International Journal of Railway Research, Vol. 9, No. 2, (2022), 75-84

Iran University of
Science and Technology

International Journal of

Railway Research

ISSN: 2423-3838

Investigating and Analyzing Trains Movement Timetable Stabilization in Railway Traffic Control Systems

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ARTICLE INFO

Article history:
Received: 12.28.2022
Accepted: 06.30.2023
Published: 07.04.2023

Keywords:
Traffic Control System
Train Movement Timetable
Delay Compensation
Robust Timetables

ABSTRACT

The stabilization of train timetables plays a significant role in railway operations. The main objective of this paper is to increase the robustness of traffic timetables. Robustness is analyzed by comparing previously used methods with newly implemented timetables through simulation, utilizing the ARENA tool. The model simulates all train departures and arrivals in the network during the daytime, employing three methods: train arrival at stations, train replacement at a central point, and route cancellation to avoid delays. This article aims to provide an understanding of robust timetables by examining and testing their stability. Robustness entails the ability of the timetable to return to the original schedule and recover despite disturbances, exhibiting low sensitivity to deviations. During disturbances, the timetable requires rescheduling, followed by the simulation to assess its robustness. However, this procedure is time-consuming, making it unsuitable for short-term scheduling practices. This article examines different timetables, makes improvements to enhance their robustness, and compares and investigates the results. Various experiments are conducted and explained, including the assessment of the effects of different methods, examination of delays, and comparison of the effectiveness of different timetables on traffic timetable robustness. The simulation results demonstrate the relationship between robustness and the increase or decrease in the number of lines in the train timetables. Furthermore, the results reveal that the number of lines is not the sole factor affecting timetable robustness; dwell times at stations also have a significant impact. The article also highlights the necessary amount of dwell time to maintain robustness and emphasizes the importance of allocating dwell times effectively when all lines may utilize them. Additionally, the line structures can also influence robustness.

[DOI: 10.22068/ijrare.310]

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1. Introduction

The traffic timetable remains unchanged only for a few days of the year, and due to unexpected disturbances, it has to be modified for the rest of the time. The disturbances could be of low or high magnitudes; though, highly demanding work is needed for modification of the timetable. The goal is to improve the robustness of the timetable.

This article aims to give an impression of how various timetables affect the overall robustness. The robustness of timetables is measured by simulation of the timetables influenced by disturbances. It will be observed how different timetable factors influence the schedule's robustness. The main objective is to shed light on those constructive factors of the timetable that infringe on the robustness of the main schedule.

The process of scheduling the timetable can be divided into several phases. It starts from the market demands, and network scheduling is the first step of the scheduling procedures. The next phase is train sets (series) scheduling so that the relation of trains from the start and terminal stations is selected, which then includes different routes and stations in between the stop points. Train series scheduling is done via timetables. At this level, departure and arrival times are set. If a suitable overtaking of the train sets is not implemented in the timetables, many iterations can occur at these levels. When the timetable is finished, the rolling stock circulation is scheduled. This phase also includes a shunting and repositioning schedule [1-6].

In Figure 1, the scheduling procedure is presented. Since all phases are related to their previous steps, at times it becomes necessary to return and make some modifications; when, for example, some unforeseen events have occurred in the previous steps.

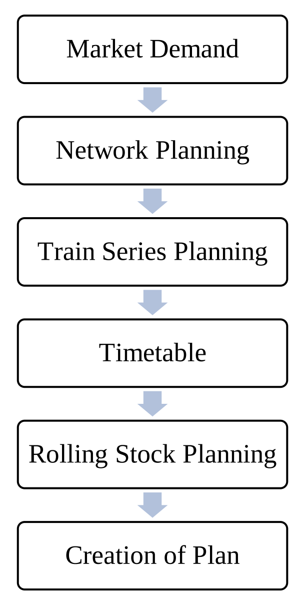

Figure 1: The Sequence of Interdependent Railway Scheduling (Planning) Phases [7]

All phases in the scheduling procedure have their effects on the final robustness. If the network comprises multiple tracks network scheduling will have an important impact on the robustness. Overtaking in case of disturbances and delays can reduce the probability of secondary delays. The number of trains and the timetable define the number of lines and train frequency, which naturally impact robustness; an example is when fewer trains and low frequencies create larger buffer times. In addition, in the timetable schedule, choosing the available routes, while also considering the headways timetable, to ensure the best trains' buffer times during disturbances, is very important. Rolling stock scheduling is also influenced by robustness. When trains with different speed limits are used, diverse headways due to various moving attributes are created, which then reduces the schedule's robustness in case disturbances occur [8].

In the rolling stock scheduling, the number of required trains is specified, and an increase in the number of trains with the same frequencies creates better shunting times and also boosts the buffer times, although it comes at higher total costs. Robustness in crew scheduling is also important, so when there is no crew available the train departures might face delays, which affects the final robustness [9-12].

Several factors are to be considered when scheduling timetables for railway lines. There is a high

[DOI: 10.22068/ijrare.310]

interdependency between multiple lines and routes when the trains are shared; therefore, tables for various lines might depend on each other. The schedule for lines also depends on safety considerations and speed limits. Naturally, the costs are important factors for planning line schedules. As a result, the time tales are optimized for minimum train usage, especially when the number of operating trains has serious financial impacts on the total train's operation cost. In other words, for having an optimal schedule, the costs and the minimum train usage are taken into account, especially when a simple disturbance might affect the entire schedule’s robustness and make requirements for modification of the total time [13-14].

An approach to creating a robust timetable is to use buffer times. Robustness means that system operation has a low sensitivity to disturbances and remains according to the proposed time schedules. Large time margins improve the robustness, though they come at higher costs to the passenger's travel times and need the presence of more trains in the railway system.

Another way of increasing the robustness of the timetable is by running fewer trains in specific series. This method creates larger time margins to decrease the probability of secondary delays; although, it increases specific trip times and would be a concern to the passengers. Inter-station headways should also be, with a specific probability for a bigger buffer time, shared evenly among all the trains [15-17].

In this section, the main causes of disturbances and delays are presented. In a complicated railway network, many reasons for delays and disturbances can occur. In busy stations with multiple platforms, there might be hundreds of train arrivals and departures, involving thousands of passengers, each day. The trains could be of various types and from various transit lines, and there would be a need to set the stations and lines free from the trains. Therefore, delays are usually related to train schedules. There is a relationship between the railway system design and how the delays are propagated through the railway lines. The relationship can be determined using different timetable simulations or some sensitivity analysis. The relationship could also affect the risk of delayed occurrences via timetable schedule. Hence, to consider the delay in the train schedule, dwell times are taken into account when they occur. The dwell times help to improve the robustness of the system and reduce the propagation of delays in the network. The amount of delay frequency also depends on the operation capacity of the network. Therefore, if the operation rate is high, the probability of delay occurrence is also high. The disturbances can be caused by accidents or by scheduling problems.

When the disturbances occur, the robustness of the system is biased. The robustness changes according to the amount of the occurred disturbances. If a system is robust enough, a small disturbance cannot affect its stability [18-23].

Figure 2 is an example of the relationship between the number of trains, heterogeneity, and robustness. It shows that robustness decreases when the number of trains increases. When a huge number of trains are under operation on the same line, the risk of disturbance propagation, and therefore influencing multiple trains, increase. Also, when the reasons for heterogeneity increase - like the utilization of many dissimilar trains or many unlike train stops in the schedule - the robustness of the system decreases. If the robustness is decreased by a large margin, the delays will happen.

Delays are of two categories: primary and secondary. The primary delays are created when the delay only affects the train itself. The primary delays cannot be eliminated, and are independent of the timetable design. Also, in theory, the primary delays are separate from the operational capacity of the line; though, the analysis of occurrences and location of primary delays can be used for the creation of reliable timetables. An example is when the primary delays lead to the creation of secondary delays. When the dwell times in the timetable are designed to be very small, a train’s delay will cause conflicts with other trains. These delays are called secondary delays. For example, if one train leaves a platform late it causes delays in the arrivals of the successive trains that would use the same platform, and would finally cause delays in multiple trains’ arrivals. In other words, if one train arrives late, it occupies the scheduled platform and might be sent to the other platforms, causing delays for the trains scheduled for those platforms too. It is important to keep the primary delay rate low so that the secondary delays are eliminated quickly. Disturbances can be eliminated using different methods; such as re-establishment of the main schedule, scheduling recovery, or recovery of the regular headways. Three strategies are examined in this section [24-28].

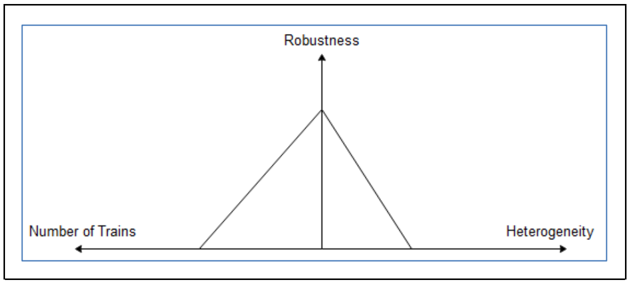

Figure 2: Robustness Stability

Various recovery strategies utilize methods such as train cancellation, delayed train substitution, or reduction of dwell times. In this strategy, traffic controllers try to solve the problems by changing the time variables (i.e., the dwell times) in the timetable. The connections between the trains might become broken, the trains might have delays, the platforms might change, and the trip and the dwell times might decrease, but the overall schedule remains intact. These strategies are mostly used when dealing with small disturbances. There might be some rules considering the amount of waiting time of trains in stations, or some rules considering reordering of the trains if only one of the trains has a delay [29-31].

In this recovery, method-specific trains or set routes might be canceled. A new schedule is established and the original schedule is discarded. The goal is the re-establishment of the original schedule; though, the original schedule might be extended to some hours or might not be established on similar days. This strategy is used when long delays, due to rolling stock faults or train accidents, occur in the railway lines. Some rules might be created for the cancellation of train routes when disturbances occur. Even if certain rules exist for the management of large disturbances, the outcome would still depend on the choices made by the traffic control operator.

The third strategy is regaining regular headways. Instead of waiting for the scheduled departure time for every train, there is a set that makes the shortest headway possible. This strategy makes it possible for the trains to use the maximum operating capacity. This recovery strategy is used in railway systems (e.g., subway systems), that have scheduled short train headways in their timetables. In very crowded platforms the exact departure time is not so important since the frequency of train departures is very high. In longer running times, when there is a disruption, the train operation returns to the original schedule.

2. Problem Statement

The primary sample for the final model is based on the information acquired from Denmark's railway line timetable. The final model is generic.

The idea behind it is that all stations in the network are displayed as similar sub-models in the ARENA simulation tool since all stations are somehow similar. Individual attributes of each station are saved in variables.

The final model is also different. For example, there is always a terminating (or end) station, data might not be saved in variables, or only one sub-model might be used for displaying all the stations. This helps to simplify the model since the number of modules is reduced.

Simple modules show all the stations in the network. Almost two digits are used for each station, which depends on the number of platforms. There is a series of routes and stations that the train should view and travel to, though all items (trains) in the model enter the same sub-model whenever they arrive at a different station. A specific set of variables display the special stations that the trains arrive at.

There are also variables for the dwell times of each station. Each entity (train) in the network has an attribute in which the scheduled departure and arrival time, the trip route, the current and the next station, the specific sequence of stations for each route, the direction of the network (i.e., northward or southward), and other train specific data are specified. The final model needs more variables for distinguishing the stations from each other when all the stations are displayed using the same module.

However, data entry is performed only once and the model is regulated into a better form. The final model is divided into the following parts:

- The main model is where the trains are created.
- The station sub-model displays all stations of the network.
- Two sub-models where regulation and reliability are calculated.
- Three sub-models with three recovery methods.
- A sub-model that reads stoppage and departure times from Microsoft Excel and saves them in a text file.
- Animation.

2.1. The Recovery Method

The Recovery methods include replacement of the trains in stations, route cancellation, or making the trains arrive early in the end stations.

The mentioned methods are selected because they are suitable for the recovery of small to moderate disruptions and have various effects on the quality of customer service. They show one selected mode of the utilized recovery methods. They also represent both the re-establishment and the return to the scheduling strategies. In this research, the following recovery methods are used.

2.2. The Route Cancellation Method

The idea behind this method is to cancel some routes in the network when there is a disturbance in the system that causes train delays.

The cancellation of the routes increases the buffer time for the remaining trains. This is a method for avoiding train delays. There is also a recovery method that determines which routes should be canceled.

2.3. The Replacement Method

The idea behind this method is that if a train has delays it should be replaced with another train according to the central station's schedule. The train with delay is taken out of operation when it arrives at the central station, and as a result, the delay time in the network increases.

Since the train with delay is taken out of operation and replaced in the central station, the secondary delays are created only on the way toward the central station and not from the central station toward the end station.

For creating a realistic recovery method, only two trains cover each line and can be scheduled for replacement at the same time (i.e., one train moves southwards and the other northward). This assumption is also made for the passengers so that no passenger is affected as a result of train replacement.

Each secondary train in each line, and all routes from the central station toward the end stations, would travel without replacement. When a train is replaced, it would stay in the central station so that it could be used later to replace other trains as well.

2.4. The Experiments

The Experiments are carried out according to the original timetable. The Experiments include verification of the recovery methods and comparison of the timetables.

Experiment cases for the timetables are:

- ❖ With delays and without recovery
- ❖ With delays and taking out recovery
- ❖ With delays and turn-around recovery
- ❖ With delays and replacement recovery

In the experiments, the following items are measured and calculated:

- ❖ Regularity (percentage of traveling trains on time)
- ❖ Average Delay
- ❖ Reliability (the number of scheduled departures to the number of real departures)
- ❖ Number of affected trains (replaced, turned around, or canceled)

In general, robustness is gained through stable regularity. Additionally, increased regularity includes more robustness. More regularity and less affected trains are also indications of higher robustness.

3. Experiments with Delay

Delays added to the model are determined via propagation, and the probability of the delay will fit regulation. Experiments are conducted to demonstrate how the probability of delays affects regularity.

Four-timetables with 9 lines (actual 2008), 10 lines with improved buffer time, and 11 and 12 lines with the probability of 0, 10, 20, …, 100-minute delays are simulated. All experiments are conducted without recovery methods.

Figure 3 represents the regularity for different probability amounts for the timetable with 9 lines. The results show that the lower probability of the delay will result in better regularity. The results also illustrate that the relationship is non-linear. The probability changes from 80% to 90% have a higher negative effect on the regularity than its change from 20% to 30%.

Experiments with other timetables show similar results only with different values on the Y-axis.

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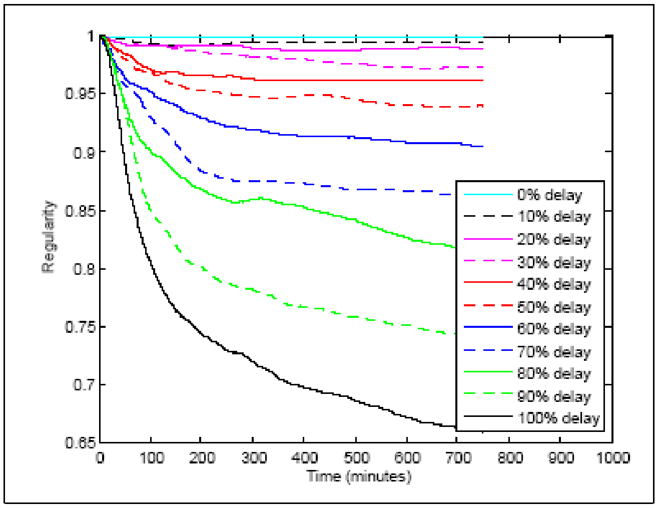

Figure 3: Regularity for Different Percentages of Delay

Figure 4 shows the regularity after 750 minutes, which is a function of the probability of delay for all timetables.

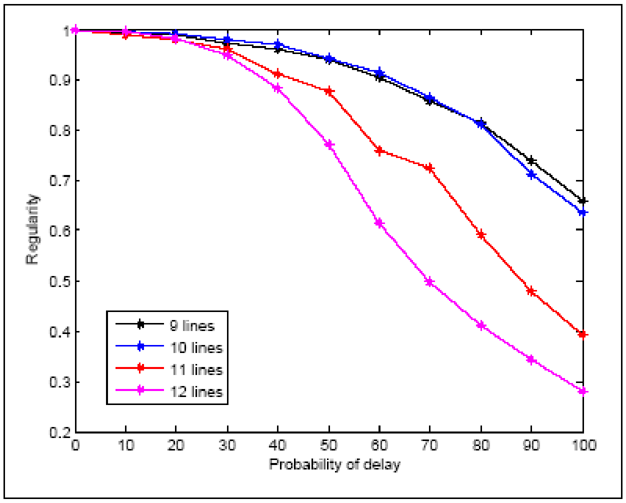

Figure 4: Regularity as a Function of Probability of Delay for 4 Timetables

The regularity decreases when the probability of delay increases. It also shows that the relationship is non-linear. The relationships can also explain the secondary delays.

4. Large and Small Delays

The additional delays in the model can be explained by the historical data. The distributions show that the delays are different for each station. For some stations, the delays are larger when compared to the actual system. For presenting the impact of the small and the large delays on the regularity, experiments with them are conducted separately, since it is difficult to recognize these delays from each other. The delays are distributed into 80 stations with the smallest delays and 81 stations with the longest delays. In the experiments with the smallest delays, all 81 distributions of the large delays are zero, meaning that there is no delay in the stations. Similarly, for the experiments with large delays, the distribution of the small delays is zero.

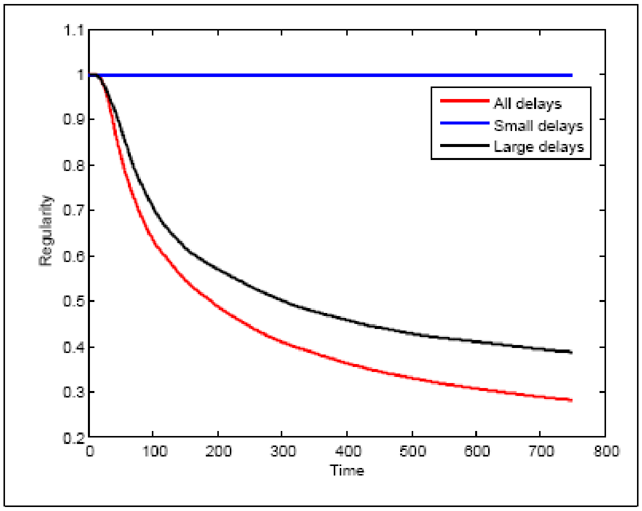

Figure 5: Timetable with 11 Lines

This means that in both experiments the delays occur only in half of the stations, while in the experiment with all delays, there is a place where the delays might occur in all stations.

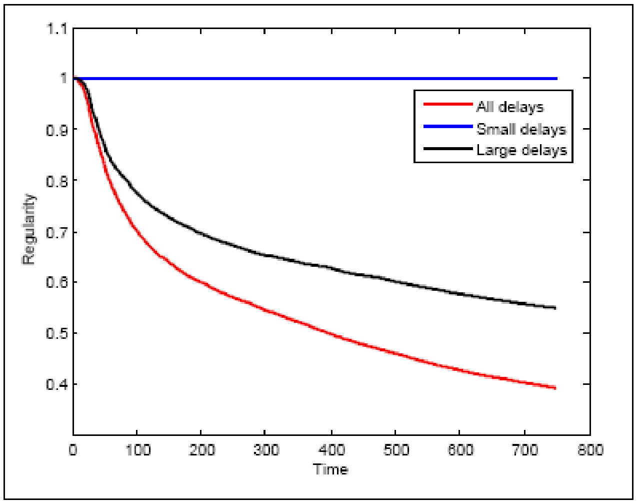

Figure 6: Timetable with 12 Lines

As a result, the experiments with all delays will yield to the lowest regularity. Other experiments on four-timetables consisting of nine lines (Actual 2008), 10 lines (created with enhanced buffer time), and 11 and 12 lines are conducted. The experiments are run without any recovery method with a 100% delay probability. This means that in stations the delay distribution is not zero. The delays are added to a station whenever a train enters it. The results of the experiments are revealed in

Figures 5 and 6. These figures show the regularity of timetables with 11 and 12 lines. The experiments with four timetables and a 50% delay percentage also present the same behavior and results. The large delays have negative effects on regularity. The small delays usually have no considerable impact on the regularity. The simulation with small delays (the blue curve) has a good regularity of almost 100%.

The reason can be that the time in each station is reduced to a minimum by decreasing the dwell time, and the time is calculated from the dwell time in each station. The experiment also proves that secondary delays have a significant impact on regularity.

Smaller delays don’t have any impacts on the regularity, though when the small gained delays are eliminated, we get a better regularity than the sum of all added delays. This is also effective in secondary delays. The experiments indicate that the large delays should be reduced, and concentration on larger delays is much more vital than on smaller delays. In other words, smaller delays might be eliminated easily which has a better result on the regularity due to the secondary delays.

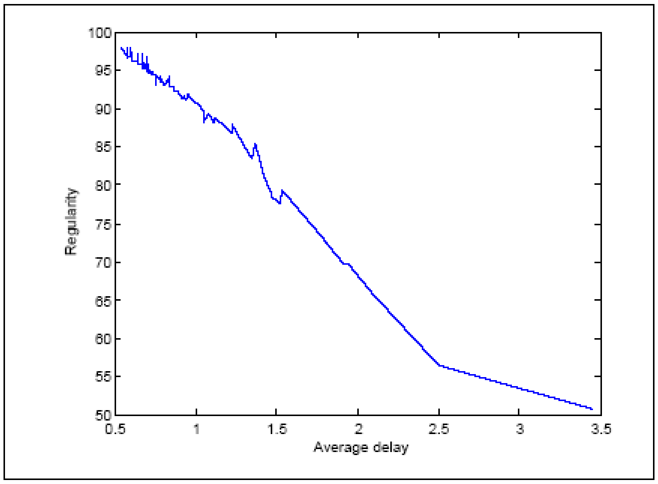

Figure 7: Average Delay and Regularity

The graph in Figure 7 shows the average delay and the regularity have a linear relationship.

5. Experiment with the Delay during the Early Rush Hours

For examining the recovery method when the delay is added in a period, the experiments are performed during rush hours. A delay in this experiment, with a probability of 60% for three hours, from 6 am to 9 am, is added. This means that during the early rush hours, the probability of delay occurrence is higher for a shorter period. Timetables with 9, 10, 11, and 12 lines are examined.

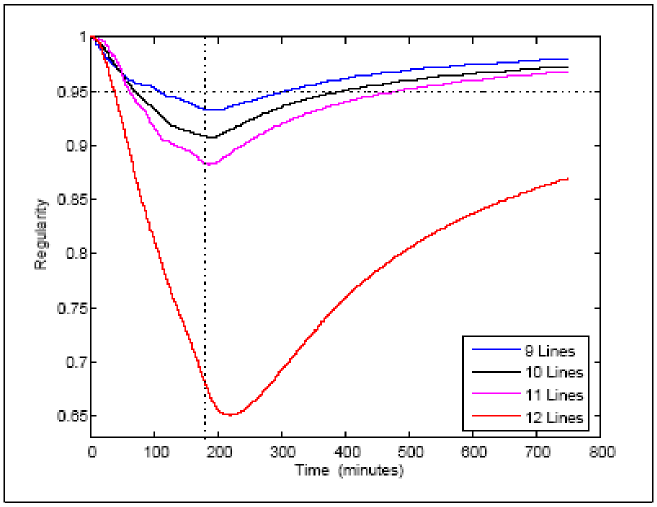

Figure 8: Experiment with Delay in Rush Hours

The regularity of each timetable when there is no recovery method is presented in Figure 8.

The black dotted vertical line is the time of rush hour after 180 minutes and the horizontal dotted line shows 95% regularity.

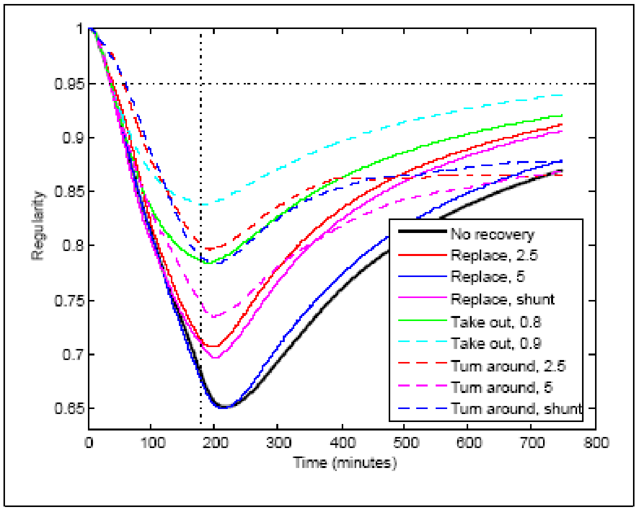

Figure 9: Timetable with 11 Lines

If the delay is added in a fixed period, the timetables with 9, 10, and 11 lines are recovered and again reach a regularity of over 95% after almost two hours (in 300 minutes), almost 3 and a half hours (in 400 minutes) and almost in 5 hours (in 480 minutes) respectively. The regularity increases for the timetables only after the end of rush hours.

The regularity of the timetable with 12 lines increases slightly; though, it won’t reach 95%.

In Figures 9 and 10 similar results are displayed for the timetables with 11 and 12 lines. In the presented graphs, the regularity when no recovery methods are used is displayed. In contrast, the timetable with 12 lines shows 95% regularity when the recovery is used.

In recovery methods, when routes are taken out, the result of regularities is usually 95%, though not until the day is finished.

In Figure 10, the recoveries when the trains turn around after 2.5 minutes give the highest regularity results. The routes that are taken out usually have similar results.

Using these recovery methods, the regularity reaches almost 95% two hours after the rush hours compared to five hours after the rush hours when no recovery method is used. The experiments prove that the recovery methods have significant effects on regularity.

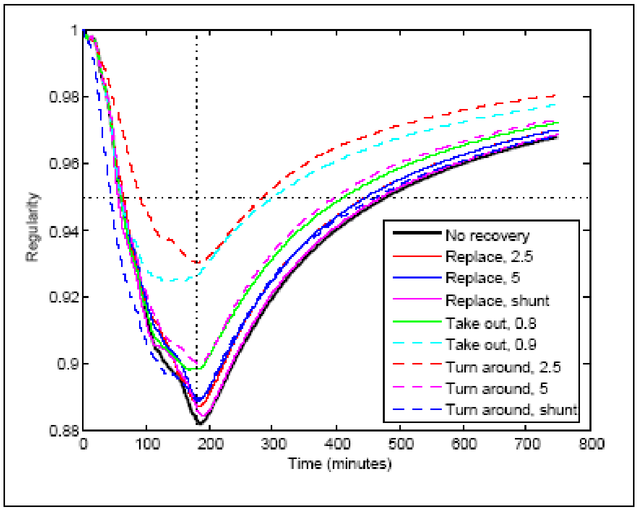

Figure 10: Timetable with 12 Lines

Figure 11 shows the regularity changes for timetables, especially those with 11 or 12 lines.

The results confirm that large numbers of lines have a low regularity and that the relation decreases non-linearly. The experiments with delays show that larger delays result in less regularity and the relationship decreases non-linearly. Another conclusion is that large delays have a greater impact on regularity than small delays.

The secondary delays have a significant effect on regularity too; therefore, small delays, just like the large delays, should also be eliminated, if possible. An important conclusion for the conducted experiments is that the amount of buffer time in the end stations has a significant impact on the regularity. Besides, the amount of the necessary buffer time is limited, which makes the results more realistic.

The addition of buffer time demands more operating trains and has a negative economic effect on the final results. When the required buffer time is limited, timetables with suitable buffer times for reaching increased regularity might be created.

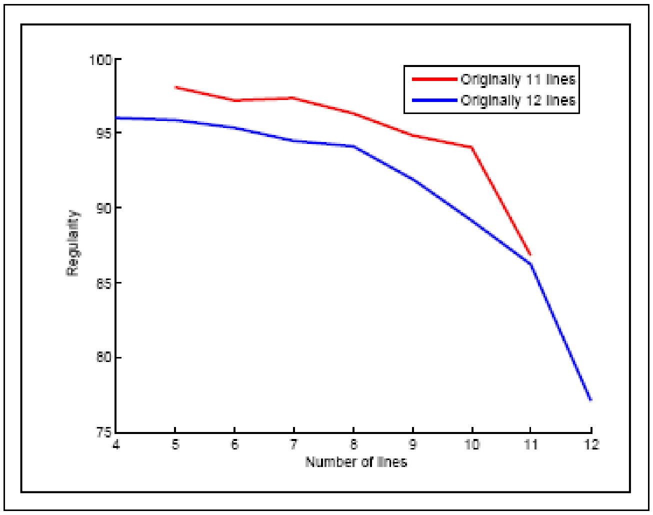

Figure 11: Regularity when the Number of Lines Increases

The conclusion from comparing different timetables is that the number of lines has an important effect on the regularity and therefore on the robustness of the schedule.

6. Conclusion

The objective of this research was to gain an understanding of the construction of robust timetables. This was done by experimenting with different timetables.

Numerous effects and causes of the robustness were investigated and examined. The robustness of timetables was measured via timetable simulation under the influences of the disturbance. The main network model was simulated and built-in ARENA.

One of the reasons for creating a precise model was the construction of the simulation with much more useful results. The constructed model in this project can simulate all trains' arrivals and departures in the network during day time. Also, three recovery methods were used to broaden the basis for the experiments. This article aimed to acquire knowledge of the various effects of timetables on the robustness of the schedule.

[DOI: 10.22068/ijrare.310]

Numerous timetables were needed for the experiments. The results indicated that the number of lines in the schedule significantly impacts the overall regularity.

The results showed that various factors influence the robustness of the timetable. The amount of buffer times in the terminating stations significantly influences the robustness. The results also showed how the overall buffer time, dedicated to various lines, was important, and how it became necessary to eliminate the buffer time in the timetable to obtain robustness. Finally structures of different lines-for having a positive effect on the robustness of the schedule - were experimented with.

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[DOI: 10.22068/ijrare.310]