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Transportation Research Procedia 00 (2018) 000–000

Transportation Research Procedia

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World Conference on Transport Research - WCTR 2019 Mumbai 26-31 May 2019

Design of passive transit signal priority control for bus rapid transit based on a simulation-based optimization model

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Abstract

The BRT (Bus Rapid Transit) system is characterized by its performance and service that can attain the level of a metro system, while its construction cost is comparatively lower. However, for BRT operation, the delay caused by signal control can be critical and relevant to the challenges of how to guarantee better progression and stabilize arrival headways to avoid bunching. Hence, the implementation of transit signal priority control strategies is of practical significance. This study focuses on passive signal priority control for the BRT system. A simulation-based optimization model combining microscopic traffic simulation software SUMO with the genetic algorithm is developed to optimize the departure headway of the BRT vehicles and signal offsets along the arterial road with consecutive intersections. The model primarily seeks to minimize the delay of BRT vehicles by determining the best offsets combination and departure headway. A case study based on the blue line of Taichung BRT System is conducted to evaluate the derived optimization model. To assess the feasibility of derived optimal timing plans, the stability of arrival headways and the impact on general traffic are further analyzed by calculating the standard deviation of arrival headways and general traffic volume. The developed model can significantly reduce the average travel time delay for the BRT system, and the optimal result comes with stable arrival headways and moderate impact on general traffic. Compared with the current operating bus system on dedicated lane, the BRT system shows better service quality on both travel time and headway stability.

Keywords: bus rapid transit; type B right-of-way; passive priority signal control; microscopic traffic simulation; genetic algorithm

1. Introduction

Continuously increasing population and private vehicle usage have led to severe traffic congestion in urban roadway networks, particularly on major arterial roads. Traffic congestion not only affects commuters' daily life, but also results in low energy efficiency and air pollution problem. Hence, many cities nowadays are planning to improve traffic condition and reduce the number of private vehicles by developing public transport systems.

Transit systems with type B right-of-way operate on dedicated lanes which are partially separated from general traffic. Although without absolute priority, they are characterized by high mobility and flexible operation as ordinary bus systems. It can also attain the service level of a metro system by ticket gates at stations and intensive departure headway. The construction period is shorter, and the cost is also comparatively lower than it of an urban railway system. These characteristics enable the transit systems with type B right-of-way to be considered a reliable alternative for urban transportation planning. There are several existing and widely adopted transit systems with type B right-of-way, such as exclusive bus lane, Bus Rapid Transit (BRT) and Light Rail Transit (LRT). To attain better service quality, bus systems operating on an exclusive lane may possess frequent but unstable headways, which often results in longer travel time and delays. Comparatively, the BRT and LRT system can maintain high service level due to stable speed control and larger passenger capacity (Chen, 2000).

Although these transit vehicles are operating over dedicated lanes, they may still encounter conflicts with other traffic and stops at signalized intersections. To maintain their progression on the dedicated lane along an urban arterial, the transit signal priority control strategy for transit vehicles is a common approach. There are two categories of signal priority control strategies, which are active signal priority and passive signal priority. Active signal priority control strategies are implemented based on vehicle detection technique; once a transit vehicle is approaching the intersection, the priority control will be activated. By predicting the vehicle travel time, the central controller will determine a suitable priority control strategy and implement it for the signal timing plan, which can reduce the delay of transit vehicles at signalized intersections. Frequently-adopted active priority control strategies in practice include green extension, red truncation, phase insertion and actuated transit phase; passive signal priority control strategies, such as cycle length adjustment and signal coordination, are fixed-time control strategies designed in a static manner according to the regular traffic pattern across the signalized intersections of interest (Chiou et al., 2005).

However, if the geometric design of the intersection is complicated or when traffic flow is heavy during peak hours, implementing active signal priority control strategies for transit may greatly impact other general traffic, and the derived strategies, such as green extension and phasing compensation for traffic in crossing direction, can be difficult in practice. Comparatively, although passive signal priority control strategies are not as flexible as the active ones, they influence other general traffic less and can be more practically viable. Accompanied with the design of signal coordination and appropriate timetable adjustment, the priority vehicles can be ensured to travel in the progression bandwidth, and the intersection delays can be reduced.

In this study, we focus on the operation of a BRT system and seek to minimize its delay by optimizing the offsets on each signalized intersection and the departure headway in the context of passive signal priority control design. Further, in regard to the derived optimal control strategies, the stability of arrival headways and the impact on other traffic are also analyzed by calculating the standard deviation of the arrival headways at every station and the traffic volume of general traffic. The smaller value of these two variables can alleviate the bunching phenomenon and enhance the feasibility of the strategies for signal priority control.

To determine the optimal passive signal control strategy for a BRT system, this study proposes a simulation-based model combined with the genetic algorithm to minimize the average travel time delay of the transit vehicles. A 2km-long section of the BRT line on Taiwan Boulevard in Taichung, Taiwan, is selected for case study. In order to provide quantitative analysis results of different transit systems with type B right-of-way for urban transportation planning, the optimal result of the BRT line is also compared with the operation of the current bus system with the dedicated bus lane.

2. Literature review

Dion et al. (2004) used the INTEGRATION microscopic traffic simulation model to evaluate the impact of active priority strategies, including green extension and green recall, on both the prioritized buses and general traffic. The simulation results indicate that the priority buses can benefit from the control strategies without causing severe impact on general traffic under lesser traffic demand. When traffic demand is high, however, the priority logic may be obtained at the expense of the overall traffic. Al Khateeb and Abdulfatah (2017) evaluated the impact of active transit signal priority by comparing several different scenarios to select the best signal consideration. After a case study on a corridor in Dubai, the results show that the impact of actuating traffic signals in the corridor after extending green time for bus approach (15 sec), buses delay is reduced by around 14.11%, while on the other hand, cars receive an increase in a delay about 57.00%. Furth and Muller (2000) compared the performance of bus system under three scenarios — no priority, absolute priority, and conditional priority. By comparison, the result of absolute priority does strongly improve schedule adherence of buses, however, it increased traffic delay at intersections significantly while conditional priority had almost no impact. These research indicate that the active signal control strategies may not be useful when considering the service level of general traffic.

Compared with the studies on active signal priority strategies above, Skabardonis (2000) reviewed the existing control strategies and further proposed a number of passive and active control strategies to improve transit performance. These strategies were tested on a major arterial. Based on the results, passive priority strategies are stated to be more easily implementable measures that are effective in simple network configurations, high bus frequency and predictable dwell times.

For passive control strategies on single signalized intersection, Ma and Yang (2007) mathematically depict the relationship between the departure frequency of a BRT line, cycle length of signalized intersection and number of Different Signal Status (DSS) when buses arrive at an isolated intersection, and proposed signal timing optimization model which can decrease average bus delay and bus headway deviation dramatically without significantly impacting motor vehicles delay.

To maximize the progression bandwidth of type B transit systems on an arterial road, Lu (2000) created a new signal timing design model, BUSBAND, according to the bus car-following concept. After compared with the original signal timing model, the BUSBAND model can reduce the bus delay and improve the bus operating performance on an exclusive lane; Jeong and Kim (2014) propose a new signal timing optimization model, TRAMBAND, which determines the traffic signal timings for tram passive priority using a left-turn phase sequence and offset. By comparing it with a traditional arterial signal optimization model, MAXBAND, the TRAMBAND model is capable of avoiding the tram system from intersection delays and stops and also maintain the general vehicle bandwidth.

There are also some studies on passive signal priority control taking both the transit system and the impact on general traffic into considerations. Tseng (2004) proposed that the traditional timing plan design according to the “vehicle delay of intersection” will lead to the vehicle prior of the timing plan. He then designed a signal control model based on passive priority signal control to minimize “average personal delay” and distribute the effective green time by using the concept “occupancy”. In the case study, the micro traffic flow simulation software PARAMICS was adopted as the analysis tools. It comes out that the controlling model which aims to minimize the average personal delay shows better result. Ramezani et al. (2015) introduces a transit signal priority strategy along a signalized, one-directional arterial route with a dedicated transit lane. To simulate the traffic flow and provide the car and transit delays as a function of signals offsets, a shockwave traffic flow model for cars and a stochastic discrete-event model for transit are proposed. The result shows that the TSP strategy can significantly reduce total passenger delay for a wide range of traffic conditions.

Estrada et al. (2009) mathematically depict the traveling behavior of bus and car flow in an urban network and propose a signal coordination optimization model. The model considers a passive signal priority system to design signal offsets in sequence and restricts the maximal incremental delay caused to car users. It is provided that the model is able to reduce bus travel times by 8.5% and maintaining the incremental car delay below 5%. Liu and Qiu (2016) further formulate the transit signal priority problem into a multi-objective optimization model. The Pareto-optimal front results were presented to evaluate the trade-offs between two objectives: minimization of private vehicle delay and of bus delay. The results provide more interesting practical options for decision makers.

Most of the existing research on design of transit signal priority are based on a mathematical optimization model. However, the mathematical formulation may not accurately describe the operating pattern of transit vehicles due to their stochastic traveling behavior on roads. Although there are some microscopic traffic simulation tools, such as VISSIM and PARAMICS, which are useful tools to assess the effect of transit signal priority by examining delays or number of stops of those transit vehicles, however, they cannot provide optimization procedure for signal timing plan. The only tool that combines microscopic traffic simulation and heuristic algorithm for signal timing optimization is Direct CORSIM optimization, which uses the genetic algorithm applied by TRANSYT-7F. Stevanovic et al. (2008) presented a genetic algorithm formulation to optimize signal timing parameters and transit priority settings using VISSIM microsimulation as the evaluation environment. The model optimizes traffic control settings for both private and transit traffic. The results show that timing plans optimized by the genetic algorithm outperformed the timing plans from the field and SYNCHRO. Comparatively, there are still less studies on optimization of signal timing for transit systems using microsimulators as the evaluation tool. In view of this, this study aims to combine a microsimulator with a heuristic algorithm as the optimization approach for design of transit signal priority.

3. Simulation-based optimization model for passive transit signal priority control

3.1. Optimization framework

To determine the optimal passive signal priority control strategy for the BRT system, this study proposes a simulation-based optimization model, which combines the microsimulator with the genetic algorithm by Python 3.6, to minimize the average travel time delay of the BRT vehicles.

The optimization process is conducted for different departure headways during peak hour to determine the best operation timetable. Instead of adjusting the cycle length and phase split, the offset at each signalized intersection is selected as the major decision variable for the passive control; it is defined as the initial difference of green phase with respect to the master control intersection. The optimization framework is depicted as Fig. 1.

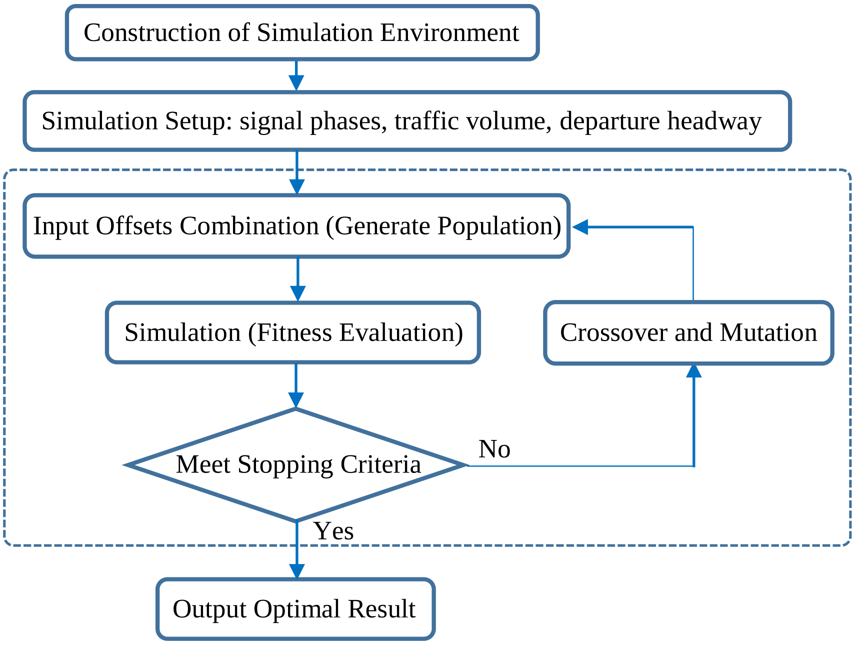

Fig. 1. Optimization framework with genetic algorithm.

3.2. Simulation environment construction

In this study, we build the simulation environment of an exclusive lane on an arterial road for BRT system by an open source microsimulator SUMO (Simulation of Urban MObility) (Krajzewicz et al., 2012). It is able to trace the traveling behavior of every individual vehicle. One can obtain several traffic assessment index, such as delay and travel time from the simulation result by setting the condition of the environment (road section and intersection geometry, location of transportation stops), the traffic volume in each direction and the signal timing plan.

To assess the proposed simulation-based model, a 2-km section of the Bus Rapid Transit (BRT) line on Taiwan Boulevard in Taichung City, Taiwan, is selected for case study. The selected part of the arterial includes five signalized intersections and three stations in both directions, as depicted in Fig. 2: A10 ~ A12 in the westbound direction and A09 ~ A11 in the eastbound direction.

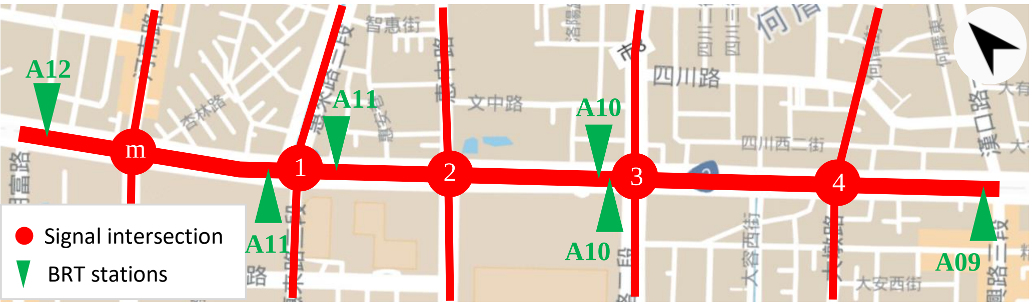

Fig. 2. Study area for case study.

3.3. Genetic algorithm

Due to the large solution space and the simulation time in this optimization model, the genetic algorithm, which is one of a widely-used heuristic algorithms for signal timing optimization, is employed to efficiently search throughout it for the optimal solution.

In the genetic algorithm, each chromosome consists of four genes, which respectively represent the signal offsets at each signalized intersection. Each chromosome is a possible solution of the optimization model. Based on the cycle length of the traffic signal on the Taiwan Boulevard is 180 seconds, the range of the signal offset value is within 0 and 180 seconds in a unit of 5 seconds. The chromosome representation is depicted in Table. 1.

Table 1. Chromosome representation.

Gene no.	1	2	3	4
Signal offsets (sec)	The offset at the 1st intersection	The offset at the 2nd intersection	The offset at the 3rd intersection	The offset at the 4th intersection

For the iteration process, 50 offsets combinations are randomly generated as the initial population. Then, the genetic operation process, including two-point crossover and mutation, is employed to generate the offspring population. In the two-point crossover method, the *i* th and the 50-*i* th chromosomes in the 50 fittest combinations are paired. Two crossover points in each chromosome pairs are chosen at random, and the offsprings are created by exchanging the chosen genes. To prevent premature convergence in the iteration process, the mutation method is employed to maintain diversity in the population. After the crossover process, five chromosomes in the population are selected at random, and one or two mutation points in each of them are chosen randomly, they will then be replaced by another offset value. The details of the genetic operations are depicted as Fig. 3 and Fig. 4.

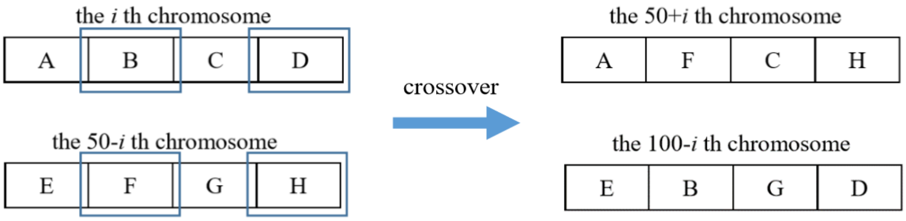

Fig. 3. two-point crossover

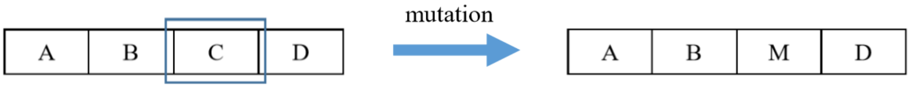

Fig. 4. one-point mutation

The fitness function to evaluate the derived solutions is defined based on the average delay of transit vehicles. By inputting the different offset combinations into the simulation environment and running the traffic simulation in the microsimulator, the fitness of every solution can be obtained by further calculating the simulation result. After the fitness evaluation process, the 50 fittest solutions are selected for reproduction. The whole algorithm iteration process terminates if there is no improvement in the objective function for 25 generations (stall generations).

4. Case study and results

In 2014, to relief the traffic congestion problem on Taiwan Boulevard, Taichung City government implemented a 17km-long BRT line along it. However, in 2015, the BRT line was then converted to dedicated bus lane due to the incomplete control system integration and severe impact on other traffic. The effect of different operating systems still need further quantitative analysis and comparison.

4.1. Signal timing optimization

In order to reduce the average delay and number of stops at intersections experienced by transit vehicles, this study aims to determine the best offsets combination with respect to different departure headways. As the BRT system features ticketing at the entrances of stations, the time needed for passengers to pay on boarding or alighting can be saved. Hence, the waiting time is set 15 seconds uniformly at each station as the case of a metro system in this study.

After the evaluation and optimization process, the results were presented below. Table 2 depicts the simulation results of the BRT performance according to the current timing plan of each departure headway. Table 3 lists the best solutions and the average delay of each departure headway. From the simulation results, the smallest delay is attained when the departure headway is 3 minutes. The iteration details of the algorithm are shown as Fig. 5 ~ 7.

Comparing the derived optimal timing plan with the current one, the average delay of each BRT vehicle can be reduced by more than 150 seconds, over 50% of the delay under the current timing plan. Fig. 8~19 show the time-space diagrams in both directions of current timing plan and the best results of each departure headway. Take the results of 3-minute headway as an example, it can be observed that the current timing plan stops the BRT vehicles at the 1st and the 3rd intersection in the east bound, and the 3rd and the 4th intersection in the eastbound direction, while in the optimal results, there are no stops at each signalized intersection, and every vehicle can have the same traveling pattern, which is likely due to the consistency between the departure headway and the signal cycle length,

Table 2. Simulation results under current timing plan.

Departure headway (min)	Offsets combination (sec)				Average delay (sec)
	Offset 1	Offset 2	Offset 3	Offset 4	
2.5	10	20	20	15	267.65
3	10	20	20	15	274.07
3.5	10	20	20	15	267.77
4	10	20	20	15	264.14
4.5	10	20	20	15	284.11
5	10	20	20	15	264.27

Table 3. Simulation results after optimization.

Departure headway (min)	Offsets combination (sec)				Average delay (sec)
	Offset 1	Offset 2	Offset 3	Offset 4	
2.5	90	70	0	170	165.94
3	90	85	0	150	115.05
3.5	95	95	0	0	154.42
4	90	110	5	15	142.60
4.5	90	85	5	15	160.03
5	90	100	0	5	143.65

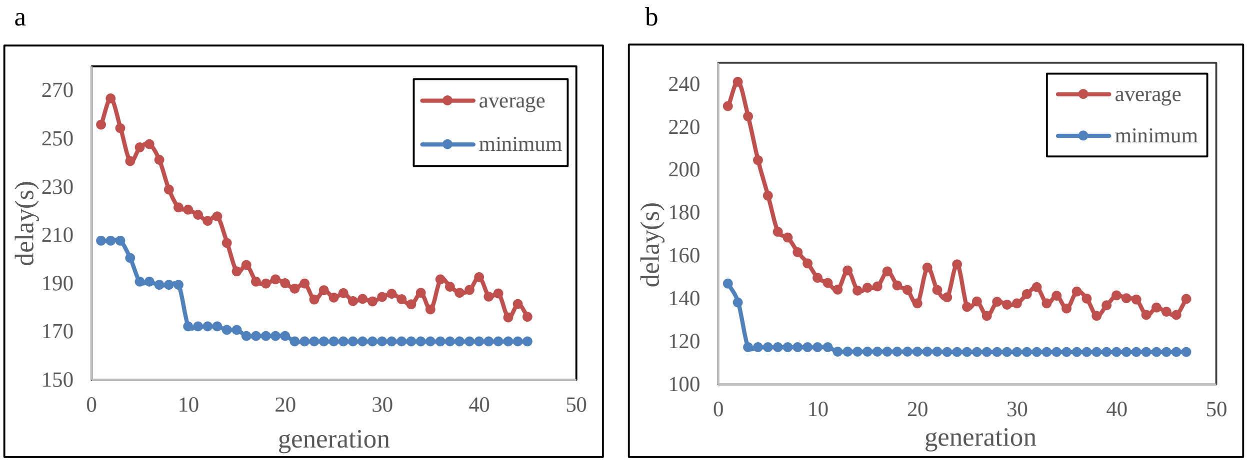

Fig. 5. Iteration process of the optimization model. (a) headway: 2.5 min (b) headway: 3 min

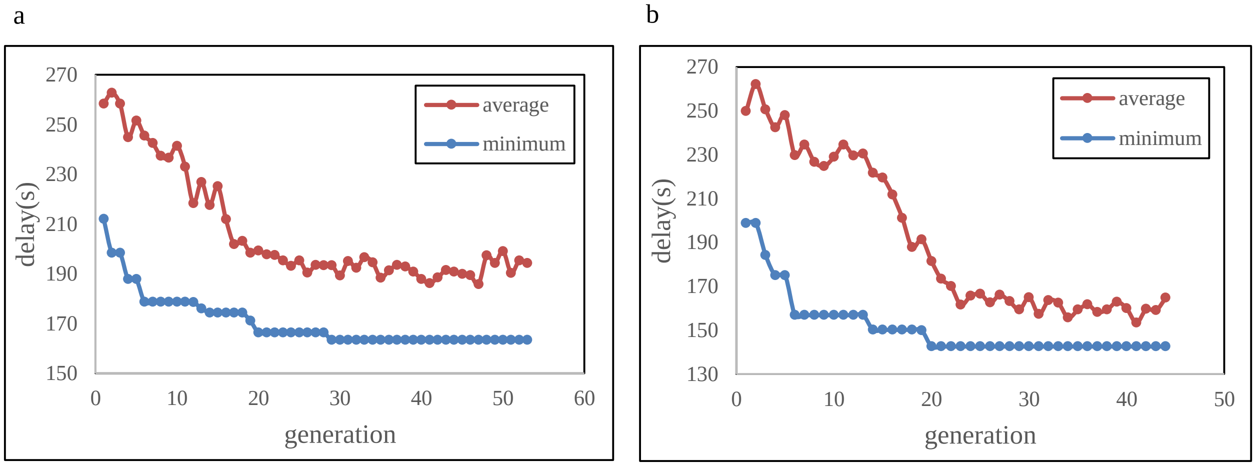

Fig. 6. Iteration process of the optimization model. (a) headway: 3.5 min (b) headway: 4 min

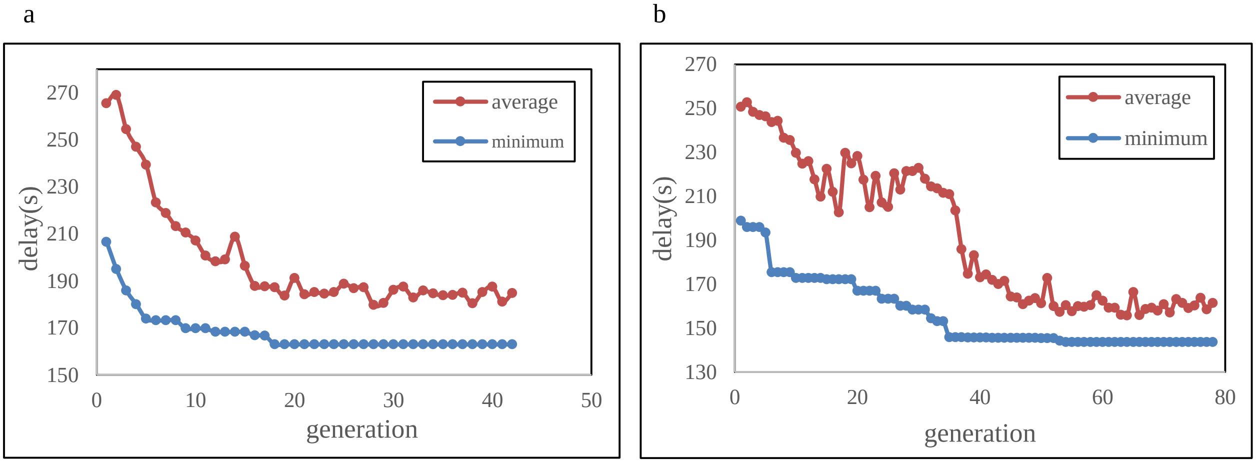

Fig. 7. Iteration process of the optimization model. (a) headway: 4.5 min (b) headway: 5 min

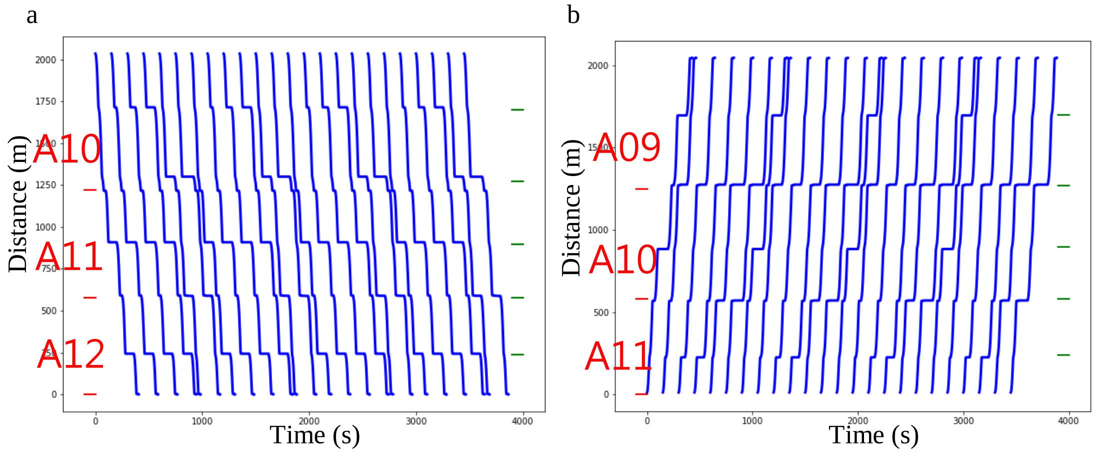

Fig. 8. Time-space diagrams under current timing plan (headway: 2.5 minute). (a) westbound direction. (b) eastbound direction.

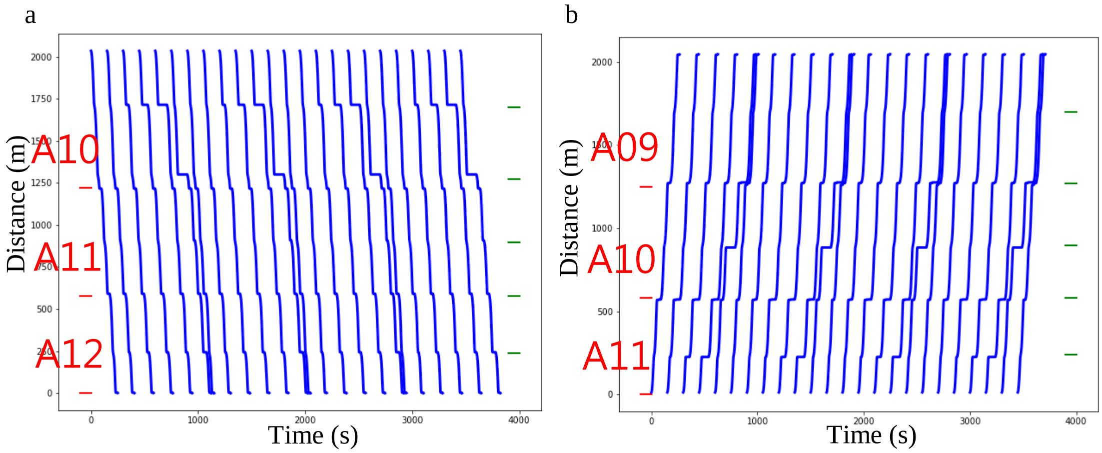

Fig. 9. Time-space diagrams of the best result (headway: 2.5 minute). (a) westbound direction. (b) eastbound direction.

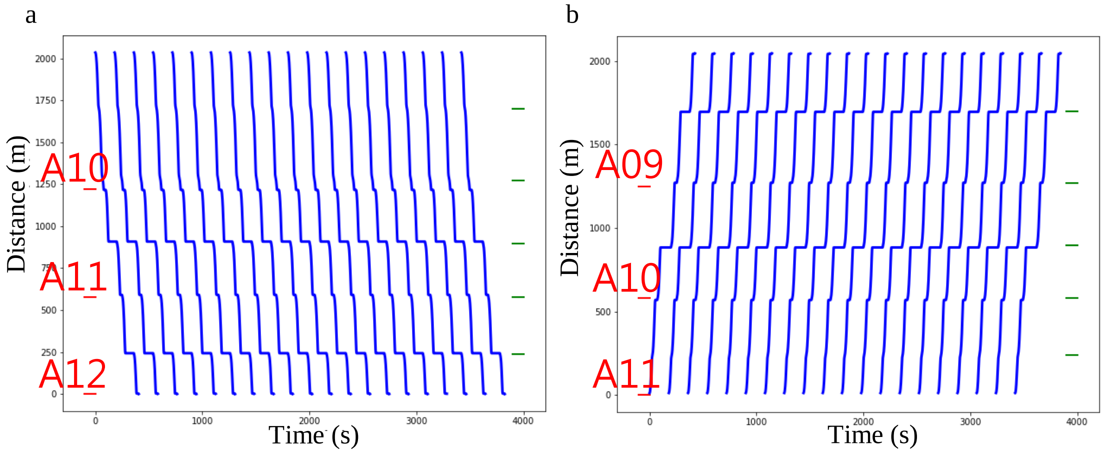

Fig. 10. Time-space diagrams under current timing plan (headway: 3 minute). (a) westbound direction. (b) eastbound direction.

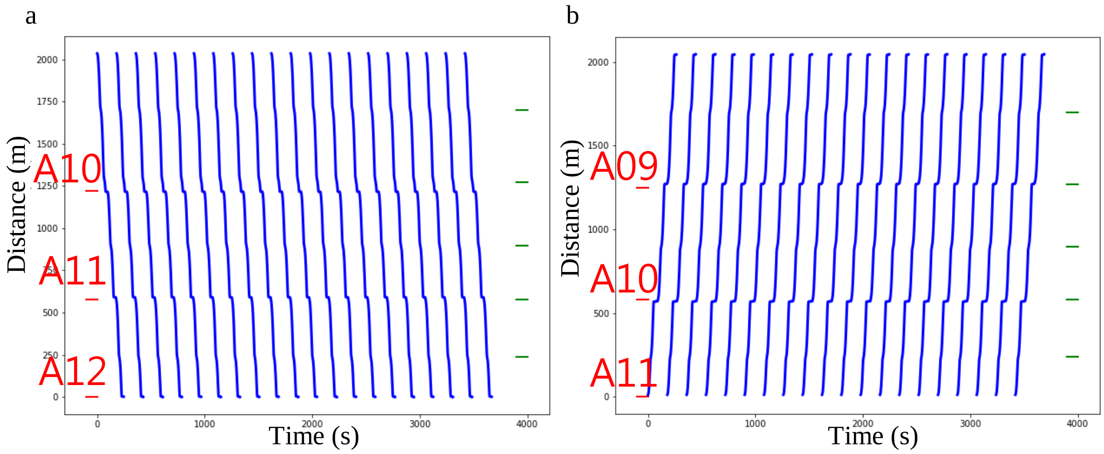

Fig. 11. Time-space diagrams of the best result (headway: 3 min). (a) westbound direction. (b) eastbound direction.

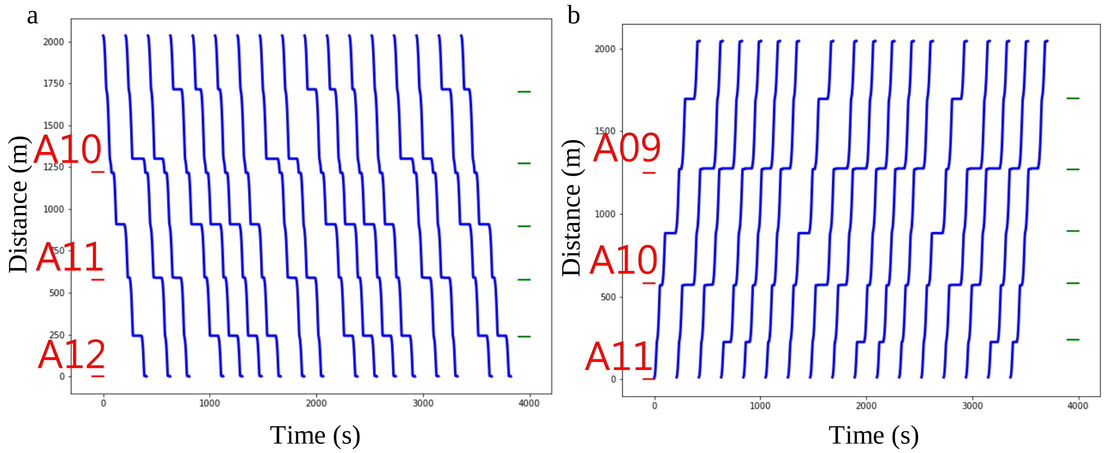

Fig. 12. Time-space diagrams under current timing plan (headway: 3.5 minute). (a) westbound direction. (b) eastbound direction.

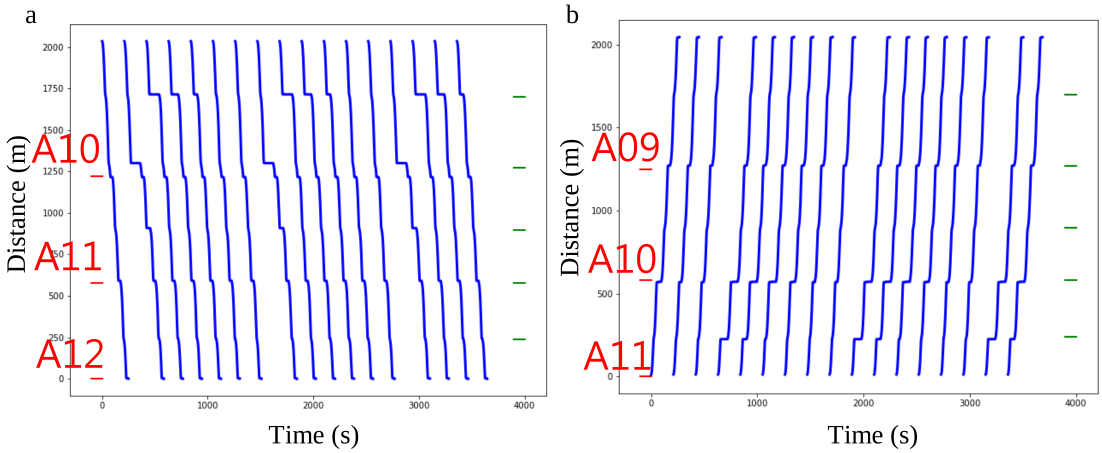

Fig. 13. Time-space diagrams of the best result (headway: 3.5 minute). (a) westbound direction. (b) eastbound direction.

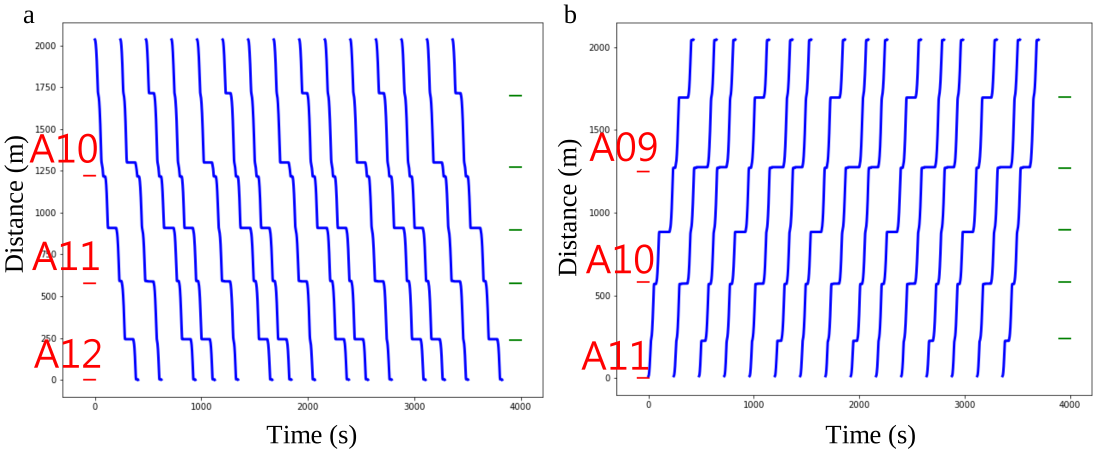

Fig. 14. Time-space diagrams under current timing plan (headway: 4 minute). (a) westbound direction. (b) eastbound direction.

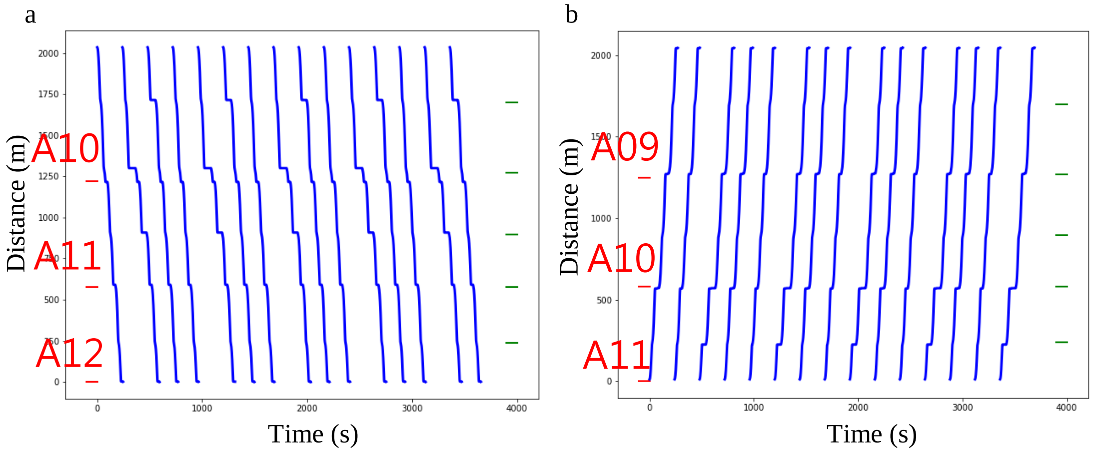

Fig. 15. Time-space diagrams of the best result (headway: 4 minute). (a) westbound direction. (b) eastbound direction.

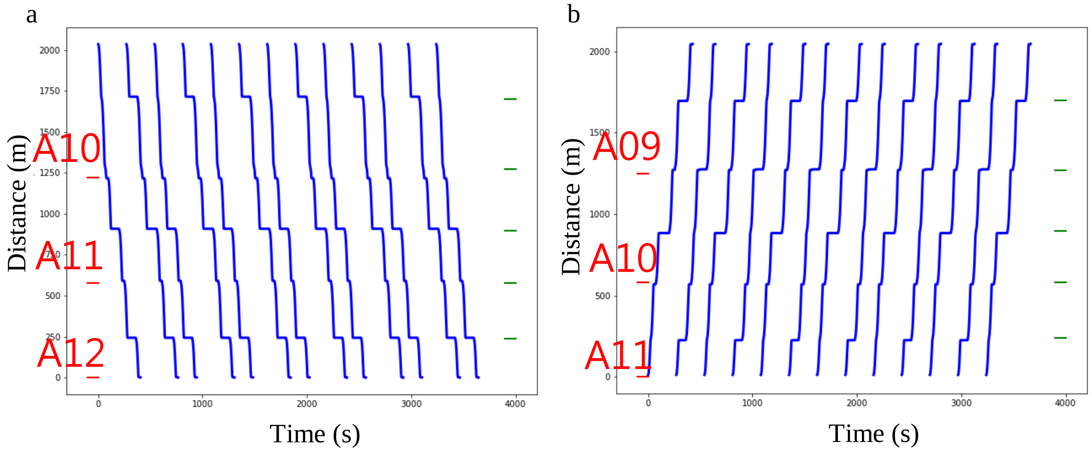

Fig. 16. Time-space diagrams under current timing plan (headway: 4.5 minute). (a) westbound direction. (b) eastbound direction.

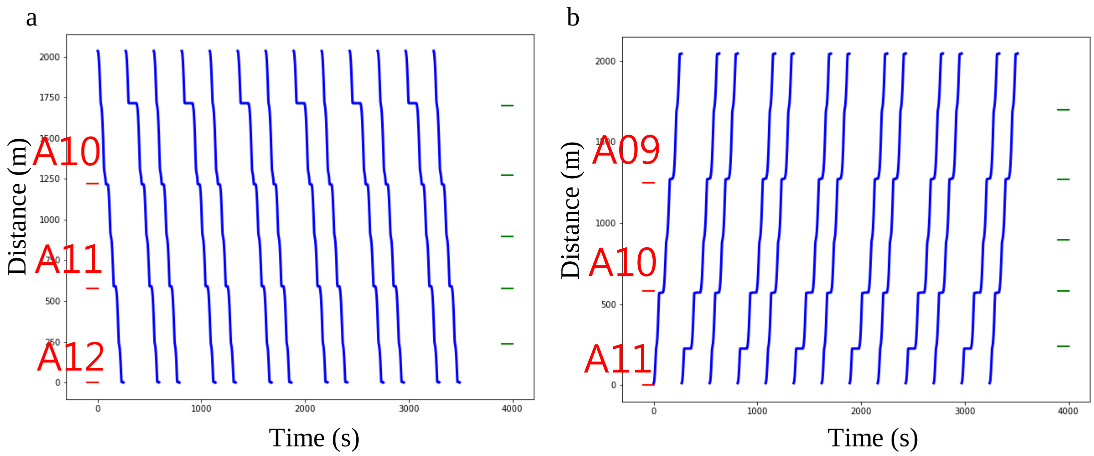

Fig. 17. Time-space diagrams of the best result (headway: 4.5 minute). (a) westbound direction. (b) eastbound direction.

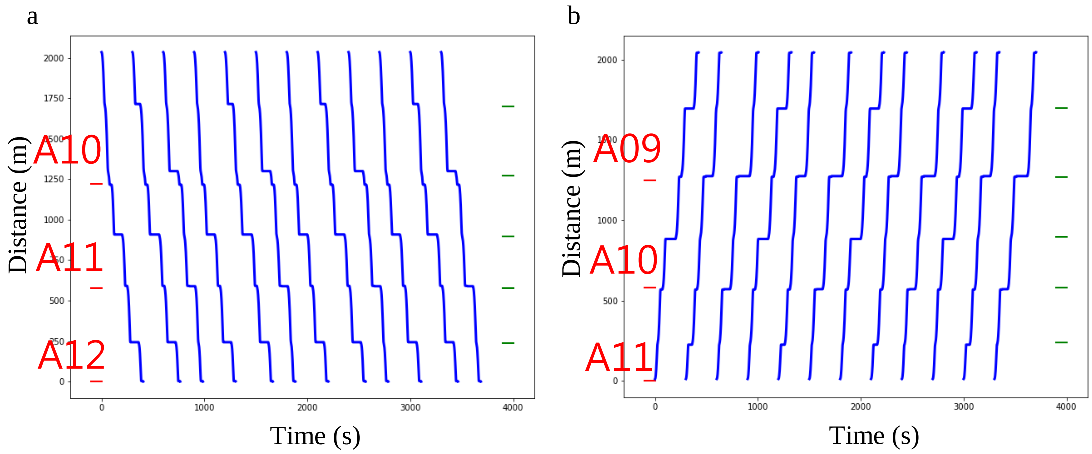

Fig. 18. Time-space diagrams under current timing plan (headway: 5 minute). (a) westbound direction. (b) eastbound direction.

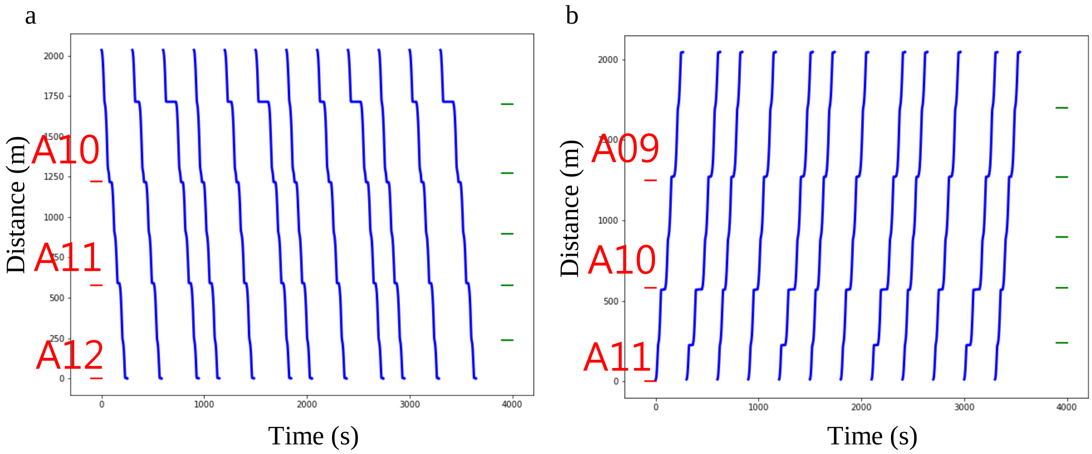

Fig. 19. Time-space diagrams of the best result (headway: 5 minute). (a) westbound direction. (b) eastbound direction.

4.2. Analysis of the stability of arrival headways

To analyze the stability of arrival headways and examine whether a serious bunching phenomenon exists, we calculate the average values and standard deviation values of the arrival headways under current timing plan and the optimal timing plans of each departure headway obtained from the optimization model, as summarized in Tables 4 and 5. From the analysis results, many of the average values of arrival headways derived from the results are not consistent with the departure headway, and the standard deviation values increase significantly. We may conclude that the minimization of travel time delay will affect the stability of arrival headways. However, as the average arrival headways is still consistent, and the standard deviation value of the arrival headways doesn't have a significant increase in the case of the 3-minute departure headway, the optimal timing plan solution of 3-minute departure headway can be the best operation strategy for the BRT system in this case study.

Table 4. Analysis of the stability of arrival headway under current timing plan.

Departure headway (min)	Offsets combination (sec)				Average arrival headway (sec)	Standard deviation of arrival headways (sec)
	Offset 1	Offset 2	Offset 3	Offset 4		
2.5	10	20	20	15	151.07	45.96
3	10	20	20	15	180.03	1.37
3.5	10	20	20	15	208.84	44.84
4	10	20	20	15	240.79	49.70
4.5	10	20	20	15	273.09	71.36
5	10	20	20	15	299.92	51.20

Table 5. Analysis of the stability of arrival headway after optimization.

Departure headway (min)	Offsets combination (sec)				Average arrival headway (sec)	Standard deviation of arrival headways (sec)
	Offset 1	Offset 2	Offset 3	Offset 4		
2.5	90	70	0	170	156.69	48.93
3	90	85	0	150	180.03	1.64
3.5	95	95	0	0	210.72	50.35
4	90	110	5	15	250.52	83.53
4.5	90	85	5	15	278.32	84.96
5	90	100	0	5	303.89	60.30

4.3. Analysis of the impact on general traffic

In order to analyze the impact on general traffic caused by the timing plan optimization adjustment, the general traffic volume of the arterial and cross-streets are further examined by investigating the simulation results. Table 6 shows the general traffic volume upon the current timing plan, while Table 7 lists the general traffic volume under the optimal timing plans of each departure headway obtained from the optimization model. The results show that the optimal results will decrease nearly 5% of the general traffic volume on cross-streets and will not significantly affect that on the arterial, indicating the optimal timing plan solutions for the BRT system derived from the optimization model will not lead to severe service degradation for the general traffic.

Table 6. General traffic volume under current timing plan.

Offsets combination (sec)				General traffic volume of the cross-streets (pcu/min)	General traffic volume of the arterial (pcu/min)
Offset 1	Offset 2	Offset 3	Offset 4		
10	20	20	15	86.27	33.62

Table 7. General traffic volume after optimization.

Departure headway (min)	Offsets combination (sec)				General traffic volume of the cross-streets (pcu/min)	General traffic volume of the arterial (pcu/min)
	Offset 1	Offset 2	Offset 3	Offset 4		
2.5	90	70	0	170	81.13	34.83
3	90	85	0	150	81.88	34.03
3.5	95	95	0	0	83.10	34.20
4	90	110	5	15	82.40	33.77
4.5	90	85	5	15	80.17	33.95
5	90	100	0	5	82.35	32.9

pcu: passenger car unit

4.4. Comparison with the dedicated bus lane

For bus operation over a dedicated lane, both the waiting time and arrival time at each station are stochastic. To create the simulation scenario for buses operating on the dedicated bus lane, survey data collected by Huang et al. (2015) at three bus stops on Taiwan Boulevard are used. The data include the distributions of 233 waiting times and 230 arrival headways of buses passing by the three stations during evening peak hours, as shown in Fig. 20 and Fig. 21.

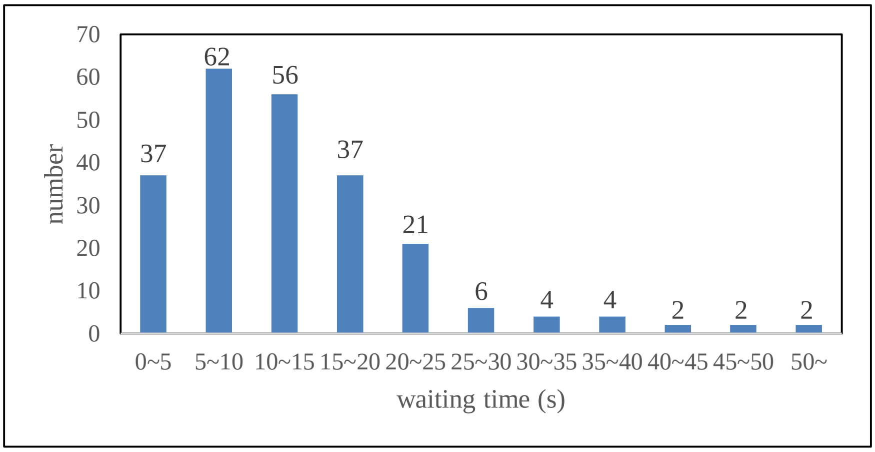

Fig. 20. Distribution of the waiting times.

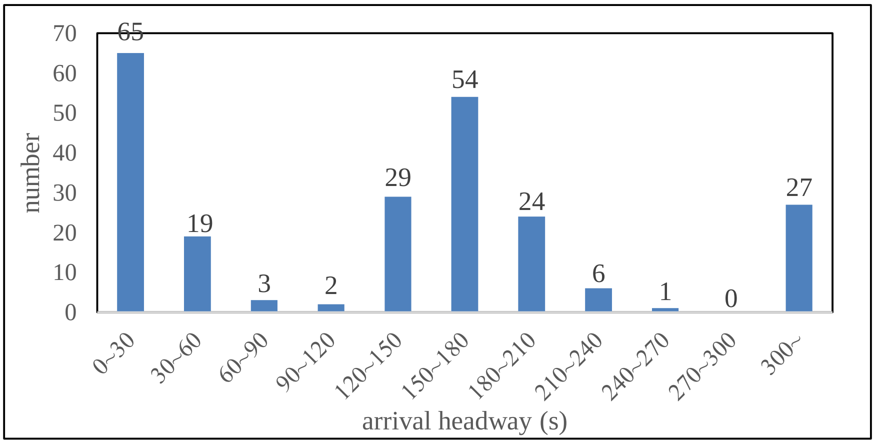

Fig. 21. Distribution of the arrival headways.

In the stochastic scenarios, the simulation procedure will be conducted several times to obtain the average delay of buses traveling on the dedicated bus lane until the change of the cumulative average delay is less than 3% for 50 consecutive iterations. Fig. 22 shows the details of the iterative process for evaluating the average bus delay. It can be observed that the value of the cumulative average bus delay remains rather stable within the 50 iterations. Table 8 shows the average vehicle delay, the mean and standard deviation values of the arrival headways of the buses traveling on the dedicated lane. The results show that both the average delay and standard deviation of the arrival headways are higher than the optimized results for the BRT system above, which implicates that there are longer travel time for buses on the dedicated lane and significant bus bunching phenomena between buses due to the intensive departure headway. Hence, the current bus system on the dedicated bus lane of Taiwan Boulevard *de facto* does not attain the service level as the BRT system does under the optimal signal timing plan.

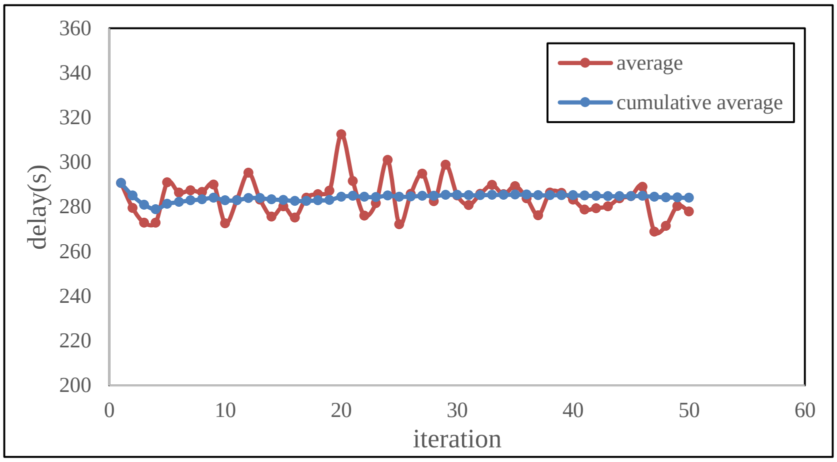

Fig. 22. Iteration process of average bus delay evaluation

Table 8. Simulation results of buses traveling on the dedicated bus lane.

Offsets combination (sec)				Average delay (sec)	Average arrival headway (sec)	Standard deviation of arrival headways (sec)
Offset 1	Offset 2	Offset 3	Offset 4			
10	20	20	15	284.40	110.05	87.35

5. Conclusion

While there have been several studies focusing on the active signal priority strategies for transit systems, the feasibility of strategies and their impact on general traffic are still the issues that need to be addressed. To optimize the progression of the BRT system while maintaining the service level for other road users simultaneously, a simulation-based optimization model incorporating the genetic algorithm into the microsimulator SUMO is developed, by utilizing the concept of passive signal priority control. The major purpose of the model is to reduce the delay of BRT vehicles and determine the best departure headway by optimizing the offsets combination. Although the case study is made based on a BRT system, the simulation-based optimization model can also be applied to other transit systems with type B right-of-way.

From the results of the case study, the optimal solution of 3-minute departure headway leads to the best operation pattern for the BRT system, which significantly reduces the number of stops and travel time delay. By further data analysis, it shows that the optimal timing plans will slightly increase the standard deviation of arrival headways as well. We may conclude that there is a trade-off between the minimization of travel time delay and the stability of arrival headways. However, the optimal timing plan of 3-minute departure headway, which doesn’t have significant increase on the standard deviation of arrival headways, can still guarantee stable arrival headways. Hence, the 3-

minute departure headway can simultaneously provide shorter travel time delay and stable arrival headways in this case study. Determining the operation timetable for the BRT system based on signal cycle length can ensure better operation efficiency and service quality.

In regard to the impact on other general traffic volume (on both the arterial and cross-streets), the results show that the optimal timing plan will decrease 5% of the traffic volume of the cross-streets, while almost no impact on the traffic volume of the arterial. Therefore, the passive signal priority control method in adopted this model will not lead to severe degradation on the service level of general traffic and can be more viable in practice. In addition, after comparing the BRT system with the current bus system on the dedicated bus lane, the results also show that the bus system has higher average delay and more unstable arrival headways. This indicates that the BRT system can operate in a more efficient manner (travel faster), and the passengers can be more evenly distributed to every transit vehicle, so as to avoid over-crowdedness in some vehicles. Hence, the BRT system can provide better service quality than a general bus system with dedicated bus lanes.

In the future work, to mitigate the impact on general traffic, the model can be converted into a multi-objective optimization model, which aims to minimize the average transit vehicle delay and restrict the increase of traffic volume of general traffic simultaneously. By doing so, the optimal timing plan of each departure headway can be more feasible for BRT operation and the signal timing implementation. Furthermore, considering varying waiting duration at each stop can also be the situation for BRT system operation, the fitness evaluation simulation process in the genetic algorithm in this model can be further extended to account for such stochasticity in determining signal timing solution for different operation scenarios. Therefore, the study can provide a more comprehensive and robust evaluation of the transit system performance.

With the time-space diagrams, the operating pattern of a transit system on an urban arterial can be observed in detail. By further establishing a mathematical optimization model for BRT based on the time-space diagrams in future research, the traveling behavior of BRT vehicles can be accurately depicted by a mathematical formulation, and the time needed for fitness evaluation can be reduced. Subsequently, the proposed mathematical optimization model can be verified by comparing the results with those of the simulation-based optimization model developed in this study.

Acknowledgements

Authors would like to thank the Ministry of Science and Technology, Taiwan, R.O.C. for the financial support for this study under MOST-107-2813-C-002-063-E.

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