:00), the waiting fare is CNY 4.6 (twice the unit fare) every 5 min. The third part is CNY 1 due to the oil price. In a TSS multimodal system, the fare cannot be very high as it would not motivate taxi users to shift to TSS transit. In this case, the fare is made up of two parts corresponding to subway and taxi-sharing modes. In Beijing, June 2014, the subway fare scheme was at a flat rate of CNY 2 for any trip. The taxi-sharing fare is a linear function of the traveled distance; for each rider in the match group, the unit fare is 2 CNY/km, which is the highest unit cost of ridesharing in Beijing (http://www.xinhuanet.com/fortune/caiyan/ksh/185.htm, accssed on 9 June 2021).

Based on the aforementioned parameters and dataset, the optimal locations of the mode transfer stations are first determined for each potential trip. The spatial similarity is then constrained by the mode transfer station and the temporal similarity is constrained by the departure time threshold, which is 10 min in this instance. According to the similarity condition and individual generalized cost-saving condition, 4448 distinct trips and 11,163 matching pairs finally entered the feasible set.

All experiments were run on a computer with an Intel (R) Core(TM) i7-4790 3.60 GHz CPU and 10 GB RAM. The model in this study was implemented in Python 3.6 and solved using Gurobi (version 9.1.1). The time required to compute the entire model involving 19,156 trips was less than 3 min.

5.3. Results of the TSS Mechanism

5.3.1. Basic Results

We solved the optimal matching model and obtained solutions involving 19,156 taxi trips during the morning peak hours. A total of 4432 trips can be achieved by TSS multimodal transit and the relative proportion of the three subtypes, TSW, WST, and TST, is 1.7:1.6:1. The number of TST types is the minimum because the match probability is much lower as the passengers need to share access, egress, and subway segments simultaneously. The match rate for all potential trips was 23.13% (*MR*). In the feasible set, approximately 99.64% of trip matches were successful. This indicates that the design of a feasible building set can effectively filter passengers and minimize the computing complexity when solving the optimized model.

We assumed that passengers who cannot be matched will continue to travel by taxi. Owing to the supply of TSS transit in the entire system, the number of taxis can decrease by approximately 9%. In addition, the taxi distance decreased by 35,000 km and the distance saving rate was 20.17% (*DR*). By sharing taxis and replacing part of the route by subway, carbon dioxide emissions in the morning rush hours were reduced by 4733 kg, which is approximately 15.16%. The proposed shared multimodal transit has a significant positive impact on alleviating road congestion and air pollution.

Based on the definitions of subway-competing, subway-extending, and subway-complement taxi trips in previous studies [4,5], we tested the categories of matched passengers. Competing trips accounted for the largest proportion (48.4%), followed by extending trips (35.4%), and, finally, the complementing trips (16.2%). The results reveal that developing the TSS intermodal mode has a remarkable effect on promoting competition between taxis and subways in collaborative relationships.

On average, shifting to multimodal TSS can save a generalized cost of approximately CNY 23.9/individual; the total travel cost-saving rate is 9.37% (*CR*). During the morning rush hours, commuter passengers accounted for a large proportion. Punctuality is an important consideration for commuters in choosing a mode of transport [57]. We found that 68.77% of TSS users took less time to complete their trips and 63.20% arrived earlier than the scheduled time. Moreover, 77.43% of passengers arrived at destinations less than 5 min later by TSS and 95.76% of passengers arrived less than 10 min later. The results show that the proposed model and solution can satisfy passenger demand with respect to cost savings and on-time performance.

Moreover, we analyzed the spatiotemporal features to understand the basic travel patterns of TSS passengers. The statistical characteristics are shown in Figure 5. Figure 5a shows the departure time distributions of matched passengers and all potential TSS passengers as red and black histograms, respectively. The subgraph shows that the total number of potential TSS passengers increases gradually over time. Matched passengers exhibited different tendencies. After a peak from 8:00 to 8:30, the number of matched passengers began to decrease and dropped rapidly from 8:50 to 9:00. This distinction indicates that the number of passengers who can share rides in the TSS system does not necessarily increase as the travel demand increases. To some extent, the ability to match passengers depends upon the similarity of itineraries and not only the amount. In Figure 5b, the travel distance distributions of the matched riders and the total potential riders are depicted by red and black histograms, respectively. It can be seen from the subgraph that taxis are mainly used for short and medium trips; however, trips that are too short are not appropriate for the TSS intermodal transit as they will lead to the overuse of traffic resources and low-level user experience, which does not have a positive effect on alleviating road congestion or environmental pollution. Among the TSS passengers, the number of short-distance trips decreases; medium-distance trips accounted for the largest proportion. This result is exactly as expected and proves that our proposed model has an autonomous selection property that can automatically filter out trips that are too short when dealing with massive trip data.

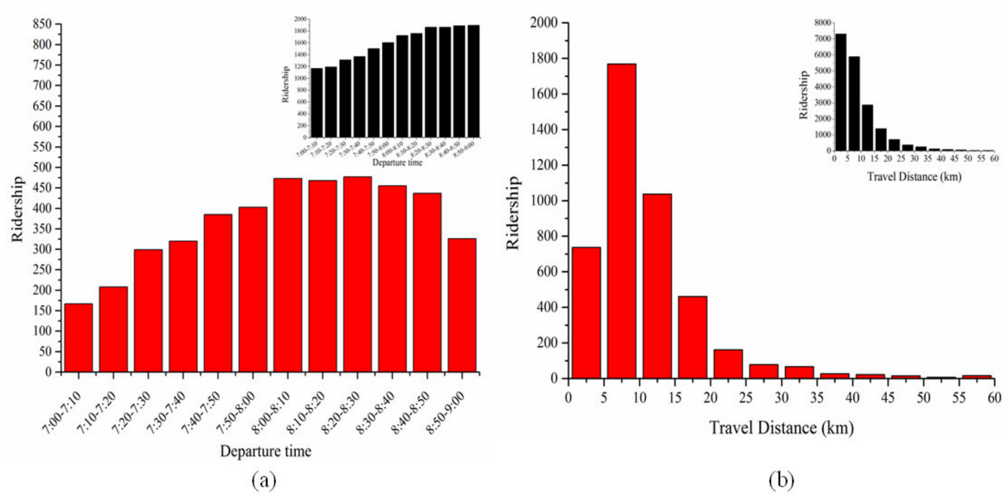


Figure 5. Distribution of (**a**) departure time and (**b**) travel distance of matched passengers.

The spatial distributions of the origins and destinations of the TSS trips are shown in Figure 6. The coverage is much less than that of taxi trips in the morning (see Figure 4). All matched passengers were located in the center of the city. One hotspot formed by the origins of the TSS passengers is the Wangjing block, a large residential area in Beijing. The use of car-like services (cars and taxis) in Wangjing is 12% higher than the average level in Beijing [58]. Trips from the Wangjing area have a high degree of similarity; more passengers in this region can save on their travel costs by TSS. Compared with the origins, destinations form five hotspots, which are the areas around Beijing West Railway Station, South Railway Station, North Railway Station, Financial Street, and the CBD. The transportation hub region and business district are the two main target places for matched passengers. Passengers who travel between hotspots have a higher probability of sharing rides with others. The TSS multimodal transit was first tested and promoted in practice in these corridors along the hotspots.

5.3.2. Impact of Participants' Attitudes on TSS Transit Performance

In this section, we aim to investigate the effect of participants' attitudes toward TSS transit on the match rate with various potential demands. In general, a higher match rate results in a better performance. The most significant differences between the taxi service and proposed TSS multimodal service are the additional subway segment and mode transfer in the total trips. Therefore, we explore the performance from the perspectives of (1) the attitude of subway travel time cost and (2) the penalty of mode transfer behavior. For a new transit mode, there is a process of the mode being accepted by the market. Usually, the demand is constantly increasing, which is simultaneously considered in this section by subsampling randomly from the total potential TSS trips. The number of TSS participants was set at 10 to 100%.

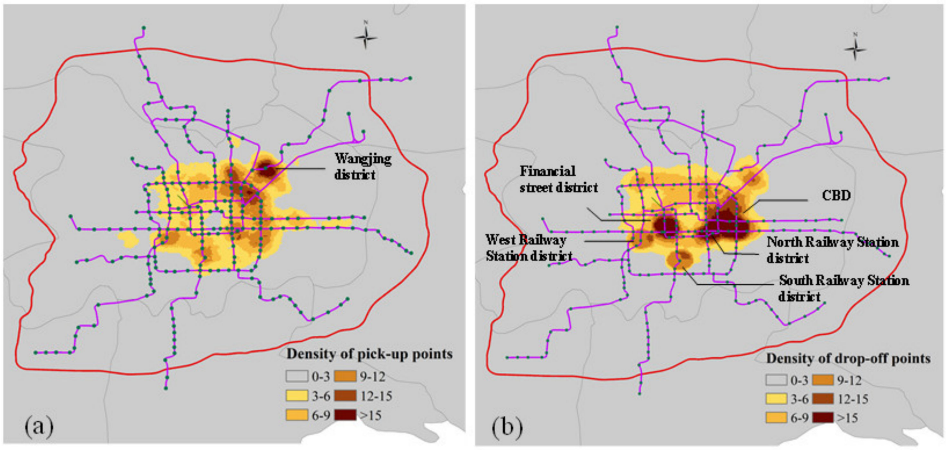


Figure 6. (**a**) Density of pick-up points of TSS trips; (**b**) density of drop-off points of TSS (person/km^2).

(1) Unit cost of subway travel time

First, the influence of the attitude of traveling by subway on the match rate in the TSS system was tested. A significant difference between taxi and intermodal transit is the subway service. Traveling by subway is an additional experience for taxi users. The parameter, subway unit cost of IVT, is examined from 0.5 CNY/min to 2.0 CNY/min in Figure 7. The lower the value of this parameter, the greater the passengers' willingness to accept the subway segment.

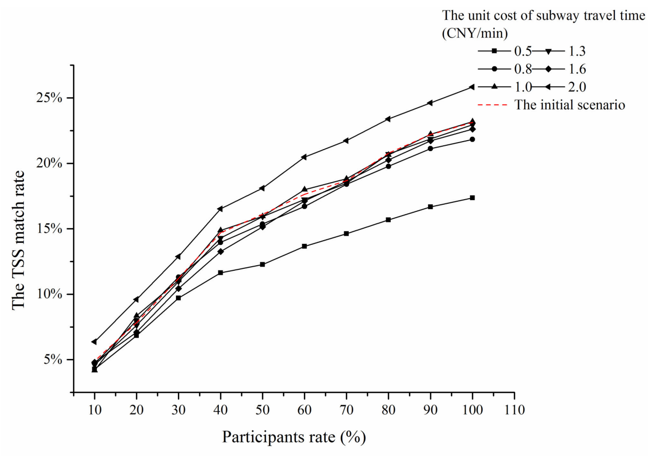


Figure 7. Impact of subway unit cost of IVT on match rate.

With an increase in the demand scale, the match rate markedly increased but the marginal growth gradually decreased. The growth rate presents a differentiation among various parameter values. When the demand is at a low level, the match rates are similar, despite the various unit costs, whereas there are different degrees of influence when the demand is at a high level. The rate of increase is the lowest when the unit cost is 0.5 CNY/min. By this time, the generalized cost of the subway part is the lowest. Conversely, when the unit cost is 2.0 CNY/min, the subway cost is at its highest but the growth rate is at its maximum. In addition to the growth rate, the lowest unit cost resulted in the lowest match rate for a given demand and the highest unit cost resulted in the highest match rate. In general, a lower unit cost will reduce the subway cost and thus reduce the total cost of TSS transit, which is conducive to the shift from the taxi to TSS service and should obtain a greater match rate; however, the results do not agree with what is assumed and appear counterintuitive. We further explored the reasons for this.

To understand the aforementioned result, we further investigate the matching process and find that a lower unit cost causes a lower spatial similarity of potential TSS passengers. The transfer station pairs between subway and taxi-sharing are heterogeneous under the lowest unit cost, which leads to a lower spatial similarity and smaller feasible sets. Therefore, the match rate is the smallest with the lowest subway unit cost and vice versa.

In addition to the extremum unit cost, the corresponding match rates of the other values are close and concentrated at the medium level. From the match rate perspective, the highest subway unit cost should be reached to obtain the highest match rate; however, this goes against the intention of the TSS multimodal service. There is a trade-off between matching performance and saving vehicle miles. Thus, we also examine taxi distance savings and determine the appropriate unit cost by balancing them. From Figure 8, it is obvious that the highest unit cost (2.0 CNY/min) results in less distance saving. The least distance savings are generated under the unit cost of 0.5 CNY/min and 1.6 CNY/min. The taxi distance savings are a maximum when the unit cost is 1.0 CNY/min. By considering the taxi mileage saved and the match rate, the most appropriate unit cost for Beijing is 1.0 CNY/min in this case. In the initial scenario, the unit cost of the subway travel time is 1.23 CNY/min and there remains scope for improvement.

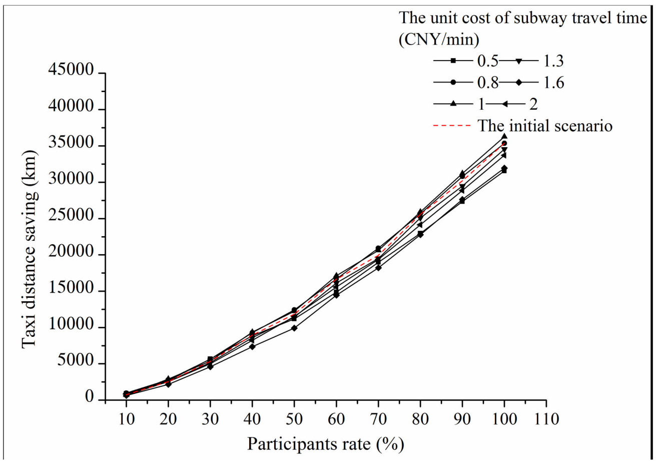


Figure 8. Impact of subway unit cost of IVT on taxi distance savings.

To improve the performance of multimodal TSS based on these results, we propose that operators should promote subway services and decision makers advertise the benefits of the subway to encourage riders to have a positive attitude toward TSS multimodal in practice. In addition, the TSS demand should be maintained at a high level; otherwise, it will be difficult to enhance performance by adjusting the subway unit costs. Hence, for the provider of the TSS service, it is crucial to attract more potential passengers during the operating period.

(2) Penalty of mode transfer

Second, the influence of the attitude of the mode transfer behavior on the match rate in the TSS system was analyzed. Transfer between different modes is the primary distinction between taxi and TSS modes. Moreover, it incurs a penalty cost for the participants. The unit cost of transfer was varied from 0.5 to 3.0 CNY/min, as shown in Figure 9. A lower value indicates that passengers have a more positive attitude toward mode transfer behavior. The aforementioned values are assumed to be around the current value according to the arithmetic sequence rule. The test aims to elucidate the trend of the TSS match rate along with transfer cost.

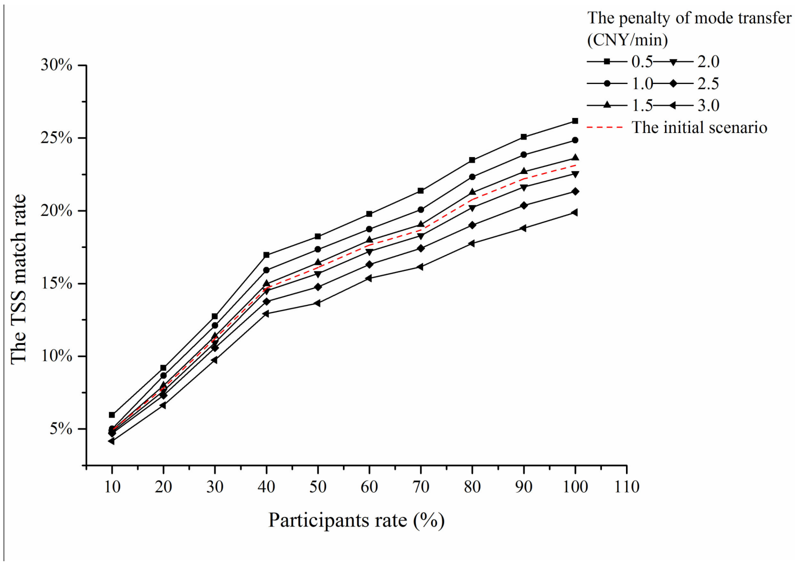


Figure 9. Impact of mode transfer penalty on match rate.

With the increase in demand scale, the match rate increases gradually and the marginal growth presents two stages: a rapid and steady growth period. The transition demand point for each stage is 40%. Among the various values, a lower penalty results in a fast growth rate and a higher penalty results in a slow growth rate. When the demand is at a low level, the influence of the transfer penalty is minimal because the match rates are close, whereas when the demand is high, the influence is appreciable. For a given demand, a lower penalty unit corresponds to a higher match rate, which is consistent with our expectations.

In addition to the match rate, taxi distance savings were computed by performing various tests, as shown in Figure 10. A greater demand results in greater distance savings and the degree of the effect of the transfer penalty is more pronounced. This also indicates that attracting more passengers is significant for multimodal services.

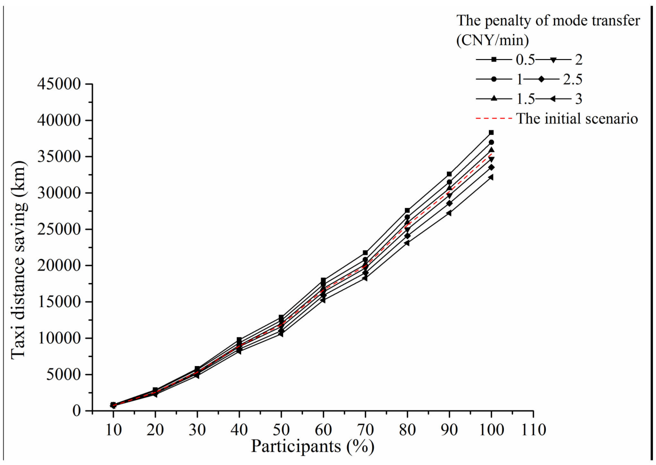


Figure 10. Impact of mode transfer penalty on taxi distance savings.

By analyzing the penalty factor, we observe that it is better to reduce the transfer penalty as much as possible to improve TSS performance. In the benchmark case study, the penalty unit is 1.75 CNY/min. To decrease the value, the transfer environment should be improved and the transfer process is simplified.

The impacts of passengers' attitudes with respect to additional subway costs and mode transfer penalties were analyzed. By comparing the effects of the two variables on the match rate and distance savings, we found that reducing the transfer penalty is more effective than controlling the subway cost. Policies to improve the interchange environment can therefore be prioritized before improving the service level of the subway.

5.3.3. Impact of Operating Scheme for the TSS Transit Performance

In this section, we analyze the effect of various operating schemes on match rate performance and attempt to determine an appropriate plan in practice. During operation, the two most important settings are the time similarity threshold and taxi-sharing fee. In the TSS multimodal mechanism, passengers send requests to the system and passengers whose scheduled departure times are within the time threshold have opportunities to be matched. After optimization, passengers receive information, including travel fares. The time threshold represents the degree of relaxation of the temporal similarity condition and the taxi-sharing fare, which is a linear function of distance and limits the generalized cost. Additionally, the proportion of participants was considered in the examinations.

(1) Temporal similarity threshold

When the time threshold decreases, a closer scheduled departure time is achieved through the matching system. If the time threshold is too large, for example, 1 h, passengers will not adopt the TSS multimodal transit because it is unreasonable. In addition, within the time threshold, the optimal result should be obtained, and feedback is provided to the passengers. Combining the aforementioned issues, we tested the match rate performance by setting the threshold from 5 to 30 min, as shown in Figure 11. In the benchmark case, the time threshold was set to 10 min.

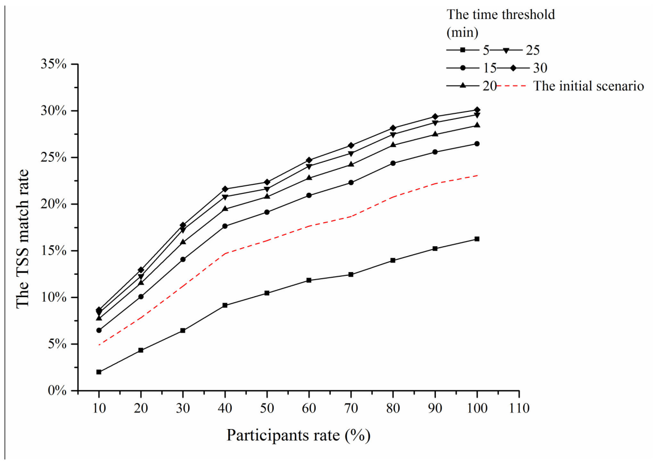


Figure 11. Impact of time similarity threshold on match rate.

For a given threshold, the match rate increases with increasing demand and the marginal increase gradually diminishes. The match rate is less affected by the time threshold at a low demand level and is more affected at a high demand level. For a given participant rate, the lowest and highest thresholds—i.e., 5 and 30 min, respectively—resulted in the lowest and highest match rates. Moreover, the match rate growth remained at a high level from 5 to 15 min and the growth rate rapidly declined. Based on the results obtained, the appropriate time threshold should be chosen as 15 min in practice, which can guarantee a better match performance and balance the response time of the TSS system. The same result is demonstrated further by taxi distance saving, as shown in Figure 12.

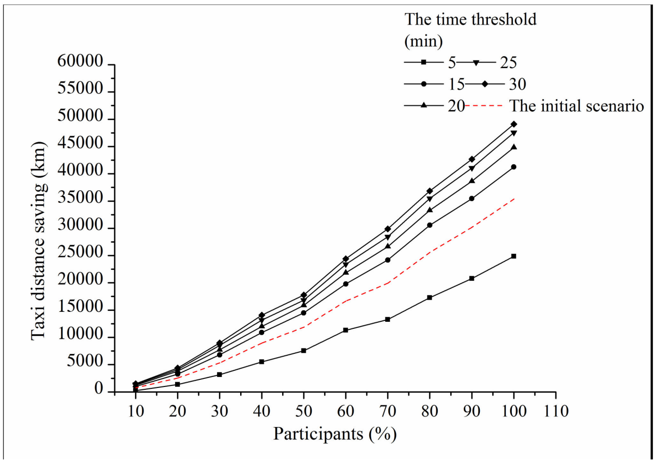


Figure 12. Impact of time similarity threshold on taxi distance saving.

(2) Taxi-sharing fare

In this study, the fare of the TSS service contains two parts: subway fare and taxi-sharing fare. The subway fare follows the flat-rate scheme and the taxi-sharing fare is determined based on the distance traveled. In the case study, the unit fare is 2 CNY/km in the taxi-sharing segment, which is an incentive mechanism to stimulate passengers to participate in shared multimodal services instead of taking taxis. In general, passengers are sensitive to travel fare; exorbitant charges lead to the loss of passengers and a very low charge is not conducive to the sustainable development of the operation department. Therefore, we explored the balance between fare and match rate performance by considering the distance-based fare scheme in the taxi-sharing segment.

Combined with passenger attitudes, the match rates reflected by the different pricing mechanisms are shown in Figures 13 and 14. The match rate is higher when the fee is lower. In most experiments, the match rate was greater than 10%. In Figure 13, for a given unit fare, the highest match rate appears when the unit cost of subway IVT is 1.3 CNY/min and the second-highest occurs when the unit cost equals 1.0 CNY/min. For a given unit cost of subway IVT, the fare increase leads to a continuous decrease in the match rate but the reduction rate gradually decreases. These results indicate that to maintain a better match rate, the taxi-sharing price can be increased when passengers have a more active attitude toward subway services. Otherwise, the unit fare should not be very high. Moreover, passengers will be sensitive to a slight increase if the initial price is low but will be less sensitive if the initial price is high.

Unit fare of taxi-sharing distance(CNY/km)	The unit cost of subway travel time(CNY/min) 0.5	0.8	1.0	1.3	1.6	2.0
2.00	17.36%	21.83%	23.19%	22.95%	22.61%	25.83%
2.50	15.35%	19.09%	20.49%	20.68%	20.06%	20.28%
3.00	14.13%	16.55%	17.99%	18.70%	17.93%	17.04%
3.50	12.86%	14.74%	15.91%	16.49%	15.93%	14.73%
4.00	11.78%	12.98%	13.92%	14.20%	13.93%	12.57%
4.50	10.88%	11.61%	12.25%	12.39%	12.02%	10.61%
5.00	10.34%	10.49%	10.81%	10.87%	10.34%	8.86%

Figure 13. Relation between taxi-sharing fare and subway cost.

From Figure 14, the relation between the fare and the transfer penalty is concise. In the case of a low penalty cost, the restriction of the ticket price can be relaxed. For example, if the penalty cost is 0.5 CNY/min, the unit fare can be set at 3.0 CNY/km to achieve a similar match rate compared with that of the benchmark; however, in the case of a high penalty cost, to ensure the match rate, the ticket price should not be high and needs to undertake the incentive role.

Unit fare of taxi-sharing distance(CNY/km) \ The unit cost of mode transfer penalty (CNY/min)	0.5	1.0	1.5	2.0	2.5	3.0
2.00	31.37%	27.94%	24.78%	21.50%	18.78%	16.04%
2.50	23.89%	22.85%	21.60%	20.47%	19.19%	18.05%
3.00	21.43%	20.27%	19.24%	18.07%	17.00%	15.96%
3.50	18.95%	17.91%	16.80%	15.92%	14.72%	13.82%
4.00	16.79%	15.82%	14.80%	13.84%	12.76%	11.82%
4.50	14.63%	13.67%	12.74%	11.85%	11.12%	10.37%
5.00	13.05%	12.14%	11.34%	10.72%	9.95%	9.27%

Figure 14. Relation between taxi-sharing fare and mode transfer penalty.

The aforementioned tests reveal fares and endogenous factors. Further, we examined the relationship using an external factor, i.e., the taxi fare. The taxi fare in Beijing was the lowest compared to other international cities (https://www.chinadaily.com.cn/travel/2014-09/23/content_18645611.htm, accessed data 23 September 2014). In addition to improving the internal service level, increasing the taxi fare is a reasonable approach. As shown in Figure 15, we increased the taxi fare by several multipliers and examined the TSS performance through various fare combinations. To maintain an appropriate match rate, the taxi-sharing price can be increased by 0.5 CNY/km for every 10% increase in taxi fare. By contrast, the increase in taxi fare has the greatest impact on the match rate and ridesharing pricing, which is consistent with previous studies that report that external forces are more effective than internal forces [59].

Unit fare of taxi-sharing distance(CNY/km) \ Taxi fares increase rates	1.0	1.1	1.2	1.3	1.4	1.5
2.00	**23.13%**	25.74%	28.05%	30.34%	32.65%	34.93%
2.50	21.06%	**23.63%**	26.09%	28.28%	30.37%	32.45%
3.00	18.60%	21.25%	**23.48%**	25.69%	27.73%	29.66%
3.50	16.34%	18.83%	21.24%	**23.38%**	25.61%	27.43%
4.00	14.32%	16.75%	19.02%	21.19%	**23.35%**	25.21%
4.50	12.29%	14.59%	16.95%	19.04%	21.16%	**23.28%**
5.00	10.98%	13.02%	15.34%	17.40%	19.34%	21.35%

Figure 15. Relation between taxi-sharing fare and taxi fare.

6. Discussion and Conclusions

In this study, we propose an emerging shared multimodal transit system that integrates taxi-sharing and subway services, namely, TSS multimodal transit. The route and partners were optimized for each participant. The proposed service does not aim to solve the first/last mile problem by taxi-sharing but provides a complete sharing scheme that considers the entire trip from origin to destination. It is a door-to-door transit service under the concept of MaaS. The TSS service is designed by considering the benefits of both the transportation system and the individual. The final goal of the TSS service is to reduce the vehicle miles by taxi; meanwhile, the generalized travel cost of each participant must be lower than the previous cost. The TSS transit mode can mitigate road congestion, air pollution, and competition between taxi and subway services.

In the TSS system, three subtypes of passengers can be identified: TSW, WST, and TST. To achieve all types of trips, we built an integer linear programming model to optimize the matching plan for all passengers; the objective was to maximize the taxi distance savings. The matching result and pick-up/drop-off sequence of passengers can be formulated synchronously; however, this model can be applied to scenarios involving large numbers of passengers. Computational efficiency can be used in dynamic systems. Moreover, this model does not require excessive data processing. It has an autonomous selection property that can automatically filter out inappropriate trips. To validate the effectiveness of the optimization model and test the practicality of the TSS strategy, we investigated this matching system based on actual data obtained from morning rush hour in Beijing. The major findings are summarized as follows:

(1) Matching results reveal that 23.13% of trips in Beijing could successfully become TSS trips. Using TSS transit, the number of taxis can decrease by approximately 9%, with a distance saving rate of 20.17%. Moreover, carbon dioxide emissions in the morning rush hours were reduced by 4733 kg, i.e., approximately 15.16%.
(2) The perceived subway time cost reflecting passengers' attitudes affects TSS performance. The subway unit cost is a two-sided factor. There is a trade-off between the match rate and distance savings when selecting the values. To balance them, 1.0 CNY/min was determined as the most appropriate unit cost of the subway travel time, which is lower than the current value.
(3) The mode transfer penalty represents another aspect of the passengers' attitudes and impacts the TSS performance. In contrast to the subway unit cost, the transfer penalty is an absolute negative factor for both the match rate and distance savings. To enhance TSS performance, it is better to reduce the penalty.
(4) In the operating scheme, the appropriate time threshold is 15 min, which guarantees a better TSS performance and sufficient response time.
(5) From the perspective of the TSS match rate and distance saving, the taxi-sharing portion of the fare cannot be very high. In general, the cost should be maintained at a moderate level, which is between the taxi and subway fares. The TSS fare will undertake an incentive role to attract more taxi users. It can be loosened within a reasonable range, with improvements in the TSS service level.
(6) To ensure the performance and societal benefit of the TSS service, it is necessary to attain a moderate participant level during the start-up phase. It is best to adjust the parameters when the passenger demand reaches a stable level.

This study can be regarded as a starting point for an extensive study on the integration of taxi-sharing and public transit. The matching model had some limitations. First, a validation test was not performed in this study. The best way of examining the performance of TSS multimodal transit is to implement it in practice; however, it is difficult and expensive for us to develop a sharing platform and operate the service. Owing to the lack of practical surveys, the actual attitudes of taxi users to the proposed TSS model in the real world is still unclear. Hence, we only considered the limited primary factors in the generalized cost function and neglected distinctions between passengers. The penalty of shifting from taxi to TSS service, the psychological cost of sharing behavior, and detour cost can be considered in the generalized cost formula. The coefficients of the different factors can also be adjusted according to individual personalities. Second, the proposed shared multimodal approach is more appropriate for metropolitan areas, especially those with road congestion and air pollution problems. In small areas, there is no need for intermodal transit. Moreover, if the taxi fare is sufficiently inexpensive and the subway is expensive in certain areas, TSS transit is less attractive. Finally, in this matching model, only two requests are allowed to share the rides. Theoretically, more requests can be matched.

Considerable work remains to be carried out to improve the performance of TSS services. First, the TSS service should be developed in practice, which can provide an opportunity to collect the actual response from users. The results validate the proposed model and optimize the operating scheme. Second, it is important to determine how to satisfy personalized demands in the system. For example, female passengers are more likely to prefer to travel with partners of the same sex for safety reasons [60], passengers would prefer not to change modes at crowded subway stations, and transfers may not be accepted in subway systems. Third, there is a need to determine how to design a better fare scheme for a TSS service that can benefit passengers and operators simultaneously. These issues will be considered in future work.

Other societal problems may be caused by the development of TSS multimodal transit, which are worth discussing in advance. Although the TSS transit containing taxi-sharing is a type of shared mobility, there may be negative effects on road congestion. If the TSS service attracts more passengers who use public transit and the number of supplied taxis increases, an issue regarding increased vehicles on the roads may arise again. To address potential problems, the number of taxis should be strictly controlled and other services, such as multimodal vanpooling and subways, can be developed. In addition, the TSS multimodal service relies on smartphones that are not friendly to the poor or elderly. The benefit of cost-saving may also be unequal for riders in the same matching group. These issues reveal the equity problem of the TSS service, which should be considered in the future. Finally, we recommend our concept and approach to other cities to improve traffic performance, considering that few studies have been conducted on this subject.

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