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Simulation model for applying operational tactics to evaluate transit system performance

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Abstract

Improvement of transit operations can increase the share of public transport in commuting daily trips in metropolises, and it has lots of benefits for passengers in increasing their satisfaction and for operators in decreasing their operational costs. The purpose of this research is to present a simulation model that can be used to analyze and evaluate system performance in the public transportation system of Tehran, Iran, by applying operational tactics and bus fleet management strategies. The considered operational tactics in this study are skip-stop, deadheading, and short-turn. Road-segment characteristics can influence the proposed discrete event simulation model, demand patterns, and transit service parameters as inputs and feedbacks outputs, including average passenger travel and waiting time as system performance indices. The presented simulation model is used to analyze and evaluate system performance in a presumed circular bus route by applying operational tactics that showed a 22% reduction in the average passenger travel time and 33% reduction in the average passenger waiting time by using skip-stop, the deadheading tactic decreased average passenger travel time and waiting time by 6% and 9% respectively. Also, the short-turn tactic showed 21% and 33% improvement in the average passenger travel time and the average waiting time as a system performance index. The results showed that operational tactics could be considered as management strategies to improve transit system performance. This research provided a simulation model as a tool that can be used for policy-makers to analyze and evaluate transit system performance by applying skip-stop, deadheading, and short-turn tactics.

Keywords – operational tactics, PT performance index, public transport, simulation model, transit operations control

1. Introduction

The public transportation (PT) system has a significant role in passenger trips in cities and the increasing need for the development of PT is a major issue in developing countries which has been exacerbated by the proliferation of urban trips in recent years. [1]. Generally, every PT system has two main phases, planning and operation. The planning phase has goals, including the design of routes, the scheduling for departures, and the coordination of departures. The operation phase is aimed at improving the performance of the transportation system [2]. The PT system involves unbalanced and heterogeneous passenger demand during peak periods which are addressed by practical policies such as fleet allocation and control tactics [3-6].

The design and operation of PT services have many issues and complexities. On the one hand, it is expected that the planned routes would have fixed schedules and frequencies. On the other hand, the demand for the origin and destination of passengers varies from one station to another as well as in different urban areas along the PT routes. Therefore, a uniform pattern for the timing and headway is not suitable for modeling passenger demand distribution. For achieving an efficient PT system, various operational tactics need to be implemented and there must be an effective tool to measure their impact. In this study, a robust simulation model is presented with the aim to provide a PT operation perspective, which enables the operators to analyze and evaluate system performance by applying operational tactics.

Many studies have been conducted to model the operational tactics in PT systems. Comi et al. [7] have reviewed the benefits of modern technology using intelligent transport systems to reduce passenger travel time. Wu et al. [8] investigated a simulated system using ITS-based data to forecast and evaluate the arrival time of buses and monitor passengers' arrivals, in which the deadheading tactic was implemented in bus departures. Furthermore, Wu et al. [9] presented a robust simulation model considering the two parameters of vehicles overtaking and unbalanced demand at stations to minimize operating costs using the skip-stop tactic. A study was conducted by Sun and Hickman [10], in which the implementation of a real-time skip-stop tactic was examined in a simulation model, and a skip-stop tactic was formulated as a nonlinear integer programming problem. A simulation model was proposed to examine the performance of several scenarios with different demand patterns. Their results showed that the skip-stop tactic is most effective in the scenario where the population is focused in the central zones of the city. Hadas and Ceder [11] conducted a study on controlling methods using operational tactics to increase the performance of the PT system for simultaneous departures. Operational tactics such as skip-stop, deadheading, and short-turn were applied to decrease the chance of simultaneous entry of two vehicles at the same station. The results of the simulation showed that the operational tactics effectively reduced the total passenger travel time in different scenarios. In another study, Hadas and Ceder's [12] demonstrated how effective operational tactics are in the optimization of PT systems. They proposed a simulation model based on different PT network parameters and the results showed the reduction in total passenger travel time and increase in transit of passengers. Furthermore, Ji and Zhang [13] applied the deadheading tactic to dynamic mode. They proposed a dynamic control tactic for monitoring buses' headways and the maintenance of unused buses. Similarly, Delgado et al. [14] conducted a study to investigate deadheading tactics in departures to enhance the PT performance index. Two control tactics were implemented in this study, including a deadheading tactic to the departure of buses and a combination of deadheading in departure and limiting the number of people boarding vehicles at each station. The tactics were evaluated in a simulation environment under different operating conditions in four scenarios to minimize the waiting time for travelers.

Choosing the proper operating tactics that enhance the level of service and operation costs is the core issue of PT policy-makers. Ibarra-Rojas et al. [15] handled this critical trade-off between the level of service and operating costs by maximizing the number of passengers and minimizing the operating costs in vehicle scheduling using two integer linear programming models, namely the timetabling and vehicle scheduling problems. Besides, Laporte et al. [16] performed a multi-objective optimization model to optimize the operator's and the users' criteria by allocating the best possible timetable for each passenger while satisfying capacity constraints. Shen et al. [17] proposed a vehicle scheduling problem to minimize the total cost and maximize the on-time performance based on stochastic trip times instead of fixed ones considering delay propagation. Traditional approaches for allocating a transport fleet based on uniform demand have been defined in a fixed timetable that did not take into account fleet capacity. This approach caused fleet delays and system inefficiencies.

Considering delays and the extra trips as two types of disruptions, Ucar et al. [18] presented a recovery solution to handle these disruptions using the multi-depot vehicle scheduling problem. The vehicle scheduling problem is designed by a column-and-row generation algorithm. Furthermore, Niu et al. [19] developed an approach using the Lagrangian relaxation method based on the variable division to allocate vehicles and decide their paths for the multi-warehouse vehicle scheduling problem. Subsequently, an optimization model that involves the integration of vehicle scheduling and passenger demand using the skip-stop operation was studied by Cao and Ceder [20]. Their research aimed to reduce total passenger travel time and the number of autonomous shuttle vehicles in use based on the deficit function. The research was conducted to consider the fleet's capacity and the delays and consider the stochastic trips originating from the non-uniform demand at different stations of the route. However, designing and building a transit network is costly for decision-makers who are generally willing to use short-term and low-cost strategies to improve system performance [20]. In this regard, using operational tactics along with transit service parameters and road-segment characteristics can be a proper strategy [21–23]. Liu et al. [24] used skip-stop operational tactics along with Monte Carlo simulation based on stochastic transit time. When a public vehicle is delayed from the scheduled time, a skip-stop option allows this mode to skip one or more stations to reduce their transit time. Furthermore, Nesheli et al. [25] investigated the optimal combination of operational tactics for coordinating the transfer of passengers through the PT system. Nesheli et al. [26] considered the PT system's road-segment characteristics and used operational tactics such as the ones used in their previous study for coordinating the departure of PT vehicles. Their study focused on providing a model for reducing passengers' travel time and increasing the direct transfer of passengers. They used 14 scenarios by applying the combination of different operational tactics, including deadheading, skip-stop, and short-turn. They used the concept of the basic factor model to validate the optimization model by generating stochastic data. Moreover, Nesheli et al. [27] conducted a study on the coordination of transporters in the PT network to increase the system's reliability, and they have proposed some indicators for the system performance index.

Alongside, some studies proposed mathematical and simulation modeling using real-time data of multiple lines [28,29]. Yap et al. [30], considered a single stop as the same stop that controls the executed strategies. Manasra and Toledo [31] developed a simulation-based optimization framework to synchronize PT operations. The simulation model implemented bus holding and changing bus velocity as control actions. The objective of the optimization model was to minimize total passenger travel time in the system within a prediction period. Their results showed that the operational strategies outperform traditional headway control and the no-control situation in terms of system performance. Also, Tang et al. [32] proposed a methodology for reducing the required number of vehicles using limited-stop, short-turn, deadheading, and mixed strategies. They developed two optimization models to minimize the passenger travel time changes and determine a set of stops served by the variable trip schedule.

The previous studies in the PT systems modeling literature have mostly intended to involve PT vehicle, network, and demand parameters in their models. Moreover, the literature review shows that few studies have considered the three short-term operational tactics in PT systems. In this research, however, a robust simulation model is designed to include all three types of input parameters and implement all three operational tactics to minimize passenger travel time, passenger waiting time, and total cycle time through several scenarios in order to find solutions that improve the system's performance.

2. Methodology

2.1. Survey design

The PT system has various correlative components. This study seeks to create a tool for analyzing and evaluating the PT system's performance. To achieve this goal, the relationships between the components and the way they operate in different situations need to be clarified. Therefore, Simulation models are the most suitable approach to overcome the complexities of relationships, their effects on each other, and the interactions between components.

2.2. Operational tactics

Numerous studies have investigated how controlling methods can be used in simulation models to improve the system's performance in certain conditions. In this study, three operational tactics, namely deadheading, skip-stop, and short-turn, are used. These tactics are explained in the following.

2.2.1. Deadheading

In the deadheading operations, the service is scheduled in a way that the vehicles start or end the route without any passengers on board, which may lead to decreased headway. Corridors are defined in this approach to compensate for the unbalanced demand between the two directions of the route, where empty buses pass the less-demanding route without any stop. This tactic may also be used when there is congestion at the stations in the middle of the route. To maintain the balance between supply and demand, the frequency in the more demanding direction should increase. Therefore, the vehicles pass the less-crowded direction empty and return to the terminal as soon as possible so that they can be rescheduled to service the route and minimize the average cycle time on the route [33].

2.2.2. Skip-stop

Skip-stop is another type of special service tactic that is broadly used for routes with high travel demand. The purpose of this tactic is that the vehicles that have fallen behind their schedule be able to stick to the specified timetable by skipping the less demanding stations. Unlike other tactics that are designed in the planning phase of the service, this tactic is determined at the moment and according to the congestion of the route. One of the disadvantages of this tactic is that the waiting time of the travelers whose origin or destination stations are skipped is increased. However, this tactic has proved to be effective in reducing the total waiting time using optimization and simulation models [34].

2.2.3. Short-turn

This operational tactic includes a system of short trips and full-length trips along the same route. This type of special service solution is suitable for routes where demand is very high and there the demand decreases as we reach the two ends of the route. The short trips only respond to the peak demand segment and full-length trips are for the entire route. The main issue in the design of short-turn services is to determine the length of the short-trip route, balance the passenger demand throughout the route, and minimize the size of the fleet and passengers' waiting time [35].

2.3. Assumptions

The simulation assumptions for evaluating operational tactics of the bus lines are as follows:

- Information about the road-segment characteristics, arrival time, and entrance station of passengers are predefined.
- The passenger demand in the simulation model is not sensitive to PT features.
- The route in this research is assumed to be a circular bus route.

2.4. Simulation model

The discrete event simulation model used in this study is composed of four sections and it involves different scenarios considering operational tactics including skip-stop, deadheading, and short-turn. This research seeks to utilize different operational tactics to improve system performance and investigate the impact of these tactics in different scenarios. The inputs of the simulation model are divided into three sections: 1- the road-segment characteristics including the physical conditions of the bus route; 2- demand parameters which involve demand patterns and passenger attributes; 3- the transit service parameters such as capacity, headway, and dwell time (the least amount of time that a bus has to stay at the station). The simulation model is composed of four steps, described as follows:

Step 1: the initial inputs are entered into the model. The road-segments characteristics include the number of stations and the vector of bus velocity and distances between stations. The demand parameters include the number of passengers, the vector of arrival and exit rates (passenger per hour) for each station, and the alighting and boarding times. The alighting time and boarding time vectors are generated based on the stations' crowd congestion levels in four conditions of quiet, semi-quiet, semi-busy, busy. Then, the origin-destination matrix, which indicates the origin and destination of each passenger, is generated stochastically using the number of passengers and their arrival and exit rates. The last type of inputs is transit service parameters, which include the headway values in the form of a timetable indicating the time of bus departures, dwell time, and bus capacity.

Step 2: after entering the initial inputs of the model, the event-based simulation process is run.

Step 3: the scenarios are defined according to operational tactics. Each operational tactic has its specific inputs. The inputs for the skip-stop tactic are the skipped stations and the departures that must skip the specified stations. For the deadheading tactic, it should be determined which of the first or last stations are skipped and which departures are included in the tactic. The short-turn tactic requires the service route (the beginning and the ending stations of the short route), the headways for the short route, and the departures that should follow the short route.

Step 4: the model's outputs are reported and the performance indices are obtained to compare the initial situation with the one in which operational tactics were used.

The presented event-based simulation model is validated through a numerical example and sensitivity analysis. The simulation model is depicted in Figure 1.

3. Results and discussion

3.1. Numerical example

According to the literature review, PT systems in the real world usually involve heterogeneous demand patterns along the transit route. Therefore, operational tactics are used in these cases to alleviate the negative effect of uneven demands in different stations. In this study, the presented simulation model is applied to a PT network based on real-world conditions.

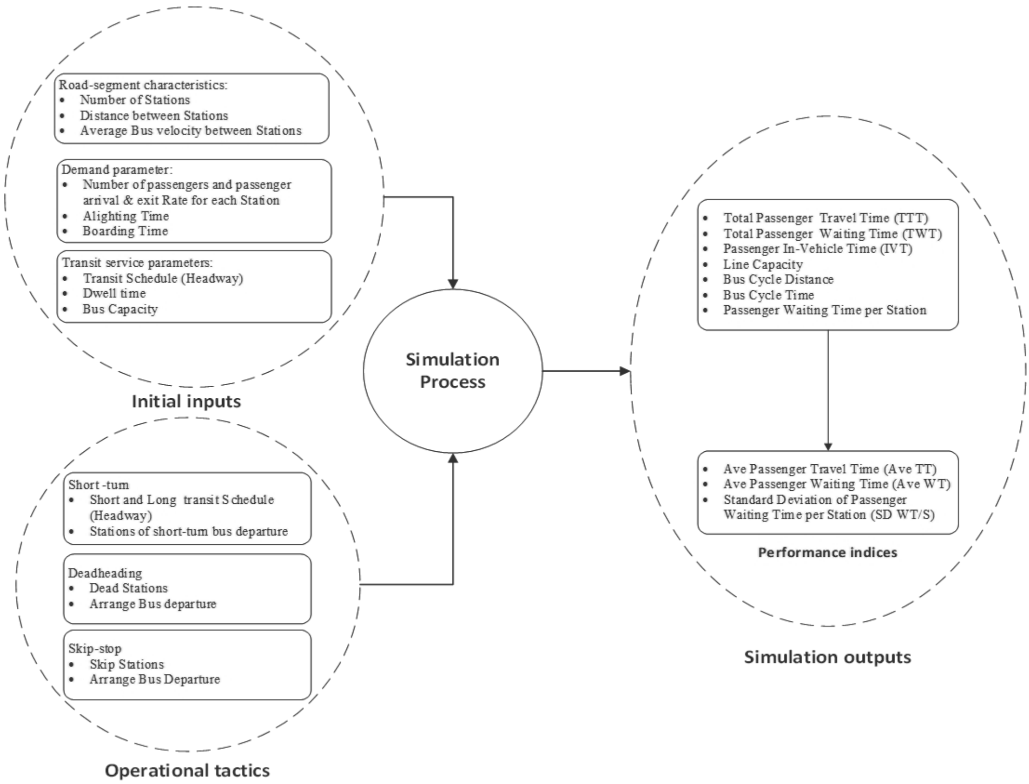

Fig. 1 - The Simulation model

Generally, the central stations in a route are more crowded and have more demand than the peripheral stations. Therefore, the parameters for the numerical example in this study are determined in a way that resembles this feature of real-world TP networks. As this section aims to investigate the effects of applying the operational tactics to a PT system in the form of different scenarios, some input parameters need to be fixed. The input parameters are explained in the following.

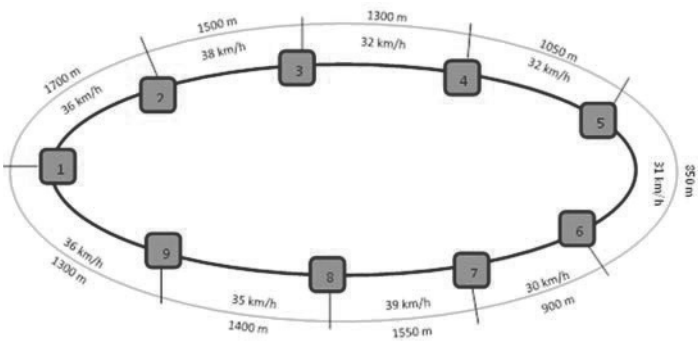

Fig. 2 - Road-segment characteristics of the numerical example

3.2. Inputs of the numerical example

The average velocity and distance between stations are introduced as vectors entered into the model to define the road-segment characteristics. In this research, the velocity vector is between 30-40 km/h and distances between stations are generated randomly, as illustrated in Figure 2. A total of 30 replications are done based on the demand matrix which is generated stochastically based on the arrival and exit rate of the stations shown in Table 1. The times required for passengers to board and alight are shown in Table 2. As seen in table 2, the boarding times are greater than alighting times. It has been discussed in the literature that alighting and boarding times depend on the stations' platform in terms of passenger flow. This means that the alighting to boarding rate can be higher or lower than 1 [36]. In this study, we have assumed that the stations' platforms are organized enough so that the alighting is not hindered by the boarding flow. The reason for the alighting and boarding times being zero for up to 5 passengers is that we have considered a minimum dwell time of 15 seconds at each station.

The capacity of the buses used in this simulation model is 42 persons and the bus departure is considered to be a fixed value. The values for headway, bus capacity, and minimum dwell time at each station are shown in Table 4.

3.3. Operating scenarios

For achieving improvement and non-improvement performance according to the conditions and demand patterns described above, 17 scenarios are defined using the operational tactic, shown in Table 4. Scenarios 1 to 8 represent skip-stop tactics with different inputs. The deadheading tactic is considered in scenarios 9 to 14, and scenarios 15 to 17 involve short-turn tactics with different routes.

Tab. 1 - The passenger arrival and exit rate at each station

Station	1	2	3	4	5	6	7	8	9
Arrival rate (p/h)	86	60	268	81	112	229	69	52	43
Exit rate (p/h)	100	36	96	99	201	52	299	58	59

Tab. 2 - Passenger boarding and alighting time

Group	Time (s)
Passenger boarding time for up to 5 people	0
Passenger boarding time for 6 to 10 people	1.5
Passenger boarding time for 11 to 20 people	1.2
Passenger boarding time for more than 20 people	1
Passenger alighting time for up to 5 people	0
Passenger alighting time for 6 to 10 people	1
Passenger alighting time for 11 to 20 people	0.8
Passenger alighting time for more than 20 people	0.5

Tab. 3 - Transit service parameter assumption

Parameters	Values
Headway	7.5 m
Minimum dwell time at each station	15 s
Bus capacity	42 persons

Tab. 4 - Scenarios definition

Scenario	Description
1	Every other bus departure skips station 3
2	Every other bus departure skips station 3
3	Every other bus departure skips station 7
4	Every third bus departure skips station 7
5	Every other bus departure skips stations 2 and 9
6	Every third bus departure skips stations 2 and 9
7	Every other bus departure skips stations 4 and 8
8	Every third bus departure skips stations 4 and 8
9	Every other bus departure starts from station 5
10	Every third bus departure starts from station 5
11	Every other bus departure starts from station 3
12	Every third bus departure starts from station 3
13	Every other bus departure starts from station 2
14	Every third bus departure starts from station 2
15	Headway is 15 minutes for a full circle departure and 7.5 minutes for the short-turn departure between stations 5 and 7
16	Headway is 15 minutes for full circle departure and 10 minutes for the short-turn departure between stations 3 and 6
17	Headway is 15 minutes for full circle departure and 10 minutes for the short-turn departure between stations 3 and 7

3.4. Outputs and performance indices evaluation

Each scenario has a different effect on the system performance indices and improves some of them. Since the demand matrices are generated 30 times stochastically based on fixed arrival and exit rates, each scenario is also run 30 times. After running all the replications, the mean values of the outputs are shown in Table 5.

Tab. 5 - Main simulation outputs

Scenario	Control tactic	TTT (h)	Average travel time (min)	TWT (h)	Average waiting time (min)	In-vehicle time (h)	Line capacity (p/h)	Total bus cycle distance (km)	Total cycle time (h)
Base	None	832	12.6	543	8.2	289.2	991	381.1	14.4
1	Skip-stop	1122	18.7	870	14.5	252.4	901	381.1	14.0
2	Skip-stop	1014	16.1	743	11.8	271.6	947	381.1	14.1
3	Skip-stop	1017	17.9	755	13.3	263.1	851	381.1	13.9
4	Skip-stop	1071	18.0	800	13.5	270.9	892	381.1	14.1
5	Skip-stop	697	10.5	406	6.1	291.3	1000	381.1	14.0
6	Skip-stop	745	11.2	454	6.8	290	997	381.1	14.1
7	Skip-stop	659	9.9	373	5.6	285.5	1000	381.1	14.0
8	Skip-stop	653	9.8	364	5.5	289.2	999	381.1	14.1
9	Deadheading	1392	23.8	1141	19.6	250.5	875	381.1	13.3
10	Deadheading	1129	18.0	857	14.7	272.2	940	381.1	13.7
11	Deadheading	872	13.2	580	8.8	292.3	991	381.1	14.0
12	Deadheading	857	13.0	567	8.6	290	986	381.1	14.1
13	Deadheading	794	11.9	502	7.5	292.5	999	381.1	14.2
14	Deadheading	788	11.9	497	7.5	291.1	996	381.1	14.2
15	Short-turn	1268	21.7	1020	17.5	248.1	875	254.1	10.6
16	Short-turn	962	17.5	700	12.8	262.6	823	276.4	11.1
17	Short-turn	659	9.9	364	5.5	287.2	1000	298.9	11.9

To evaluate the results of scenarios, the indices should be obtained from Table 5 and be compared with the base scenario (the scenario in which no operational tactics are used). Table 5 shows the main simulation outputs and also Figure 3 shows the average travel time (Ave TT), the average waiting time (Ave WT), and the standard deviation of passenger waiting time in each station (SD WT/S). According to Figure 3, scenarios 8 and 17 produced the best performance among others, as the improvement rates for scenario 8 are respectively 22% and 33% for Ave TT and Ave WT. The reason for this improvement is that this scenario is a skip-stop tactic in which the less crowded stations with less demand are skipped by every third bus. Consequently, the fleet allocated to the more crowded stations can provide a better level of service, and the fleet capacity is used more efficiently in these stations, leading to improvements in passengers' average waiting and travel times are decreased. Also, scenario 17 showed 22% and 32% improvement for average Ave TT and Ave WT, respectively. This is because this scenario executes a short-turn tactic between stations with the highest demand.

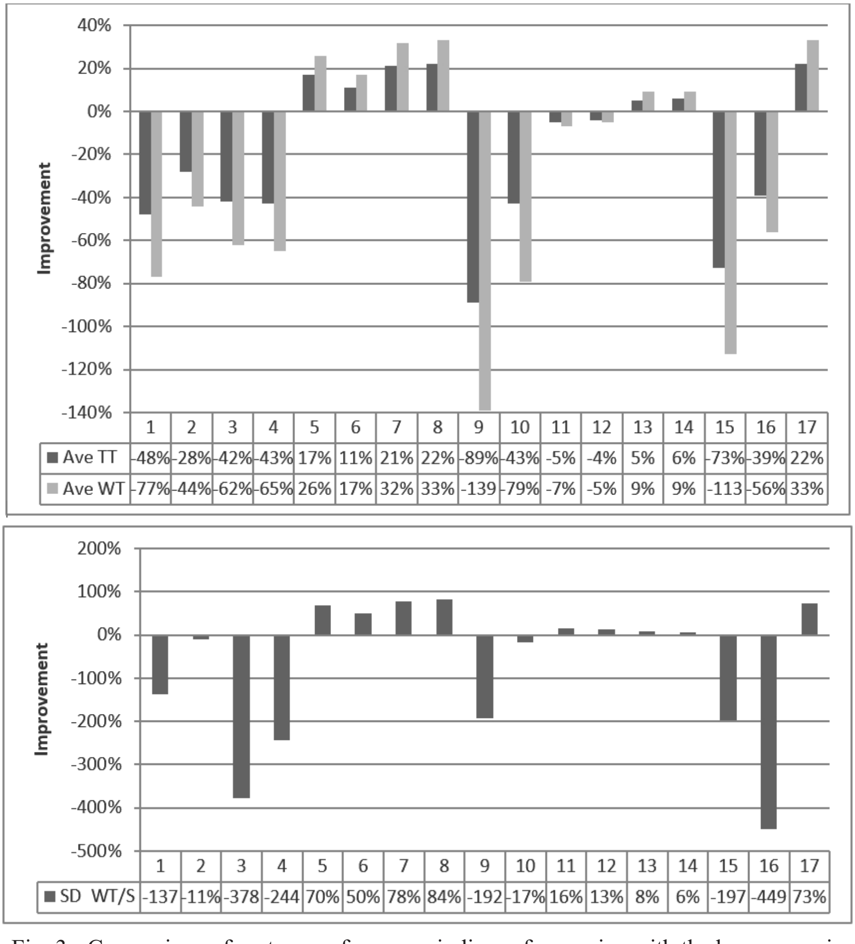

Fig. 3 - Comparison of system performance indices of scenarios with the base scenario

As the result, more buses will be available in the central stations with higher demands, which leads to reduced average waiting and travel times. This model was simulated using MATLAB programming, and it was evaluated according to different scenarios in a personal computer with a Core i5 processor, 8 gigabytes of random-access memory, and a runtime of 6.32 seconds.

3.5. Sensitivity analysis

Among the various parameters included in the simulation model, the sensitivity analysis is conducted for parameters that significantly impact the results. The effect of these parameters is calculated on the average passenger travel time, as shown in Table 6. Figure 4 illustrates a Tornadodiagram of the sensitivity analysis's results.

The sensitivity analysis determines which parameters have the most significant potential impact on the average passenger travel. As seen in Figure 4, the system is most sensitive to the headway between departures. This is justified by the fact that the number of buses significantly affects the transit service quality by increasing the transit capacity as the passenger's waiting time in a PT largely depends on how long they wait for a vehicle to arrive. For the same reason, bus capacity is the second most effective parameter. It should be noted that it is considerably costly to improve the headway and bus capacity in PT systems.

Therefore, system operators prefer to use operational tactics to improve system performance. The average velocity has also shown a considerable impact on the average travel time because the more quickly buses traverse the route, the more passengers they can transfer in a certain period. Moreover, the tornado diagram suggests that has a trivial effect on passengers' average waiting time.

Tab. 6 - Results of sensitivity analysis and comparison with the base scenario

No.	Variable	Unit	Max	Min	Expected	Maximum of target function (min)	Minimum of target function (min)	Difference
1	Headway	minute	10	5	7.5	22.86	7.00	15.86
2	Bus Capacity	passenger	120	40	42	14.24	8.23	6.01
3	Average velocity	km/h	50	20	[30,40]	16.75	11.16	5.59
4	Dwell time	second	20	0	15	12.86	11.68	1.18

* The target function in the expected state is 12.6 minutes.

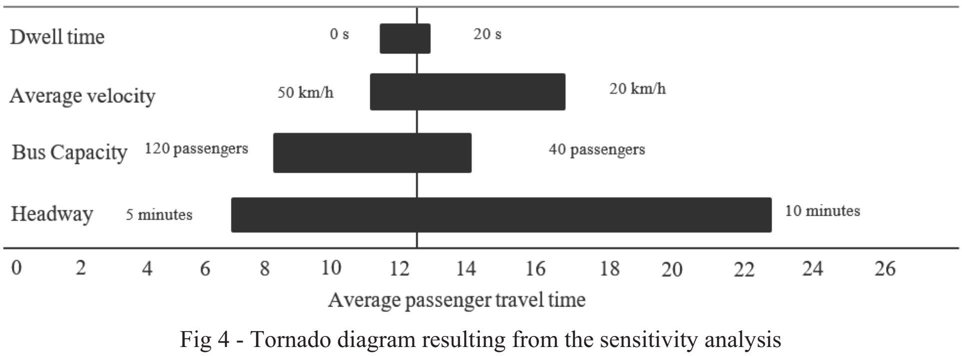

Fig 4 - Tornado diagram resulting from the sensitivity analysis

4. Conclusion

The operation of the PT system is one of the crucial issues in transportation and many researchers have been striving to present practical solutions. Among all possible ways to improve the system's performance, operational tactics produce low-cost and short-term solutions.

Therefore, in this paper, three broadly-used operational tactics, namely skip-stop, deadheading, and short-turn, are utilized to improve the PT system performance and compare it with the base scenario. The event-based simulation model used in this study is a tool that can be used to analyze and evaluate system performance when operational tactics are applied.

The initial inputs of the model include road-segment characteristics, demand parameters, and transit service parameters. The model was validated through a numerical example, in which 17 scenarios were examined to improve the system's performance. Results suggest that the skip-stop tactic had an improvement rate of 22% in average passenger travel time and an improvement rate of 33% in the average passenger waiting time. Moreover, the short-turn tactic reduced the average travel time by 21%, and the average waiting time by 33%. However, the deadheading tactic showed 5% and 9% of improvement in average passenger travel and waiting time.

Consequently, the presented simulation model has shown better improvement rates for skip-stop and short-turn tactics compared to the deadheading tactic in the circular bus route. The results of the sensitivity analysis showed that the headway and bus capacity parameters have the most significant effects on the average passenger travel time as the system performance index. The results of this research may be used for system operators to analyze and evaluate transit system performance by applying operational tactics under various road-segment characteristics, demand parameters, and transit service parameters.

Future research suggestions

According to the results of this research, some areas for future studies include:
1) simulation model of the transit system using the combination of operational tactics.
2) online simulation model of bus routes based on real-time operational tactics.
3) optimization using a simulation model to evaluate transit system performance.

Authors' contributions

M. Ghodsi performed the literature review, Simulation design, analysis and evaluate the data. S. Seyedabrishami helped in the design and interpretation of the simulation model. A. Ardestani prepared the manuscript text and manuscript edition.

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