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Shakibayifar, Masoud; Sheikholeslami, A.; Corman, Francesco; Shafahi, Y.

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Simulation analysis of the effect of doubling and electrification on the reliability of the rail networks: A Case Study of Tehran-Mashhad railroad

M. Shakibayifar [a,*], A. Sheikholeslami[b], F. Corman[c], Y. Shafahi[d]

[a] Department of Transportation Engineering and Planning, School of Civil Engineering, Iran University of Science & Technology, Email: m_shakibayi@civileng.iust.ac.ir,
Mobile phone: 09122070623

[b] Department of Transportation Engineering and Planning, School of Civil Engineering, Iran University of Science & Technology, Email: sheikh@iust.ac.ir

[c] Department of Marine and Transport Technology, Delft University of Technology, Mekelweg 2, 2628 CD Delft, The Netherland, Email: f.corman@tudelft.nl

[d] Department of Transportation Engineering and Planning, School of Civil Engineering, Sharif University of Technology, Email: shafahi@sharif.ir

Abstract:
The reliability assessment of the railway services is a complex procedure that is affected by many different factors. A railway system is reliable when the trains arrive at their destination within the allowed delay threshold. The objective of this study is to investigate the effect of the infrastructure doubling and electrification on the reliability of the train schedules. In this study, advanced event-driven stochastic simulation software is developed to determine the reliability of the train movements. The calculation of the average train delay as a benchmark is provided to evaluate performance. We compared average train delay with the acceptable delay to define a new benchmark to determine the reliability of the train movements. We also analyzed the delay cascading effect along the railway line in order to better illustration of a number of correlations between the arrival and departure delays at different stations. The model has been validated through a real-world case study of Iranian railway. Successful validation of the developed simulation system demonstrated that the model provides accurate reliability estimations in both congested and non-congested situations. Furthermore, the experimental results showed that electrification and doubling improve the reliability significantly.

Keywords:
Reliability, electrification, average delay, infrastructure doubling, simulation modeling, railway

1. Introduction

Railway operation planning is extremely complex, mainly because it is a decision problem under many uncertainties [1]. Several uncertain factors may eventually result in some minor or major deviations from the pre-planned timetable. Train delays depend on the traffic volume and the capacity utilization and comprise a significant percentage of the travel time. Furthermore, the delays cause high costs of passenger dissatisfaction and penalties for late deliveries of freight for railway companies [2]. In this situation, the management of train services is a complex procedure [3]. One of the common criteria to evaluate the quality of rail systems is the reliability of train movements [4]. Reliability is the ability of a system or component to perform its required functions under stated conditions for a specified period of time [5]. Rail transit systems seek to schedule trains in order to avoid passenger dissatisfaction and to improve the service reliability [6]. The existence of single-track segments causes problems in overtaking and crossing of trains, which increase delays in the rail network. One practical way of improving the capacity is the process of expanding a single-track rail segment to double-track which is called doubling. An important question is how to obtain a trade-off between capacity and reliability. The methods for capacity analysis can be divided into simulation, optimization and analytical methods [7]. Mathematical optimization models have been extensively employed to measure train delays and to determine the train timetables as well as the operational capacity; see e.g. Corman, D'Ariano [8], [9], and Morant, Gustafson [10]. In addition, simulation approaches seem to be an effective and promising method to appraise the trade-off between capacity and reliability [11]. Simulation technique allows the evaluation of a system prior to its creation, makes it possible to compare different executable options without disrupting the actual system, and finally it is usable by many people because of its uncomplicated structure and accessibility to simulation-specified computer languages [12]. Simulation modeling has been used extensively in railway applications as a flexible and powerful approach to evaluate the robustness and reliability of train timetable; see e.g. Sajedinejad, Mardani [13], Hasannayebi, Sajedinejad [14], [4], Hassannayebi, Sajedinejad [15], and [16].

The present study is motivated by the situation where the reliability of the service is of concern. In Iranian rail network, the important causes of passenger train delays are unscheduled waiting time at overtaking stations, engine breakdown, infrastructure failure, and unplanned stops [17]. According to the archived data from Iranian Railways, the average delay from 2005 to the end of 2009 was nearly 30 minutes for each passenger train [18]. Literature shows that the optimal investment on the rail infrastructure can improve the reliability of the system for both the existing and new train services [19]. The objective of this study is to analyze the effect of doubling and electrification on the reliability of the rail networks. A stochastic event-based simulation system is developed to determine timetable reliability. Thus, the aim is to analyze to what extent the electrification and doubling can increase trains' movement reliability. The designed simulation system considers stochastic parameters associated with train characteristics e.g. stochastic train running time, probabilistic dwell time, and random failure of rail infrastructure. As a case study, we conduct a reliability analysis of Tehran-Mashhad corridor and the results are presented. In order to investigate the effect of doubling on the timetable reliability, we consider two cases. In the first case, the railway system is partially single and double-tracks. In the second case, the whole route consists of double-track segments. In order to compare electrified and non-electrified railways, we compare them in the same setup. A method is proposed to make a fair comparison of these two cases.

The contributions of the present study to the research community are as follows: First, an advanced event-driven simulation system is developed to calculate the reliability of the train schedules. As will be explained in more detail below, the reliability of the train services is referred to the total train delay at destinations against allowed intervals. Second, in order to conduct a fair comparative analysis, the operational parameters of the electrified routes are modified and implemented in the non-electrified route.

2. Literature Review

Reliability is one of the important factors in railway, both for passengers and for cargo. Reliability of railway transportation is a complex matter since there are many causes of conflict and at least as many causes for delays to spread around in space and time [20]. Different possible explanations of the reliability have been used in the literature. Rietveld, Bruinsma [21] define the reliability in seven different ways: 1. Punctuality, i.e. the probability that trains arrive less than *x* minutes late; 2. the probability of an early departure; 3. the mean difference between the expected arrival time and the scheduled arrival time; 4. the mean delay of an arrival given that one arrives late; 5. the mean delay of an arrival given that one arrives more than *x* minutes late; 6. the standard deviation of arrival times; 7. the adjusted standard deviation of the arrival times (ignoring the early arrivals), and various other more complex measures to represent the seriousness of unreliability. Another measure of the reliability has been defined as the value of average delay divided by the value of travel time. The ‘‘average delay’’ is a good measure for timetable reliability [20]. The term reliability is used quite broadly, in this research, when a railway system is reliable, the trains run properly most of the time within the allowed delay threshold. Thus, our reliability definition is the most similar approach to the third definition of Rietveld, Bruinsma [21].

In the context of railway transportation systems, improving the service quality under the uncertain condition is a real challenge [22]. In what follows, we refer to the most relevant simulation studies determining unreliability in the rail network. Hallowell and Harker [23] developed a prediction method for the schedule reliability of a partially double-tracked rail route. A simulation model has been designed for the generation of a reliable schedule. Huisman and Boucherie [24] developed a stochastic analytical model for analyzing delays at a double-track route. Their models were based on train frequencies and running times only, not on detailed timetables with arrival and departure times. Carey and Carville [25] focused on the improvement of the generated timetables by reducing the consequences of delay propagation in large stations by simulation approach. Yin, Lam [26] presented a simulation-based approach to measure the transit reliability. The developed model addressed the interaction between network performance and passenger’s route choice behavior.

Vromans, Dekker [20] developed a simulation package being called SIMONE (a discrete-event simulation model) has been used as simulation platform of a given timetable. In SIMONE many complex details in railway systems such as interactions between trains, headway times on the tracks, platform occupations, and connections for travelers, were taken into account. They developed a rule to decrease the propagation of delays and present new measures to show a strong correlation between speed differences and reliability. Furthermore, an innovative stochastic linear program has been presented to evaluate and optimize timetables. Dingler, Lai [27] attempted to provide a better understanding of the impacts of various aspects of train type heterogeneity to enable more effective planning and efficient rail operations. Train dispatching simulation software has been used to analyze the effect of various combinations of intermodal, unit and passenger trains on a hypothetical signalized, single-track line. They also suggest certain operating strategies that may increase the capacity caused by train type heterogeneity.

Murali, Dessouky [28] suggested a simulation-based technique that generates delay estimates over track segments as a function of traffic conditions, as well as network topology. Marinov and Viegas [29] designed a simulation model to study and evaluate freight train operations. To capture the global impact of freight operation over the whole network, the model separated rail networks into components such as rail lines, stations and so on, and then puts all these components into an interconnecting queuing system. Zheng, Zhang [30] presented the definition of the carrying capacity reliability of railway network. They developed a model for capacity calculation and conducted a numerical experiment with different levels of origin-to-destination (OD) demand. The result shows that the fluctuation of OD demand directly affects the carrying capacity of railway networks.

Simulation in combination with optimization techniques can be adopted to logistic problems; see e.g. Eskandari, Rahaee [31], and Ilati, Sheikholeslami [32]. Corman, D'Ariano [33] investigated the application of an optimization-based framework for the evaluation of different robust timetables under stochastic disturbances. A real case has been used in a Dutch railway network with heavy traffic. A trade-off has been found between the train delays and the passenger travel time. In railway context, Quantifying the relations of delays among the sequence of stations are important supportive for forecasting potential train conflicts, generating robust train dispatching procedures, generating robust train timetables, and evaluating the quality of train dispatching algorithms. Guo et al, (2015) analyzed the relations among delays in different stations, in order to arrange for predictive train dispatching. Statistical methods were adopted for deriving probability distribution functions of both train arrival and departure delays at the individual station using historical train record data. Hassannayebi, Shakibayifar [34] proposed mathematical modeling approaches for the integrated train scheduling and infrastructure upgrading in railway networks. A mixed-integer linear programming formulation has been proposed that deals with the optimum schedule of trains and the best segments for doubling. Two heuristics were proposed to reduce the complexity of the problem. The result of the proposed methodology demonstrates that it can significantly decrease the total delay of trains with the most emphasis on the bottleneck segments. Hassannayebi, Sajedinejad [35] adopted a discrete-event object-oriented simulation model, which implements variable neighborhood search algorithm in order to recover the system performance after disturbance. The simulation model has been tested against different probabilistic disturbance scenarios. Shakibayifar, Sheikholeslami [36] presented a simulation-based optimization approach to reschedule train traffic in uncertain disruptions. The train conflicts are resolved using a dynamic priority rule with the aim of minimizing the total delay time. The proposed simulation model has been tested on real instances of the Iranian rail network. The outcomes specify that the optimization approach has considerable advantages when compared to existing solution methods.

To the best of the author's knowledge, a few numbers of studies analyzed the effect double-tracking and electrification on the reliability of the rail networks. The main motivation of the current study is to quantify the reliability of a railway system by using a simulation-based decision support framework considering random failure and the stochastic disturbances of train operations. The next section provides the description of the problem.

The structure of the paper is organized as follows. In Section 3, the problem is described in details. Afterward, the details of the methodology are presented in Section 4. The framework of the simulation method is presented in Sections 5. The researchers organize and interpret the results of extensive simulation experiments on a real case in Section 6, which followed by conclusions in Section 7.

3. Problem statement

In order to better describe the formulation, we first state the problem and the situation in which the reliability analysis is conducted. The network diagram is a single bi-directional route including both the single and double-track segments. The corridor includes K stations and K-1 block segments. Suppose a different set of eastbound and westbound trains (Fig. 1). Each block of the route can be a single-track or double-track segment. A double-track railway usually involves running one track in each direction, compared to a single-track railway where trains in both directions share the same track. Train crossing is possible either at stations or parts of the route with double-track railways and overtaking is only possible at stations. A train starts from the origin according to the initial schedule and passes intermediate blocks to arrive at the destination. The aim is to analyze the effect of doubling and electrification on the train delays. The next section describes the proposed methodology of reliability assessment.

Fig. 1.

4. Methodology

This study is primarily purposed to present an operational and consistent simulation system to find the extent that the reliability of the train services can be improved subject to two factors: doubling and electrification. The input data of the simulation model is provided in Table 1. The developed simulation system has some new features compared to other simulation methods existing: first, it considers most important sources of randomness in train operations e.g. stochastic running time of trains on block sections, breakdown/failure probabilities at both rail segments and inside stations. Second, the simulation model configuration has been customized by the inclusion of railway operations, rules exist in the Iranian railway network (e.g., the train stops for praying services). We first give a detail description of the simulation model. The discussion will be continued to present the assumptions and the system explanation.

4.1. A simulation model for reliability analysis

This section presents the simulation logics and algorithms, including input and output data. By considering a set of stochastic parameters, the train operations along the route are simulated. Thereby, an analysis of the delays that may occur in the network is possible. The presented simulation model is an event-based stochastic simulation system to analyze the reliability of the rail system.

C# programming language is used in software development. The application is designed by high-level NET Framework object-oriented language. The simulation model will be able to include input data e.g. geometric data of blocks and stations, locomotives and wagons technical specifications, traction and resistance relationships to generate outputs such as travel times of trains on the block and the entire route, the fuel consumption, instantaneous and average train speed, traction resistance moment diagram (including arc resistance, slope, tunnels, and Davis resistance).

Table 1.

The core of the simulation system includes a train movement control module. A basic of the main steps of the proposed simulation algorithm is shown in Fig. 2. As can be seen, our simulator uses a priority rule-based event-list in order to find a feasible train timetable. All unscheduled trains are sorted in ascending order of their priorities. The trains depart according to the pre-planned timetable. The train with the highest priority is dispatched first until it crosses through the entire line. Subsequently, the next train from the predefined list is scheduled and so on, till all trains are reached to their destinations. The main routine of the dispatching algorithm is described below:

The main routine of the dispatching algorithm

1. Set simulation clock (t=0)
2. Initialize system state
3. Prepare event list (ascending order of time)
4. Consider the first event and invoke event routine
5. Using a look-ahead procedure finds out the new event (either stop at current station or move to next station)
6. Update the system states and the associated variables (train positions, current utilization, and so on)
7. Check the feasibility of the train departure
8. Insert new event at appropriate time position
9. Check whether an event list is empty
10. Generate output reports
    - Train timetable graphs (time-station diagrams)
    - Train delays at destinations.

Fig. 3 shows the flow diagram of train dispatching model. This part of the simulator controls the priority list and dispatch train in the pre-specified order. In the continued procedure, the Train movement license is checked (Fig. 4). The availability of the track is controlled by detecting the type of the segment

(Fig. 5). Likewise, the availability of a free track at the next station is checked through the procedure represented in Fig. 6. The train movement control module works as follows: In the first step, the algorithm finds the next segment where the train can stop. Afterward, the algorithm checks whether the path is free to that position or not. If the train is allowed to dispatch, it reserves a free path (a free block section and a free track at the nest stations). After that, the departure time is logged and the train moves to the next segment or section. After the dwelling or the running time operation, the train releases the segment or a track of the station just when it left. The algorithm then returns to the second step, until the destination station is reached.

Fig. 2.

Fig. 3.

Fig. 4.

Fig. 5.

Fig. 6.

4.2. Train operation modeling

This section provides the assumptions made on the train operation during the simulation experiments. The stochastic parameters here are train running times and random failure at stations. The first step toward train operation modeling is to construct train timetables. The blocks' occupancy depends on the priority of trains. Duration of dwell time at a station for a train is calculated as Equation (1).

$$Dwelling\ time\ duration\ at\ a\ station\ = max\{S, P, F\} + R \tag{1}$$

where

- S denotes scheduled dwelling time, including boarding and alighting of passengers, refueling, water refilling, etc.
- P denotes the duration of the pray service (if a stop is scheduled for pray service).
- F denotes failure maintenance time in the stochastic simulation condition (assuming that agents detect the problem at the moment of arrival), and
- R denotes required time to avoid crossing and overtaking that is calculated by the simulator.

For a train to depart from a station and enter to the next connecting block, block switches are controlled at first. In single-track blocks, the railroad switches must be controlled in both directions while in double-track blocks only the one in the same direction must be checked. The train timetable can be constructed using the developed simulation system.

4.3. Data input modeling

4.3.1. Running Times Distribution

According to the disturbances in train movements along the route, running time on the blocks generally varies with their scheduled running time and it can be considered as a random variable. In fact, both factors of structural and operational characteristics are effective in this regard. The actual running time for a single train is a function of some factors, e.g. the length of the segment, weather conditions, train loads and the train operator behavior. The actual running time of a train may deviate from the scheduled one and result in an extra delay. An important cause of the deviation is the random failures related to the locomotive driver who becomes unable to take the train to the destination on-time (due to random variables such as a train breakdown or debris on the track or other driving conditions. In this condition, the central controlling system commands that communicate, i.e., acceleration or deceleration commands to the driver, in order to minimize train delays.

In order to find an appropriate statistical distribution of this random variable, the running time information of all trains on different blocks of the routes has been collected over a three-month time period, and statistical tests for the best distribution fitting for all of the blocks were carried out separately. Actual running time in each block has been obtained by subtracting the train's "departure time from one station" from "the arrival time to the next station." Frequency distribution of these delays on blocks separated by the different scheduled running times of the trains in each block for each round-trip route was determined. An example of results for a specific block is shown in Fig. 7. Statistical analysis indicated that the running time distribution does not depend on the time of the day.

Fig. 7.

```
Distribution Summary                                 Data Summary
Distribution:            = Normal                    Number of Data Points        = 88
Expression:              = Normal(15.3,1.54)         Min Data Value (minutes)     = 11
Square Error:            = 0.025822                  Max Data Value (minutes)     = 19
                                                     Sample Std Dev               = 1.54
Chi-Square Test
Number of intervals      = 5                         Histogram Summary
Degrees of freedom       = 2                         Range                        = 10.5  to 19.5
Test Statistic           = 12.1                      Number of Intervals          = 9
Corresponding p-value    > 0.005
```

In order to find the probability distribution function of random failures, we need to discover the number observations that the actual running time is higher than the scheduled one. The superfluous traveling times are most likely due to the occurrence of damage or unusual happenings during the train's passage on the block. The failure data in each block segments and their impacts on running times are extracted from the database. Table 2 shows the summarized results of these test experiments. This graph demonstrates the occurrence frequency of normal probability distribution as the best fit. A review of the results showed that in almost 60% of observations, the best-fitted distribution to the block running times is the normal distribution for all blocks. The tests conducted on other blocks where normal distribution did not result in better distribution still showed that a normal distribution can also be accepted as having very good fitness in these same blocks. Accordingly, the normal distribution is selected as the distribution of the block running times in this study.

Table 2.

4.3.2. Distribution of Dwell Times

The same type of statistical analysis has been completed of dwell time at stations. A train's dwelling time at stations is usually respected according to the regulated schedule, but when delays occur, operators try to reduce the total delay by minimizing the dwelling time of passengers in the stations. Dwell time at the station is calculated by subtracting the train's "arrival time to the station" from "the departure time from the same station." The dwell time is generally observed according to the timetable but when there are delays in train movement, it is attempting to decrease the total delay by minimizing stop times in stations. The actual stop time in station equals the sum of scheduled stop time and random part related to delay. Thus, the stop time can be calculated using the departure and arrival times. The data analysis shows that the difference between real stop time in the station and its scheduled time in Tehran – Mashhad route, changes from -2 to 5 minutes approximately. The theoretical probability function of this difference is determined. According to the obtained result (Table 3), Erlang distribution is chosen as the best distribution describing the data.

Table 3.

In order to obtain the probability distribution of the dwell times, the differences in actual dwelling time at stations is computed compared to the scheduled time for the Tehran–Mashhad corridor. The probability function of this difference has been determined using the Arena input analyzer toolbox and Erlang distribution, which were selected as the best tools for describing the distribution of these data. Fig. 8 shows the frequency of delays for both routes. The coefficients of the Erlang distribution function, however, are different for various stations. According to the route-cause analysis, the dwell time deviation is affected by driver faults. In the case of deviation from the initial plan, the central control commands to compensate for the occurred delays in disturbances.

Fig. 8.

Distribution Summary		Data Summary	
Distribution:	= Erlang	Number of Data Points	= 4809
Expression:	= -5.5 + ERLA(0.8567)	Sample Mean	= 0.492
Square Error:	= 0.161	Sample Std Dev	= 2.51

4.3.3. Failure modeling on the block sections

Simulation models are capable of modeling disturbances of running times in the schedules. The data required to calculate the probability of failures is prepared according to the historical database. When a train fails at a station, it causes a primary delay. Fig. 9 illustrates the frequency of train failures on the blocks of the Tehran–Mashhad route. As can be seen, these events occur heterogeneously along the route. The probabilities of failure in a block section for fast non-electric trains, other non-electric trains, and electric trains are calculated as 0.35%, 0.6%, and 0.15%, respectively. Likewise, the average failure durations are 21, 27 and 15 minutes, respectively.

Fig. 9.

4.3.4. Failure modeling on the stations

The probability of random failures at the stations has been calculated for two train categories through examining the existing data of the Tehran–Mashhad route, it is observed that the failure probability of the non-electric high-speed train is 0.15%, while for other trains, the amount is 0.4%. Furthermore, for the electric trains, the probability of a failure at a particular station is observed by 0.09%. Various tests on the available data show that trains' dwell times in such cases follow the Weibull distribution. Fig. 10 shows a diagram of processed mentioned data.

Fig. 10.

Distribution Summary		**Kolmogorov-Smirnov Test**	
Distribution:	= Weibull	Test Statistic	= 0.19
Expression:	= 25 + WEIB(25.6,0.526)	Corresponding p-value	> 0.1
Square Error:	= 0.034497		

In order to determine the failure events in stations, the probability of occurrence of these events is calculated for different classes of trains (Table 4). The outcomes of the test experiments on the real data demonstrate that the failure at station conforms to the Weibull probability distribution.

Table 4.

4.4. Reliability assessment

Assuming that the movement of each train from the origin is based on the given schedule, the reliability of a train movement can be obtained through comparison of the train arrival delay with allowable delay. However, the train arrival or departure time is supposed to be a constant, but in practice, trains are affected by failure and disruptions. These disruptions generate delays in trains schedule and also affect the timetable of the other trains. In this paper, the train reliability criterion is calculated using Equation (2). It calculates the percentage of trains arrived at destination within the allowable delay range:

$$r = 1 - \frac{\sum_{i=1}^{m} \gamma_i N_{Af(i)}^{i} + \sum_{j=m}^{n} \gamma_j \widehat{N}_{Af(j)}^{j}}{n} \qquad i \in I, \qquad j \in J \tag{2}$$

In the above equation, index i represents the departing train and index j represents the arriving trains which is a member of index set of J and n represents the number of trains. The number of inbound and outbound trains are m and $n-m$, respectively. The importance weight of train i is denoted by γ_i. Let $f(i)$ and $f(j)$ denote the destinations of the departing train i $(i \in I)$ and arriving train j $(j \in J)$, respectively. Furthermore, $n_{Af(i)}^{i}$ and $\hat{n}_{Af(j)}^{j}$ show the maximum allowable delay of trains i and j, arriving at their destinations. For each train, the allowable delay of arrival is decided by the rail operator. The variables $N_{Af(i)}^{i}$ and $\widehat{N}_{Af(j)}^{j}$ are defined as follows:

$$N_{Af(i)}^{i} = \begin{cases} 1 & if\ forward\ train\ i\ has\ a\ delay\ smaller\ than\ n_{Af(i)}^{i}\ in\ destination\ f(i) \\ 0 & otherwise \end{cases}$$

$$\widehat{N}_{Af(j)}^{j} = \begin{cases} 1 & if\ return\ train\ j\ has\ a\ delay\ smaller\ than\ \hat{n}_{Af(j)}^{j}\ in\ destination\ f(j) \\ 0 & otherwise \end{cases}$$

The reliability index in k^{th} replication is denoted by r_k. The reliability (R) is calculated after system simulation for a number of replications (n) and the expected value can be calculated through Equation (3). It measures the reliability of the train timetable, based on probabilistic information of train's delay.

$$R = \frac{\sum_{k=1}^{n} r_k}{n} \tag{3}$$

5. Case study

The Islamic Republic of Iran Railways (RAI) is the national state-owned railway system of Iran. Some 33 million tons of goods and 29 million passengers are transported annually by the rail transportation network, accounting for 11% of the whole transportations in Iran. In this study, Tehran–Mashhad route is selected as a case study (Fig. **11**). The Tehran–Mashhad route is the country’s most important rail corridor for passenger trains and consists of 49 stations. Although both passenger and cargo trains are operating on this route, passenger trains share is more than 85% and annually around 20 million passengers are traveling along this route.

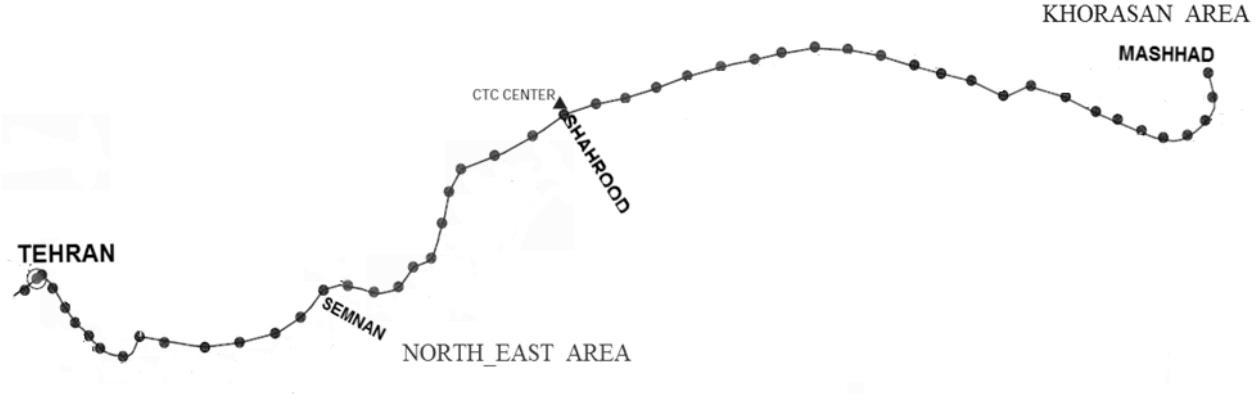

Fig. 11.

5.1. Input data

The simulation model developed has several data inputs, is given as follows: infrastructure, train operation, timetable and simulation conditions. Their details are stated below.

Infrastructure data: Data related to railway infrastructure includes the scheme of a railway route, the distance between the stations, the location of the crossing loops, the number of tracks, the type of the block segments, and failure probability of the track segments. Basing on the infrastructure data, the simulation model is developed that allows full train movement simulation along the route. The infrastructure data of Tehran-Mashhad corridor is summarized in Table 5.

Operational data: The input data for our train operation model contains the train route (origin and destination), train priorities, delay penalty for delay of each train, stochastic running times on block sections as well as dwell time at stations.

Timetable data: The departure time of the trains from their origins, and the planned arrival times at each station are the data associated with train timetables.

Simulation conditions data: In order to simulate the trajectory of the train along the railway network, some parameters must be decided to get valid results. The simulation parameters include the observation period, the number of replications, and the desirable accuracy of the simulation outputs (95%).

5.2. Data Processing

This section provides input data modeling using records of train data. The historical data of train movements include the real circulation time in blocks and the whole of the route, the real time of stops in stations, the reason of stops, reason, and frequency of failures that this data exist in the control center of the Railroad Company. Trains schedule data includes departure time, scheduled block time, scheduled dwell time, as well as the praying services. This study considers trains as service recipient and every station and block as the server.

In order to compare electric and non-electric systems, both cases should be modeled in the same system. According to the existing situation and the available data of the non-electric Tehran-Mashhad route, we need to derive the required operational parameters of the electrified rail system. It is required to derive probability distribution functions of running time at block sections, dwell time at stations and failures in blocks and stations. It should be noted that the comparative analysis of the electrified and non-electrified cases must be performed under similar operating conditions. Thus, extracted parameters of electrified train (Tabriz – Jolfa route) have been adopted for the simulation model of Tehran – Mashhad route. The extracted parameters are the random operational data of Tabriz-Jolfa route in electric mode. These parameters include random failures in the block segments and rail stations, dwell time at stations, and running times of trains on block sections. The best-fitted distribution of the above-mentioned parameters is determined through the least squares error method. This tool calculates probability distribution parameters and the statistic of Chi-square and Kolmogorov- Smirnov (KS) tests. In order to find an appropriate statistical distribution for random variables, data of different real block times of all the trains on the route were gathered for three months. The results of fitting of running time distribution for the Tehran–Mashhad corridor are presented in the last column of Table 5. The outcomes show that in almost 60% of all cases, the normal distribution is the best-fitted distribution for running times.

After accepting normal distribution as the appropriate travel time distribution for blocks, the next problem would be estimating the parameters of this distribution (mean and standard deviation) for different blocks. Obviously, various factors influenced the mean value and standard deviation of travel times in blocks. In this study, different factors such as maximum slope, summation of curve degrees in the block and others were considered; then, using linear regression is used to calculate the actual average travel time of electric and non-electric trains in each block, following simple equations, were fitted and suggested:

$$\text{Average Travel Time}_{\text{Electric Trains}} = \underset{(t=0.434)}{0.614} + \underset{(t=16.046)}{0.904} \times (\mathit{Scheduled\,Travel\,Time}) \qquad R^2=0.97 \tag{4}$$

$$\text{Average Travel Time}_{\text{non-Electric Trains}} = \underset{(t=1.027)}{1.996} + \underset{(t=7.129)}{0.929} \times (\mathit{Scheduled\,Travel\,Time}) \qquad R^2=0.836 \tag{5}$$

In these equations mean value of actual travel time is assumed to be a linear function of scheduled travel time. Scheduled travel time is the time calculated by the railway administration office for each block. Considering results obtained from several studies and experiments to estimate the standard deviation of travel time in blocks, it is not possible to suggest an acceptable equation for travel time standard deviation of blocks in terms of different parameters. The approach to estimating the standard deviation of travel times of blocks is to assume this amount to be random and estimate a suitable distribution function to represent that. Therefore, a method for estimating a suitable distribution function for the standard deviation of travel times of blocks was developed. Experiments revealed that the normal distribution with a mean value of 1.93 and standard deviation of 0.7 for electric trains and an average mean value of 2.39 and standard deviation of 0.79 for non-electrical trains is a suitable distribution for these parameters. If this calculation is accepted, the method to estimate standard deviation for each block in the simulation model will produce normal random variables with mentioned characteristics and apply that in every simulation model repetition.

Table 5.

6. Result and discussion

In this section, we outline the experimental results obtained by running our simulation model through several test cases. Four various tests with random parameters are used to determine the trains movement reliability (Table 6). These tests were analyzed in two cases regarding a number of tracks. The first case refers to the situation when the segments of the Tehran – Mashhad route are partially single and double-tracked (past situation). There were only 21 double-track blocks in the whole network and the rest are single-track. The second case refers to the layout that the whole of the route is double-tracked. In this case, the number of stops for crossing and overtaking decrease significantly. This separation is made in order to compare the difference between partially single and double-tracked case and a complete double-track situation. Regarding the type of traction, test experiments are divided into electrified and non-electrified. In the case of non-electrified, Tehran – Mashhad data were used. For electrified, the processed data of Tabriz – Jolfa electrified route has been implemented in Tehran – Mashhad route. As shown in Table 6, Tehran – Mashhad blocks in the first and second tests were combined and in the third and fourth tests, the whole route has been changed to a double-track route. On the other hand, the first and third tests were done for the non-electrified system and the second and forth for the electrified system. In all test experiments, the failure in blocks and stations are considered.

Table 6.

6.1. Verification

The simulation model is executed for n=100 replications. Table 7 provides the values of reliability per given amount of delay for electric and non-electric systems. As shown in Fig. 12, the advantage of the double-track case over the single and double-track case is significant. For example, for an allowable delay of 56 minutes, the reliability of Test 3 is almost 200% better than the Test 1. This means that doubling can greatly improve the reliability of train movements. As can be seen, for allowable delay of 56 minutes, the electrification of the railway has resulted in 14% improvement in reliability. One of the important applications of reliability is calculating the penalties paid by railway companies for delays more than allowable delay to passengers. According to the Iranian railway company, if the actual delay is beyond the allowed delay, then the whole ticket fee must be returned to the passengers. For the case when the allowable delay is 56 minutes, the rail company does not have to pay the penalties to a passenger with the probabilities of 25.1%, 39.3%, 74.9%, and 90.0% in Test 1, Test 2, Test 3, and Test 4, respectively (. 12). Currently, the Tehran-Mashhad route is a complete double-track line and operates non-electric trains (as described in Test 3). The travel time is about 12 hours. In this case, the railway company has determined the allowed delay as 90 minutes. Consequently, it can be determined that the railway company must pay back to the passengers with the probability of 4%.

Table 7.

Fig. 12.

6.2. Statistical analysis of service reliability

Because of the stochastic nature of the simulation models, one single outcome is not representative. Therefore, a number of observations are required in order to obtain reliable results with a desirable level of accuracy. The reliability of the result is represented by confidence interval that indicates the probability (usually 95%) that the output variable is within the range specified. For every performance measure (PFM), an observation w_i is collected after each observation period i. Each statistic is estimated based on the raw data $w_1, w_2, \ldots, w_n$, where n is the number of replications [12]. The lower bound and upper bound of the confidence interval (CI) are obtained from the equation (6). The values $t_{n-1,1-\frac{1}{2}\alpha}$ and $\mu_{1-\frac{1}{2}\alpha}$, are obtained from a table of t-values, where $\alpha = 1 - Reliability$.

$$\mathrm{CI} = \begin{cases} \bar{w} \pm t_{n-1,1-\frac{1}{2}\alpha} \cdot \frac{s}{\sqrt{n}} & n \leq 30 \\ \bar{w} \pm \mu_{1-\frac{1}{2}\alpha} \cdot \frac{s}{\sqrt{n}} & n > 30 \end{cases} \tag{6}$$

To show further analysis of the reliability, the results of statistical analysis of test experiments are provided in Table 8. As can be seen, the result includes the average and standard deviation of the reliability and the 95% confidence interval. The outcomes indicate a significant difference between the average reliability of the test cases.

Table 8.

6.3. Train delay cascading effect along the railway line

This section provides the interdependency analysis of train delays caused by cascade effect within the rail system. We investigate the relations of delays along the rail line by Chi-square independence test and Pearson product-moment correlation test. The correlation coefficients are then used to describe relations between delay events along the route.

6.3.1. Independence test

Independence test measures whether paired observations on two variables are independent of each other. In our implementation, Chi-square independent test is used to testify if there is any significant relation between the train delay at one middle station and delays at the subsequent stations. The null hypothesis is that the manifestation of these results is statistically independent. Each observation is assigned to one element of a two-dimensional array according to the values of the two outcomes. If there are r rows and c columns on the table, the “theoretical frequency” for an element can be expressed formulaically as:

$$E_{ij} = \frac{row\ total\ \times\ column\ total}{sample\ size} = \frac{\sum_{n_c=1}^{c} O_{i,n_c} * \sum_{n_r=1}^{r} O_{r,n_r}}{N} \tag{7}$$

In other words, the expected count for each element is calculated by multiplying the marginal row and column totals for that element and divide by the total sample size (N). The chi - square test is continued by comparing each element's observed count to its corresponding expected count. This Chi-square test statistic is then computed as follows:

$$\chi^2 = \sum\nolimits_{1=1}^{r} \sum\nolimits_{J=1}^{c} \frac{(O_{ij} - E_{ij})^2}{E_{ij}} \tag{8}$$

The decision is made by comparing the value of the test statistic to a critical value. The critical value for the Chi-square test is χ^2_α with degree of freedom= $(r-1)*(c-1)$. According to the statistical analysis, the obtained P-value indicates that all independent coefficients are about 0.0159 which is much less than the significance level (0.05). Thus, we conclude that there is a strong relationship between train delays at the individual station and delays at the following stations.

6.3.2. Correlation test

Pearson product-moment correlation test is performed to determine if there is a correlation between delays at the individual station and the delays at the following stations. For doing this, we calculate the correlation coefficient (r). This coefficient is defined as the covariance of the two variables separated from the product of their standard deviations. The correlation coefficients are less than or equal to 1. The range obtained for the correlation coefficient specifies the type of the relation which is expressed as:

$$\text{correlation coefficient } = \begin{cases} r < 0.2 & \text{linear relation is extremely weak} \\ 0.2 \le r < 0.4 & \text{linear relation is weak} \\ 0.4 \le r < 0.6 & \text{linear relation is moderate} \\ 0.6 \le r < 0.8 & \text{linear relation is strong} \\ r > 0.8 & \text{linear relation is extremely strong} \end{cases} \tag{9}$$

Accordingly, correlations equal to 1 or −1. In order to better analyze the cascading effects, we conduct our examination on the main stations on the route. Correlation coefficients of the train delay at different stations are obtained in

Table **9**. It can be observed from this table that the correlation coefficients are greater than 0.8 which means there is an extremely strong linear correlation between delays at an individual station and delays at the following stations. The correlation between delays between the major stations is plotted in Fig. 13. As can be seen, the cascading effect of the delay is diminished gradually at the end of the route. We can also find that the correlation is stronger when the arrival/departure delays are closer especially on the same station. The results show that the correlation coefficient is larger for the stations that are close to each other. Garmsar, Semnan, and Shahrood are the main stations along the route. Especially, Shahrood station is a traffic control center and it manages the traffic flow in several neighboring station controls. The train delays at Garmsar, Semnan stations are gradual with the highest correlation (over 0.75 to 0.80). After Semnan station (the main station on the route) the delay correlation is greatly reduced. The results show that the main station on the route (Semnan station) as well as the traffic control centers, has been able to properly manage the train delays.

Table 9.

Fig. 13.

6.4. Capacity Consumption analysis Using UIC406 Method

A simple, useful and yet fast method to appraise the capacity consumption of rail routes is proposed in the UIC406 method [37]. The method of the UIC406 booklet is applicable for both single track and double-track blocks. This method is based on railway route and timetable. According to this method, the railway will be broken into smaller segments such as blocks based on data of train movement graph; then train movement graph will be compressed and capacity of every small segment will be calculated; finally route's capacity consumption will be calculated. The capacity consumption of planned timetables can be exhibited virtually by approximation of stairway of impasse times as much as possible; however, this is done irrespective to buffer times and without altering trains' order and is called compression method. In compression method, below actions are performed to analyze a planned timetable:

1. Identification of buffer times in the traffic graph;
2. Finding the critical buffer chain, for example, a route in the graph which has the least total of buffer times; and
3. Calculation of route occupancy in every time window of the critical segments.

In the UIC406 method, the capacity consumption is calculated using total infrastructure occupancy times, buffer times and supplementary times according to equations (10) and (11):

$$k = A + B + C + D \tag{10}$$

$$K = \frac{k}{U} \times 100 \tag{11}$$

where k is the total consumption time (min), A denotes the infrastructure occupancy (min), B represents the buffer time (min), C indicates the supplement for single-track lines (min), D stands for supplements for maintenance (min), K is the capacity consumption rate (%) and U represents the chosen time window (min). Capacity consumption of a route varies according to the reference time that can be a day, a week or a season. If the route is closed during some hours due to maintenance operations, the maintenance time would be subtracted from 1440 minutes. In order to assess the capacity of a route, an analysis shall be carried out for every single block along the route. The highest capacity consumption value on any section of the route shall determine the capacity consumption of the route. Capacity and bottlenecks for a route are assessed according to the UIC406 booklet recommendations which are shown in Table 10. This table demonstrates the critical capacity consumption rates based on crossing traffic type, which can be dedicated suburban passenger traffic, dedicated high-speed lines and passenger-freight mixed-traffic lines and the time window that can be peak hour or daily period.

Table 10.

As an example, the maximum acceptable capacity consumption rate in a daily time window for mixed-traffic lines is equal to 60%. With the aim of maintaining the quality of service, railway's capacity consumption shall not exceed the corresponding values in Table 10. This means that the average buffer time between two trains should not be less than the average time headway of the line. However it is still possible to impose greater capacity consumption rates to single track routes with long distances among their stations, and also to double track routes with small differences between train speeds [38]. In case that the capacity consumption of a route or a block is equal to or greater than the presented values of Table 10, the route or block would be recognized as a bottleneck and a mechanism to increase its capacity should be thought.

6.4.1. Occupancy Rate analysis using UIC406

The capacity of a route can be expressed in the form of a delay chart. This chart shows the average delays of every train as a function of a number of trains (in the unit of time). Delay time is one of the main operation quality measurements. Using a delay chart, it is possible to suggest a proposed range for the route's capacity. By simulations of numerous European railways, it is perceived that the minimum relative sensitivity of delays is obtainable from a traffic flow in the range of 50 to 60 percent of route's physical capacity [38]. In Fig. 14, the chart of average travel times versus a number of trains is exhibited in order to demonstrate an analytical tool for evaluation of route's physical capacity. Train movement simulation is repeated 10 times for the summer period. It can be observed from the figure that travel times of trains increase as a number of trains rises. The main cause of this increment in trains' travel times is due to the growth of meet/pass times caused by the raised number of trains. The least number of trains that leads to sharper grow of trains' travel time afterward is about 90 trains in this case.

Fig. 14.

In order to investigate the relationship between routes' occupancy rate and the delays, various conditions were examined. Tehran-Mashhad railway route was analyzed using simulation outcomes and based on UIC406 method. A number of trains were also examined, starting from 26 trains per day by steps of 4 trains until reaching to 114 trains per day. Trains' dwelling times (average value of every train on every trip), scheduled dwelling times (average value of every train on every trip) and total stopping times caused by meet/pass and accidental happenings (average value of every train in every trip) were calculated separately for inbound and outbound trip directions. In Table 11, the capacity consumptions are calculated for all blocks of the route. In accordance with the proposed methodology, railway route is broken into blocks and capacity of every block is calculated day by day. Whole route's capacity consumption is equal to that of the block with the highest capacity consumption and mentioned block would be considered as the critical block. In every examination, capacity consumption is also calculated for each of inbound and outbound trips. In this regard, train movement graphs are compressed and on this basis occupancy rate of blocks are calculated. Therefore, capacity consumption in every scenario is equal to the value in the last row of Table 11. For instance, in the case of dispatching of 60 trains per day, the occupancy rate of blocks is equal to 53.7% in inbound and 58.9% in outbound directions, respectively.

Table 11.

In Fig. 15 and Fig. 16, the occupancy rate variation trends in the route are illustrated respectively for inbound and outbound directions. Relationship between total delays and route's occupancy rate is illustrated in Fig. 17. Occupancy rate in inbound direction increases from 23.3 to 89.9% and in reverse direction rises from 25.5% to 98.1%. By enlarging the number of trains, capacity consumption percentage grows. Based on the results obtained from calculations and proposed recommendations for capacity consumption in Table 11, the double track route of Tehran-Mashhad in the scenarios with 68 to 100 operating trains has critical blocks (colored cells in Table 11). These critical blocks are the bottlenecks of this route because their capacity consumption is more than 60%. Therefore, dispatching more than 60 trains in this route would lead to a reduction of its performance and operational desirability.

Fig. 15.

Fig. 16.

Fig. 17.

7. Conclusion

Reliability is one of the most important measures of performance in railway systems. The previous studies were limited to operational stability of rail transportation systems and there is a lack of research on the effect of the electrification and infrastructure development on the reliability of the rail system. The present research is conducted to find the extent of factors that affect the reliability of train services. Therefore, the effects of the doubling and electrification on reliability were studied. A simulation system is implemented to assess the reliability of the train's movements. The developed simulation model considers the detailed train operation and random disturbances. The simulation model uses the historical data of train movements such as probability distribution of the running time in block sections, dwelling at the station and infrastructure failures.

In this paper, the reliability of the train service is calculated as the percentage of the number of trains arrived at destination in the allowable delay range. Four various tests with random parameters were used to determine the trains movement reliability. In order to compare electrified and non-electrified cases, they have to be compared with similar conditions. For this purpose, we used train movement parameters of Tehran-Mashhad and Tabriz-Jolfa railways for non-electric and electric trains, respectively. The operational characteristics of the existing electrified route (Tabriz–Jolfa) have been implemented on the Tehran–Mashhad route. These tests were analyzed and the results showed that doubling and electrification greatly improve the reliability. According to the experimental results of the present research, double-track route causes the elimination of crossing delay and on the other hand electrification reduce the probability of infrastructure failure and causes fewer failures compared with the non-electrified case. The result justifies that the effect of doubling and electrification on the reliability of train services is significant. Furthermore, the relationship between occupancy rate of the railways and delays of trains was studied using UIC406 method. To model train movements, the technique of simulation in stochastic mode was implemented. In the simulation model, the details of train movements were applied on railways in a stochastic manner. To investigate the relationship between occupancy rate and delays of trains, different conditions were evaluated for the Tehran-Mashhad route. According to the calculations, delays increased severely by dispatching more than 90 trains in the route. The main cause of this increment in average travel times was due to the rise in the meet/pass times caused by dispatching excess number of trains in the route. Moreover, delays reached to nearly 2 hours at 80% of route's occupancy. Occupancy rate in direction increased from 23.3 to 89.9 percent and in reverse direction rose from 25.5 to 98.1 percent. In this regard, the proposed model is succeeded to provide the ability of choosing the desired operational condition considering a suitable delay time and performance cost. Therefore, the proposed model can be considered as a suitable tool to analyze and evaluate the performance of Iranian railways.

As accounted for the future research, many of the modeling characteristics can be adapted to situations that are more realistic. One important extension of the current study is to consider the network case. In addition, it is worth mentioning that the simulation model can be extended to analysis other performance measures such as punctuality and robustness. Apart from the above-mentioned research directions, the authors aim to find the causes e.g. different distance between adjacent stations or different train specifications, which lead to the different pattern for delay correlation along the route. This valuable information can be used to assess the reliability of the service or identifying the possible action to control the cascading effects of the delays along the route.

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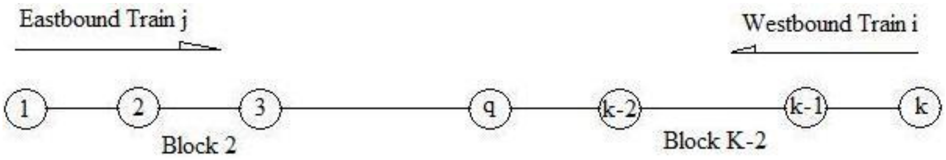


Fig. 1. The network infrastructure under investigation

Table 1. The input data of the simulation model

Category Information	**Details**
1-geometry of axis rail	Including geographical location, slope, arches, bridges, tunnels, train speed of axes complications
2-geometry of stations.	Including geographical location, the slope of the station, and the elevation above sea level.
3. The non-geometric properties of blocks	The number of lines per block, maximum speed train passing through the block, wind speed, time blocking blocks, blocks maintenance time
4- The non-geometric characteristics of stations	Including the order of the stations, the number of stations and platforms including acceptance and deployment and supply lines, maximum speed train passing through the station, chapel, underpass, the dispatch system, the symptoms lines, type and number of needles, intersection, open or closed stations
5. The technical information and specifications of locomotives	Including train power, speed, weight of Locomotives, maximum braking force, the number of axes, burst speed, sticking coefficient, length, engine power for different gears, fuel consumption for different ribs, introduced Davis relationship or other relationship resistance, resistance relationship for speed higher than a specified limit
6. Technical Information of wagons	Including name, weight, length, effective area, the number of axes, the relationship Davis (user selectable), the type of brake
7. Technical Information of trains	Train numbers, maximum train speed, the number of instruments constituting each train transporter (It should be noted characteristics such as weight or length according to the type of trains locomotives and wagons and their number is calculated by the application.), Diesel or electric, to move the train.

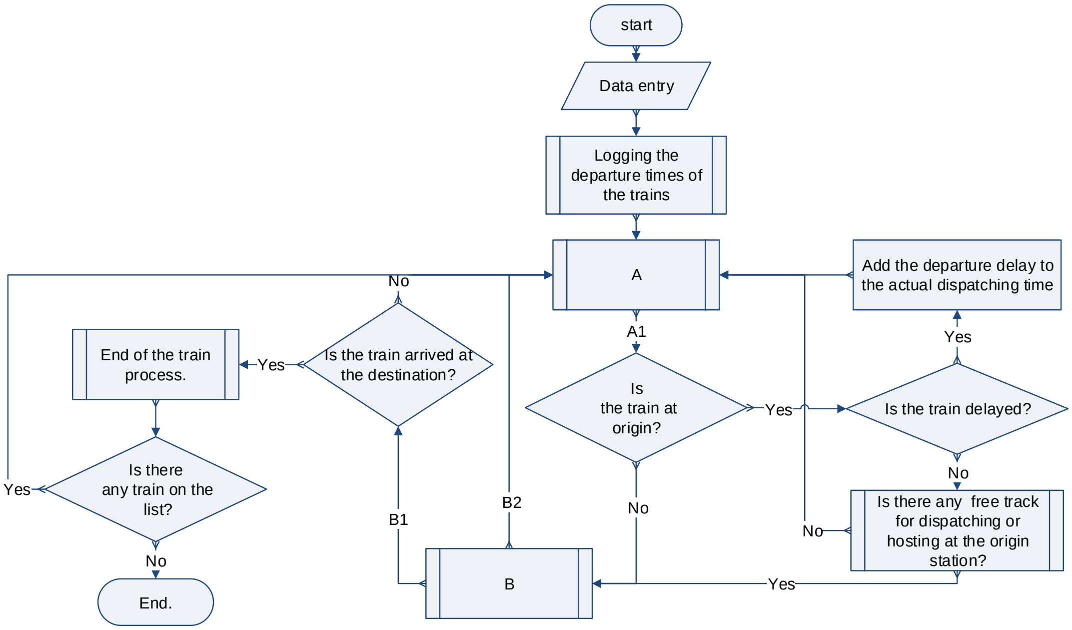


Fig. 2. Diagram of the train movement simulation

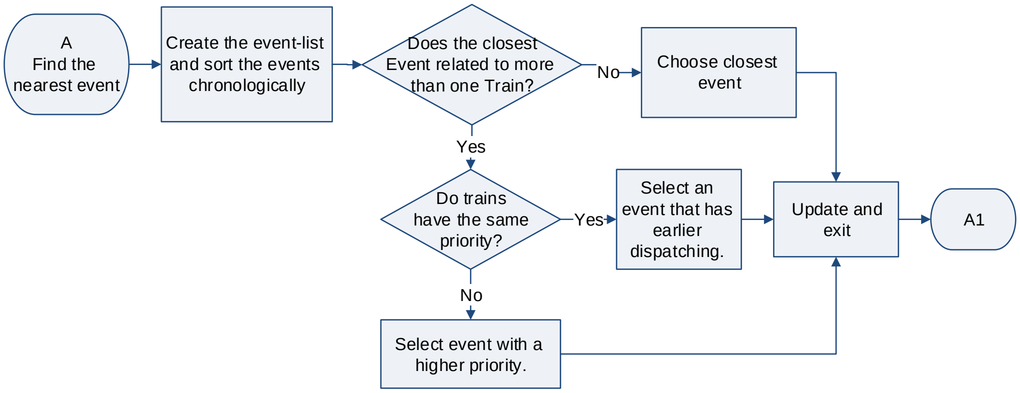


Fig. 3. Diagram of the train movement simulation (Part1: Selection of the next event, according to the event calendar)

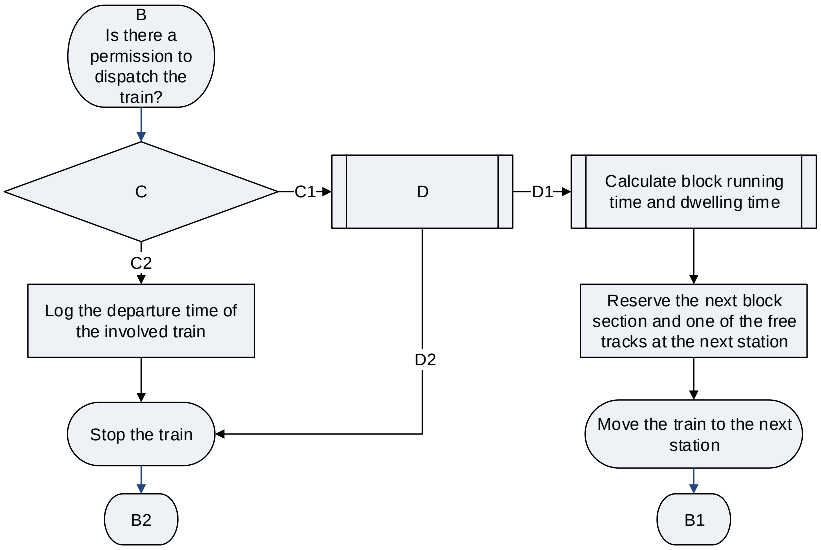


Fig. 4. Diagram of the train movement simulation (Part2: Train timetable calculations)

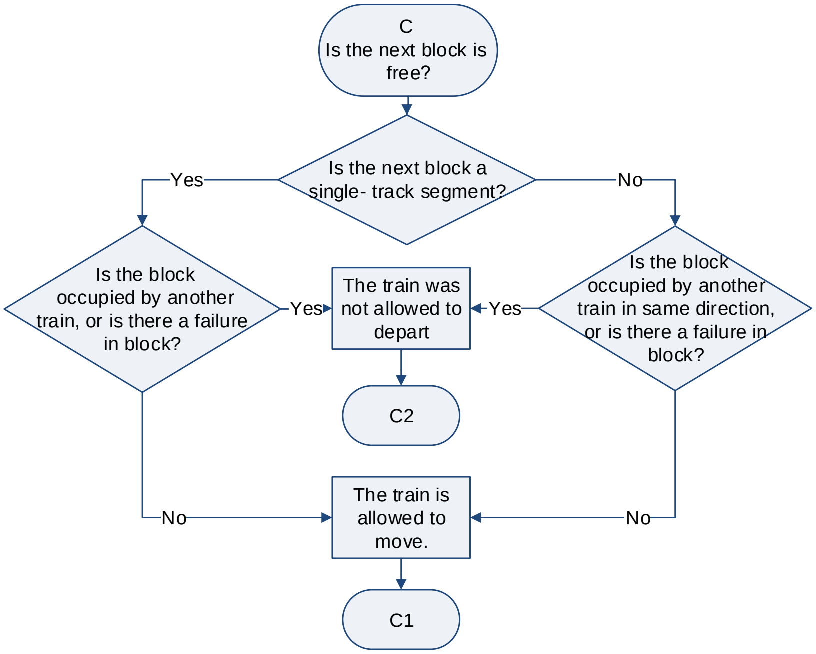


Fig. 5. Diagram of the train movement simulation (Part3: The train departure authorization)

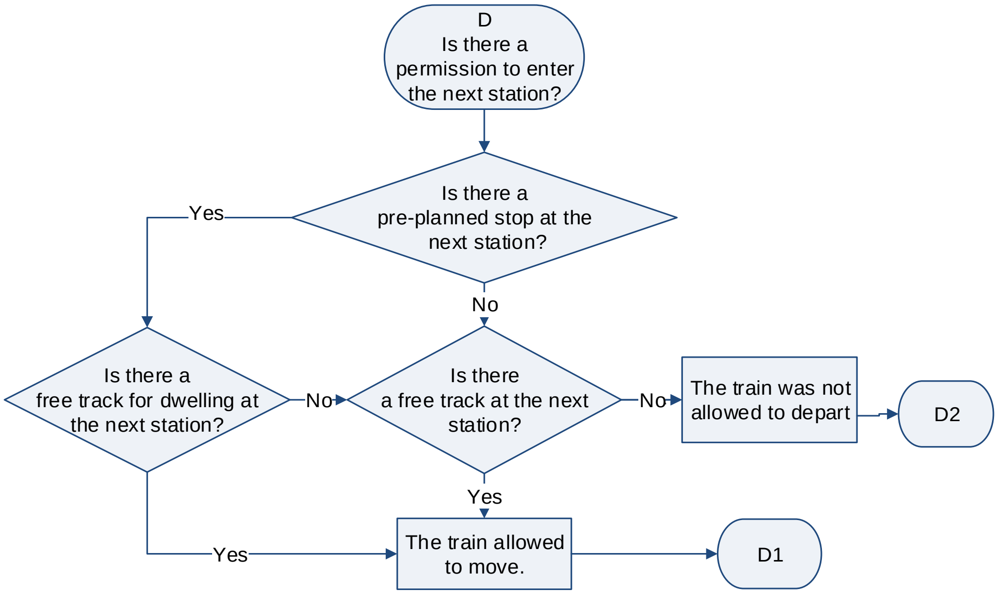


Fig. 6. Diagram of the train movement simulation (Part4: Train stop control)

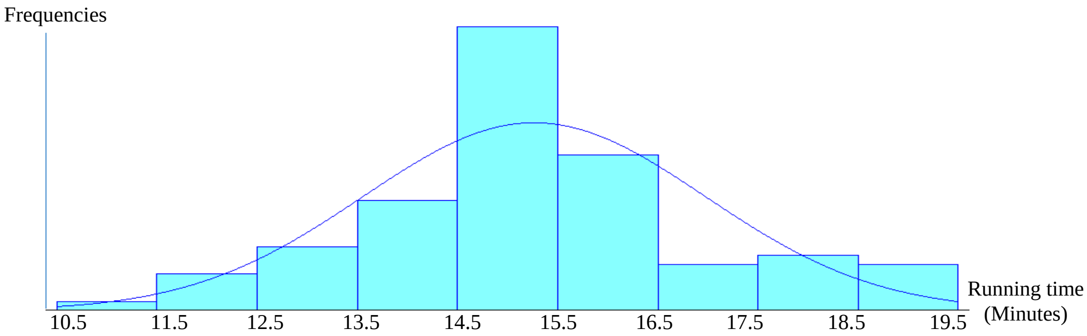


Fig. 7. An example of histogram of the running time

Table 2. The result of fitting for different block sections

Route	**Normal**	**Beta**	**Erlang**	**Weibull**	**Gamma**	**Triangular**	**Exponential**	**Total**
Inbound	28	5	5	3	3	1	3	49
Outbound	26	4	6	3	9	1	0	49

Table 3. The result of fitting for dwell time

Route	**Normal**	**Beta**	**Erlang**	**Weibull**	**Gamma**	**Triangular**	**Exponential**	**Total**
Inbound	4	2	32	5	3	1	3	50
Outbound	2	4	29	7	5	1	2	50

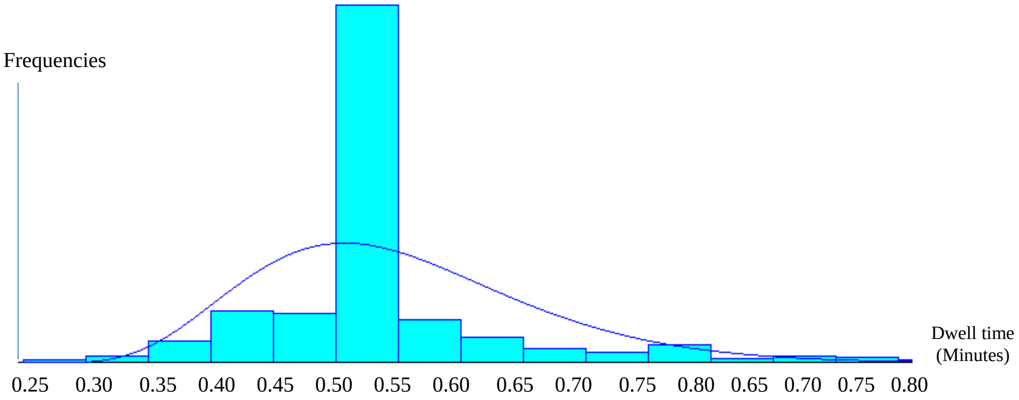
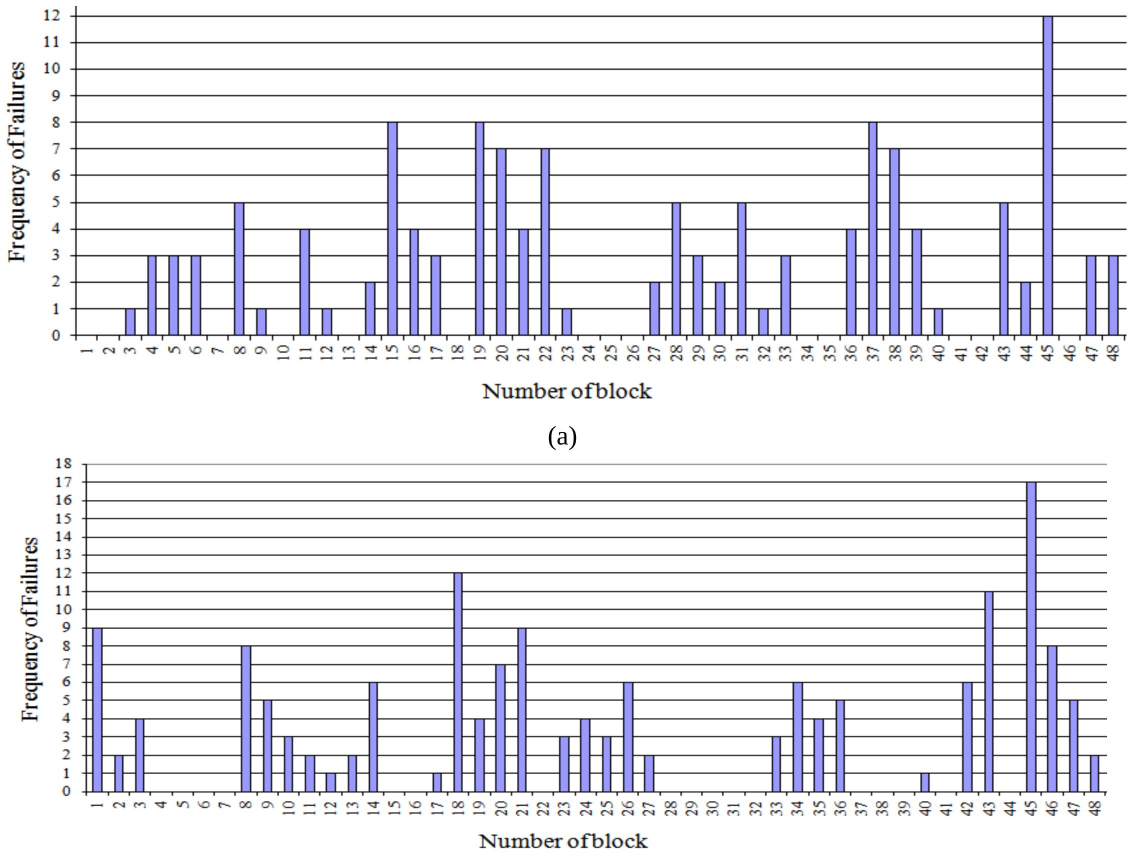


Fig. 8. An example of histogram of dwell time delays at station



(a)

(b)

Fig. 9. Diagram of failure occurrences in blocks: (a) inbound trains (b) outbound trains.

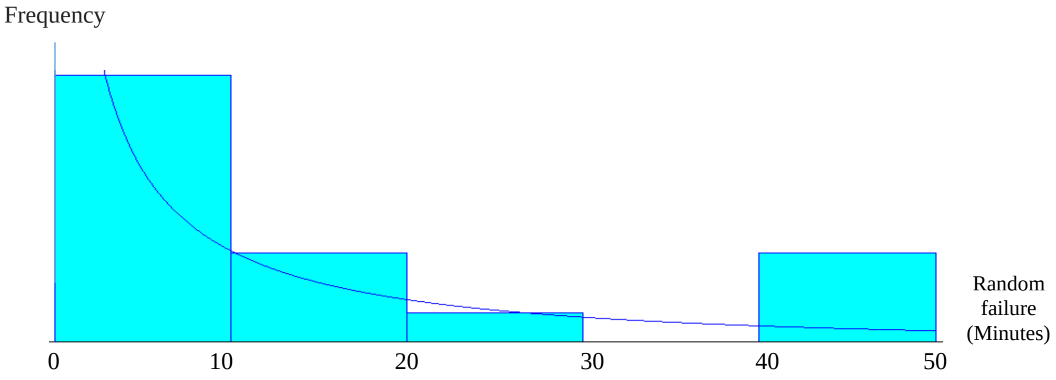


Fig. 10. Histogram of random failure times at the station (Tehran–Mashhad corridor)

Table 4. The results of failure modeling for different class of trains

Type of train	**Failure at block sections**		**Failure at stations**	
	The occurrence probability	**Average failure duration (minutes)**	**The occurrence probability**	**Probability distribution**
Non-electric high-speed train	0.35%	21	0.15%	Weibull
Other non-electric trains	0.6%	27	0.4%	Weibull
Electric train	0.15%	15	0.09%	Weibull

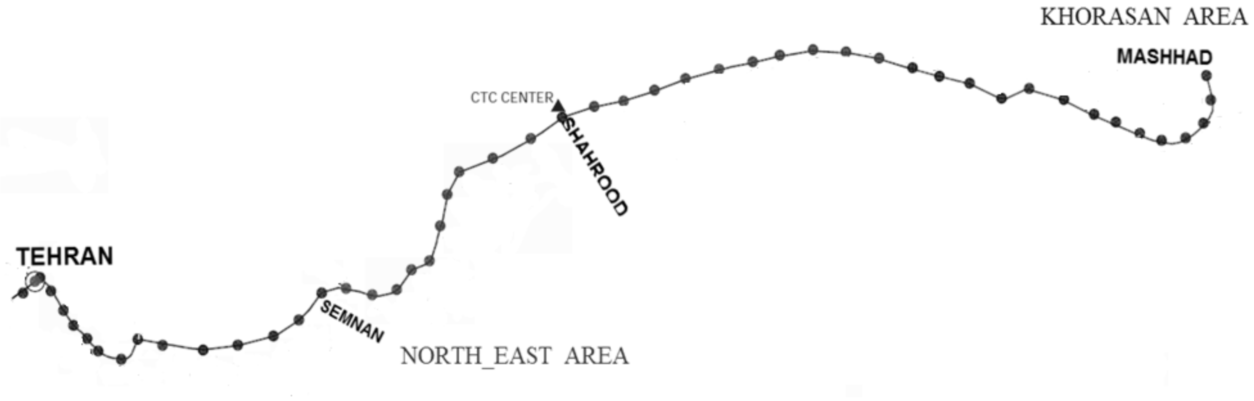


Fig. 11. Tehran-Mashhad double-track route

Table 5. The operational, infrastructure and running time distribution data of Tehran-Mashhad route

Block number	Block length (km)	Number of tracks	Planned running time (minutes)		Maximum block speed (km/hour)		Running time parameters		Best fitted running time distribution
			Inbound	Outbound	Inbound	Outbound	Average (minutes)	Standard (minutes)	
1	9.9	double	15	14	40	40	15.90	2.7	Normal
2	16.5	double	12	13	115	90	12.92	1.5	Normal
3	17.4	double	12	13	115	90	13.51	1.8	Beta
4	8.8	double	9	10	115	90	8.86	2	Normal
5	12	double	9	10	115	90	9.30	.9	Erlang
6	17	double	15	20	115	90	15.34	3.1	Normal
7	17	double	16	20	115	90	17.31	3.3	Normal
8	17	single	12	12	115	115	13.52	2	Gamma
9	21.9	single	12	12	115	115	13.58	2.1	Triangular
10	15.5	single	11	11	115	115	10.30	1.9	Normal
11	20.5	single	13	11	115	115	12.32	1.8	Weibull
12	21.2	single	12	12	115	115	14.97	2.3	Erlang
13	18	single	13	13	115	115	15.61	2.2	Normal
14	18.5	single	13	12	110	110	15.20	2	Exponential
15	16.3	single	14	12	90	90	15.64	1.8	Normal
16	15.5	single	15	12	70	70	14.18	2.1	Normal
17	15.1	single	15	13	70	70	16.78	2.2	Normal
18	14	single	12	15	70	70	14.44	2.5	Normal
19	12.8	single	12	13	70	70	12.17	2.8	Normal
20	13.5	single	10	14	70	70	11.16	2.4	Beta
21	15.9	double	10	10	115	115	10.95	2.1	Weibull
22	14.3	double	10	10	115	115	11.04	1.7	Normal
23	22.8	double	13	14	115	115	14.86	2.7	Normal
24	23.8	double	14	13	115	115	15.85	1.8	Erlang
25	18.9	double	15	13	115	115	17.09	2.6	Normal
26	20.6	double	13	13	115	115	13.37	2.5	Normal
27	20.3	double	12	12	115	115	13.03	1.7	Gamma
28	18.3	single	12	12	115	115	11.59	1.5	Normal
29	20.6	single	12	12	115	115	13.88	1.7	Normal
30	22.2	single	15	13	115	90	14.60	2.3	Beta
31	19.5	single	15	14	90	90	14.38	1.6	Erlang
32	22.2	single	18	18	80	80	18.99	3	Normal
33	20.2	single	15	15	90	90	17.37	2.6	Weibull
34	19.5	double	13	14	115	90	16.82	2.5	Normal
35	19.2	double	13	14	115	90	13.72	2.6	Exponential

Block number	Block length (km)	Number of tracks	Planned running time (minutes)		Maximum block speed (km/hour)		Running time parameters		Best fitted running time distribution
			Inbound	Outbound	Inbound	Outbound	Average (minutes)	Standard (minutes)	
36	23.3	double	15	17	115	90	15.86	3.9	Normal
37	20.5	double	13	15	115	90	12.30	2.4	Erlang
38	20.4	double	13	15	115	90	16.09	2	Normal
39	22.6	double	15	18	115	90	16.79	1.9	Normal
40	23.6	single	19	19	80	80	18.75	1.6	Gamma
41	23.6	single	19	19	80	80	18.41	1.8	Exponential
42	22.1	single	19	19	80	80	18.79	3.4	Normal
43	22.2	single	19	19	80	80	20.14	2.7	Normal
44	23.2	single	19	19	80	80	18.59	1.9	Normal
45	17.4	single	15	16	80	80	17.54	2.1	Beta
46	18.6	single	16	17	80	80	18.24	3	Normal
47	18.8	single	16	19	80	80	19.33	3.8	Normal
48	18.5	double	14	19	115	80	13.76	2.1	Beta

Table 6. Characteristics of the test experiments

Infrastructure\system	Non-electrified	Electrified
Partially single and double-track	Test 1	Test 2
Complete double-track	Test 3	Test 4

Table 7. Different values of reliability for various test cases

Allowed delay (minutes)	Reliability			
	Partially single and double-track section		Complete double-track	
	Non-electrified	Electrified	Non-electrified	Electrified
	Test 1	Test 2	Test 3	Test 4
0	0.10%	0.06%	2.07%	1.33%
8	0.25%	0.35%	5.59%	7.12%
16	0.88%	1.56%	13.00%	17.38%
24	1.43%	3.88%	23.37%	28.29%
32	3.76%	7.69%	35.90%	43.38%
40	6.97%	15.27%	48.53%	61.33%
48	13.84%	25.45%	62.84%	78.11%
56	25.12%	39.33%	74.93%	89.66%
64	38.17%	52.40%	83.54%	94.65%
72	53.69%	68.25%	88.97%	97.34%
80	68.36%	82.01%	93.20%	99.11%
88	80.49%	90.34%	96.16%	99.88%
96	87.72%	94.80%	98.37%	100.00%
104	93.22%	97.51%	100.00%	100.00%
112	96.31%	98.90%	100.00%	100.00%
120	98.33%	99.60%	100.00%	100.00%
128	98.68%	99.83%	100.00%	100.00%
136	99.34%	99.88%	100.00%	100.00%

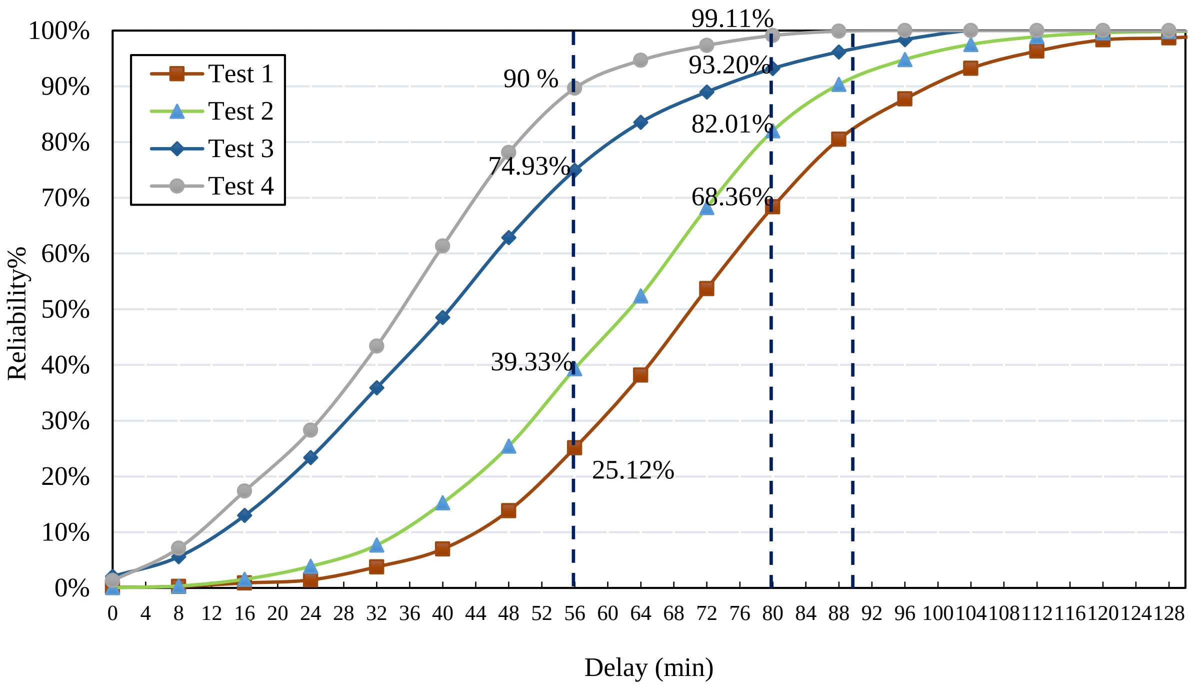


Fig. 12. Average reliability per given amount of delay

Table 8. The simulation result of the test experiments for a given delay threshold (64 minutes)

Test	Average reliability	Standard deviation	Lower bound (95%)	Upper bound (95%)	Minimum	Maximum
Test1	0.382	0.062	0.351	0.413	0.084	0.450
Test2	0.524	0.054	0.497	0.551	0.244	0.637
Test3	0.835	0.051	0.810	0.861	0.488	0.894
Test4	0.947	0.043	0.925	0.968	0.563	0.990

Table 9. Correlation coefficients of the train delay at different stations

Stations	Garmsar	Dehnamak	Lahore	Semnan	Abgharm	Larestan	Damghan	Shahrood	Bkran	Abrisham	Jajarm	Sankhast	Neghab
Garmsar	-	0.91	0.84	0.76	0.71	0.57	0.44	0.31	0.08	0.11	0.16	0.22	0.21
Dehnamak	-	-	0.86	0.8	0.73	0.57	0.44	0.32	0.1	0.15	0.19	0.24	0.23
Lahore	-	-	-	0.84	0.79	0.6	0.46	0.34	0.09	0.16	0.18	0.22	0.21
Semnan	-	-	-	-	0.75	0.65	0.5	0.39	0.12	0.18	0.23	0.23	0.26
Abgharm	-	-	-	-	-	0.65	0.51	0.38	0.09	0.18	0.19	0.2	0.22
Larestan	-	-	-	-	-	-	0.65	0.42	0.22	0.1	0.18	0.25	0.19
Damghan	-	-	-	-	-	-	-	0.48	0.37	0.13	0.21	0.31	0.23
Shahrood	-	-	-	-	-	-	-	-	0.35	0.31	0.36	0.29	0.38
Bkran	-	-	-	-	-	-	-	-	-	0.36	0.48	0.48	0.41
Abrisham	-	-	-	-	-	-	-	-	-	-	0.62	0.34	0.41
Jajarm	-	-	-	-	-	-	-	-	-	-	-	0.51	0.6
Sankhast	-	-	-	-	-	-	-	-	-	-	-	-	0.57
Neghab	-	-	-	-	-	-	-	-	-	-	-	-	-

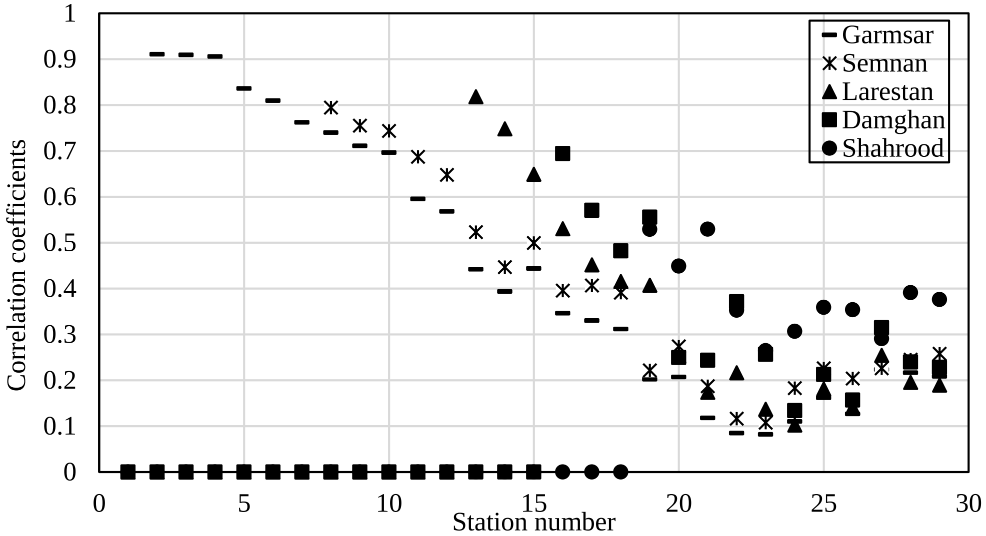


Fig. 13. The correlation between delays between the major stations

Table 10. Recommended Capacity Consumption Constraints (UIC Leaflet 406, 2004)

Type of line	Maximum Capacity Consumption Rate in	
	Peak hour	Daily period
Dedicated suburban passenger traffic	85%	70%
Dedicated high-speed line	75%	60%
Mixed-traffic lines	75%	60%

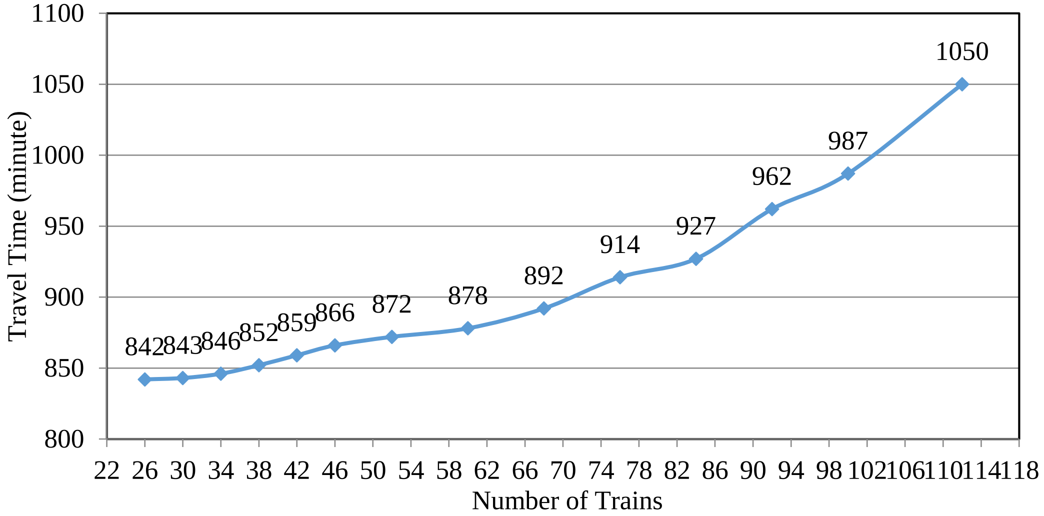


Fig. 14. Dispatching Number versus Travel Times

Table 11. Capacity consumption of Tehran-Mashhad route

Block	Number of dispatched trains in outbound direction										Number of dispatched trains in inbound direction									
	26	34	46	52	60	68	76	84	92	100	26	34	46	52	60	68	76	94	92	100
1	16.7	21.8	29.6	33.4	38.6	43.7	48.8	54.0	59.1	64.3	16.4	21.4	28.9	32.7	37.7	42.8	47.8	52.8	57.9	62.9
2	15.8	20.7	28.0	31.7	36.6	41.4	46.3	51.2	56.1	60.9	13.8	18.1	24.4	27.6	31.9	36.1	40.4	44.6	48.9	53.1
3	15.9	20.8	28.2	31.9	36.8	41.7	46.6	51.5	56.4	61.3	13.5	17.7	23.9	27.0	31.2	35.3	39.5	43.6	47.8	51.9
4	9.7	12.7	17.2	19.5	22.5	25.5	28.5	31.5	34.5	37.5	9.3	12.2	16.5	18.6	21.5	24.3	27.2	30.1	32.9	35.8
5	10.7	14.9	19.0	21.5	24.8	28.2	31.5	34.8	38.1	41.4	9.6	12.5	17.0	19.2	22.1	25.1	28.0	31.0	33.9	36.9
6	17.6	23.0	31.1	35.2	40.6	46.0	51.4	56.9	62.3	67.7	16.7	21.8	29.5	33.4	38.5	43.7	48.8	54.0	59.1	64.2
7	20.4	26.8	36.2	40.9	47.2	53.5	59.8	66.1	72.4	78.7	18.9	24.7	33.4	37.8	43.6	49.4	55.2	61	66.8	72.6
8	15.3	19.9	27.0	30.5	35.2	39.9	44.6	49.3	54.0	58.7	14.4	18.8	25.4	28.7	33.1	37.6	42.0	46.4	50.8	55.2
9	14.2	18.6	25.1	28.4	32.7	37.1	41.5	45.8	50.2	54.6	14.7	19.2	26.0	29.4	34.0	38.5	43.0	47.6	52.1	56.6
10	11.0	14.4	19.5	22.0	25.4	28.8	32.2	35.6	39.0	42.4	11.1	14.6	19.7	22.3	25.7	29.2	32.6	36.0	39.4	42.9
11	14.1	18.5	25.0	28.3	32.6	37.0	41.4	45.7	50.1	54.4	19.0	24.9	33.6	38.0	43.9	49.7	55.6	61.4	67.3	73.2
12	14.2	18.6	25.2	28.5	32.9	37.2	41.6	46.0	50.4	54.8	16.3	21.3	28.9	32.6	37.6	42.7	47.7	52.7	57.7	62.7
13	15.1	19.8	26.8	30.3	34.9	39.6	44.2	48.9	53.5	58.2	17.1	22.3	30.2	34.2	39.4	44.7	49.9	55.2	60.4	65.7
14	15.8	20.6	27.9	31.5	36.4	41.2	46.1	50.9	55.8	60.7	20.5	26.8	36.2	41.0	47.3	53.6	59.9	66.2	72.5	78.8
15	14.5	19.0	25.7	29.1	33.6	38.0	42.5	47.0	51.5	55.9	19.1	24.9	33.7	38.1	44.0	49.8	55.7	61.6	67.4	73.3
16	15.0	19.7	26.6	30.1	34.7	39.3	44.0	48.6	53.2	57.9	18.2	23.8	32.2	36.4	42.1	47.7	53.3	58.9	64.5	70.1
17	15.9	20.9	28.2	31.9	36.8	41.7	46.7	51.6	56.5	61.4	18.5	24.3	32.8	37.1	42.8	48.5	54.2	59.9	65.6	71.3
18	17.6	22.9	31.1	35.1	40.5	45.9	51.3	56.7	62.1	67.5	15.6	20.4	27.6	31.2	36.0	40.8	45.6	50.4	55.2	60.1
19	17.5	22.9	31.0	35.1	40.5	45.9	51.3	56.7	62.1	67.5	13.1	17.2	23.3	26.3	30.3	34.4	38.4	42.5	46.5	50.6
20	17.4	22.8	30.8	34.8	40.2	45.5	50.9	56.2	61.6	66.9	12.3	16.1	21.8	24.7	28.5	32.3	36.0	39.8	43.6	47.4
21	12.8	16.8	22.7	25.6	29.6	33.5	37.5	41.4	45.4	49.3	11.7	15.3	20.7	23.4	27.0	30.6	34.2	37.8	41.4	45.0
22	11.3	14.8	20.0	22.6	26.1	29.5	33.0	36.5	40.0	43.4	12.1	15.8	21.4	24.2	27.9	31.6	35.3	39.1	42.8	46.5
23	17.0	22.2	30.0	33.9	39.2	44.4	49.6	54.8	60.1	65.3	16.2	21.2	28.7	32.5	37.5	42.5	47.5	52.5	57.5	62.5
24	15.7	20.5	27.7	31.3	36.1	41.0	45.8	50.6	55.4	60.2	17.2	22.4	30.3	34.3	39.6	44.9	50.1	55.4	60.7	66
25	15.3	20.0	27.0	30.5	35.2	39.9	44.6	49.3	54.0	58.7	18.9	24.7	33.4	37.8	43.6	49.4	55.3	61.1	66.9	72.7
26	17.2	22.5	30.4	34.4	39.7	45.0	50.3	55.6	60.9	66.2	18.2	23.8	32.2	36.3	41.9	47.5	53.1	58.7	64.3	69.9
27	16.3	21.3	28.9	32.6	37.7	42.7	47.7	52.7	57.7	62.8	15.2	19.9	27.0	30.5	35.2	39.9	44.6	49.3	53.9	58.6
28	16.0	20.9	28.2	31.9	36.8	41.7	46.6	51.5	56.4	61.4	12.3	16.1	21.8	24.6	28.4	32.2	36.0	39.8	43.6	47.3
29	14.4	18.9	25.6	28.9	33.3	37.8	42.2	46.7	51.1	55.6	14.8	19.4	26.2	29.6	34.2	38.7	43.3	47.8	52.4	57.0
30	17.5	22.9	31.0	35.1	40.5	45.9	51.3	56.7	62.1	67.5	15.8	20.7	28.0	31.6	36.5	41.4	46.2	51.1	56.0	60.9
31	18.4	24.1	32.6	36.9	42.6	48.2	53.9	59.6	65.3	70.9	15.9	20.7	28.1	31.7	36.6	41.5	46.4	51.3	56.1	61.0
32	19.8	25.9	35.1	39.7	45.8	51.9	58.0	64.1	70.2	76.3	20.8	27.2	36.9	41.7	48.1	54.5	60.9	67.3	73.7	80.1

Block	Number of dispatched trains in outbound direction										Number of dispatched trains in inbound direction									
	26	34	46	52	60	68	76	84	92	100	26	34	46	52	60	68	76	94	92	100
33	18.0	23.5	31.8	36.0	41.5	47.1	52.6	58.1	63.7	69.2	18.9	24.7	33.5	37.9	43.7	49.5	55.3	61.1	67	72.8
34	17.0	22.2	30.0	33.9	39.1	44.3	49.6	54.8	60.0	65.2	17.9	23.5	31.7	35.9	41.4	46.9	52.4	58.0	63.5	69.0
35	16.8	22.0	29.7	33.6	38.8	43.9	49.1	54.3	59.4	64.6	17.8	23.3	31.6	35.7	41.2	46.7	52.2	57.6	63.1	68.6
36	23.3	30.4	41.2	46.5	53.7	60.9	68	75.2	82.3	89.5	21.0	27.5	37.2	42.0	48.5	54.9	61.4	67.8	74.3	80.8
37	18.9	24.8	33.6	37.9	43.8	49.6	55.5	61.3	67.1	73.0	17.9	23.4	31.6	35.7	41.2	46.7	52.2	57.7	63.2	68.7
38	18.2	23.8	32.1	36.3	41.9	47.5	53.1	58.7	64.3	69.9	17.2	22.5	30.4	34.4	39.7	45.0	50.3	55.6	60.8	66.1
39	18.7	24.5	33.1	37.4	43.2	48.9	54.7	60.4	66.2	71.9	18.0	23.5	31.8	36.0	41.5	47.1	52.6	58.2	63.7	69.2
40	20.0	26.2	35.5	40.1	46.2	52.4	58.6	64.7	70.9	77.1	20.0	26.1	35.3	40.0	46.1	52.3	58.4	64.5	70.7	76.8
41	19.8	25.9	35.0	39.6	45.7	51.8	57.9	64.0	70.0	76.1	19.9	26.0	35.2	39.8	45.9	52.0	58.2	64.3	70.4	76.5
42	20.8	27.2	36.8	41.6	48.0	54.3	60.7	67.1	73.5	79.9	20.6	27.0	36.5	41.3	47.6	54.0	60.3	66.7	73.1	79.4
43	21.8	28.6	38.7	43.7	50.4	57.2	63.9	70.6	77.3	84.0	21.7	28.4	38.4	43.4	50.1	56.7	63.4	70.1	76.8	83.4
44	19.3	25.3	34.2	38.6	44.6	50.5	56.4	62.4	68.3	74.3	20.0	26.2	35.4	40.1	46.2	52.4	58.6	64.7	70.9	77.1
45	17.9	23.5	31.7	35.9	41.4	46.9	52.4	57.9	63.5	69.0	18.9	24.7	33.4	37.7	43.5	49.3	55.1	61.0	66.8	72.6
46	20.3	26.5	35.9	40.5	46.8	53.0	59.3	65.5	71.7	78.0	19.2	25.1	33.9	38.3	44.2	50.1	56.0	61.9	67.8	73.7
47	25.5	33.4	45.1	51.0	58.9	66.7	74.6	82.4	90.3	98.1	23.3	30.4	41.2	46.6	53.7	60.9	68.1	75.2	82.4	89.6
48	19.1	24.9	33.7	38.1	44.0	49.9	55.7	61.6	67.5	73.4	15.1	19.8	26.7	30.2	34.9	39.5	44.2	48.8	53.5	58.1
49	21.2	28.1	38.0	42.9	49.6	56.2	62.8	69.4	76.0	82.6	16.7	21.9	29.6	33.4	38.6	43.7	48.9	54.0	59.2	64.3
Occupancy rate	25.5	33.4	45.1	51.0	58.9	66.7	74.6	82.4	90.3	98.1	23.3	30.4	41.2	46.6	53.7	60.9	68.1	75.2	82.4	89.6

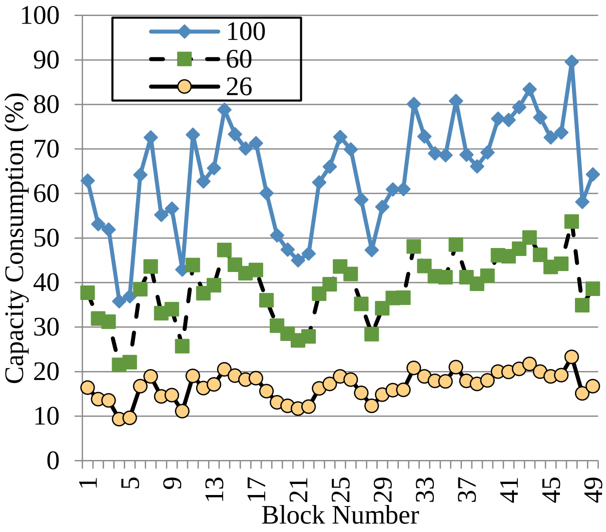


Fig. 15. East Direction

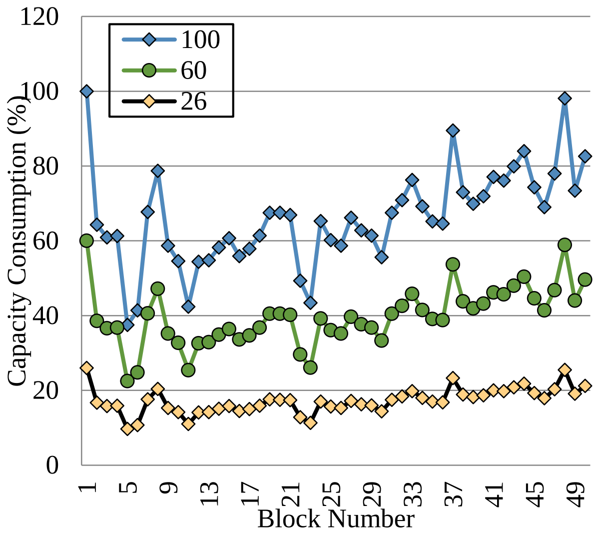


Fig. 16. West Direction

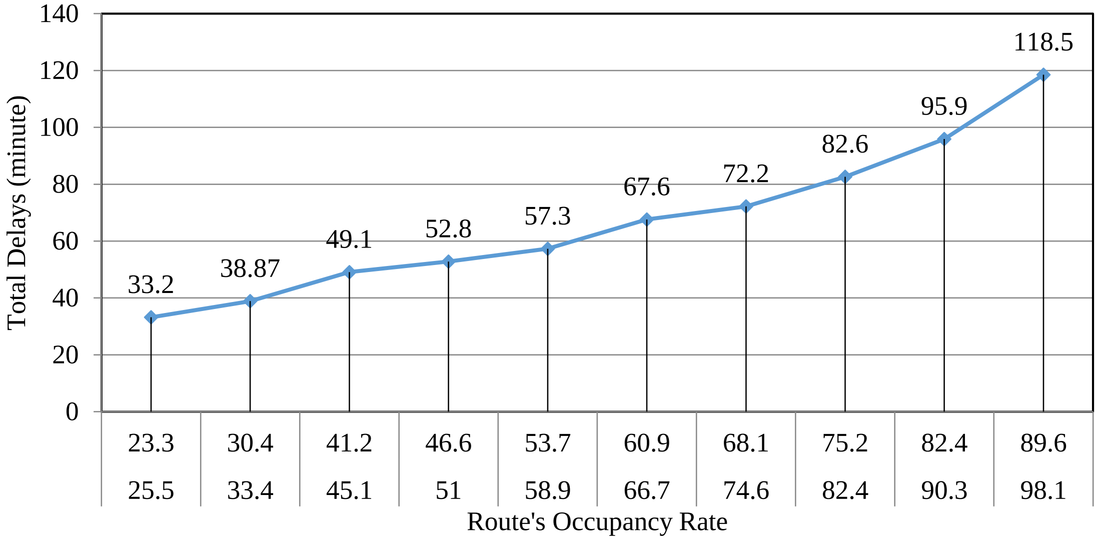


Fig. 17. Relationship between total delays and route's occupancy rate

Masoud Shakibayifar

Mr. Masoud Shakibayifar is Ph.D. candidate in Department of Transportation Engineering and Planning, School of Civil Engineering, Iran University of Science & Technology (IUST), Email address: m.shakibayi@civileng.iust.ac.ir .

He doing the Ph.D. thesis entitled: “Train Re-Scheduling model for Reducing Delay under Disturbances”. This research focuses on designing simulation-optimization methods for train traffic rescheduling in railways systems.

His research interests are railway electrification, railway scheduling and rescheduling, and optimization of transportation systems under uncertainty.

He gets B.Sc. (1997-2001) & M.Sc. (2004-2006) in civil engineering at Sharif University of technology. He manages more than 15 transportation planning projects in Iranian Railway Company and the ministry of roads and urban development. Recently, he has managed a research project related to the design of railway traffic simulation software for Iranian Railway Company.

Abdorreza Sheikholeslami

He is Associate Professor in Department of Transportation Engineering and Planning, School of Civil Engineering, Iran University of Science & Technology (IUST), Email address: sheikh@iust.ac.ir
He received his B.Sc. and M.Sc. degrees from IUST. He received his Ph.D. degree in "Transportation Engineering and Planning" from Iran University of Science and Technology in 2006.

His research interests are transportation planning, transportation economics, railway scheduling, disturbance management, mathematical models and optimization techniques for designing transportation systems

He is elected as the top student in technical and engineering group in Iran at 2001. He has experienced with more than 20 years in teaching at IUST. He has published more than 80 scientific papers in ISI journals and international conferences.

Francesco Corman

Dr. Ir. Francesco Corman is an assistant professor in transport engineering and logistics, TUDelft, and guest professor at KULeuven.

His research interest relates to optimization of transport networks under uncertainty. This substantiates in optimization and automation in supply chain networks and logistic systems, especially with interconnected systems and modes; mathematical models and optimization techniques for traffic control in railways systems; optimal coordination strategies, and equity issues in logistics; robustness, reliability, resilience of transport networks under stochastic phenomena; Analytics, information and uncertainty dynamics; A-priori and online data collection and assessment of quality of information

He has more than 25 high impact articles in journals and book chapters, and more than 100 scientific papers in journals or peer-reviewed international conferences; he received numerous awards and nominations.

He has been involved in organizing and chairing of the International Conference on Computational Logistics 2015, among others. He has been General Chair of Problem Solving Competition, Informs Railway Application Section 2015 and 2016. He is a guest editor of major transportation journals (TRC, TRE, Public Transport), and participates actively in TRB and Informs community. He is the initiator of much international research exchange and coordination networks.

Yousef Shafahi

Dr. Yousef Shafahi is a full professor at Sharif University of Technology, Department of Civil Eng., 2014-Now. He is currently Member of the board of Air Transportation Scientific Society: 2009 – Now and Head of Transportation Engineering & Planning Division, Civil Engineering Department, Sharif University of Technology, 2014-Now. He received his Ph.D. in Civil Engineering, University of Maryland, College Park, MD, USA, 1997

His research interest relates to transport planning e.g. urban transportation planning; road, rail, and air transportation; transit networks design and scheduling; Applications of Operation Research, Soft Computing, and Simulation in Transportation. He conducted comprehensive urban and suburban transportation planning project e.g. a model for finding the threshold to electrify railroads of Iranian Railways. Objectives include designing a system to address some important management questions in the railway industry, such as (a) When should we start to electrify a railway system (b How does variation of different relative weighting factors such as construction, operation, and maintenance costs, travel time, and reliability affect the threshold of electrification. His teaching experiences are transportation engineering, transportation planning, systems simulation railway engineering airport planning and design, advanced engineering mathematics, operation research, statistics, probability theory, mathematics.