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Sustainable urban mobility: Flexible bus service network design in the post-pandemic era

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ABSTRACT

The excessive traffic congestion in vehicles lowers the service quality of urban bus system, reduces the social distance of bus passengers, and thus, increases the spread speed of epidemics, such as coronavirus disease. In the post-pandemic era, it is one of the main concerns for the transportation agency to provide a sustainable urban bus service to balance the travel convenience in accessibility and the travel safety in social distance for bus passengers, which essentially reduces the in-vehicle passenger congestion or smooths the boarding–alighting unbalance of passengers. Incorporating the route choice behavior of passengers, this paper proposes a sustainable service network design strategy by selecting one subset of the stops to maximize the total passenger-distance (person × kilometers) with exogenously given loading factor and stop-spacing level, which can be captured by constrained non-linear programming model. The loading factor directly determines the in-vehicle social distance, and the stop-spacing level can efficiently reduce the ridership with short journey distance. Therefore, the sustainable service network design can be used to help the government minimize the spread of the virus while guaranteeing the service quality of transport patterns in the post-pandemic era. A real-world case study is adopted to illustrate the validity of the proposed scheme and model.

1. Introduction

Public transportation, which is economical and environmentally friendly, is one of the most effective ways to mobilize passengers. It thus plays an indispensable role in reducing transport congestion and improving the city environment. The study of bus operation optimization remains one of the most popular topics in the transportation field, including fleet allocation, network design, passenger behavior analysis, and timetable optimization (Ceder & Wilson, 1986; Ibarra-Rojas et al., 2015; Shao et al., 2022). But in recent years, the urban public transportation system has become one of the main mediums for the spread of the epidemic because of dynamic passenger boarding and alighting and uncertain in-vehicle movement (Borjigin et al., 2023; Jardim et al., 2022; Qian & Ukkusuri, 2021). Public transportation has been significantly affected by the coronavirus disease, and ridership in major cities worldwide has dropped about 60% to 95% (Fernandez Pozo et al., 2022), which has caused a dramatic reduction in fare income and considerable budget deficits. Therefore, the public transportation system faces the new challenges and the efficient pandemic control policies on the public transportation system is the main concern of the researchers (Gkiotsalitis & Cats, 2020; Lara et al., 2023; Zhang et al., 2023).

The in-vehicle traffic congestion is one of measurements adopted by passengers to keep a proper social distance between individuals even in the post-pandemic era (Huang et al., 2023; Limsawasd et al., 2022; Manzira et al., 2022). Therefore, this paper aims to develop a sustainable service network design strategy by selecting one subset of the stops according to the in-vehicle occupation ratio and stop-spacing level set by the transportation agency. The in-vehicle occupation ratio directly determines the in-vehicle social distance with the consideration of epidemic prevention and control. The stop-spacing level is introduced to capture the distance between two sequential bus stops, which can efficiently reduce the ridership with short journey distance. Balancing the passenger travel demand and pandemic control is very important for operators of urban public transport services during the post-pandemic. To address this problem, a mathematical model is proposed to calculate the disutility of passengers and evaluate the objective value of the flexible service network to design an efficient

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and sustainable service bus network considering the impact of COVID-19. The design strategy is based on the stop-skipping scheme, which means some passengers will have to walk further to the nearest stop to take buses or give up service. Notes, the walking behavior of passengers increases the disutility of travel. The theoretical study for strategy implementation under pandemic control proposes that adopting a sustainable service network to achieve the stated restriction goals of the passenger occupation ratio is essential. The proposed methods allow transport operators to quickly adjust bus lines and timetables during an outbreak based on dynamic passenger demands and the characteristic of the pandemic. Therefore, this proactive approach to controlling the pandemic reflects the operators supporting the responsibilities of the government in post-pandemic era.

The structure of this paper is organized as follows. Section 2 reviews the literature related to the public transport system optimization during COVID-19. Section 3 gives a brief description of the research problem and assumptions. Section 4 gives rigorous mathematical models and algorithms. Section 5 investigates the sustainable service network in a real bus system to illustrate the validity of the proposed models and algorithms. Section 6 discusses the policy implications of the proposed strategy. The last section concludes the work of this study.

2. Literature review

During the past four years, Covid-19 has wreaked havoc on the public transport system, including the travel behavior of passengers. To protect the health and safety of transit customers, many researches have been published to optimize the public transport network to guarantee the essential services operating. The related literature could be classified into two groups. The first group is leading the passenger travel pattern discretization from the supply-side policy. Another group is limiting the passenger demand from the demand-side policy.

The supply-side policy is to adjust the public transportation service in the whole or part of the cities with and without considering the travel behavior of passengers, such as Manila, Danville and Washington (Washington Metropolitan Area Transit Authority, 2020). In the urban system, Borjigin et al. (2023) proposed scaling down the frequency of shuttles and/or buses to respond to significantly lower ridership and additional safety requirements during the pandemic. But a low service frequency would result in overcrowding in the platform or vehicles. Qian and Ukkusuri (2021) developed a systematic model with travel contagion to capture the infections of COVID-19 in the public transportation system and proposed an effective entrance control strategy under limited resource allocation. Chen et al. (2021) built a nonlinear integer model to reduce the risk of passengers infected the COVID-19 by controlling the numbers of boarding and alighting passengers in the public transport system. But this kind of policy is not friendly for passengers boarding at the last few stops if all stops are still visited. Cutting bus service is one of the policies widely adopted during the lockdown, but it has a disproportionately effect on mass that most reliant on public transport, which caused the lower mobility and unequal for commuters to access transport (Hasselwander et al., 2021; Hsiang et al., 2020). These kinds of short-run policies produce inconvenience for passengers without private cars. The other policies are designed from the demand-side to control the loading factor or occupation ratio of vehicles. In Harris County, Texas, the transportation agency explicitly limits the load factor to less than 50% (Texas, 2022). Once the passenger loading factor reaches the required limitation, the electronic display board will inform the remaining passengers to wait for the next bus. Moreover, transit agencies in the United States and Canada have published physical social distancing measures. For example, passengers are required to be seated at intervals and mandatorily wear masks (Ku et al., 2021).

More commonly-used policy combines the demand and supply sides of the public transportation to design the operational plan according to the behavior of passengers. From a policy perspective, Gkiotsalitis and Cats (2020) and Tirachini and Cats (2020) reviewed the related implemented transport measures facing COVID-19 and analyzed the impact of the pandemic on passenger travel behavior or preference. Serval appropriate transport strategies and research needs during COVID-19 were proposed to help the transport system to fulfill its societal role. Muren et al. (2022) jointly considered the passenger demand and the efficiency of pandemic control and prevent, and built a mixed integer programming model to reduce contact congestion by a flexible working schedule during the recovery of industrial activity under the post-pandemic era. This kind of customized bus is one of the efficient methods to control the loading factor with an online booking service. However, it is suited for a relatively low passenger demand and operates in some local urban zones.

Our proposed sustainable service network design strategy is similar to the short-run stop-skipping scheme adopted by Chicago transportation agency in order to flexibly respond to the epidemic while ensuring the travel demand of residents (Chicago, 2022). Stop-skipping, or 'limited-stop service', is a widely used policy to improve the resilience of the transport system during peak hours, which is a strategy of vehicles only serve serval stops for each trip on a typical bus or metro line (Liu et al., 2013). The stop-skipping scheme is also used to deal with the uncertain passenger demand. One of main concerns for the scheme is to balance the passenger cost and operational cost. Chen et al. (2022) focused on high-frequency urban transport and explored a nonlinear programming model of the stop-skipping scheme to minimize the timetable deviation of train departure time, control cost and waiting passengers on the platform while considering the dynamic passenger flows. The proposed sustainable service network design strategy can also be used under the regulation of the carbon emissions when the relationship between the supply and demand of public transportation is changed (Li et al., 2023; Liu et al., 2022; Shang & LV, 2023).

Most previous studies about the short-run stop-skipping scheme mainly focused on the passenger travel cost directly affected by the scheme, without considering the long effect of the coronavirus disease on the travel behavior of passengers, such as, in-vehicle social distance. Limsawasd et al. (2022) studied the stop-skipping strategy for a metro system under a vigorous physical-distancing policy, where the metro system with more stability and operability compared to the bus system. The authors proposed a bi-objective optimization model that minimizes the total travel time and unserved passengers, and a two-stage algorithm based NSGA-II is proposed, where the first stage is to determine the stop-skipping pattern, and the second stage is to design an efficient schedule. However, the passenger transfer behavior was not considered by Limsawasd et al. (2022). Unlike the metro service, the distance between two neighboring bus stops is closer. Therefore, passengers can usually transfer to the closest upstream or downstream operating stops for taking buses. For a rational person, if the neighborhood distance is large enough, the passenger would choose to adopt other transport modes, such as metro service, bike sharing, or taxi. Furthermore, the stop-skipping scheme obtained by Limsawasd et al. (2022) would affect the passengers with long journey and cannot deal with the imbalance of the loading factors along the bus line. We thus introduce one of practical measurements of the sustainable service network to rule out the short journeys and smooth the in-vehicle numbers by forcing the passengers to adjust their boarding/alighting stops. Moreover, Huang et al. (2023) also focused on bus system optimization to control the infection during the pandemic by resetting the bus headway. A bi-level model was formulated, where the lower-level model is the passenger travel path choice model, and the upper-level model is to minimize the total passenger travel time and infected passengers. Notes, the passenger walking behavior was also not considered in Huang et al. (2023). When the bus headway changes, the passenger can also walk to neighboring bus lines with high frequency or less headway. Headway design is also an efficient strategy for pandemic control. But, frequency settings such as enlarging headway and/or strictly limiting the bus capacity are difficult to execute. Most passengers would not give up the original travel patterns and choose to wait a long time on the platform, which would increase the risk of stampede accidents. However, considering the combination of headway design and stop-skipping strategies to deal with the public health event in the transport system would be interesting.

3. Problem description and assumptions

In order to design an efficient sustainable service network in the public transport system considering the impact of COVID-19, we propose a mathematical model to calculate the disutility of passengers and evaluate the objective value of the sustainable service network. Consider a typical bus line in the urban bus system with a set of stops, $\mathcal{N} = \{1, 2, \dots, N-1, N\}$. The distance between stop i and the first stop is denoted by l_i, $i \in \mathcal{N}$. The research period of a day, for example, the peak hour from 6:00 to 10:00 am, can be divided into T time intervals with Δ minutes, denoted by $\mathcal{T} = \{1, 2, \dots, T-1, T\}$. Moreover, the vehicle run set is defined as $\mathcal{K} = \{1, 2, \dots, K-1, K\}$ during the T periods. A pre-determined passenger flow from stop i to stop j at time interval t is q^t_{ij}, where $i < j$ and $i, j \in \mathcal{N}$, $t \in \mathcal{T}$.

3.1. The sustainable service network

Due to the effect of the epidemic, such as COVID-19, the agency can adopt a sustainable service network to mitigate the spread of the infectious disease and promote low-carbon travel for passengers. Under the sustainable service network, the agency sets distance criteria D (meters) to select a subset of bus stops for all bus lines so that the distance between adjacent stops must be larger than D. In practice, the scheme is similar to the stop-skipping policy (Liu et al., 2013). The aims of the sustainable service network and stop-skipping policy are totally different. The latter is to improve the operational efficiency of the bus system by reducing the journey time of vehicles or passengers. The former is to reduce in-vehicle occupation by increasing the distance between adjacent stops and reducing the willingness of passengers to take buses.

Let vector $\mathbf{X} = \{x_i, i \in \mathcal{N}\}$ be a sustainable service network where $x_i = 0$ represents stop i is skipped by the scheme, and $x_i = 1$ otherwise. For stop i, we introduce a measurement called **Neighborhood Distance** to capture the minimum distance of stop i to its nearest stop, which is not skipped by the scheme. To do this, we first define two distance measurements. For all upstream stops of i denoted as j with $j < i$, $d_{ji} = l_i - l_j x_j$, and for all downstream stops of i denoted as j with $j > i$, $d_{ij} = (l_N - l_i) - (l_N - l_j)x_j$. The upstream and downstream adjacent stops i^- and i^+ can be captured by

$$\begin{cases} i^- = arg\min_j \{d_{ji} : j < i\}, \\ i^+ = arg\min_j \{d_{ij} : j > i\} \end{cases} \tag{1}$$

Specially, if $\min\{d_{ji} : j < i\} = l_i$, we know that $i^- = 1$, and $\min\{d_{ij} : j > i\} = l_N - l_i$, we must have $i^+ = N$. Then, the neighborhood distance for a stop i can be defined by $d_i = \min\{d_{i^- i}, d_{ii^+}\}$. A sustainable service network is feasible for a neighborhood distance D, meaning that any stop which is not skipped by the scheme must have a neighborhood distance not less than the neighborhood distance D, namely, for any stop with $x_i = 1$, $d_i \geq D$, $i \in \mathcal{N}$.

Note that the sustainable service network, $(\mathbf{X}, D)$, is to lower the willingness of passengers with short journey lengths by setting a neighborhood distance D. If the neighborhood distance is too larger, the bus line has a larger interval distance and some stops are skipped. As a result, the passengers starting or ending at the skipped stops must walk to other no-skipped stops. Some passengers have to adjust their origin and/or destination and even cancel their journeys. It is clear that the sustainable service network has a more significant effect on passengers with short distances. The neighborhood distance D is a crucial factor to affect the passenger demand, which depends on the tension of the agency to control infectious diseases. Furthermore, the scheme can also improve the operation efficiency of the bus system since some stops are skipped, which reduces the dwelling time at stops.

3.2. The travel adjustment of passengers

In this section, we move to examine the adjustment of passengers' original travel patterns under a sustainable service network $(\mathbf{X}, D)$. For the passengers from stop i to stop j, if both stops i and j are not skipped, the passengers are still to take the bus without any change. When stops i and/or j are skipped by the scheme, there would be several choices. Walking from i to j is clearly one of the options when the accessibility is quite bad for the passengers under the scheme. Riding buses is still considered by the passengers when the accessibility under the scheme is acceptable. In this case, either upstream or downstream adjacent stop of i, i.e., i^- or i^+, would be chosen as a new boarding stop when $x_i = 0$, and either upstream or downstream adjacent stop of j, i.e., j^- or j^+, would be chosen as a new alighting stop when $x_j = 0$.

In summary, when $x_i = 1$ and $x_j = 1$, the passengers do not change their travel behaviors. When $x_i = 0$ and $x_j = 1$, the passengers adjust their boarding–alighting pairs from (i, j) to (i^-, j) or (i^+, j). When $x_i = 1$ and $x_j = 0$, the passengers adjust their boarding–alighting pairs from (i, j) to (i, j^-) or (i, j^+). When $x_i = 0$ and $x_j = 0$, the passengers adjust their boarding–alighting pairs from (i, j) to (i^-, j^-), (i^-, j^+), (i^+, j^-) or (i^+, j^+). For the latter three cases, the passengers would also choose to walk. The feasible boarding–alighting pairs between stops i and j under the sustainable service network $(\mathbf{X}, D)$ is denoted by $\Omega_{ij}(\mathbf{X}, D)$, which could be $\{(i, j)\}$, $\{(i^-, j), (i^+, j)\}$, $\{(i, j^-), (i, j^+)\}$ or $\{(i^-, j^-), (i^-, j^+), (i^+, j^-), (i^+, j^+)\}$. Fig. 1 shows a simple example of the passenger choices from skipped stop 3 to skipped stop 6, where passenger 5 choose to walk from origin to destination and other passengers choose alternative riding routes.

A passenger who travels from i to j must pay a fare τ USD under the sustainable service network. After implementing the sustainable service network, if the passenger takes the bus and chooses a boarding–alighting pair w in $\Omega_{ij}(\mathbf{X}, D)$, the travel distance of taking buses and the walking distance are represented by d^1_{ijw} and d^2_{ijw}, respectively. Then the disutility of the passenger can be calculated as $C_{ijw} = \tau + \alpha \left(\frac{d^1_{ijw}}{v_1} + \frac{d^2_{ijw}}{v_2} \right)$. It is easy to calculate the travel distance d^1_{ijw} for any given boarding–alighting pair. For example, $d^1_{ijw} = d_{i^+ j}$ with $w = (i^+, j)$, and $d^1_{ijw} = d_{i^+ j^+}$ with $w = (i^+, j^+)$. Similarly for walking distance, there have $d^2_{ijw} = d_{ii^+}$ with $w = (i^+, j)$, $d^2_{ijw} = d_{ii^+} + d_{jj^+}$ with $w = (i^+, j^+)$, and the special case, $d^2_{ijw} = 0$ with $w = (i, j)$. Specially, to unify our expression, the walking mode, denoted by w_0, can be included in the feasible set of the boarding–alighting pairs $\Omega_{ij}(\mathbf{X}, D)$. The disutility of the passenger who adopts walking mode from stop i to j can be expressed as $C_{ijw_0} = \alpha \frac{d_{ij}}{v_2} = \alpha \frac{l_j - l_i}{v_2}$.

Note that it is hard to make a certain choice of boarding and/or alighting stops for a passenger. We adopt the Logit model (Shao et al., 2022; Tan et al., 2020) to capture the choice uncertainty of passengers under a sustainable service network. Namely, the number of passengers between i and j at time t choosing a feasible boarding–alighting pair w, $w \in \Omega_{ij}(\mathbf{X}, D)$, can be calculated by

$$\bar{q}^w_{ijt} = \frac{q_{ijt} \exp\left(-\beta C_{ijw}\right)}{\sum_{w' \in \Omega_{ij}(\mathbf{X}, D)} \exp\left(-\beta C_{ijw'}\right)}. \tag{2}$$

In model (2), even both stop i and stop j are not skipped by the sustainable service network, some passengers would also shift to walking mode. However, if the neighborhood distance is quite larger, the proportion is very small. The β is a calibration parameter to scale the disutility. With model (2), the number of passengers between a feasible boarding–alighting pair w under the sustainable service network $(\mathbf{X}, D)$, can be calculated by

$$\bar{q}^t_{ij} = \sum_{i', j' \in \mathcal{N}} \left(\bar{q}^w_{i'j't} | w = (i, j) \in \Omega_{i'j'}(\mathbf{X}, D) \right), \quad \forall i, j \in \mathcal{N}, \quad t \in \mathcal{T} \tag{3}$$

where (i', j') is a feasible stop pair under the scheme to which all passengers would change their original boarding–alighting pairs before implementing the scheme.

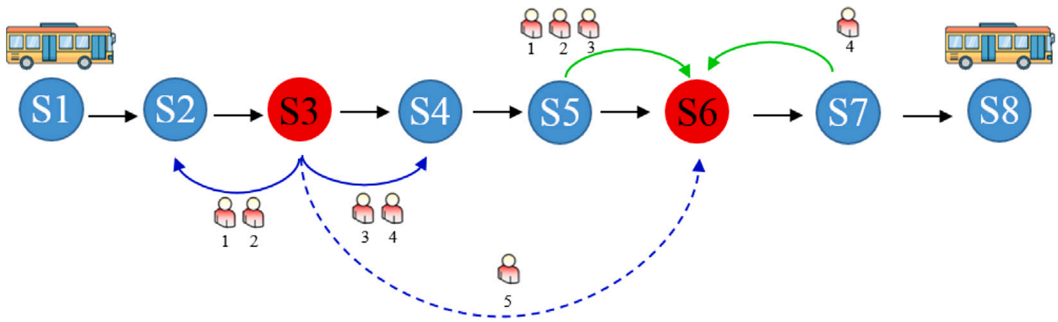


Fig. 1. An example of passenger choices under the sustainable service network.

Moreover, the headway of K runs during the T periods is $\frac{T\Delta}{K}$. Let the arrival time of vehicle k at stop i be defined as A^i_k, and the arrival time for the kth vehicle at the first stop equal the dispatch time of the last bus at the first stop plus the headway. Notes, the arrival time of the first vehicle at the origin stop is determined. If the bus stop i is not skipped, the dwell time equals λ, otherwise equals 0. Moreover, the driving speed of the vehicle is defined as v_1, and the arrival time of vehicle k at stop i is the departure time at the previous stop plus the travel time between the previous stop and i.

Based on the above definition, we assume the passenger arrives at stop i in the middle of period t, and the average walking speed of the passenger is v_2. Therefore, for passenger willing to board at stop i', which is skipped, but final boarding at stop i, the passenger arrival time at stop i equals $(t-\frac{1}{2})\Delta + \frac{|l_i - l_{i'}|}{v_2}$. Furthermore, if the passenger arrival time is between $[B^i_{k-1}, B^i_k]$, the passengers would choose take vehicle k at stop i. By accumulating the passenger allocation during T periods, the amount of passengers at vehicle k for departing from stop i and reaching at stop j is obtained, which is denoted as u^k_{ij}. Given the beginning time and fixed headway, we can calculate the passenger number between each stop with passenger travel demand u^k_{ij}. The in-vehicle occupation ratio of vehicle k between stop $i-1$ and i equals

$$\pi^i_k = \sum_{i'=1}^{i-1} \sum_{j'=i}^{N} \frac{u^k_{i'j'}}{Y}, \quad \forall i = 1, \dots, N; \quad k = 1, \dots, K; \tag{4}$$

where Y is the capacity of the bus.

4. Model formulations and solution algorithm

With the discussion in previous sections, we know that, given any the sustainable service network $(\mathbf{X}, D)$, the passengers would adjust their travel behaviors according to their disutility. During peak hours, increasing the frequency of a bus line is hard since all vehicles are overburdened. Therefore, the frequency or timetable for the bus line is assumed to be fixed. The objective of the transportation agency is to transport passengers as much as possible by selecting scheme $(\mathbf{X}, D)$ and reduce the in-vehicle occupation ratio as lower as possible. Due to the aim of the sustainable service network is to reduce the travel intentions of passengers with short travel distances, we introduce the passenger distance to capture the capacity of the bus line, namely,

$$L(\mathbf{X}, D) = \sum_{k=1}^{K} \sum_{i=2}^{N} \sum_{i'=1}^{i-1} \sum_{j'=i}^{N} u^k_{i'j'} (l_i - l_{i-1}) \tag{5}$$

Function $L(\mathbf{X}, D)$ given by Eq. (5) is the total travel distance of all passengers taking the bus line under the sustainable service network $(\mathbf{X}, D)$, which is a traditional measurement to capture the capacity of transportation system (Ning et al., 2022). The problem of the transportation agency can be formulated as the following programming model, where $\hat{\pi}$ is the target level of in-vehicle occupation. For example, the in-vehicle number of passengers is limited to half of the total capacity of a vehicle in Harris County, Texas, during the epidemic period. In another word, the target in-vehicle occupation ratio $\hat{\pi} = 0.5$. $\hat{D}$ is the required minimum neighborhood distance announced by the local government. Therefore, the optimization model of the sustainable service network could be formulated as follows.

$$\max L(\mathbf{X}, D) \tag{6}$$

subject to

$$\pi^i_k \le \hat{\pi}, \quad \forall k = 1, ..K; \quad i = 1, \dots, N \tag{7}$$

$$d_i \ge \hat{D}, \quad \forall i = 1, \dots, N \tag{8}$$

The formulation (6) is the objective function that maximizes the travel distance of all travel passengers. The constraint (7) guarantees in-vehicle occupation ratios of all buses between each stop, defined in Eq. (4), are less than required $\hat{\pi}$. The constraint (8) gives the boundary of the neighborhood distance between adjacent stops.

The above model solves the optimal sustainable service network for a target in-vehicle occupation level and neighborhood distance limitation. All stops and routes are homogeneous, and optimal schemes of bus lines are adopted for public transport control during the new normal era. However, if some areas break an aggregated pandemic, a lockdown policy would be implemented to prevent the transmission of the virus. Notes, the lockdown policy in this paper means to close risk communities. Buses are forbidden to stop in the lockdown areas, and the sustainable service network obtained by the above model are not applicable under emergency situations and need to be adjusted timely according to the pandemic prevention regulation. To handle this situation, we defined the lockdown center point and the lockdown radius, which declared the lockdown area. Stations in the control zone are allowed to pass through but cannot stop. We define the set of stops in the lockdown area as $\mathcal{M} \in \mathcal{N}$, and there have $\{x_i = 0, i \in \mathcal{M}\}$ as extra constraints for proposed models. Within the limits of above constraints, stops in lockdown areas will be forced to skip.

In order to obtain an efficient sustainable service network solved by the constrained non-linear programming model described above, an optimization framework is developed, which could satisfy the passenger travel demand during the pandemic while reducing the risk of infection of COVID-19. Apart from seeking a reasonable sustainable service network under the regular epidemic prevention and control, the novelty of this study also covers the scenario of the epidemic outbreak in serval areas. Thus, targeted epidemic-control can be achieved to improve the resilience and practicality of the public transport system. As shown in Fig. 2, the optimization framework consists of four modules: data collection, mitigating the COVID-19 spread modal, bus line evaluation, and optimization. In the data collection module, some prerequisite data must be gathered first, including the bus line network information, passenger boarding–alighting time and the disease parameters, and a detailed description of the data will be introduced in the case study section. The feasible sustainable service network could be generated through input data based on neighborhood distance D and stop-spacing matrix $\mathbf{X}$. Then, the efficiency of the sustainable service network can

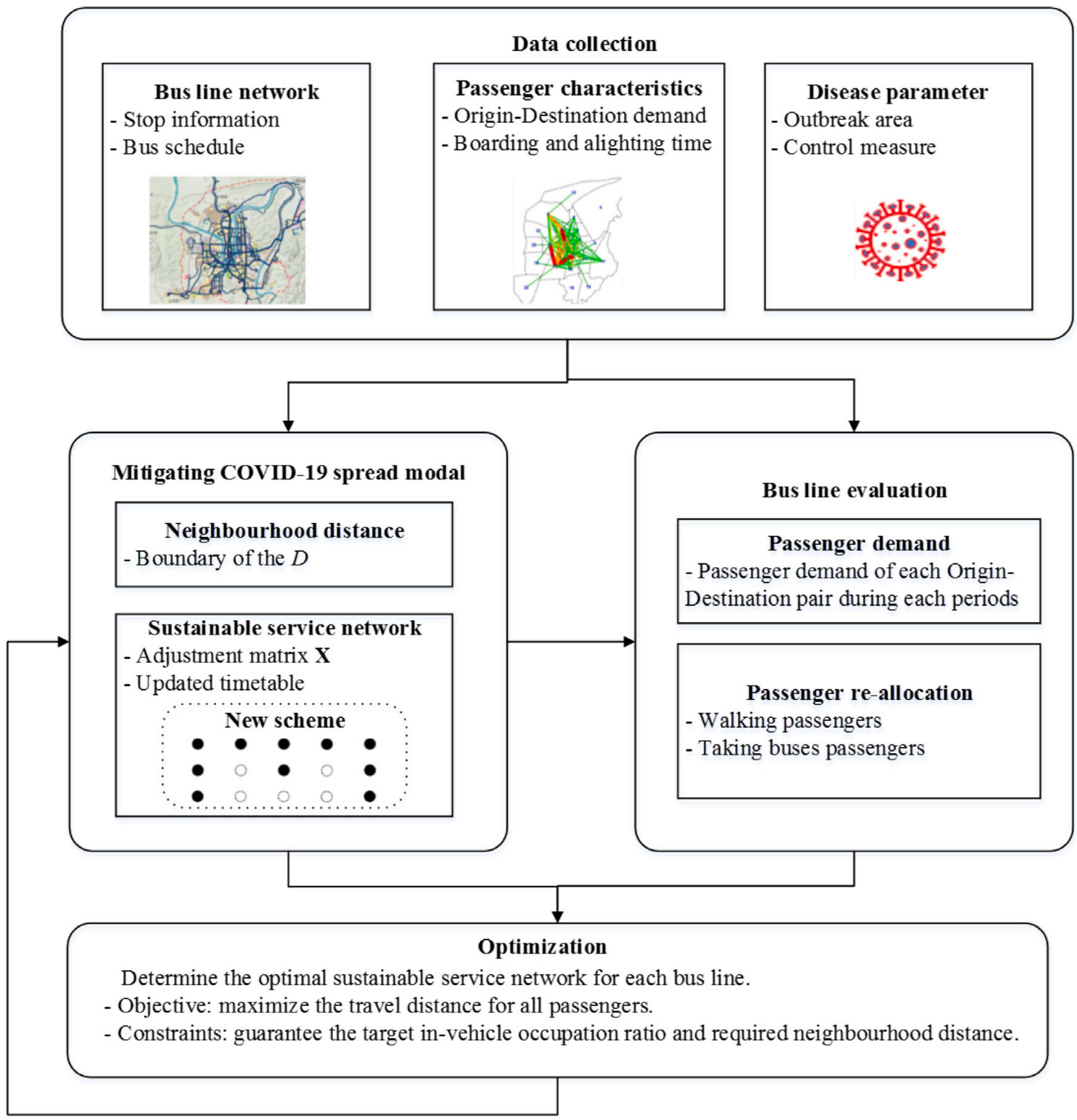


Fig. 2. Flowchart of the optimization framework.

to be evaluated by Eq. (5), where the passenger boarding–alighting demand is reallocated during each period. Note that the passenger decision is determined by the disutility of feasible boarding–alighting pairs, which can be calculated from Eqs. (2) and (3). Finally, the optimal sustainable service network is optimized by the proposed model.

The optimization model proposed in Eqs. (6) to (8) is nonlinear since the passenger behavior choice model assumed in Section 3.2 is exponential, and it is difficult to get an optimal solution by the exact algorithm. Moreover, for a typical bus line with N stops, all stops may be skipped except for the first and last stop, which must be visited, and there will be 2^{N-2} schemes. For each scheme, it is necessary to evaluate its feasibility and optimality under the condition of required neighborhood distance $\hat{D}$. Finally, an optimal sustainable service network can be obtained with enormous computation scope. Therefore, a heuristic method based on the genetic algorithm is developed to solve it, and the genetic algorithm has been widely used to estimate the efficiency of the stop-skipping strategy (Limsawasd et al., 2022; Liu et al., 2013).

The genetic algorithm process includes the initial solutions generation, crossover, mutation, evaluation and survival processes. First, we evaluate the maximum in-vehicle occupation ratio $\underline{\pi}$ with a deadheading scheme, where the bus line only serves the first and last stops. The bus line will be canceled if constraint (7) still be violated under the deadheading scheme. Otherwise, we process to initialize σ chromosomes. Specifically, we randomly generating a neighborhood distance $D' \in [\max\{\underline{D}, \hat{D}\}, \bar{D}]$, where $\underline{D}$ is the minimum distance between two adjacent stops of the whole bus line and $\bar{D}$ is the distance between the first stop and the last stop. From the starting stop, if the distance between two sequential stops is less than or equal to D', the stop is forced to skip. Otherwise, the stop is visited, as shown in Fig. 3. In the crossover process, κ chromosomes randomly collected and crossed, as shown in Fig. 3. New generated chromosomes whose neighborhood distance $D \geq \hat{D}$ are survived. In the mutation process, randomly collect ω chromosomes and conduct the mutation operation. Specifically, sample an integer number n between $[2, N-1]$ randomly, and change the value of n genes (from 0 to 1, or from 1 to 0), as given in Fig. 3. Finally, newly generated chromosomes with neighborhood distance $D \geq \hat{D}$ survived. Notes, the solution feasibility needs to be checked whether the in-vehicle occupation ratio satisfies formulation (7) for crossover and mutation operators. Each chromosome represents one bus scheme in the evaluation process, and the objective function value of each scheme is calculated by the model Eq. (5). In the selection process, the first μ chromosomes are selected in order of maximal

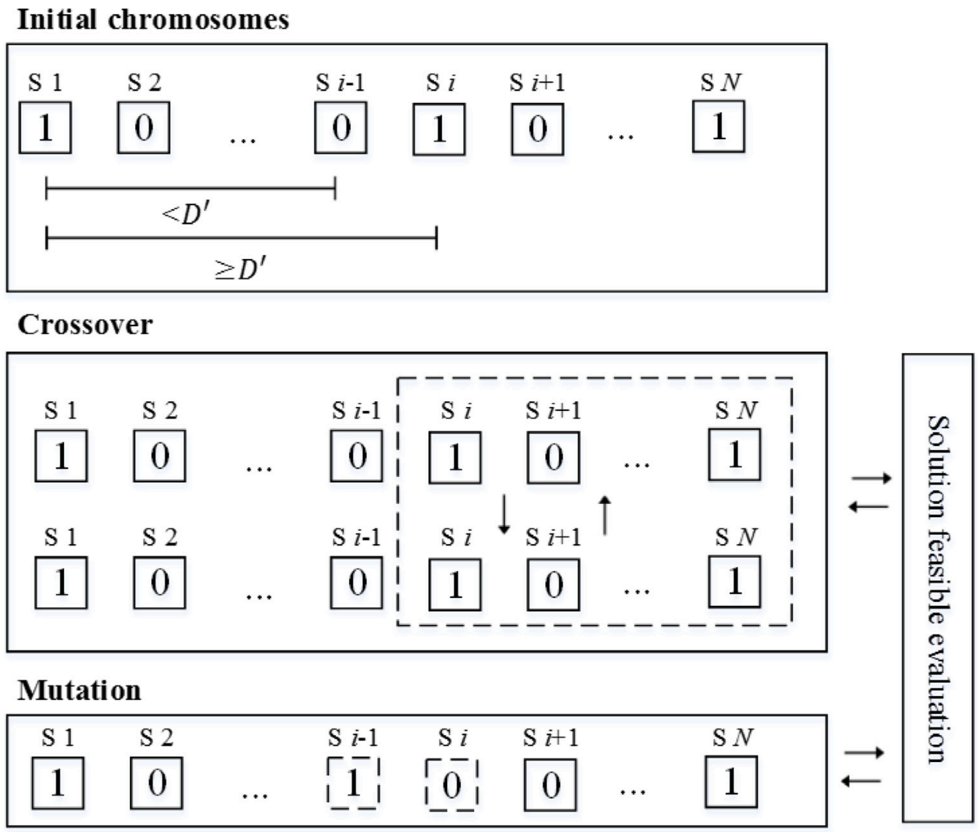


Fig. 3. Operators of the genetic algorithm.

objective values. Moreover, the process terminates once the iteration reaches the maximum predetermined generation.

5. Case study

In this section, we use a case study based on a real bus operation system operating in Liuzhou city, China, as an example to illustrate the effectiveness of the proposed sustainable service network that takes into account the neighborhood distance and target in-vehicle occupation to reduce the transmission of COVID-19 and improve the resilience in the bus system. At the same time, the passenger behavior under the sustainable service network will be further investigated.

5.1. Data description

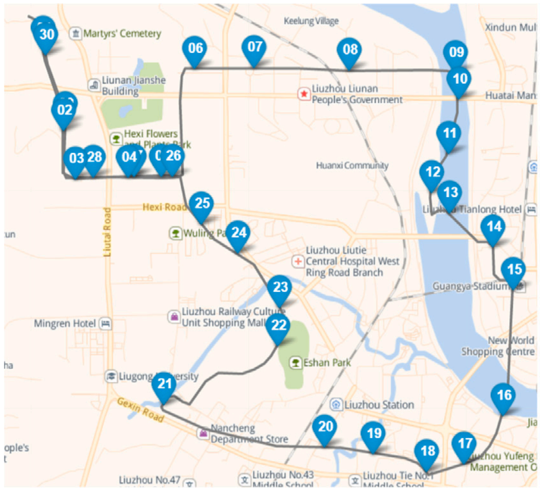
The Liuzhou bus system includes 114 bus lines with 838 stops, and the total operating length is approximately 2862 km. The bus line network information, including the stop number, stop coordinates, and map distance between two adjacent stops. The passenger demand information consists of the passenger boarding and alighting time from the origin to the destination. Moreover, most bus lines service from 6:00 am to 21:30 pm each day, and the sustainable service network optimization focuses on peak hours 7:30 to 11:30 am. Table 1 gives the information of the top crowded 15 bus lines, including the bus line No., stop number, passenger demand number and bus headway. The distance $\underline{D}$ is the minimum distance between adjacent stops, and $\tilde{D}$ is the average spacing distance between stops of the bus line, and $\bar{D}$ is the total length of the bus line. Moreover, $\underline{\pi}$ and $\bar{\pi}$ are the in-vehicle occupation ratio when the bus line only services the first and the last stop and without a sustainable service network, respectively.

Moreover, the initial parameter settings are listed in Table 2. The monetary value of one passenger-hour travel time equals 3.7 USD/h (Gong et al., 2021). In most cities in China, the full fare of a conventional bus is 1 RMB for each trip, which equals 0.14 USD. The dwell time of buses is determined by the boarding and alighting passenger number. To simplify our calculation, we assume the dwell time λ is fixed and equals 1 min if the stop is visited, otherwise equals 0. The passenger demand is divided into $T = 24$ periods by unit time Δ equals 10 min. The bus capacity directly influences the in-vehicle occupation ratio and is set as 45 seats. Moreover, the average walking speed of passengers and driving speed of vehicles are set as 1.5 m/s and 30 km/h, respectively.

5.2. Determination of optimal sustainable service for a typical line

In order to explore the characteristics of the proposed model and the influence of related parameters on the optimal solution, a typical line 111 with 30 stops is presented under the sustainable service network. As listed in Table 1, there have 1569 trip records in bus line 111 during the peak hour, and the minimum and maximum occupation ratios are 0.48 and 1.62, respectively. The map description of bus line 111 is shown in Fig. 4. This bus line is a circle line with 30 stops, and the distances between each adjacent stop are listed, where the shortest and longest distances are 274 m and 1704 m, respectively.

Firstly, we process to investigate the optimal sustainable service network when the target in-vehicle occupation ratio $\hat{\pi}$ is tightened from 1.7 to 0.5 and the required neighborhood distance $\hat{D}$ is increased from 500 to 4000. Notes, when the target in-vehicle occupation ratio changes, the neighborhood distance constraint is free or set as $\hat{D} \le \underline{D}$. After the optimization is implemented, the non-dominated sustainable service networks are identified under different target in-vehicle occupation ratios, as shown in Fig. 5. Generally, the sustainable service network with more stops will serve more passengers but inevitably produce higher in-vehicle occupation or less social distancing. As the target in-vehicle occupation ratio decreases, more stops are skipped to push more passengers to give up riding the bus. However, the number



Leg	Distance (m)	Leg	Distance (m)
1→2	868	16→17	636
2→3	507	17→18	394
3→4	541	18→19	571
4→5	338	19→20	503
5→6	1154	20→21	1704
6→7	608	21→22	1309
7→8	975	22→23	393
8→9	1093	23→24	705
9→10	274	24→25	477
10→11	560	25→26	569
11→12	445	26→27	397
12→13	278	27→28	414
13→14	561	28→29	618
14→15	484	29→30	738
15→16	1291		

Fig. 4. The map location of bus line 111 and distances between stops.

Table 1
The information of top 15 crowded bus lines.

No. of bus line	Number of stop	Number of passenger	Headway (min)	$\underline{D}$ (m)	$\tilde{D}$ (m)	$\bar{D}$ (m)	$\underline{\pi}$	$\bar{\pi}$
241	32	1874	9.47	161	589	18 847	0.83	2.00
51	34	1212	5.45	358	693	23 551	0.40	1.76
91	36	1026	10.00	202	478	17 193	0.60	1.69
701	53	329	90.00	222	495	26 256	0.43	1.69
161	37	1092	9.47	216	531	19 630	0.60	1.67
111	30	1569	5.81	274	647	19 405	0.48	1.62
541	39	646	18.00	124	737	28 733	0.28	1.60
551	32	646	16.36	53	703	22 481	0.50	1.60
641	58	486	25.71	285	532	30 840	0.25	1.60
351	32	736	11.25	46	805	25 773	0.25	1.53
301	37	1053	12.00	205	467	17 278	0.65	1.47
261	43	836	13.85	161	526	22 623	0.48	1.42
271	39	1228	6.92	315	608	23 704	0.38	1.42
251	33	1236	7.20	228	494	16 302	0.55	1.36
151	40	156	90.00	133	764	30 571	0.13	1.33

Table 2
Parameters setting.

Parameter	Value	Sources
The time value of passenger α	3.7 USD/h	Gong et al. (2021)
The ticket charge of bus τ	0.14 USD	Luo et al. (2022)
The dwell time of the bus at stop λ	1 min	–
The unit time of each duration Δ	10 min	–
The capacity of bus Y	45 seats	Dai et al. (2020)
The average driving speed of vehicle v_1	30 km/h	Russo et al. (2022)
The average walking speed of passenger v_2	1.5 m/s	Marra and Corman (2020)

of stops does not always reduce as the target in-vehicle occupation ratio tightens. For example, the number of stops when $\hat{\pi} = 0.9$ is greater than the number of stops when $\hat{\pi} = 1.0$, which is caused by the heterogeneity of passenger demand at each boarding–alighting pair. Similarly, the stop distribution is identified under different required neighborhood distances, while the in-vehicle occupation ratio constraint is free or set as $\hat{\pi} = \bar{\pi}$. It is evident that the stop distribution becomes more and sparser with $\hat{D}$ increases. Therefore, the constraint (8) could guarantee passenger fairness and avoid the visited stops densely. The transport agency could choose one of the optimal solutions during different periods of the pandemic.

To further examine the sustainable service network impact on occupation erasing during the COVID-19 pandemic, Fig. 6 gives the received in-vehicle occupation between each stop after implementing the sustainable service network. Notes, under a loose sustainable service network or target in-vehicle occupation ratio greater than 1.2, the occupation peak is apparent between stops 20 and 25. However, the occupation peak is becoming more and more smooth as the target in-vehicle occupation ratio $\hat{\pi}$ stricter. When the target in-vehicle occupation ratio tightens to $\hat{\pi} = 0.5$, few stops have been visited, and in-vehicle occupation are well-proportioned between each stop. Therefore, the optimal sustainable service network efficiently erases the in-vehicle occupation peak during the pandemic.

To present the passenger travel behavior adjustment, Fig. 7 gives the passenger number of each boarding–alighting pair after executing the sustainable service network, which is the optimal scheme with $\hat{\pi} = 0.8$ and $\hat{D} = 500$ (m). If the origin or destination is skipped, the passenger number at boarding–alighting pairs equals 0, marked red. Moreover, the original boarding–alighting passengers can adopt to riding at adjacent stops, making the neighborhood stops more crowded. However, under the target in-vehicle occupation, the sustainable service network would push passengers in serval boarding–alighting pairs with short travel distances to give up riding and choose walking or other transport modes. Unlike the directly enlarged headway strategy, the sustainable service network could avoid over-crowding in the bus system during the pandemic crisis. The original demand is reallocated to its adjacent stops. The new boarding–alighting matrix only has 1302 passengers compared to 1569 passengers without sustainable service network.

To further investigate the passenger behavior under the sustainable service network, Fig. 8 gives the passenger adjustment at each stop. The red and blue bars are the boarding passenger numbers with and without sustainable service network at no-skipped stops. Due to some stops are skipped, the travel cost increase for passengers in the skipped boarding–alighting pairs, and passengers would give up riding. Therefore, the

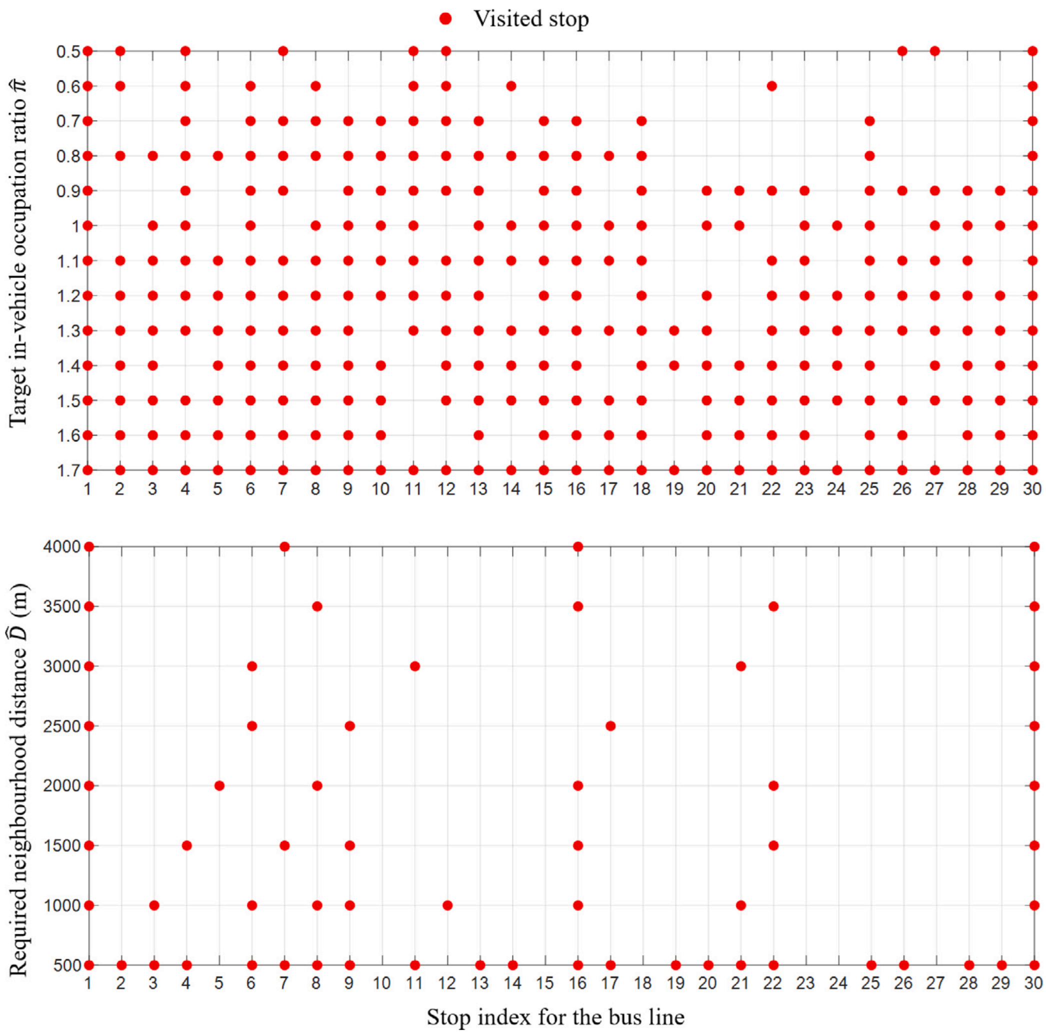


Fig. 5. Stops distribution under different $\hat{\pi}$ and $\hat{D}$.

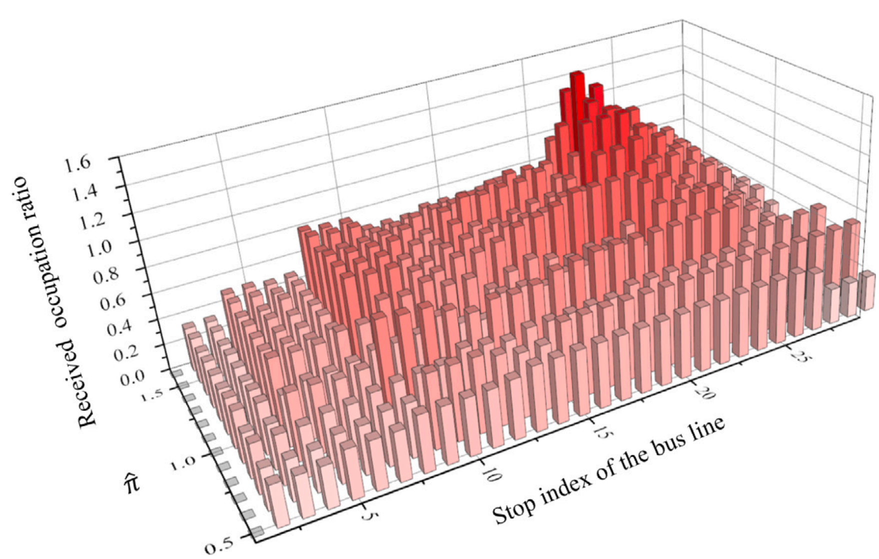


Fig. 6. The received in-vehicle occupation ratio between different stops.

board passenger number at some stops is reduced after carrying out the sustainable service network, which usually occurs in stops far away from the skipped stops. However, some passengers still adopt to walk to the nearby stops for riding, resulting in an increase in passenger numbers of adjacent stops compared to no sustainable service network, which mainly occurs near the skipped stops. Moreover, the green and

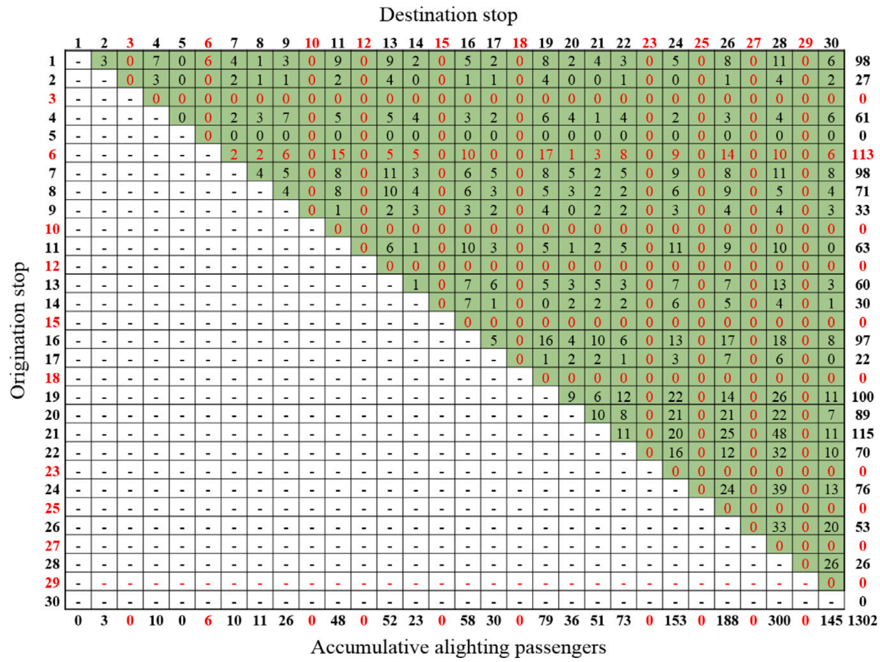


Fig. 7. Reallocated boarding–alighting passengers under the sustainable service network.

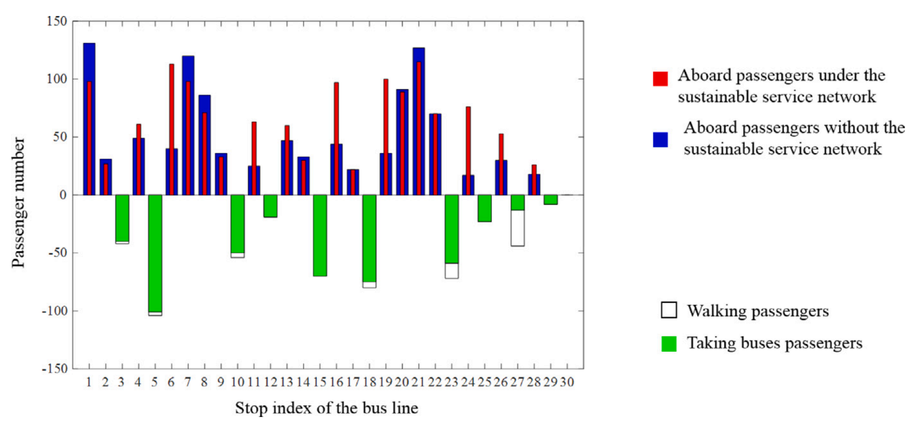


Fig. 8. The passenger choices under the sustainable service network.

whiter bars with negative values mean the passengers that turn to near stops and give up riding for walking, respectively. The result shows that only a few passengers adopt walking, and most passengers turn to nearby stops under the sustainable service network, but the in-vehicle occupation has a significant reduction compared to without the sustainable service network.

Furthermore, we conduct a sensitivity analysis of the passenger volume of the sustainable service network under different target in-vehicle occupation ratios $\hat{\pi}$ and required neighborhood distance $\hat{D}$. The number of boarding passengers under different combinations of $\hat{\pi}$ and $\hat{D}$ are represented by colors ranging from red to blue, as shown in Fig. 9. Consequently, with the in-vehicle occupation ratio relaxed and neighborhood distance enlarged, the total aboard passenger number increased generally. However, under the same neighborhood distance constraint, there would be fewer boarding passengers compared to tightening in-vehicle occupation ratios due to the objective function defined in Eq. (6) to maximize the total passenger travel distance rather than total passenger loading. In other words, loading fewer passengers with long travel distances would have a larger objective value compared to loading more passengers with short travel distances. Moreover, with the target in-vehicle occupation ratio relaxed, the optimal sustainable service network would not change because it is bounded by the neighborhood distance $\hat{D}$. Notes, when required in-vehicle occupation $\hat{\pi} \leq 0.4$ or neighborhood distance $\hat{D} \geq 6500$ (m), there would not have a feasible sustainable service network, and the bus line would be canceled during the pandemic.

5.3. Sustainable service network for the whole city

In this section, we investigate the sustainable service network of all bus lines in the whole city. It has to be noted that the passenger travel route would be affected after implementing the sustainable service network, where the passenger could choose other routes that are also accessible for the determined boarding–alighting pair. Notes, the accessible routes for each boarding–alighting pair could be obtained by the traditional shortest path algorithms, like Dijkstra and Clarke-Wright algorithms. The passenger choice between different routes for a determined boarding–alighting pair also could be gotten by the Logit model. If the passenger transfer behavior is considered, the sustainable service network with different bus lines need to be jointly optimized. However, due to the enormous calculation of a single bus line, jointly considering bus lines of the whole city would be impracticable in a reasonable time. Moreover, commuters travel in the peak hour regularly

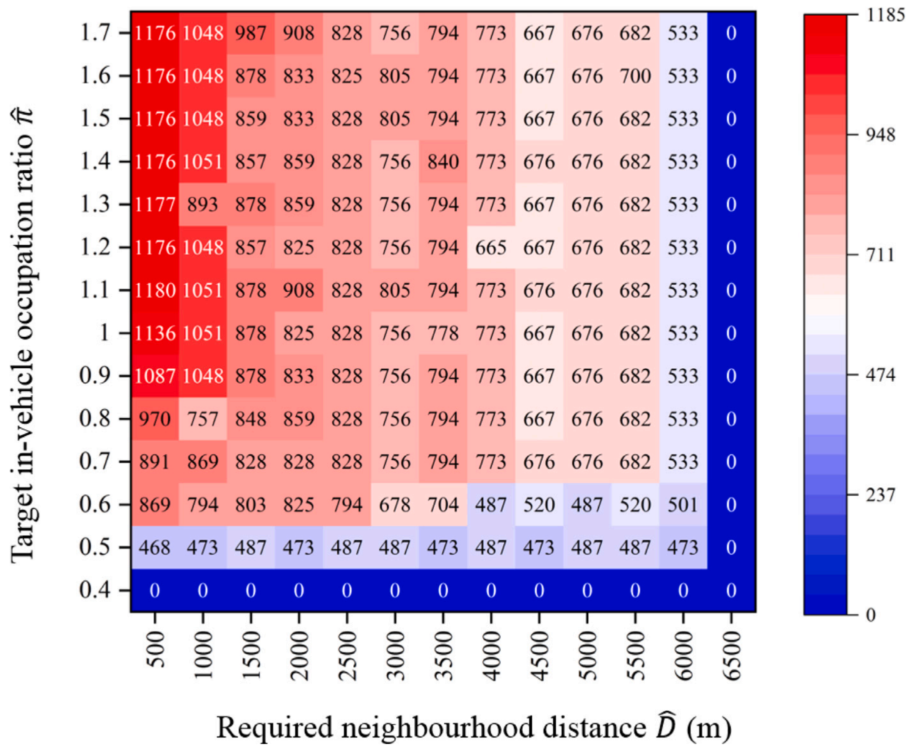


Fig. 9. The boarding passenger number under different combination of $\hat{\pi}$ and $\hat{D}$.

with fewer interchanges. Therefore, this paper has not considered the inner-coupling effect of different lines on passenger behavior.

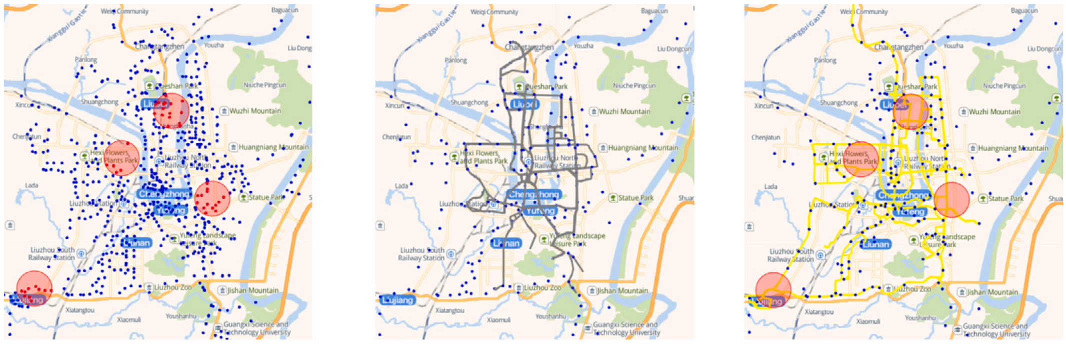
First, the stops distribution in the Liuzhou bus system is introduced in Fig. 10(a). Moreover, we assume four areas break out COVID-19, and the control distance published by the government is one kilometer around the risk center, which is marked as the red circle on the map. Then, a uniform sustainable service network, in which the target occupation ratio $\hat{\pi} = 0.5$ and the required neighborhood distance $\hat{D} = 1000$ (m). Fig. 10(b) shows the remained stops under the sustainable service network for all bus lines without considering the risk area, where the gray bus lines are canceled since the deadheading scheme could not satisfy the target in-vehicle occupation ratio. Furthermore, when COVID-19 breaks out, as shown in the risk area, stops located in the risk areas are required not to stop. Then, the sustainable service network needs to be re-optimization under extra constraints described in Section 4. Fig. 10(c) shows the remained stops under optimal sustainable service network with risk areas consideration, where the yellow bus lines are affected by the risk area. In summary, the results show that the remaining stops are more evenly distributed on the map after the sustainable service network implementation compared to most stops concentrated in the city center without traffic control.

Furthermore, we consider another scenario where various outbreak areas with different risk levels. Therefore, bus lines crossed in different risk areas need to adopt different control standards. Assume there are two risk regions with different infection numbers and other regions under regular control. Generally, the entire city is classified into three risk levels. Specifically, the in-vehicle occupations are separately set as 0.5, 0.75, and 1 according to risk levels. Correspondingly, the neighborhood distances are set as 500, 1000, and 1500 m. A more flexible public bus network can be built through different bus trips that are allowed to provide different services. Fig. 11(a) shows two risk areas with different radiation ranges. The red area has a higher infection number, and the radiation distance is 1 km. The corresponding control standards are set as $\hat{\pi} = 0.5$ and $\hat{D} = 500$, and bus lines that cross this region are also labeled as red. Moreover, another risk area is pictured in yellow, and the green lines are under regular control. Fig. 11(b) gives the optimization result of all bus lines with different control levels. Apparently, the proposed method allows for the development of reasonable operating services for different bus routes in different regions according to the severity of the epidemic, thus making the entire bus network more flexible and elastic.

Finally, we present in Fig. 12 a meaningful visual representation of the impact of COVID-19 on public transport in Liuzhou, two heatmaps of the passenger boarding distributions at different target occupation ratios. Obviously, the ridership drastically dropped after the target in-vehicle occupation ratios strict from 1.0 to 0.5, especially for passengers around the downtown. Moreover, the passenger density in the downtown area is higher than suburbs due to high-frequency bus services. The sustainable service network efficiently reduces passenger contact contagion by pushing several passengers to give up bus service and adopt other transport models. It is beneficial to prevent and control the epidemic when the number of passengers decreases in the public transport system, but the transportation cost of passengers also increases accordingly. Therefore, while preventing and controlling the COVID-19 epidemic, transport agencies can reasonably announce the target in-vehicle occupation ratio or/and sustainable service network according to the actual situation of the local COVID-19 epidemic.

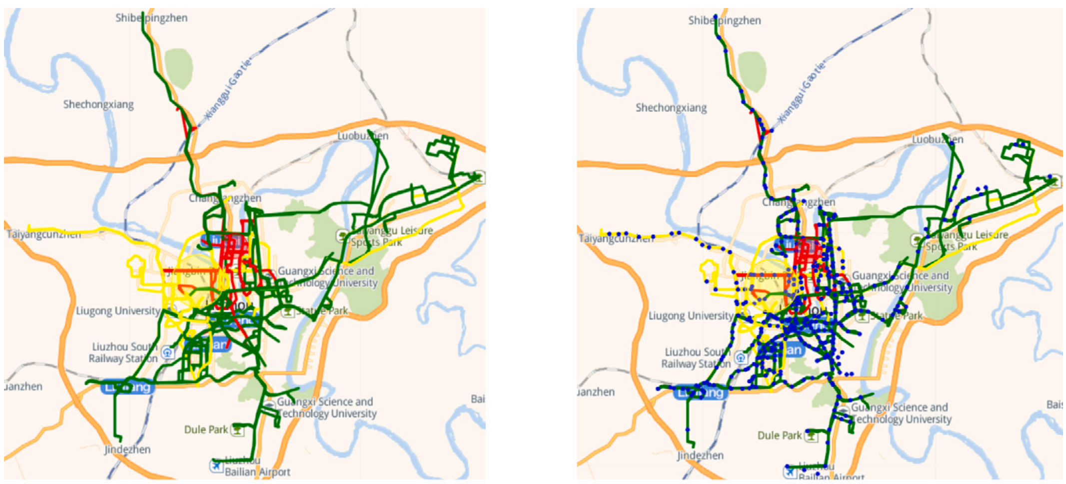
6. Policy implications

The government has taken many effective measures to better balance the travel demands of urban residents and the epidemic prevention and control. Social distance control or in-vehicle occupation requirements as one of efficient strategies to reduce the risk of contagion in urban public transport system, governments have built strict regulations to limit the number of boarding passenger. In order to respond to the policy of the government and conduct a theoretical study for strategy implementation in the pandemic control, this paper proposes the adoption of a sustainable service network to achieve the stated restriction goals of passenger occupation ratio by considering the passenger behavior. Specifically, the impact of the proposed strategy is multifaceted and can be summarized in the following three aspects.



(a) $\hat{\pi} = \bar{\pi}; \hat{D} = \underline{D}$; (b) $\hat{\pi} = 0.5; \hat{D} = 1000$; (c) $\hat{\pi} = 0.5; \hat{D} = 1000$; (Lockdown)

Fig. 10. The sustainable service network considering lockdown policy.



(a) Bus lines classify by different risk levels. (b) Sustainable service network under different control levels.

Fig. 11. The sustainable service network under different control levels.

(a) Aboard passenger distribution under $\hat{\pi} = 1.0$ and $\hat{D} = 1000$ (b) Aboard passenger distribution under $\hat{\pi} = 0.5$ and $\hat{D} = 1000$

Fig. 12. The boarding passengers distribution in the map under different target in-vehicle occupation ratios.

6.1. Commuters

For commuters, the proposed method can effectively reduce the in-vehicle occupation for the whole bus system based on different boarding–alighting demands, thus resulting in passengers keeping a reasonable social distance and reducing the risk of infection. In addition, due to serval stops being skipped, the total travel time for each trip is shortened, and the travel time of the riding passengers is saved. However, no strategy simultaneously satisfies the requirement of epidemic prevention and control and guarantees the service level of the bus system. The sustainable service network also has a negative impact on the riding experience of passengers. Specifically, this strategy rule passenger demands with a short distance out of the bus system. In the simulation results, about 17.64% of passengers give up taking the bus from 7:30 to 11:30 am if the required in-vehicle occupation ratio is set as 1 to avoid overcrowding. Moreover, this proportion will rise to 53.7% if the required in-vehicle occupation tightens to 0.5.

6.2. Transport operators

For transport operators, the sustainable service network helps operators quickly make adjustments to bus routes during an outbreak based on dynamic passenger demands and the characteristic of the pandemic. Meanwhile, the proposed strategy can shorten the round trip time, and it earns time for sanitization in the daily operation. Notes, the proposed approach is calculated by an efficient scientific method rather than a simple man-made decision. Compared to a 'one-size-fits-all' strategy, such as cut off the bus service, the proposed strategy allows the bus company to receive limited profit revenue for living. However, the reduction of passenger demand due to the skipped stops must lead to a sharp decline in the fare revenue for bus agencies. Therefore, in order to balance the fare loss of the bus company, the government can provide appropriate financial subsidies to help bus companies through the epidemic crisis.

6.3. Policymakers

For policymakers and regulators, setting reasonable control parameters for in-vehicle occupancy according to the severity of the local epidemic and passenger demands is a strong response to the national guidelines for epidemic prevention and control. The proposed strategy can effectively reduce the risk of infection caused by people's movement, ensure the health of the population, and improve the flexibility and efficiency of urban transportation during the epidemic, especially for some passengers who must take public transportation transit. Therefore, a proactive approach to controlling the pandemic reflects the responsibility of the government. Moreover, the proposed framework is not only suited for COVID-19 but also be applicable to other public health events in the future, which could ensure the regular operation of the public transportation system while reducing the spread of the virus.

7. Conclusions

The public transport system plays the primary role for residents to improve the accessibility of life, which has been significantly impacted by COVID-19 since the end of 2019. The transport agency faces a tremendous challenge in balancing ticket revenue and the risk of contact infection, and practical technical tactics are urgent for the government to build a sustainable public transport system. It is essential for transport agencies to design a sustainable urban system service to balance the in-vehicle social distance and the pandemic prevention and control, especially during the post-pandemic era. This paper proposes a strategy to build a sustainable service network that provides neighborhood distance between stops and in-vehicle occupation ratio as indicators to control social distance during the post-pandemic or new normal era. The objective is to maximize the passenger-distance (person × kilometers) of all passengers at each boarding–alighting pair. The passenger behavior is reallocated by a Logit model, determined by the disutility of different travel patterns. A heuristic method based on the genetic algorithm is designed to solve the proposed constrained non-linear programming model, where each feasible sustainable service network is coded as a chromosome. The Liuzhou bus system, including the detailed passenger travel record, bus line information and timetable, are imported to illustrate the validity of the proposed model and method, which could efficiently obtain the optimal sustainable service network under different target in-vehicle occupation ratios or required neighborhood distances. The proposed model and algorithm could help the regulator design an operational urban transport system, which could jointly minimize the spread of the virus and guarantee the level of urban bus service during the post-pandemic era.

However, there have serval limitations in the current research. First, the passenger behaviors between different lines, such as transfer routes, are not considered. Notes, the transfer behavior is practical and has a direct influence on the evaluation of the sustainable service network. If it is considered, the number of passengers giving up riding would decrease because they can use the network connectivity, and the neighborhood distance would be further enlarged. Second, some interesting research topics will explore further the complex relationships between various transport modes, combined by the metro system, bus system, sharing-bike system, and other systems, and the passenger behavior and virus spread in the multi-model transport system could also be analyzed. Finally, modeling and solving the problem by jointly optimizing headway, bus fleet, and network design is another further research direction.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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