A New Approach to Waiting Time and Dispatch Frequency Guided Bus Timetable Optimization

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***Abstract*—The current bus departure time intervals are usually fixed without timely exploring the diversity of passenger flow in various periods, which inevitably leads to a sub-optimal solution to the passenger waiting time and the bus company's benefit. Therefore, to optimize the bus timetable, we propose a new waiting time and dispatch frequency guided approach, which builds on a new departure time interval expression (DTIE) that simultaneously considers the effects of the fluctuation in passenger flow and the number of bus stops. Specifically, we first construct a vehicle space-time matrix (VSTM) that records the running states of each bus, and then combine the VSTM and real passenger travel data to find the optimal parameters for DTIE, through a simulation experiment searching for the optimal parameters that simultaneously minimize the waiting time and the number of bus dispatched. We evaluate the proposed optimization method on three typical bus lines in Shenzhen, China, and the results demonstrate its effectiveness and superiority, in comparison with the bus scheduling scheme currently used by the bus company.**

***Index Terms*—Departure time interval, optimization, vehicle space-time matrix**

I. INTRODUCTION

Nowadays, to mitigate the increasing traffic congestion problem caused by the use of private cars, more and more cities encourage their residents to commute by bus. Therefore, an optimized bus timetable is beneficial to both bus companies and passengers. To optimize the bus schedule, various types of methods have been proposed.

Genetic algorithms were widely used in bus timetable optimization [1], due to their searching capacity for a complex scheduling problem. With diverse conditions and practical demands, linear programming was adopted to obtain the optimal bus timetable [2], [3]. Furthermore, several models to determine bus timetables considered the benefits of both the bus company and passengers [4], which is more reasonable. As a result of passenger demand fluctuation in the bus operation, diverse sizes of vehicles were also exploited [5]. Moreover, heuristic procedures were constructed to tackle various depot vehicle scheduling problems with route time constraints [6], and an integer linear program was formulated under the emission constraints [7].

Most of the above-mentioned studies verified the effectiveness of their proposed schemes through simulated data. They can not well exploit the true historical travel data of bus lines where fixed departure time intervals are currently adopted. In addition, compared with the fixed departure time intervals, the flexible data-driven intervals, which consider the fluctuation in passenger flow in various periods, can be more efficient for the bus line operations.

Therefore in this paper, we propose a new optimization method, which is guided by passenger waiting time and bus dispatch frequency through exploiting historical travel data, to promote optimal data-driven intervals. The intuition behind our proposal is simple: in the peak period of passenger flow, bus companies should shorten the departure time interval to relieve the passenger travel pressure; while in the off-peak period, to reduce the operation costs, bus companies should appropriately elongate the departure interval; and the optimal departure time intervals should be determined by mining the true historical data of each bus line.

Technically, to better express the inherent relationship between departure time interval and passenger flow, we put forward a new departure time interval expression (DTIE) to calculate the departure time interval in each period. In addition to the influence of passenger flow fluctuation, the DTIE also considers the impact of the number of bus stops on the departure intervals. Then, to determine the optimal parameters in the DTIE by using the historical travel data, we design a simulation scheduling experiment based on a Passenger Set, which records the travel information of all passengers, and a vehicle space-time matrix (VSTM), which records the state of each bus in any time period. With the optimal DTIE and the travel data, an optimized bus timetable for bus lines can be derived. The experiments with the historical travel data on three typical bus lines in Shenzhen, China, confirm the effectiveness and superiority of the proposed method for optimal bus departure time intervals, in comparison with the current scheduling scheme used by the bus company.

The rest of the paper are organized as follows. Section II describes the derivation and interpretation of the DTIE in detail. A scheme guided by passenger waiting time and bus dispatch frequency to optimize the parameters in DTIE with the Passenger Set and the VSTM is presented in Section III. Section IV shows the implementation and results of simulation experiments by applying the proposed method to three bus lines. Conclusions are drawn in Section V.

II. THE PROPOSED DEPARTURE TIME INTERVAL EXPRESSION (DTIE)

To our knowledge, many bus companies in Chinese cities like Shenzhen formulate the bus dispatch plan based on bus drivers' experience, and the departure time intervals are usually fixed, which is not timely adjusted to the ever-changing passenger flow on the bus lines. However, as we expect from an optimal solution, in the peak hour, bus companies should shorten the departure time interval to relieve passenger travel pressure; while in the off-peak hour, the bus company can appropriately increase the departure interval to reduce their operating costs. That is, the company should fully tap the line's historical passenger flow to optimize the departure time intervals. To this end, we first need to explore the relationship between passenger flow and departure time intervals.

To derive the expression of the relation between passenger flow and departure time interval, we define the following notations, in a way similar to [5]:

V_p: the passenger flow of a bus line in one hour;

N_m: the maximum capacity of a bus;

γ: the average occupancy rate of buses;

t_s: the departure time interval (unit: minute) of buses;

S^*: the total number of stops on a bus line;

α: a time regulator factor through which the number of stops influences the departure time interval.

As with [8], when the bus departure time interval in an hour is fixed as t_s, the number of buses dispatched from the starting station in that hour can be estimated as $60/t_s$, and the total capacity of these buses in that hour is

$$N = \frac{60}{t_s} N_m \ , \tag{1}$$

with the unit of t_s being minute. The average occupancy rate of buses in that hour can be then obtained as

$$\gamma = \frac{V_p}{N} \ . \tag{2}$$

Therefore, based on V_p, N_m, and γ, we can get the departure time interval t_s in that hour. Usually, the departure time interval is an integer, so we round up the expression as

$$t_s = \lceil \frac{60 \cdot N_m \cdot \gamma}{V_p} \rceil \ . \tag{3}$$

However, the departure time interval defined in Eq.(3) only considers the effect of passenger flow. In fact, the number of stops also shapes the departure time intervals in [9], [10]. Under the same passenger flow, considering two extreme cases, buses travel on a bus line with two stations or an infinite number of stations. Obviously, in the first case, all passengers get on at the starting point and get off at the terminal. During the bus running, passengers would feel crowded and have poor travel experience. In the second case, passengers can selectively get on or get off at many stations, so the number of passengers on the bus would not be excessive, and passengers could have a pleasant travel experience. To some extent, this shows that more stops can increase passengers' benefits with the same departure interval.

Nevertheless, for bus companies, they naturally hope the bus is full at any time to reach the maximum profit. Therefore under the same passenger flow, when the number of stops increases, bus companies intend to enlarge their benefits by increasing the departure interval.

Based on the above analysis, we add a term into Eq.(3) to take into account the number of stops in the expression.

Intuitively, compared with the increase in the number of bus stops from 12 to 22, the increase from 2 to 12 can more alleviate the congestion of bus passengers in a relative sense. That is, as the number of platforms continues to increase under the same increment, the relative benefit that this brings to passengers will be smaller and smaller. Hence the increment in departure time interval should also be lower. Based on this intuition, we adopt a logarithmic function to describe the relationship between the departure interval and the number of stops. In addition, the departure time interval should be minimal if there are only two stations on the bus line. Therefore, with all the considerations above, we propose a new departure time interval expression (DTIE) as

$$t_s = \lceil \frac{60 \cdot N_m \cdot \gamma}{V_p} \rceil + \lceil \alpha \cdot \log_2(S^* - 1) \rceil \ . \tag{4}$$

It is noteworthy that the first term on the right-hand side of Eq.(4) can be regarded as the departure interval of the bus lines with only two stops.

III. Determination of Parameters α and γ

For a designated bus line, the value of N_m and S^* in Eq.(4) can be easily obtained from the bus company. Moreover, the passenger flow V_p of each period can be calculated through true historical travel data. Therefore, we only need to determine the values of α and γ in Eq.(4), such that the bus timetable can be optimized based on the DTIE. Hence, a simulation experiment is designed to find the optimal parameters. The establishment of the simulation requires a Passenger Set M and a vehicle space-time matrix (VSTM). The flow chart of the proposed method is shown in Fig.1, and we shall explain each component in detail in the following sections.

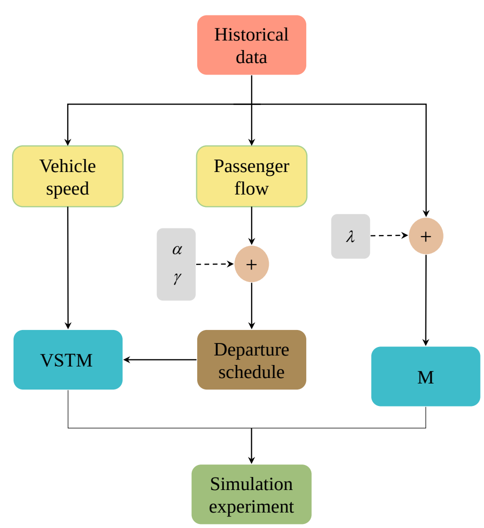

Fig. 1. The flow chart of the proposed optimization method. The information of vehicle speed and passenger flow can be acquired from historical data. M denotes the Passenger Set.

A. Description of the Passenger Set M

The information of passengers getting on and off the bus is essential for building the simulation experiment. We retrieve these information from the historical travel data and establish a set $M = \{m_1, m_2, \ldots, m_\psi\}$ to record the information, where ψ represents the total number of passengers traveling on the bus line and

$$m_i = (a_i, b_i, c_i) \ , \tag{5}$$

where a_i and b_i are the indexes of boarding stop and alighting stop for the ith passenger, respectively, and c_i is the moment of arriving at the boarding stop for the passenger.

Actually, with the true historical data provided, we can only get the passenger's boarding moment from the bus record, while the moment of passengers arriving at the platform cannot be acquired. Since the arrival time of passengers is random, we define the arrival moment of passengers as follows:

$$c_i = t_i^* - \lceil \lambda \rceil \ , \tag{6}$$

where t_i^* is the boarding moment for the ith passenger that can be obtained from the travel data, and λ is a random variable. Please note that the value of λ represents passengers' waiting time for the current scheme that has been used in the real bus line, and its distribution can be empirically set with the suggestion from bus companies.

B. Interpretation of the VSTM

In addition to the travel information of passengers, the simulation requires the running states (e.g., the distance of the bus from the starting stop) of each bus in real time. Hence, we creatively build a vehicle space-time matrix (VSTM) $G_{2880\times3\times\xi}$ to record all buses' running states, where ξ is the total number of buses dispatched from the starting station. The construction of the VSTM can be achieved based on the bus dispatch schedule and the speed of buses in different periods.

For the bus dispatch schedule of a designated bus line, the values of N_m, S^* and the passenger flow V_p can be attained from the bus company. Hence, as shown in Eq.(4), the DTIE can be used to calculate the departure time interval t_s in each particular period after we initialize parameters α and γ. Please note that the initialized parameters may not be optimal. Based on the departure time interval in each period, we can calculate the initial bus timetable for the bus line. That is, the departure moment of every bus from the starting station can be acquired. Then, to capture the running states of buses in real time, we need to know the bus velocity.

The speed of a bus can be estimated from the historical travel data, and the expression is defined as

$$\bar{v}_j = \lceil \frac{1}{\eta_j} \sum_{i=1}^{\eta_j} \frac{d_i^j}{\Delta t_i^j} \rceil \ , \tag{7}$$

where d_i^j is the movement distance of the ith bus during time Δt_i^j, and η_j is the number of buses on the bus line in the jth hour of a day. It is worth noting that $\bar{v}_j$ is the average bus speed in the jth hour of a day in the simulation experiment.

With the bus dispatch schedule and speed in different periods, we can construct the VSTM $G(x, y, z)$, where $x = 1, 2, \ldots, 2880$, $y = 1, 2, 3$, and $z = 1, 2, \ldots, \xi$. The entries and some symbols of the matrix are described as follows:

ξ: the total number of buses dispatched from the starting station and it can be calculated through

$$\xi = \sum_{j=\tau}^{\delta} \lceil \frac{60}{t_s^j} \rceil \ , \tag{8}$$

where τ and δ are the hour of first and last departures, respectively, with their values being the integer values in the range of [1, 24], and t_s^j represents the departure time interval for the jth hour of the day based on Eq.(4).

$G(x, 1, z)$: the xth minute in two days; as some buses start late and may run over two days, and each day has 1440 minutes, the total duration is 2880 minutes. The $G(x, 1, z)$ for the zth bus in the xth minute is expressed as

$$G(x, 1, z) = x = 60 \cdot \mu_z^x + \rho_z^x \ . \tag{9}$$

For the zth bus, Eq.(9) indicates that the xth minute is in the μ_z^xth hour and the ρ_z^x minutes in that hour, where the values of μ_z^x and ρ_z^x are integers in [1,47] and [0,59], respectively.

$G(x, 2, z)$: the distance of the zth bus from the starting station on the xth minute. If the departure moment is θ for the zth bus in the initial bus timetable, in other words, the departure moment is in the μ_z^θth hour and the ρ_z^θ minutes in that hour, $G(x, 2, z)$ can be obtained as

$$G(x, 2, z) = (60 - \rho_z^\theta)\bar{v}_{\mu_z^\theta} + 60 \cdot \sum_{i=\mu_z^\theta+1}^{\mu_z^x-1} \bar{v}_i + \rho_z^x \bar{v}_{\mu_z^x} \tag{10}$$

Please note that Eq.(10) holds if x is greater than θ, otherwise $G(x, 2, z)$ is equal to 0, namely, the zth bus is still at the starting station.

$G(x, 3, z)$: the state of the zth bus on the xth minute. There are four bus states: 10, 11, 20, and 21, in which 10 indicates that the bus is not in operation on the first day. This means that the bus may be at the starting station or at the terminal station. If the bus is running on the first day, the state of the bus is 11. By analogy, 20 or 21 indicate that the bus is out of service or in operation on the second day.

C. Construction of the Simulation

There are many uncontrollable factors in the real bus dispatching process, such as bus breakdown and bus line congestion. People usually make some assumptions to simplify the simulation [11]. In our simulation study, we follow this manner and make the following assumptions:

1. Passengers follow the first come first board principle;
2. There is no traffic jam on the bus line;
3. The maximum capacity of all buses is the same;
4. Buses operate normally on public transport lines.

Up to now, we possess the Passenger Set M and the VSTM for the initialized parameters α and γ and the historical travel data. The Passenger Set M records the boarding stop, the alighting stop and the arrival time in the boarding stop of all passengers. In addition, the operation state of each bus at any time can be obtained from the VSTM. Hence, based on the above assumptions, we only need to traverse the time, then the bus simulation scheduling experiment can be completed after the boarding rules are built up.

Passenger boarding rules are as follows:

$$0 < (T_i^W = x_z^{a_i} - c_i) < T_h \ , \tag{11}$$

where, for the ith passenger, $x_z^{a_i}$ is the moment of the zth bus arriving at the a_ith stop that can be obtained from the VSTM. c_i is the moment of the passenger arriving at the same stop that is recorded in the Passenger Set M. Accordingly, T_i^W represents the waiting time of the passenger for the bus. T_h is a time threshold that passengers are willing to wait for the bus. This means that if passengers' waiting time is longer than the threshold, they will choose to give up the bus travel. In addition, the number of passengers on board must be less than N_m under the boarding rules. When these two conditions are satisfied, passengers choose to get on the bus.

After the simulation, we can acquire the waiting time T^W of every passenger. For bus companies, the goal is to have as few number of bus departures as possible. However, passengers prefer short waiting time for the bus [12]. Under these circumstances, to get the optimal parameters α and γ that can balance the interests of passengers and bus companies, we define the objective function of the dispatch plan as

$$L = w_1 \cdot \sum_{i=1}^{\psi} T_i^W + w_2 \cdot \xi \ , \tag{12}$$

where w_1 and w_2 are two weights, ψ is the total number of passengers traveling on the bus line, and ξ is the total number of buses dispatched from the starting station. Once w_1 and w_2 are determined, for each pair of parameters α and γ, we can obtain the value of L based on the simulation experiment.

Therefore, through grid search to minimize L, we can obtain the optimal parameters, then the optimal departure time interval based on the DTIE, and finally the optimal timetable.

IV. Case Study

To verify the validity of the proposed bus timetable optimization method, we evaluate the method on true historical travel data of a bus line in Shenzhen, China, as a case study. As mentioned in Section III, the optimal parameters α and γ used in the optimization method can be obtained through the above-introduced simulation experiments, the procedure of which can be summarized as follows.

From the historical travel data, we can attain the average bus speed $\bar{v}$, the distribution of passenger flow V_p, and the Passenger Set M with the designated distribution of the random variable λ, as shown in Fig.1. Then, an initial departure schedule of buses can be acquired after initializing the parameters α and γ. With this departure schedule and the $\bar{v}$, the initial VSTM can be obtained. Finally, we can accomplish the simulation experiment with the initial VSTM and the Passenger Set M, and obtain the value of objective function L in Eq.(12). Through grid search to minimize L, the optimal values of parameters α and γ can be achieved. We will describe each step in detail below.

A. Passenger Flow and the Initial Departure Schedule

The passenger flow V_p of a bus line in one hour can be calculated as follows. With the historical travel data, we can count the number of passengers traveling on the bus line in each period, as shown in Fig.2. Thus, the value of V_p for each period can be obtained. For instance, the passenger flow from 10:00 am to 11:00 am is the passenger volume corresponding to 11 on the time axis of Fig.2. We can see that the passenger flow fluctuates with time, which indicates the necessity of adjusting the departure time intervals to accommodate the fluctuation for an efficient operation of the bus line.

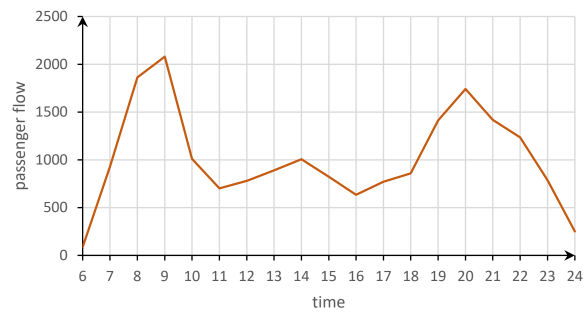

Fig. 2. Passenger flow V_p on the bus line. We can see that the passenger flow in various periods is fluctuant, which demonstrates dynamic departure time intervals are essential.

The initial departure schedule can be then acquired as follows. The values of N_m, the maximum capacity of a bus, and S^*, the total number of stops on the bus line, provided by the bus company are 65 and 60, respectively. As a result, we can get each hour's initial departure time interval based on the DTIE in Eq.(4) after initializing the parameters α and γ to 1 and 0.5, respectively, as shown in Table I.

TABLE I
Initial departure time interval in each period

Departure schedule			
Time period	Interval(min)	Time period	Interval(min)
0:00-5:00	∞	14:00-15:00	9
5:00-6:00	29	15:00-16:00	10
6:00-7:00	9	16:00-17:00	9
7:00-8:00	8	17:00-18:00	9
8:00-9:00	7	18:00-19:00	8
9:00-10:00	8	19:00-20:00	8
10:00-11:00	9	20:00-21:00	8
11:00-12:00	9	21:00-22:00	8
12:00-13:00	9	22:00-23:00	9
13:00-14:00	8	23:00-24:00	14

From Table I, we can find that the value of τ (Eq.(8)), the hour of first departure, is 6. Thus, the departure moment for each bus is obtained with the departure time interval t_s in various time periods, and the initial bus timetable is built as shown in Table II.

TABLE II
INITIAL BUS TIMETABLE

5:00	5:29	6:58	6:00	6:09	6:18	6:27	6:36
6:45	6:54	7:00	7:03	7:08	7:16	7:24	7:32
7:40	7:48	7:56	8:00	8:04	8:07	8:14	8:21
8:28	8:35	8:42	8:49	8:56	9:00	9:03	9:08
9:16	9:24	9:32	9:40	9:48	9:56	10:00	10:04
10:09	10:18	10:27	10:36	10:45	10:54	11:00	11:03
11:09	11:18	11:27	11:36	11:45	11:54	12:00	12:03
12:09	12:18	12:27	12:36	12:45	12:54	13:00	13:03
13:08	13:16	13:24	13:32	13:40	13:48	13:56	14:00
14:04	14:09	14:18	14:27	14:36	14:45	14:54	15:00
15:03	15:10	15:20	15:30	15:40	15:50	16:00	16:09
16:10	16:18	16:27	16:36	16:45	16:54	17:00	17:03
17:09	17:18	17:27	17:36	17:45	17:54	18:00	18:03
18:08	18:16	18:24	18:32	18:40	18:48	18:56	19:00
19:04	19:08	19:16	19:24	19:32	19:40	19:48	19:56
20:00	20:04	20:08	20:16	20:24	20:32	20:40	20:48
20:56	21:00	21:04	21:08	21:16	21:24	21:32	21:40
21:48	21:56	22:00	22:04	22:09	22:18	22:27	—

Please note that the departure interval t_s of some time periods cannot be exactly divided by 60, which cause that the departure time interval is inconsistent, so we can see that the departure moment of the last bus in the current time period is in the next time period. For example, the departure moment for the last bus in 6:00-7:00 is 7:03 in Table II. In the simulation experiment given each pair of parameters α and γ, we found that there were no passengers in the last few buses. That is because when the buses departed from the starting station, there were still some passengers on the bus line, but after they had been running for some time, these passengers had already boarded the bus that had departed early. For this reason, the bus departure time period is 5:00-22:30 in the simulation process.

B. Bus Speed and the Initial VSTM

The average bus speed $\bar{v}$ is calculated here. Using the provided travel data, we get passengers' boarding station a, alighting station b, boarding moment t^*, and alighting moment, so the average velocity in each period can be calculated by using Eq.(7) and the results are shown in Table III.

TABLE III
BUS SPEED IN EACH TIME PERIOD

Time period	$\bar{v}$(m/min)	Time period	$\bar{v}$(m/min)
0:00-5:00	388	14:00-15:00	320
5:00-6:00	344	15:00-16:00	320
6:00-7:00	310	16:00-17:00	320
7:00-8:00	309	17:00-18:00	337
8:00-9:00	309	18:00-19:00	362
9:00-10:00	321	19:00-20:00	369
10:00-11:00	344	20:00-21:00	361
11:00-12:00	364	21:00-22:00	370
12:00-13:00	355	22:00-23:00	388
13:00-14:00	340	23:00-24:00	388

Because the amount of travel data from 0:00-5:00 is relatively small, we replace the average speed in this period with the average velocity in Table III from 23:00-24:00.

With the initial bus timetable in Table II, we can know that the value of ξ, the total number of buses dispatched from the starting station, is 143, so the construction of the vehicle space-time matrix (VSTM) $G_{2880\times3\times143}$ to record all buses' running states can be achieved, after we determine the values of $G(x,1,z)$, $G(x,2,z)$ and $G(x,3,z)$.

For $G(x,1,z)$, it records the xth minute in two days and its value is the first element x. The distance of the zth bus from the starting station on the xth minute is recorded in $G(x,2,z)$ and it can be calculated with the initial bus timetable in Table II and the bus speed of each period in a day in Table III. As for $G(x,3,z)$, it records the state of the zth bus on the xth minute and its value is determined by $G(x,1,z)$, $G(x,2,z)$ and the departure moment θ of the zth bus in Table II. For instance, if $G(x,1,z)$ is larger than θ and less than 1440, and $G(x,2,z)$ is less than the distance from the starting station to the terminal station, the state $G(x,3,z)$ is 11. In the end, with $G(x,1,z)$, $G(x,2,z)$ and $G(x,3,z)$, we can obtain the VSTM based on the initialized parameters α and γ.

C. Passenger Set M and the Initial Value of L

The Passenger Set M consists of each passenger's boarding station a, alighting station b and the moment c of arriving at the boarding stop. We can attain the Passenger Set M with the provided travel data after determining the random variable λ representing passengers' waiting time for the current scheme that has been used on the real bus line. Here, λ is a random variable following an exponential distribution with a mean of 10 minutes as suggested by the company.

To obtain the L in Eq.(12), we need to finish a run of simulation first. With the VSTM that records the operation state of each bus at any time and the Passenger Set M, we can accomplish the simulation through traversing the time under the passenger boarding rules. Here, the value of T_h, the time threshold that passengers are willing to wait for a bus, is set to 75 in the rules, since the bus from the starting station to the terminal station time is about 150 minutes. After the simulation, we acquire each passenger's waiting time T^W under the condition that parameters α and γ are 1 and 0.5, respectively. Hence, the total waiting time $\sum T^W$ is 43955 and the value of ξ is 143 from Table II.

For the value of L, in addition to the above-mention $\sum T^W$ and ξ, we require to determine the weight coefficients w_1 and w_2. To eliminate the influence of the order of magnitude and balance the benefits of both the bus companies and the passengers, w_1 and w_2 are set to the reciprocal of the passengers' total waiting time $\sum T^W$ and the total number of departures ξ in the current scheme, respectively. The ξ for the current scheme used in the real bus line is 120 as retrieved from the historical travel data. Moreover, the $\sum T^W$ of the current scheme is 56407 with the exponentially distributed λ and the travel data. Thus, we acquire the value of L is 1.9710 under the initial parameters α and γ.

D. Optimal Results on the Bus line

For each pair of initialized parameters α and γ, we can get the corresponding value of objection function L with the simulation. Hence, through the grid search to minimize L, the optimal values of parameters α and γ can be obtained. We note that, in addition to minimizing L, we expect that, under the optimal parameters, the passengers' total waiting time $\sum T^W$ and the total number of departures of buses ξ should be reduced in comparison with the current scheduling scheme, for the benefits of both bus companies and passengers. In our experiment from the historical travel data, the minimum value of L is 1.8819 under the optimal values of parameters α and γ as 1.19 and 0.31, respectively. With the optimal parameters, the optimal bus timetable is shown in Table IV.

TABLE IV
OPTIMAL BUS TIMETABLE

5:00	5:22	5:44	6:00	6:10	6:15	6:20	6:30
6:40	6:50	7:00	7:09	7:10	7:18	7:27	7:36
7:45	7:54	8:00	8:03	8:09	8:18	8:27	8:36
8:45	8:54	9:00	9:03	9:10	9:20	9:30	9:40
9:50	10:00	10:10	10:20	10:30	10:40	10:50	11:00
11:10	11:20	11:30	11:40	11:50	12:00	12:10	12:20
12:30	12:40	12:50	13:00	13:10	13:20	13:30	13:40
13:50	14:00	14:10	14:20	14:30	14:40	14:50	15:00
15:10	15:20	15:30	15:40	15:50	16:00	16:10	16:20
16:30	16:40	16:50	17:00	17:10	17:20	17:30	17:40
17:50	18:00	18:09	18:10	18:18	18:27	18:36	18:45
18:54	19:00	19:03	19:09	19:18	19:27	19:36	19:45
19:54	20:00	20:03	20:09	20:18	20:27	20:36	20:45
20:54	21:00	21:03	21:09	21:18	21:27	21:36	21:45
21:54	22:00	22:03	22:10	22:20	22:30	—	—

Passengers' total waiting time $\sum T^W$ and the total number of bus dispatches ξ for the current scheduling scheme and the scheduling scheme under the optimal parameters α and γ are shown in Table V.

TABLE V
COMPARISON OF SCHEDULING SCHEMES ON THE BUS LINE

Method	$\sum T^W$ (min)	ξ
current scheme	56407	120
our optimized scheme	50685	118

From Table V, we can observe that both the passengers' total waiting time and the total number of departures are all reduced, particularly the waiting time, compared with the current scheme. This means that the proposed bus timetable optimization method is superior to the current bus scheduling scheme used by the company.

TABLE VI
COMPARISON OF SCHEDULING SCHEME ON TWO OTHER BUS LINES

Method	$\sum T^W$ (min)	ξ
current scheme (Line 2)	54136	134
our optimized scheme (Line 2)	47332	130
current scheme (Line 3)	75463	151
our optimized scheme (Line 3)	65173	150

E. Simulation Results on Two Other Bus Lines

To further verify the validity of the proposed optimization method, we also perform experiments on two other bus lines (Line 2 and Line 3) in Shenzhen. The results are shown in Table VI, from which we can also observe that our proposed optimized scheme is better than the scheme currently used in Shenzhen, in terms of the passengers total waiting time and the total number of buses dispatched, particularly the former.

V. CONCLUSION

Reasonable dispatching time intervals are beneficial for improving the bus dispatching efficiency and reducing the passenger waiting time. In this paper, we propose a new data-driven bus timetable optimization method, which is built on a new departure time interval expression (DTIE) and guided by simultaneously optimizing the passenger waiting time and the bus dispatch frequency. In the construction of DTIE, both the fluctuation in passenger flow in various period and the number of bus stops are taken into consideration, which makes the timetables produced by our optimization method more efficient for the bus lines. To verify the validity of the proposed method, we use the true historical travel data to perform simulation experiments on three typical bus lines of Shenzhen, China, which clearly demonstrate the effectiveness and superiority of the proposed method, in comparison with their current bus scheduling schemes.

REFERENCES

[1] B. Yu, Z. Yang, and J. Yao, "Genetic algorithm for bus frequency optimization," *Journal of Transportation Engineering*, vol. 136, no. 6, pp. 576–583, 2010.

[2] A. Löbel, "Vehicle scheduling in public transit and lagrangean pricing," *Management Science*, vol. 44, no. 12, pp. 1637–1649, 1998.

[3] A. Fügenschuh, "Solving a school bus scheduling problem with integer programming," *European Journal of Operational Research*, vol. 193, no. 3, pp. 867–884, 2009.

[4] S. Yan and H.-L. Chen, "A scheduling model and a solution algorithm for inter-city bus carriers," *Transportation Research Part A: Policy and Practice*, vol. 36, no. 9, pp. 805–825, 2002.

[5] D. J. Sun, Y. Xu, and Z.-R. Peng, "Timetable optimization for single bus line based on hybrid vehicle size model," *Journal of Traffic and Transportation Engineering (English Edition)*, vol. 2, no. 3, pp. 179–186, 2015.

[6] A. Haghani and M. Banihashemi, "Heuristic approaches for solving large-scale bus transit vehicle scheduling problem with route time constraints," *Transportation Research Part A: Policy and Practice*, vol. 36, no. 4, pp. 309–333, 2002.

[7] L. Li, H. K. Lo, and F. Xiao, "Mixed bus fleet scheduling under range and refueling constraints," *Transportation Research Part C: Emerging Technologies*, vol. 104, pp. 443–462, 2019.

[8] A. Ceder, "Public-transport automated timetables using even headway and even passenger load concepts," in *Proceedings of the 32nd Australasian Transport Research Forum (ATRF'09)*, vol. 17, 2009.

[9] J. G. Strathman, T. J. Kimpel, K. J. Dueker, R. L. Gerhart, and S. Callas, "Evaluation of transit operations: Data applications of tri-met's automated bus dispatching system," *Transportation*, vol. 29, no. 3, pp. 321–345, 2002.

[10] W.-H. Lin and R. L. Bertini, "Modeling schedule recovery processes in transit operations for bus arrival time prediction," *Journal of Advanced Transportation*, vol. 38, no. 3, pp. 347–365, 2004.

[11] D.-r. Tan, J. Wang, H.-b. Liu, and X.-w. Wang, "The optimization of bus scheduling based on genetic algorithm," in *Proceedings 2011 International Conference on Transportation, Mechanical, and Electrical Engineering (TMEE)*. IEEE, 2011, pp. 1530–1533.

[12] A. Mauttone and M. E. Urquhart, "A route set construction algorithm for the transit network design problem," *Computers & Operations Research*, vol. 36, no. 8, pp. 2440–2449, 2009.