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September 2022


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Department Transport & Planning,
Faculty of Civil Engineering and Geosciences,
Delft University of Technology

# Master Thesis

## The effectiveness of alternative graph-based rail traffic rescheduling models versus infrastructure layouts and traffic patterns

TU Delft

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# Preface

*Our help is in the name of the LORD, who made heaven and earth*

*Psalm 124:8*

Dear reader,

At the moment, I am at the end of a 19-year-period of education. In January 2003, I set my first footsteps in primary school and with this master thesis, I hope to conclude this period. Yet I did not experience these 19 years as a long time. Each time there were new challenges and new worlds opened up for me.

After my secondary school period, I slid into the lecture benches at the Bachelor of Civil Engineering at the Delft University of Technology. During this period, I travelled between Amersfoort and Delft every day. These journeys often went smoothly and for me they were moments of relaxation. Those few times when there were disruptions, I never experienced them as very inconvenient: I always wondered, how are the dispatchers going to solve this disturbance now and why are they doing it in this way. Little did I know that this question was going to be an essential part of my master thesis: How do railway traffic management systems solve disturbances and why are they doing it a certain way? After obtaining the bachelor's degree, I decided to pursue the Transport and Planning master, again at the Civil Engineering faculty of the TU Delft. This master also gave me the opportunity to obtain the Railway Systems annotation. This route also fitted very well with my passion for mobility, especially for railways.

This study path led me to my master thesis which I was able to do internally at ProRail at the Prestatie Analyse Bureau (PAB). This thesis project resulted from ProRail's request to develop an assessment methodology in which a railway traffic rescheduling model could be evaluated to gain insight into its effectiveness when applied to different infrastructure layouts and traffic patterns.

I experienced my graduation as a very enjoyable and instructive period. It was quite a switch to be responsible for a project that runs for 9 months instead of completing several courses every quarter. I enjoyed the mix of rail, timetables, mathematics and programming that this graduation project offered me. It was also a cool experience to be able to do this project internally at ProRail. By joining the PAB, and attending departmental meetings and drinks, I got to know the company better. It was also great fun to have the opportunity to attend one of the last rides on the Hilversum-Utrecht Malibaan line with a historic train. The contact and sociability with the colleagues, the lunch walks and working at the Inktpot also gave me a lot of positive energy during my graduation.

I could never have completed this graduation project without the help of many people. First of all I would like to thank the colleagues at ProRail who gave input and contribution from their expertise. A special thanks to Rosa and Wilco for their guidance from ProRail, putting me in touch with the right people, tips and tricks, thinking along and the useful weekly discussions. I would also like to thank my supervisors at TU Delft for their feedback and support during my work. Egidio as daily supervisor for the regular meetings, which fortunately took place in Delft again since March, and the quick responses to my questions via e-mail. Rob as chair of the committee for the valuable feedback during the main meetings, and Gonçalo as supervisor from another department with a different perspective looking at my research, very valuable!

I would also like to thank my family. I missed the 10.30 coffee moments we had together in corona time since I was often in the Inktpot. Henno, Joanne, Colinde and Pieter, thank you for the enjoyable times when I was not busy with my thesis. I hope I will have more time for a game in

the near future! In particular a word of thanks towards my parents, Arie and Marjon, who actually facilitated everything so that I had all the space I needed to focus fully on this research.

I have placed a Bible text from Psalm 124 at the top of this preface. This text had often been a source of support for me during my graduation process, also at more difficult times. It is the Lord Who, time and again, gave me the wisdom and insight to do this work. Soli Deo Gloria!

Arnoud de Jong

Amersfoort, September 2022

# Summary

A railway network without any delays is, unfortunately, still unthinkable in 2022. Delays can occur for all sorts of reasons, causing trains to run behind their schedule. These delayed trains can cause conflicts. This means that two trains want to use the same piece of infrastructure (a block section) at the same time, which is infeasible. The resolving of conflicts has traditionally been placed on train dispatchers, who make decisions according to their own expertise and by certain rules and guidelines. With the modernization of the railways (regarding the development of an improved European signalling system ERTMS and the development of automatic train operation (ATO)), in recent years research has been carried out into automated systems based on mathematical optimization models, which are suitable for detecting and resolving conflicts.

However, in most research, these *Traffic Management Systems* (TMS) or *Rail Traffic Rescheduling Models* (RTRM) are only implemented and evaluated on one specific dispatching area (the area which is controlled by an RTRM). A literature review showed there is still not much literature about how the effectiveness and the overall benefits of such models are influenced by the type of infrastructure layouts and traffic patterns. It remains unclear whether an RTRM developed for a certain dispatching area under certain operational conditions is also effective for another area with different operational conditions.

The objective of this research is to investigate the applicability and effectiveness of an alternative graph-based RTRM on different infrastructure layouts and traffic patterns and to prove the sensitivity of the performance of an RTRM for different network characteristics. The developed methodology can also be used in the assessment of other RTRMs. This research is performed under the following main question:

> *How are the benefits provided by an alternative graph-based RTRM influenced by infrastructure layouts and traffic patterns?*

Based on the findings of a literature review, an evaluation framework was developed to assess an RTRM by using different infrastructure layouts and traffic patterns. This framework is applied to an own developed RTRM, which is based on the predefined alternative graph model (Mascis and Pacciarelli, 2002), however reformulated as a MILP (Mixed-Integer Linear Programming). In this way, the model could be formulated in a generic way, which made the application of the model on different layouts and timetables possible, and the objective function could be adapted to minimizing the weighted sum of consecutive delay. (The consecutive delay is the difference between the final delay and the unavoidable delay).

In the framework, the RTRM is applied to different infrastructure layouts and different traffic patterns, which potentially could influence the performance of an RTRM. These infrastructure and operational scenarios were compiled based on the results of the literature review and based on expertise present at infrastructure manager ProRail. The number of infrastructure layouts was reduced to four layouts, on which only one form of route interaction (ways in which different routes of trains overlap) can take place. Two layouts are added in which (common) combinations of route interactions can take place. All these layouts have the same dimensions, but different topologies. Using a timetable generation module, timetables were generated for these layouts based on operational characteristics. These operational characteristics are based on the characteristics of a timetable, namely traffic pattern (which includes train types with stopping patterns and the sequence of trains), running time supplement (running time extensions to catch up on delays) and infrastructure occupation rate (the minimum technical cycle time divided by the timetable cycle time).

On each infrastructure and operational scenario, a set of randomly regenerated delay scenarios is applied. The RTRM is used to generate for each scenario a Real-Time Traffic Plan (RTTP) resolving the conflicts that occur due to the initial delays. These RTTPs are assessed using various Key Performance Indicators (KPIs). In addition, Simple Dispatching Rules (SDRs) were used, like First Come First Served (FCFS) or maintaining the timetable order, to show the relative improvement of the RTRM over these SDRs. In table i.1, the whole of scenarios, KPIs and SDRs used in the evaluation framework is given.

*Table i.1. Overview assessment parameters used in the evaluation of an RTRM*

| **Scenarios:** | **Characteristic:** | **Value:** |
|---|---|---|
| Infrastructure scenarios: | Infrastructure layouts | Cross-over, merge, overtaking, single track, cross-over & merge, merge & overtaking |
| Operational scenarios: | Traffic pattern | Homogeneous/heterogeneous operation,<br>homogeneous/heterogeneous routes,<br>sequence of trains,<br>with/without scheduled overtaking (overtaking layouts)<br>location of scheduled train passages (single track layout) |
| | Running time supplement | 0%, 5%, 10% |
| | Infrastructure occupation rate | 50%, 75%, 90%<br>*Related to timetable cycle time and frequency* |
| Disturbance scenarios | Initial delay | Small (2-6 min initial delay), medium (6-10 min initial delay), large (10-15 min initial delay) |
| **Assessing an RTRM:** | | **Value:** |
| Key Performance Indicators (KPIs) | | Weighted consecutive delay, sum consecutive delay, sum final delay, maximum final delay, relative delay, punctuality, optimization runtime |
| Simple dispatching rules (SDRs) | | FCFS, timetable order, prioritise intercity trains, prioritise on-time trains, prioritise delayed trains |

The results of the evaluation framework showed that the performance of the observed RTRM, and the benefits of the RTRM compared to the SDRs, differs per layout. This is shown in figure i.1, which shows the relative improvement (η) by the RTRM over the SDRs for the weighted sum of consecutive delay (which is also the objective used in the RTRM) per layout. In this figure, a distinction is made between heterogeneous and homogeneous traffic patterns and timetables with different rail traffic intensities (which is expressed by the infrastructure occupation rate). The color of the bar represents the SDR that performs best for this layout and traffic pattern (and is used in the computation of η).

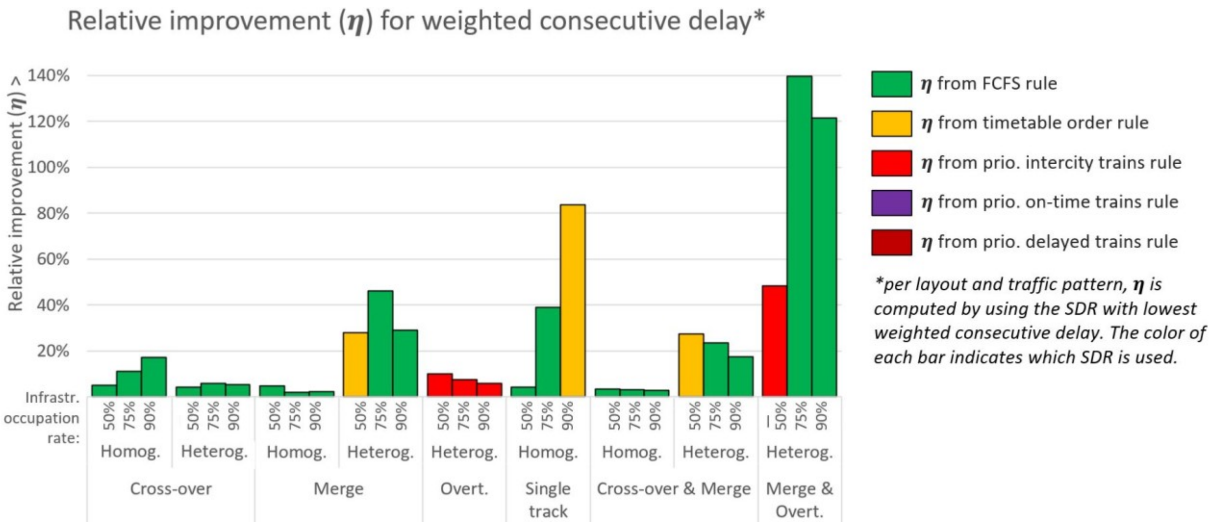



*Figure i.1. Relative improvement (η) for different infrastructure layouts and traffic patterns*

Regarding the different layouts, the RTRM proved to be more capable of reducing delays for layouts with more decision freedom. This is especially the case for one of the 'combined' layouts (the merge & overtaking layout) where the weighted sum of consecutive delay for the prioritise intercity trains rule is 137% higher than for the RTRM itself (over all scenarios of that layout). Also, the η for the merge and cross-over & merge layouts is high for the heterogeneous traffic patterns (43% and 26%). It is different for these layouts with homogeneous operation, where for these layouts the FCFS rule would be sufficient and the RTRM does not have much added value (η of 2% and 3%). For the cross-over and overtaking layout, the relative benefit is also low and the application of the FCFS rule (for cross-over layout) and prioritise intercity train rule (for overtaking layout) would be sufficient.

Regarding the traffic intensity, it appeared that for almost all layouts with an infrastructure occupation rate of 50% an SDR is sufficient (see figure i.1). Exceptions to this are infrastructure layouts with a merge with heterogeneous operation: For that layouts -even with a low infrastructure occupation rate- SDRs are not always capable to make the right trade-off of which train to leave ahead at the merge. For timetables with a high traffic intensity with an infrastructure occupation rate of 75% and 90%, for most layouts, the RTRM is more effective than for a low traffic intensity. It should be noted that, except for the cross-over and single track layout, the η for a 75% infrastructure occupation rate is larger than for a 90% infrastructure occupation rate. This is caused by the little remaining capacity available for high infrastructure occupation rates. As a result, the difference in the amount of consecutive delay which could be reduced by an advanced control approach becomes smaller compared to applying the FCFS rule (both approaches lead to high amounts of delay).

In future research the developed framework can be used for analyzing larger infrastructure layouts, to show the effects on the effectiveness of an RTRM if combining the observed small pieces of infrastructure layouts (analyzed in this research). Also, aspects like rolling stock circulation, connecting trains and personnel planning can be regarded. In addition, the framework can be extended by including stochasticity in running and dwell times.

Based on this research, it is recommended to ProRail that research into the assessment of the effectiveness of an RTRM should in any case include several case studies, as the results of only one case study are not a good representation of the performance of the investigated RTRM at other infrastructure layouts and traffic patterns. In addition, there are situations, for example at a cross-over layout or at layouts with a homogeneous traffic pattern, where it is not worthwhile investing in an advanced algorithm, but suffices with an SDR rule like the FCFS rule (see figure i.1). On the contrary, the implementation of an RTRM is most effective (and recommended) on layouts with the most freedom to apply control actions.

# Glossary

| | | |
|---|---|---|
| AG | - | Alternative graph |
| FCFS | - | First Come First Served |
| MILP | - | Mixed-Integer Linear Programming |
| KPI | - | Key Performance Indicator |
| RTRM | - | Rail Traffic Rescheduling Model |
| RTTP | - | Real Time Traffic Plan |

# Content

# 1. Introduction

## 1.1 Background

The railway is an essential means of transport in today's society. It offers a solution for various mobility and environmental problems and provides sustainable use of space in densely populated areas. However, the success of this modality also depends on its reliability. Delays and poor punctuality can lead to a reduction in attractiveness causing a modal shift (people changing to other modalities). To prevent a modal shift, the reliability of railways can be improved by eliminating possible causes of delays to prevent the occurrence of delays.

However, it appears that 100% punctuality is unfeasible, even the Japanese railways which are known for their high punctuality rates, don't reach this with an average delay of 0.7 minutes on the Tokaido Shinkansen high-speed line (Central Japanese Railway Company, 2018). As 100% punctuality is unfeasible, it is also important that if traffic deviations occur, the propagation of delay remains limited. If a train is delayed, there may be conflicts with other trains (which means that two or more trains want to use the same infrastructure at the same time, which is impossible). To make the timetable conflict-free again, real-time adjustments have to be made like retiming, reordering and rerouting trains. Those adjustments are proposed and implemented by dispatchers based on their experience, guidelines and rules of thumb (Corman and Quaglietta, 2015).

Although dispatchers have expertise, they still have their limitations. They are not always able to fully understand the impact of their dispatching actions, in particular, if traffic densities are high or with heavy disturbances (Törnquist, 2012). To support dispatchers, since the 1990s automatic tools based on mathematical optimization models have been developed, which could support decisions of dispatchers in taking optimized decisions to minimize the impact of delays even over complex infrastructure layouts and traffic patterns. These *Train Management Systems* (TMS) or *Rail Traffic Rescheduling Models* (RTRMs) can vary in conflict detection models (which show where new conflicts may arise) and conflict detection and resolution models (which detect conflicts and offers conflict-free solutions which the dispatcher can implement).

## 1.2 Problem definition

Most researchers in this field agree that real-time RTRMs are effective. However, after more than 30 years of research in this field, there are hardly any examples of implemented and actively used rescheduling models resolving conflicts in the railway industry (Boccia et al., 2013). Various reasons may prevent infrastructure managers from using such a system to support or replace human dispatchers, which are described in section 2.1.3.

One reason is the unclarity of whether an RTRM is effective in reducing delays and improving punctuality for every infrastructure type and traffic pattern, as opposed to manual dispatching or simple dispatching rules. In the literature, most developed RTRMs are tested, simulated or implemented on a certain infrastructure layout with a certain traffic pattern. There is still not much literature about how the effectiveness and the overall benefits of such models are influenced by the type of traffic patterns and infrastructure layouts. This complicates deliberate decision-making by infrastructure managers regarding which RTRM to implement, while it is not known how these models (which are proved to be effective in one particular case study) perform on their particular network.

The Dutch infrastructure manager ProRail questions to what extent the performance of an RTRM is sensitive to differences in infrastructure and operational characteristics of a dispatching area. The purpose of this question is to gain more insight into whether a particular RTRM, developed and tested in one area, is adaptable and still effective in other dispatching areas with different infrastructure and operational characteristics.

This research is restricted to the evaluation of one RTRM which is alternative graph-based and suitable for conflict detection and resolution of disturbances. This alternative graph (AG) model is an often applied way to express the railway traffic rescheduling problem microscopically (Mascis and Pacciarelli, 2002). It models train operations (a train entering a block section, arriving or departing a station) as nodes, while the order of operations is modelled as the arcs that connect the nodes. Alternative arcs describe the choice of the sequence of trains at a given location. The model is suitable for retiming and reordering in case of disturbances. In the future, ProRail could use a microscopic model with such a model formulation. By applying this RTRM to different infrastructure layouts and traffic patterns, statements can be made on the effectiveness of this RTRM in different dispatching areas. In future research, the evaluation framework can also be used for the evaluation of other RTRMs.

To the best of our knowledge, no research has yet been conducted into the influence of infrastructure and operational characteristics on the performance of an RTRM.

## 1.3 Research objective

The objective of this research is to perform an analysis of an AG-based RTRM across different railway infrastructure layouts and traffic patterns for a set of disturbances to understand the applicability and effectiveness of those algorithms in mitigating delay impacts in different rail market segments and traffic conditions.

- This research provides insight into which infrastructure layouts and traffic patterns the selected RTRM performs relatively well or poor.
- It shows which infrastructure and operational characteristics affect the effectiveness of the rescheduling model.
- The methodology can be used and applied to other RTRMs to determine their sensitivity to network characteristics (which could be attractive for infrastructure managers to decide which rescheduling model to implement).

## 1.4 Research questions

The objective of this research can be caught in the following main research question:

> *How are the benefits provided by an alternative graph-based RTRM influenced by infrastructure layouts and traffic patterns?*

To answer the main question, the following sub-questions should be answered:

1. Which types of RTRMs exist and how are these evaluated in the literature?
2. How can an RTRM be implemented and evaluated over different infrastructure layouts and traffic patterns?
3. Which infrastructure, operational and disturbance scenarios are relevant to consider to evaluate an RTRM?
4. How sensitive is the performance of an RTRM to different infrastructure layouts and traffic patterns?

## 1.5 Report outline

In each of the chapters of the report, one of the different sub-questions is answered. Chapter 2 is aligned with the first sub-question and contains a literature review on the implementation and different forms of RTRMs and on how RTRMs are assessed in the literature, showing which Key Performance Indicators (KPIs), Simple Dispatching Rules (SDRs) and case studies are used.

Chapter 3 contains the methodology in which a methodological framework is proposed to evaluate an RTRM over different infrastructure layouts and traffic patterns and an RTRM is implemented (according to the second sub-question). Chapter 4 corresponds to the third sub-question where scenarios are developed for different infrastructure layouts (infrastructure scenarios), traffic patterns (operational scenarios) and disturbances (disturbance scenarios). In chapter 5 an analysis of the results is performed concluding how sensitive the performance of the observed RTRM is to different infrastructure layouts and traffic patterns. Chapter 6 contains conclusions by answering the research questions and recommendations for future research and to ProRail.

# 2. Literature review

This chapter refers to the first sub-question: 'Which types of RTRMs exist and how are these evaluated in the literature?'. By means of a literature review, it provides an overview of which research has been done within the field of microscopic real-time rescheduling for disturbances in the past years. In the form of a table, it provides an overview of general papers which perform a case study on which an RTRM is applied and evaluated. The goal of this literature review is to identify which types of real-time RTRMs exist and identify how these RTRMs can be evaluated.

Section 2.1 provides a general overview of which RTRMs exists and how rail traffic control using an RTRM functions. This is done by discussing a framework for rail traffic control based on the literature. A general classification of RTRM types is given and the complexity of implementing an RTRM is briefly discussed.

Section 2.2 contains an evaluation of 25 papers, in which RTRMs are developed and assessed on a certain case study. For all of these papers characteristics of the considered RTRM, evaluation method and case study(s) are listed in a table. In this section, it is also mentioned which papers apply a comparison of the performance and effectiveness of an RTRM on different infrastructure layouts and traffic patterns.

Section 2.3 provides a summary and concludes where there is a research gap.

## 2.1 Rail traffic control by an RTRM

As described in the introduction section, in a railway system perturbations can occur resulting in delayed trains which can lead to conflicts (two or more trains want to use the same infrastructure at the same time). These perturbations are managed through a set of control options like reordering, retiming or rerouting of trains (making use of the available infrastructure and capacity) to reduce the delay propagation over the scheduled traffic as much as possible. Traditionally rail traffic control is performed by human dispatchers. In the last decades, automatic tools based on mathematical optimization models are developed. These *Train Management Systems* (TMS) or *Rail Traffic Rescheduling Models* (RTRM) could support dispatchers in taking optimized decisions to minimize the impact of delays even over complex infrastructure layouts and traffic patterns.

### 2.1.1 Classification Rescheduling Models

In the variety of these developed rescheduling tools, models and algorithms, there is a distinction between models dedicated to disturbances and models dedicated to disruptions. Disturbances are relatively small perturbations that can be handled by retiming and rerouting trains, while disruptions are relatively large incidents, mostly with parts of the infrastructure unavailable for a certain period, requiring modifications of the timetable and the crew and rolling stock planning (Cacchiani et al., 2014). As stated in the introduction, this research is restricted to rescheduling models dedicated to disturbances.

Regarding disturbances, several models have been developed that address the real-time train rescheduling problem. The approaches differ from automatic systems with full automation control (Flamini and Pacciarelli, 2008) to only advisory decision support tools for the dispatcher (Schöbel, 2007). Table 2.1 contains a general overview of different characteristics belonging to RTRMs dedicated to disturbances. For a more extensive elaboration on the types of rescheduling models, we refer to Josyula et al. (2020).

*Table 2.1. Characteristics for RTRMs dedicated to disturbances*

| RTRM characteristic | Value |
|---|---|
| Infrastructure granularity | Macroscopic, mesoscopic and microscopic approach |
| Model formulation | Alternative graph-based, mixed linear integer programming-based and heuristic-based |
| Solution approach | Branch and bound, heuristics and commercial solver |
| Rescheduling actions | Retiming, reordering and rerouting |
| Objective (function) | Minimizing total delay, minimizing consecutive delay, maximizing punctuality and more (see section 2.2.3) |
| Control loop | Open-loop (one-time computation of an RTTP), rolling horizon open-loop (computation of an RTTP at a certain rescheduling interval) and closed-loop (continuous computation of RTTPs) |

Regarding granularity, in recent years mainly microscopic RTRM have been developed given the currently available computation power. It was therefore decided to limit this literature review to microscopic rescheduling models. Model formulation, solution approach, objective and rescheduling actions still differ in the literature. These are further discussed in section 2.2. The control loop indicates how often an RTRM is run to generate an RTTP, which is can be once (for example at the request of the dispatcher), at a certain rescheduling interval or continuously.

### 2.1.2 Control framework

To provide insight into how railway traffic control functions with the help of these RTRMs, a control framework from the literature is used and explained in the next paragraphs. This control framework, given in figure 2.1, corresponds globally with the framework presented in Corman and Quaglietta (2015).

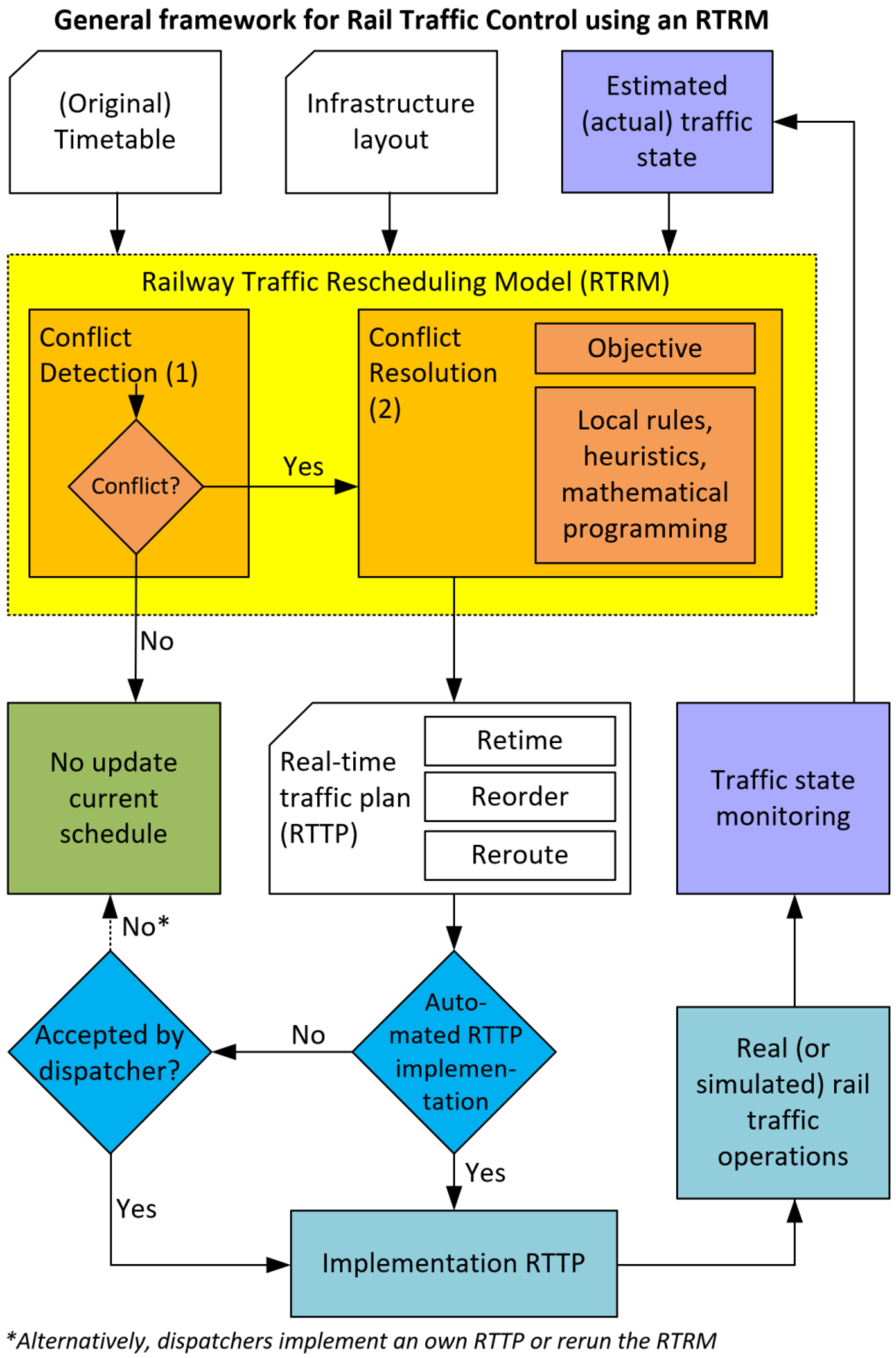



*Figure 2.1. A general framework for rail traffic control using an RTRM from literature*

As can be seen in figure 2.1, an RTRM uses as input the original timetable, infrastructure layout (with interlocking and signalling constraints) and the actual traffic state. The traffic state is estimated and predicted, based on data provided by sensors. As the sensors are not fully reliable, the traffic state prediction could be erroneous. The period for which a prediction is done is called the prediction horizon (Corman et Quaglietta., 2015).

An RTRM consists of two main elements namely the conflict detection and conflict resolution module, which are executed one after the other. In the conflict detection module, based on the traffic state prediction, timetable and infrastructure layout, conflicts are detected within the regarded prediction horizon. If no potential conflicts are detected, the original schedule does not have to be updated and can be maintained. If there are conflicts, the conflict resolution module should be run, which resolves the detected conflicts, by making use of local rules, heuristics or mathematical programming (Josyula et al., 2020). Depending on the implementation, either the conflict detection module has to be run again (to check whether new conflicts do arise) and a conflict-free solution is found in an iterative process, or the conflict resolution module finds immediately an conflict-free solution. This conflict-free solution is also called a *Real-Time Traffic Plan* (RTTP). An RTTP contains updated block entry times of the block sections (retiming), an updated sequence of trains (reordering) and route changes (rerouting). The objective function is often decisive in which RTTP the model outputs. In some implementations, the model provides diverse RTTPs, while the responsible dispatcher may choose which one to implement.

Depending on the level of automation the RTTP is accepted by a dispatcher or immediately the RTTP is implemented. If the plan is implemented, the interlocking and signalling systems are updated, train drivers are informed and travellers' information is updated (e.g. announcements of platform changes or delays). The time between the computation and the implementation of the plan is called the control delay (Corman and Quaglietta, 2015). If the RTTP is rejected by the dispatcher then the original plan is maintained, or the dispatcher carries out his own plan (based on his own experience or rules of thumb), or the dispatcher reruns the algorithm to get a different solution.

The framework in figure 2.1, is an open-loop or a closed-loop system, where the rescheduling model computes for every rescheduling interval or continuously new RTTPs. In an open-loop control cycle, an RTRM is run only once (e.g. on request of a dispatcher) and the arrow between 'Real rail traffic operations' and 'Traffic state monitoring' is missing.

### 2.1.3 Difficulties surrounding implementation of an RTRM

Although many papers state (based on a case study comparing an RTRM with simple heuristics like the FCFS rule) that the implementation of RTRMs is effective, there are only a few examples of implemented tools for real-time traffic control in the railway industry (Boccia et al., 2013). Possible issues that complicate the implementation of an RTRM are described below.

*Erroneous traffic information* - As shown in the framework in section 2.1.2, the actual traffic state should be monitored to be able to forecast future traffic state and predict where conflicts could occur. However, due to missing or erroneous traffic information (Corman and Quaglietta, 2015), it is hard to make an accurate estimate of the current traffic state, let alone forecast the traffic state in the future. Forecasts about the future traffic state are dynamic (Corman and Meng, 2014) and influenced by stochastic external disturbances (Corman and Quaglietta, 2015). This could cause an RTRM to resolve conflicts that in reality are not there at all, or conversely conflicts arise that are not detected by the conflict detection module.

*Control delay* - There is a certain time between the estimation of the actual traffic state and -finally- the implementation of an RTTP, the so-called control delay. This control delay can cause the RTTP to become infeasible or no longer the optimum solution at the time of implementation, since the traffic state may have changed in the meantime (Corman and Quaglietta, 2015).

*Limitations in size of the dispatching area* - Due to the required microscopic level and limited computation time, the size of the dispatching area controlled by one RTRM is limited (Corman and Meng, 2014; D'Ariano and Pranzo, 2009). In some papers, it is proved that a trade-off has to be made between how many variables to include in the model versus the desired computation time (Corman et al., 2010b; Corman et al., 2010c; D'Ariano et al., 2007a; Flamini and Pacciarelli, 2008). On the one hand, the calculated RTTP should be reliable and on the other hand, the RTTP should be found within a certain time. According to Larsen et al. (2013) the need to quickly find solutions has directed most efforts to develop advanced heuristic methods that find good solutions with a limited computation effort in rescheduling railway operations.

## 2.2 RTRMs and assessment in the literature

This section contains an analysis of which RTRMs have been developed and how they are assessed, based on 25 papers published in the last decades. Only papers are selected which develop and assess microscopic train-oriented RTRMs, dedicated to disturbances, to keep close to the research objective.

In many of these observed papers, a new model is proposed or an existing model is implemented for a specific case. Other papers address a certain problem (such as reduction of computation time) and make use of earlier developed models. All of these papers have in common that the development of a model is followed by a case study, in which the model is applied for certain scenarios and evaluated by using certain KPIs. Often the performance of an RTRM is also compared with the performance of some SDRs like FCFS or maintaining the original order. In most cases, only one case study is used.

An overall overview of analyzed papers can be found in table 2.2. This table indicates for each paper what type of model is used (expressed in model formulation, solution approach, rescheduling actions and objective function). In addition, it is indicated how the model is assessed (which KPIs and which SDRs -as reference material- are used, and how the KPIs are obtained). Furthermore, the table contains details about the case studies (indicating under which infrastructure configurations, traffic patterns and distribution instances the case studies have been performed).

For every paper, the (sub)goal of the paper (in relation to this research) is indicated, mostly cited from the abstract of the paper. If the research specifically focuses on one of the aspects in the table, this is marked with **.

*Table 2.2: Published literature in the research field of microscopic real-time rail traffic management models*

| Author (Year) | Goal paper | Mathematical model | Solution algorithm or method | Control actions | Objective function | KPIs | KPIs from RTTP or simulation | Simple dispatching rule (reference) | Case study (Type infrastructure) | Railway Market segment + infra. Configuration | Traffic pattern | # trains | # disturbance scenarios | Disturbance (stochastic processing times) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Caimi et al. (2012) | Proposal RTRM for Complex Central Station Area + considering many important rerouting options | MILP | Commercial MILP solver | RT RO L-RR** | Min weighed sum of reliability and passenger (dis)satisfaction | Tot delay, comp time | Simulation | - | Bern (Station Area) | Railway: SA + connected MLs+RLs** | Hetr: intercity, regional and freight trains | 1500 per day | Not specified | Initial delays (5-60 min) |
| Corman and Quaglietta (2015b) | Address influence RTRM on train performance when interfaced with railway operations | AG (ROMA) | Truncated B&B alg | RT RO | Min max cons delay | Avg tot delay, avg cons delay, max cons delay, punct (5 min), # and % reordered trains | Simulation | TO, FCFS | Utrecht - Den Bosch (Line) | Railway: ML (with overtaking) | Hetr: intercity (4) and regional (4) trains (alternating) | 8 per hour (one direction) | 30 | Initial delays (weibull distr), dwell time ext (weibull distr) |
| Corman et al. (2010b) | Present a RTRM to control trains in a network divided into two complex dispatching areas | AG (ROMA) | Truncated B&B alg | RT RO | Min max and avg cons delay (in lexicographic order) | Avg cons delay, max cons delay, comp time | | FCFS, ARI | Utrecht Centraal (Station Area) | Railway: SA + connected MLs | Hetr: intercity, regional and freight trains | 80 per hour | 540 | Initial delays {90} (avg 90s, max 390s), infrastr blockage scenarios {6} |
| Corman et al. (2010c) | Incorporate effective rescheduling algorithms and local rerouting strategies in a tabu search scheme | AG (ROMA) | Alternate fast heuristic & truncated B&B alg** | RT RO L-RR | Min max cons delay | Avg cons delay, max cons delay, comp time | RTTP | - | Utrecht - Den Bosch (Line) | Railway: ML (with overtaking) | Hetr: intercity, regional and freight trains | 40 per hour | 48 | Initial delays {24} (avg 320s, max 1000-1800s) + infrastr blockage scenarios {24} |
| Corman et al. (2011a) | Propose a multi-class rescheduling problem iteratively optimizing for different train classes | AG | Truncated B&B alg | RT RO | Min max cons delay (with steps/train classes 1,2,3,4) | Avg cons delay (per class), max cons delay (per class) | RTTP | - | Utrecht Centraal (Station Area) | Railway: SA + connected MLs | Hetr: intercity (34), regional (40) and freight (5) trains** | 79 per hour | 100 | Initial delays (avg 30s, max 675s) |
| Corman et al. (2011b) | Compare a RTRM (ROMA) with straightforward rules and the current approach in the Netherlands | AG (ROMA) | Truncated B&B alg | RT RO, RT RO L-RR** | Min sum cons delay | Avg tot delay, avg cons delay, max cons delay, punct (3 min), comp time | | TO, FCFS, ARI | Utrecht Centraal (Station Area) | Railway: SA + connected MLs | Hetr: intercity, regional and freight trains | 80 per hour | 65 | Initial delays {40} (weibull distr) + dwell time ext {15} (weibull distr) |
| D'Ariano et al. (2007a) | Develop a B&B algorithm, which includes implication rules enabling to speed up the computation | AG | Heuristics + truncated B&B alg | RT RO | Min max cons delay | Avg cons delay, max cons delay | RTTP | FCFS, FLFS | Schiphol (Station Area) | Railway: SA (bottleneck) | Hetr: intercity, regional and freight trains | 54 per hour | 60 | Initial delays (gaussian distr) |
| D'Ariano et al. (2007b) | Adopt an AG model, taking into account speed coordination issues among consecutive trains | AG | Heuristics + truncated B&B alg | RT RO | Min max cons delay | Avg tot delay, max tot delay, comp time | RTTP | FCFS, FLFS | Schiphol (Station Area) | Railway: SA (bottleneck) | Hetr: intercity, regional and freight trains | 54 per hour | 12 | Initial delays (gaussian/uniform distr, 14 or 27 trains, avg 30-125s, max 200-400s) |
| D'Ariano et al. (2008a) | Describe the implementation of a real-time traffic management system (ROMA) | AG (ROMA) | Truncated B&B alg | RT RO L-RR | Min max cons delay | Avg cons delay, max cons delay, comp time, % rerouted trains | RTTP | ARI, ARI + L-RR | Utrecht - Den Bosch (Line) | Railway: ML (with overtaking) | Hetr: intercity, regional and freight trains | 40 per hour | 36 | Initial delays {24} (avg 320s, max 1000-1800s) + infrastr blockage scenarios {12} |
| D'Ariano and Pranzo (2009) | Decompose a long time horizon into tractable intervals to be solved in cascade | AG | Truncated B&B alg | RT RO L-RR | Min max cons delay | Avg cons delay, max cons delay, comp time, # iterations | RTTP | FCFS | Utrecht - Den Bosch (Line) | Railway: ML (with overtaking) | Hetr: intercity, regional and freight trains | 40 per hour | 81 | Initial delays, rerouted trains, blocked trains, additional dwell times (for categories small/medium/large) |
| Fan et al. (2012) | Classify and compare problem models for rescheduling in railway networks | Dynamic programming, Decision tree-based elimination, Ant colony optimization alg, Tabu search, Simulated annealing, Genetic alg** | | RT RO | | Delay costs, comp time | RTTP | FCFS, Brute Force (considering all possible solutions) | North Stafford and Stenson (Junction) | Railway: J (with 4 MLs) | Hetr: intercity (4), regional (4) and freight (4) trains | 12 per 20 min | Not specified | Not specified |
| Flamini and Pacciarelli (2008) | Propose a RTRS for (metro) railway terminus + different nr of trains (vs comp time) | AG | Heuristics | RT | Min tardiness (weighted cons delay) and optimize headway (in lexicographical order) | Punct (2 min), regularity (metro), computation time | RTTP | - | Metro terminus | Metro: TA | Hom: sub-urban trains | 5, 10, 15, 20, 25, 30 per hour** | 60 | Initial delays (avg 120s, max 480s) |
| Josyula et al. (2020) | Propose evaluation framework and algorithms for train rescheduling | (1) heuristic-based (2) MILP-based exact alg** | | RT RO L-RR | (1) Min tot delay and min tot pass delay (2) Min tot del, tot pass del, tot cons del, track reassignments and deviations | Delay, delay propagation, pass delay, Punct., Comp time, Track reassignments, freight train performance | RTTP | Closeness to optimal point | Karlskrona - Malmö (Network) | Railway: N with MLs and LLs | Hetr: intercity, regional and freight (15%) trains | 81, 96 | 30 | Initial delays {10} (1 train, 7-25min) + additional tt {10} (1 train, 20-100% increase tt) + malfunctioning tracks {10} (1 track, 2-6 min additional tt for all trains) |
| Khosravi et al. (2012) | Propose three different modified versions of the shifting bottleneck (SB) procedure | MILP | 3 versions of shifting bottleneck heuristic** | RT RO L-RR | Min tot tardiness (weighted cons delay @dest) | Tot delay | Simulation | FCFS | London Bridge (Station Area) | Railway: TA + connected MLs | Hom: arriving and departing passenger trains | 27 per 30 min | 18 | Initial delays (0-15 min {minor}, 15-30 min {general}, 30+ min {mayor}) |
| Larsen et al. (2013) | Assess sensitivity of various rescheduling algorithms to variations in process times. | AG (ROMA) | Truncated B&B alg | RT RO | Min max cons delay | | Simulation | FCFS | Utrecht Centraal (Station Area) | Railway: SA | Hetr: intercity and regional trains | 80 per hour | 40 | Initial delays (weibull distr) + stochasticity in processing times {weibull distr}** |
| Mascis et al. (2008) | Develop new optimization models and algorithms for rail traffic management | AG | Fast heuristic alg | RT RO | Min tardiness (weighted cons delay) and energy consumption | Tardiness (weighted cons delay @dest), Energy c. | RTTP | FCFS (FIFO) | Breda (Junction) | High-speed: J | Hetr: high-speed and intercity trains | 10 | 2 | Initial delays |
| Mazzarello and Ottaviani (2007) | Introduction RTRM with speed regulation | AG | Heuristics + truncated B&B alg | RT RO L-RR | Min tot delay @dest | Avg tot delay @dest., Avg Tt, Punct (3 min) | RTTP | - | Schiphol (Station Area) | Railway: SA (Bottleneck) | Hetr: intercity and regional trains | 19,23,37,29,32 per hour** | Not specified | Initial delays (Pearson distr), dwell time ext (normal distr) |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Pellegrini et al. (2012) | Consider the timetable rescheduling problem for a given subset of trains delayed due to a disturbance in the network | MILP | Heuristics | RT RO L-RR | Min max cons delay | Comp time, # constraints, # variables | RTTP | - | Lille Flandres (Station Area) | Railway: SA + connected MLs | Hetr: high-speed and conventional trains and shunting movements | 589 per day | 30 | Initial delays (5-15 min, uniform distr, 20% random selected trains) |
| Pellegrini et al. (2016) | Assess actual impact of the application of RTRM | MILP (RECIFE) | Commercial MILP solver | RT RO, RT RO L-RR** | Min sum cons delay | Tot sec delay, energy consumption | Simulation | FCFS, most punct train first, real behaviour dispatchers** | Rouen-Rive-Droite (Line) | Railway: ML (with overtaking) | Hetr: passenger and freight trains | 47,38,27 per hour** | 31,25,4 | Initial delays (2 - 20 min), dwell time ext (2 - 15 min) |
| Quaglietta et al. (2013) | Address stability of railway dispatching plans | AG (ROMA) | Truncated B&B alg | RT RO | Min max cons delay | # reordering instructions, # reordered trains | Simulation | - | Utrecht - Den Bosch (Line) | Railway: ML (with overtaking) | Hetr: intercity and regional trains | 16 per hour | 30 | Initial delays (weibull distr) + dwell time ext (weibull distr, minor or major) |
| Quaglietta et al. (2016) | Introduces a framework for the automatic real-time management of rail traffic, designed for being standard and interoperable across different European railways | AG (ROMA) | Truncated B&B alg | RT RO L-RR | Min max cons delay | Max cons delay, sum dep delay @station | Simulation | TO | East Coast Main Line (London-Sandy), UK | Railway: HSL/ML | Hetr: high-speed (7), regional (18) and freight trains (4) | 58 per hour | 1 | Departure delay @station (10 trains, 180-520 sec) |
| | | RECIFE alg | | RT RO L-RR | Min sum cons delay @all stations | Max cons delay, sum dep delay @station | Simulation | TO | Utrecht - Nijmegen - Eindhoven (Network) | Railway: N with MLs and RLs | Hetr: intercity (8) and regional (12) trains | 20 per 30 min | 1 | Initial delay (10 min, 1 train) |
| | | AG (ROMA), RECIFE algorithm** | Both: Truncated B&B alg + RECIFE alg** | RT RO L-RR | Min max cons delay, Min sum cons delay @all stations | Max cons delay, sum dep delay @station | Simulation | TO | Iron Ore Line (Narvik - Svappavara/Sjiskja), Sweden | Freight: FL (single track) | Hetr: regional (3) and freight (12) trains | 15 | 1 | Speed restriction part line |
| Sama et al. (2015) | Develop a multi-criteria decision support methodology to help dispatchers in taking more informed decisions when dealing with real-time disturbances | MILP | Commercial MILP solver | | Min sum tot delay @main st./dest., Min sum cons delay @main st./dest., Min max tot delay @dest., Min max cons delay @dest., Min avg weighted delay @dest., Max punct, Min deviation schedule, Min sum arr **times @dest., Min sum tot tt. | Sum tot delay @main st./dest., sum cons delay @main st./dest., max tot delay @dest., max cons delay @dest., avg weighted delay @dest., punct, comp time, deviation schedule, sum arr times @dest., sum total tt. | RTTP | - | Utrecht - Arnhem - Den Bosch (Network) | Railway: N with MLs and RLs | Hetr: intercity and regional trains | 99, 154 | Not specified | Not specified |
| Thielen et al. (2019) | Present a Conflict Prevention Strategy (CPS) usable in practice and able to solve very large and complex networks, very quickly, and with good performance | | | RT RO L-RR | Min train delay, min pass delay** | Cons delay, pass delay, avg comp time, max comp time | Simulation | TO, FCFS | West and East Flanders (Network) | Railway: N with MLs and RLs | Hetr: intercity, regional and freight trains | 240 per hour | | Initial delays (exponential distr, avg 3 min, max 15 min, 20-80% random selected trains) |
| Toletti et al. (2020) | Propose a coordination approach for adjacent local rescheduling algorithms | MILP | Commercial MILP solver | RT RO L-RR | Min weighed sum of reliability and passenger (dis)satisfaction | Sum tot delay, comp time, # stops at signals, # bracking for route, # retimings, # reroutings | Simulation | TO | Part SBB Network | Railway: N with MLs and RLs | Hetr: intercity, regional and freight trains | Not specified | 5 | Not specified |
| Wegele et al. (2008) | Compare two advanced support systems for real-time rescheduling of train operations | AG (ROMA); Genetic Algorithm** | B&B algorithm; Heuristics** | RT RO | Min sum tot delay | Tot tt | RTTP | - | Utrecht - Den Bosch (Line) | Railway: ML (with overtaking) | Hetr: intercity, regional and freight trains | 40 per hour | 1 | Initial delays (two trains in network) |
| Xu et al. (2017) | Present a rescheduling model, which is able to solve the critical problem of effective disruption management | AG | | RT RO | Min cons delay | Sum tot delay | RTTP | TO, FCFS | Wuhan-Guangzhuou (Line) | Hight speed: HSL | Hetr: high-speed trains with different speed levels | 98 per day | 20 | Initial delays (Weibull distr), additional running time |
| # = number | | *AG = Alternative Graph, MILP = Mixed integer linear programming* | *Alg = Algorithm, B&B = Branch and bound* | *RT = Retime, RO = Reorder, L-RR = Local Reroute* | *Arr = Arrival, Cons = Consecutive, Dest. = Destination, Min = Minimize, Max = Maximum, Pass = Passenger, Tot = Total* | *Arr = Arrival, Cons = Consecutive, Dest. = Destination, Min = Minimum, Max = Maximum, Pass = Passenger, Punct = Punctuality, St.= Station, Tot = Total, Tt = Travel time* | | *TO = Timetable (Order) FCFS = Frist come first served, FLFS = First left first served ARI = priority rules L-RR = local rerouting* | | *FL = Freight line, HSL = High-speed line, J = Junction, ML = Mainline, N = network (more lines), RL = Regional line, SA = station area, TA = Terminal area* | *Hom = Homogeneous Hetr = Heterogeneous* | | | *Avg = average Distr = distribution Ext = extention* |

*** Paper is focused on this aspect*

In the following sections, the various parts of the table are further discussed. If necessary, conclusions are drawn based on these results.

### 2.2.1 Mathematical model and solution algorithms methods

In an RTRM the conflict detection and resolution module are often described as a job-shop scheduling problem. The job-shop scheduling problem is the problem of allocation of machines to competing jobs over time, subject to the constraint that each machine can handle at most one job at a time (Mascis and Pacciarelli, 2002). For the train rescheduling problem block sections (in which a maximum of one train can be located) are represented as machines and train operations (trains passing block sections) are represented as jobs. The order of how machines complete the jobs is fixed by constraints. There are different methods to model these constraints.

*Alternative graph (AG)* – An often applied way to model train rescheduling problems microscopically is to use AGs. In AGs, each train operation (a train entering a block, arriving or departing a station) is represented as a node (see figure 2.2, where two trains enter the same block section). 'Fixed arcs' are used to model the sequence of fixed train operations (in the sequence of block sections a train passes, the solid arcs in the figure). Using 'alternative arcs', the sequence of trains approaching a certain block section is determined (the dashed arcs in the figure). Alternative arcs are always paired with always one of both activated to determine the order of two trains. The solver selects the arcs for which the length of the longest path is minimized. This length equals the maximum consecutive delay (which an AG model minimizes). The consecutive delay is the difference between the final delay and the unavoidable delay (Corman and Quaglietta, 2015). The problem can be solved by the branch and bound method. AGs were introduced first by Mascis and Pacciarelli (2002). They are used in the real-time traffic management system called ROMA (Rail traffic Optimization by Means of Alternative graphs) developed by D'Ariano et al. (2008a). ROMA is used as RTRM in 10 more considered papers.

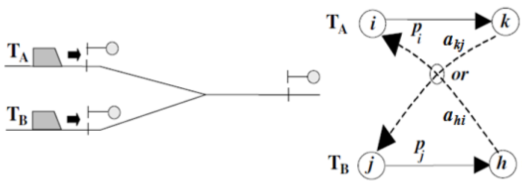



*Figure 2.2 Visualization AG formulation (D'Ariano et al., 2007b)*

*Mixed-integer linear programming (MILP)* – A way to model train rescheduling problems is using mixed-integer linear programming. The AG approach can also be formulated as a MILP, which allows more general objective functions. MILP uses binary variables indicating the order of successive trains and continuous variables representing the arrival and departure times of trains at stations (Cacchiani et al., 2014). Often a MILP is solved by a commercial solver or by heuristic methods. An example of an RTRM based on MILP is RECIFE, which is introduced by Pellegrini et al. (2014). It is also used in 2 more considered papers.

Table 2.2 shows that most papers focus on one specific rescheduling system, model, or algorithm. Only in a few papers, different RTRMs are compared or elements within an RTRM are adjusted (like the objective function). These papers are mentioned below:

- Wegele et al. (2008) state that there is a lack of computational studies that underline the practical value of dispatching support tools. It compares two advanced support systems namely the ROMA system (D'Ariano et al., 2008a) and the GADis (Genetic Algorithm Dispatching) system on a main line with some stations where trains can overtake each other.

- Fan et al. (2012) compare algorithms with different solvers like dynamic programming, decision three-based elimination, ant colony optimization, tabu search, simulated annealing and generic algorithm. It concludes which algorithms are appropriate in simple and complex scenarios and which algorithms are the quickest and simplest methods.
- Quaglietta et al. (2016) compare two different rescheduling models (the ROMA system (D'Ariano et al., 2008a) and the RECIFE (Pellegrini et al., 2014)) on different case studies (high-speed line, conventional network with main lines, single track freight line). For the last case study, both models are applied for the same traffic structures and disturbance scenarios.
- Josyula et al. (2020) propose an evaluation framework for railway rescheduling algorithms and experiment to compare two multi-objective algorithms (a heuristic versus a MILP-based algorithm) using the proposed framework.

### 2.2.2 Rescheduling actions

In disruption management rescheduling actions like retiming, reordering and local rerouting are the most common. Local rerouting is changing routes within interlocking areas, like platform changes at stations (not to be confused with global rerouting). In the literature, most papers apply retiming and reordering, while local rerouting is applied in only 15 papers. The complexity of the problem increases when more rescheduling actions are considered (Corman and Quaglietta, 2015). RTRMs, only using rescheduling actions retiming and reordering, are often modelled by AG formulation. If local rerouting is considered MILP formulation is often applied, as the original AG model cannot be used for rerouting. With some adaptions, AG formulation can be used for local rerouting as well (Corman et al., 2010c).

### 2.2.3 Objective function

As can be seen in table 2.2, there is no generic objective function for the timetable rescheduling problem. The chosen objective function is often formulated in such a way that what is important from infrastructure managers perspective, is optimized. This in turn can depend on the regulations or performance requirements set by the government.

In many proposed RTRMs, the objective function is limited to one aspect such as minimizing the total delay or maximizing punctuality (Corman and Quaglietta, 2015). Another approach is weighing combinations of aspects in one objective function, such as in Caimi et al. (2012). Other papers use more than one objective, which are solved in lexicographical order (Corman et al., 2010b; Flamini and Pacciarelli, 2008). Corman et al. (2011a) optimize in different steps for different train categories (trains with the same stopping pattern and speeds, like intercity trains or regional trains) to prioritise more important train categories.

In most papers, the objective value is determined at the point trains leave the area and is summed equally over the trains. Some papers apply a weighting factor based on train priorities, like in Khosravi et al. (2012).

A comparative analysis between RTRMs with different objective functions is seldom performed in the literature. In Sama et al. (2015) 11 different objective functions are evaluated for a case study of a part of the Dutch railway network. 11 solutions optimized for the different objective functions are evaluated against each other using the 11 objective values as KPIs. In Thielen et al. (2019) a comparison is done between the minimization of train delay and passenger delay as an objective function of the RTRM.

In most cases, the objective is also used as one of the KPIs. The objective as a KPI is a suitable measure to demonstrate to what extent the model can achieve its own objective. For this reason, the different objectives used in the literature are not discussed separately here, but can be found under the next section about KPIs.

### 2.2.4 Key performance indicators (KPIs)

In the assessment of RTRMs, KPIs are often used to express the performance of an RTRM. KPIs are also used for other purposes such as to evaluate a timetable (as in Goverde and Hansen (2013)), to evaluate an RTTP, as a tool for dispatchers to choose from different RTTPs (Corman et al., 2012; Sama et al., 2015) or are processed in the objective function of the model (Corman and Quaglietta, 2015). Not all papers mention literally 'KPIs', often they speak about 'evaluation of results'.

As shown in table 2.2, in some papers the values of the KPIs are directly obtained from the RTTPs. Other papers obtain the KPIs from a simulation in which an RTRM is used for rail traffic control. If more than one (disturbance) scenario is used (for which an RTRM is applied), the KPIs are averaged over the different scenarios.

The KPIs found in the literature can be classified into KPIs related to delay, punctuality, computation time of the algorithm and various other KPIs, which are discussed in the following paragraphs.

*Delay* – In almost all investigated papers, the delay is used as KPI albeit in different forms. A first distinction between 'delays' is the final delay and consecutive delay. The total delay or final delay is the difference between the actual and scheduled arrival time and also includes primary delays (e.g. initial delays). The consecutive delay is the difference between the final delay and the unavoidable delay (Corman and Quaglietta, 2015). Because the consecutive delay gives an extent of how much trains are hindered by other trains, due to conflicting operations (Corman and Quaglietta, 2015), it is used more often in the literature. Another distinction is the use of the sum, average or maximum delay over the trains.

There are different approaches which locations are taken into account for the computation of the delay: Most common is the usage of the terminus of a train, or the point that the train leaves the controlled dispatching area. Another approach is also using the main intermediate stops so that the importance of arriving on-time at the intermediate stations is also taken into account by the KPIs.

Thielen et al. (2019) and Josyula et al. (2020) also use passenger delay as a KPI, which is a good measure from the perspective of the users of the network. For passenger-oriented rail traffic rescheduling, we refer to Josyula and Törnquist (2017). Besides most papers use more than one KPI for the delay, such as Corman and Quaglietta (2015) who use average consecutive delay, average total delay and maximum consecutive delay.

*Punctuality* – Punctuality is used as KPI in two different forms in the literature, namely the percentage of early and on-time trains or the percentage of delayed trains, for various threshold values (Josyula et al., 2020). The punctuality KPI can be calculated for the trains leaving the area or having their terminus in the area. Another way to determine punctuality is to include all main stations. Although this KPI says something about the number of trains that are delayed, nothing can be said about the size of the delays based on this KPI.

*Computation time* – The time required by the algorithm to calculate an RTTP is used as a KPI in various papers. This is also relevant given the limited time available in practice for calculating the solution. This KPI is also used in papers where smarter heuristics are tested that would influence the computation time. D'Ariano and Pranzo (2009) also use the number of iterations, and

Pellegrini et al. (2012) also use the number of constraints and the number of variables as an indicator of problem complexity to evaluate the quality of the algorithm.

*Energy consumption, variation rolling stock, variation crew, regularity (interval between trains) and Throughput (Bottlenecks)* – Various other factors that depend on real-time traffic rescheduling can be included as KPI. This list can be supplemented according to the objectives of the parties involved.

### 2.2.5 Simple dispatching rules (SDRs)

The KPI can help provide insight into the performance of an RTRM. However, reference material is needed to show how beneficial an RTRM is. In the literature, simple dispatching rules (SDRs) or simple heuristics are used for this purpose, which represents the null situation if an RTRM had not been applied. These SDRs are often used by dispatchers as a rule of thumb in the decision-making process (D'Ariano, 2007a).

Decisions made by dispatchers themselves are the best reference material, but the lack of good material and complexity to carry out this comparative analysis means that the literature often turns to SDRs that represent the decisions of dispatchers in a limited sense. This can be done by developing scenarios where you ask dispatchers what they would do, or by simulating a real scenario from historical traffic data (with revealed decisions from dispatchers). In Pellegrini et al. (2016) a comparison between an RTRM based on a MILP formulation and human dispatchers is performed. This is done by analyzing three scenarios based on historical traffic data (with revealed decisions from dispatchers). This approach can only be used for a limited number of scenarios (dependable on the available data) and requires a highly accurate simulation to make a fair comparison.

The following SDRs are used in the literature to compare an RTRM against:

*Timetable order (no interventions)* – The original planned order and succession of trains are maintained, according to the timetable.

*First come first served (FCFS) or First in first out (FIFO)* – The trains able to enter a block section first are served first. This SDR does not take into account further downstream effects.

*First left first served (FLFS)* – Trains able to leave a common section first are served first. In D'Ariano et al. (2007a) an FLFS approach is proposed. FLFS is a compromise between two commonly used dispatching rules of (i) giving priority to the intercity trains over the regional trains and (ii) giving precedence to the train arriving first. This approach is especially beneficial for intercity trains, while regional trains have to give priority even at small delays and may therefore receive a high additional delay.

*Predefined priority rules* – In various papers predefined priority rules are used to simulate dispatcher behaviour, which work according to certain dispatching rules. One approach is prioritizing punctual trains over delayed trains, which is used in Pellegrini et al. (2016). Another approach is prioritizing train categories over other train categories. Corman et al. (2010b; 2011b) and D'Ariano et al. (2008a) introduce an 'ARI-like' dispatching approach, derived from the Dutch automatic route setting system ARI (Automatische Rijweg Instelling). It assigns the sequence of trains according to the timetable for conflicting trains requiring the same track and according to the FCFS rule for conflicting trains requiring different incompatible tracks, if both conflicting trains have an initial delay below 3 minutes. If at least one of the conflicting trains is delayed by more than 3 minutes, conflicting trains are scheduled based on train priorities.

### 2.2.6 Infrastructure types

As shown in table 2.2, most papers contain only one case study on which an RTRM is applied and tested. Most of the papers apply a case study on a certain mainline (ML) or station area (SA). In more recent papers also case studies are applied to larger networks (N), which require more computational power or efficiency. In only two papers (Flamini and Pacciarelli, 2008 and Khosravi et al., 2012) a terminal area (TA) with turning trains is used. Mascis et al. (2008) and Fan et al. (2012) use a junction as a case study. In addition, some papers use specific infrastructure topologies, which are suitable to test different frequencies on. This is done by D'Ariano et al. (2007a) and Mazzarello and Ottaviani (2007) who use the Schiphol Station Area as infrastructure layout.

The papers written by Quaglietta et al. (2016) and Mazzerello and Ottaviani (2007) are the only reviewed papers in which more case studies on different railway market segments are used. However, both papers apply different RTRMs for the cases and are not written and intended to compare the performance of an RTRM on different railway market segments. In the literature, no papers are found comparing the performance of RTRMs on different infrastructure configurations (with the same rescheduling model and under the same operational conditions). In most case studies conventional infrastructure configurations are used (like main lines with heterogeneous traffic consisting of intercity and regional passenger trains and freight trains). Only in a few of the regarded researches, a high-speed line (HSL), a dedicated freight line (FL), or a sub-urban railway line is used. A reason for this could be that on these types of infrastructure, rail traffic is more homogeneous and it could be argued that the consequences of rail traffic control actions are limited. In most cases, rail traffic in both directions is considered. In only one of the considered researches, a single track line is considered, namely in Quaglietta et al. (2016).

### 2.2.7 Traffic patterns

As shown in table 2.2, in most of the case studies a heterogeneous traffic pattern is used. These traffic patterns are composed of trains from different train categories. Train categories are trains with the same stopping patterns and speeds *as* regional/commuter trains, intercity/long-distance trains, high-speed/international trains and freight trains.

An advantage of investigating heterogeneous traffic patterns is that the impact of dispatching decisions is higher in general (for example if an intercity train is running behind a regional train without the possibility to pass). The only case studies in which homogeneous traffic patterns are used are applied to a terminal area, where all trains have to stop at the terminal and have logically the same speed (so different traffic patterns would not make sense).

Pellegrini et al. (2016) is the only reviewed paper which investigates different traffic patterns. They compare timetables at different times of the day, namely at the peak hour (with relatively many passenger trains), in the period between peak and off-peak, and during off-peak hours (with relatively many freight trains). However, for the different timetables also different disturbance scenarios are used and no statements are made about the performance of the evaluated RTRM over the different traffic patterns. In Flamini and Pacciarelli (2008) and Mazzerello and Ottaviani (2007), the number of trains is varied over a period and statements are made about the performance of the evaluated RTRM under different operational conditions. These papers prove that the consecutive delay and computation time increase as the frequency increases. However, no statement has been made on whether an RTRM performs better in comparison to other control strategies (or dispatchers) if the frequency changes.

### 2.2.8 Disturbances

As shown in table 2.2, the following kind of disturbances is applied in the case studies belonging to the evaluation of an RTRM in the literature.

- *Initial delays* – where a set of trains are delayed (at the location they enter the network). In some papers, delayed trains are randomly selected. The initial delays vary from 0 to 30 minutes and are mostly randomly chosen with a Weibull, Gaussian or uniform distribution.
- *Dwell time extensions* – where some trains have a longer dwell time at a station than planned. Often dwell time extensions are randomly chosen with a Weibull or uniform distribution.
- *Stochasticity in processing times* – where stochasticity in running times of trains is incorporated in the evaluation of the RTTP obtained from an RTRM, as done in Larsen et al. (2013).

Some papers use specific cases, with only a few disturbance scenarios. In most papers, more than 15 disturbance scenarios are used to ban out the influence of randomness on the results. In some papers, a classification in the size of the delay is used like in Khosravi et al. (2012) with minor, general and major delays.

## 2.3 Summary

In summary, it can be concluded that for most of the considered papers, the assessment of an RTRM remains limited to one case study (with a certain infrastructure topology and a certain traffic pattern) on which an RTRM is applied and assessed.

A few papers are comparing different (forms of) RTRMs namely Wegele et al. (2008) (AG-based vs genetic algorithm), Quaglietta et al. (2016) (AG vs MILP algorithm) and Josyula et al. (2020) (heuristic-based vs mixed-integer based algorithm). Different solution algorithms or heuristics are compared by Mannio and Mascis (2009) (2x), Fan et al. (2012) (6x), Khosravi et al. (2012) (3x) and Törnquist (2012) (2x). Comparisons are also made for different objective functions by Sama et al. (2015) (11x) and Thielen et al. (2019) (2x). However, the comparisons between algorithms are limited to only one case study.

Some papers conduct different case studies on different infrastructure configurations as Quaglietta et al. (2016) (high-speed line, conventional railway network and freight line) and Mazzerello and Ottaviani (2007) (bottleneck station area, mixed freight and passenger lines). However, in both papers, traffic patterns are different over the case studies and even different RTRMs were used. Therefore, no direct comparisons are made between the different case studies for the performance of an RTRM.

Some papers observe different traffic patterns (for one specific infrastructure configuration). Pellegrini et al. (2016) investigate for one layout (mainline with overtaking possibility) different traffic patterns namely a heterogeneous traffic pattern and a traffic pattern mainly consisting of freight trains. In Mazzarello and Ottaviani (2007) (bottleneck station area) and Flamini and Pacciarelli (2008) (metro terminus), the frequency of trains is varied. These papers conclude that as the frequency increases the computation time and the total delay increase, however, statements about the relative improvement by the algorithm versus human dispatching remain undiscussed. Mentioned papers are limited to only one infrastructure configuration (nothing can be said for example about single track regional lines). No papers are testing the performance of an RTRM under varying running time supplements.

In conclusion, no papers are found that investigate the sensitivity of the performance of an RTRM to different infrastructure configurations under the same operational conditions. In addition, the performance of an RTRM versus different operational conditions has been seldomly investigated (however only for limited kinds of infrastructure configurations). So, there is still not much literature about how the effectiveness and the overall benefits of an RTRM are influenced by the type of traffic patterns and infrastructure layouts. This literature gap is hence filled in by the research in this thesis.

# 3. Methodology

This chapter refers to the second sub-question: ‘How can an RTRM be implemented and evaluated over different infrastructure layouts and traffic patterns?’. It describes the used methodological framework to evaluate an RTRM over different infrastructure layouts and traffic patterns and how it is implemented.

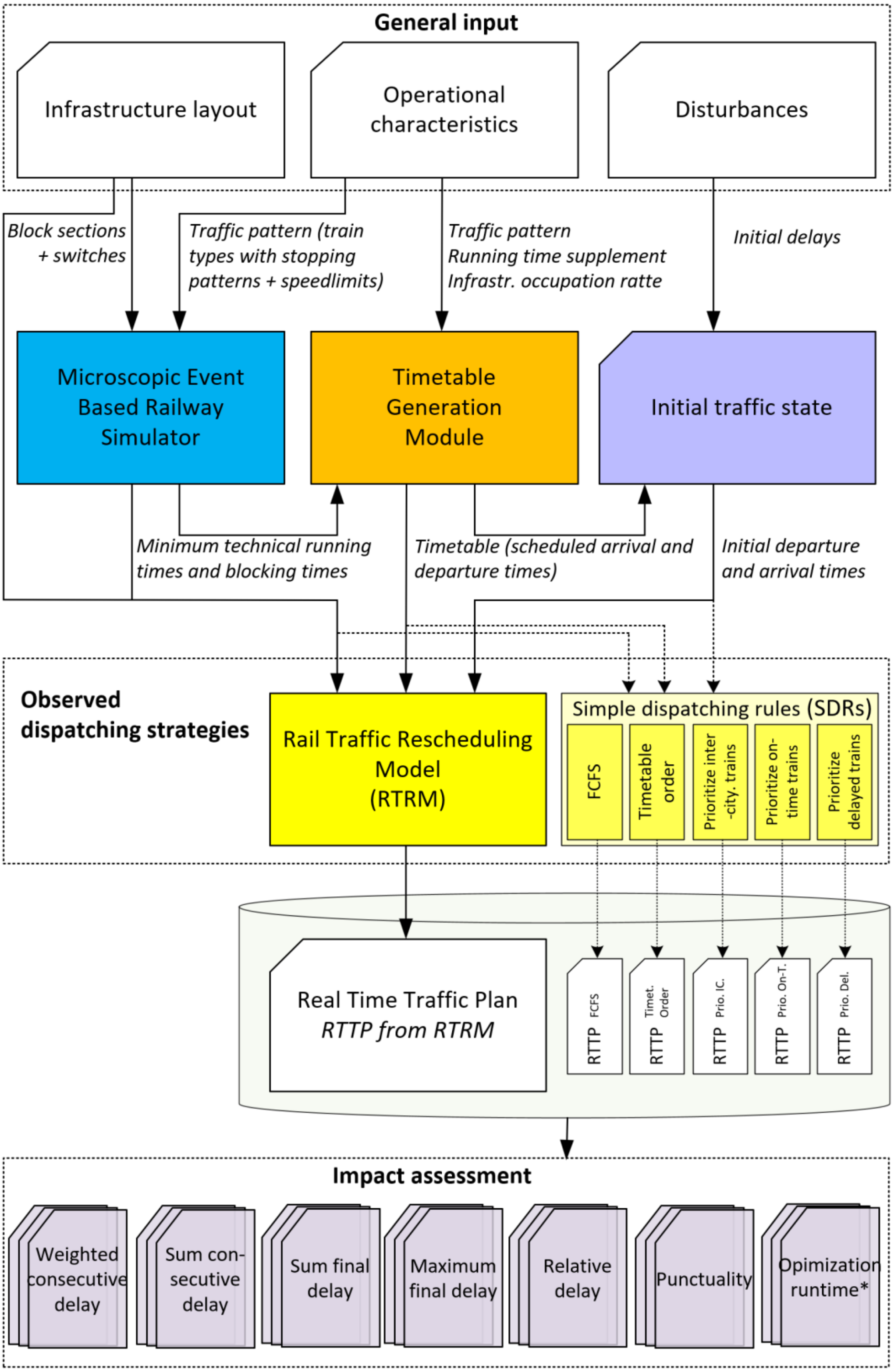
In section 3.1 a methodological framework is proposed to assess an RTRM on different infrastructure layouts and traffic patterns. It indicates which inputs are used for the framework, which SDRs are used as comparative material and how the obtained RTTPs are evaluated by KPIs.

In section 3.2 details are given about the used alternative graph-based RTRM with its problem formulation and used objective function.

Section 3.3 provides an overview of the used RTRM, KPIs and SDRs in the framework.

## 3.1 Methodological framework for assessing RTRM

To perform a comparative analysis for a certain RTRM over different infrastructure layouts and traffic patterns, an evaluation framework is developed. A schematic overview of this framework can be found in figure 3.1. In the next sections, different aspects of the framework are more specified.




*KPI only used for RTTPs from RTRM

*Figure 3.1. Schematic overview methodological framework of RTRM over different infrastructure layouts, traffic patterns and disturbances*

Central in the framework is the RTRM which is evaluated across different infrastructure and operational scenarios with a set of disturbance scenarios. The RTRM generates an RTTP for each scenario. This is done once for every disturbance scenario (in reality at the beginning of a control period), so an open-loop approach is used.

The initial traffic state contains the initial departure and arrival times, which are derived from the original timetable, and randomly generated disturbances. These disturbances consist of randomly generated initial delays (which are forecasted in the real world). Disturbances like dwell time extensions and travel times extensions are not regarded, as they are not known at the moment of computation (see also section 4.3).

A microscopic event-based simulator is used to obtain the minimum technical blocking and running times. These are used to develop conflict-free timetables and these are used in the RTRM (so to generate a conflict-free RTTP).

In parallel to the RTRM, also RTTPs are generated by using SDRs to express the relative improvement by the RTRM in comparison to these SDRs. These RTTPs are also assessed using KPIs. In this way, the relative difference or improvement with the RTTP of the rescheduling model can be expressed.

### 3.1.1 General input

As shown in figure 3.1, the general input of the framework is the infrastructure layout, the traffic pattern (from which timetables can be generated) and disturbances. More details on which infrastructure layouts, traffic patterns and disturbances are used, can be found in chapter 4. This section only describes how these are related to the framework.

*Infrastructure layout* – The infrastructure layout is made up of different block sections and switches that are connected in a certain way and together form a layout. For the block sections, the lengths and speed limits are specified. For the switches, the connected block sections are specified. It is used as input for the simulator (to obtain minimum blocking and running times) and as input for the RTRM.

*Operational characteristics* – The operational characteristics are used to generate the timetables for the different infrastructure and operational scenarios (in the timetable generation module). It contains the traffic pattern (which includes train types, with routes, stopping patterns and speeds, and the sequence of trains), running time supplement and infrastructure occupation rate (which is used as variable, instead of frequency, from which the timetable cycle time is computed in the timetable generation module). The infrastructure occupation rate is the minimum technical cycle time (the minimum time required to operate trains of one timetable cycle, on a given railway infrastructure according to a given traffic pattern) in percentage over the timetable cycle time. It thus depends on the traffic pattern and running time supplement. By fixing the infrastructure occupation rate (and not the timetable cycle time or frequency) for all scenarios (independent of layout, traffic pattern and running time supplement) the same share of the capacity of the infrastructure is used. The traffic pattern (including train types, with routes, stopping patterns and speeds) are used as input for the simulator (to obtain blocking and running times). The traffic pattern, running time supplement and infrastructure occupation rate are used for the timetable generation, where for each infrastructure and operational scenario conflict-free timetables are developed.

*Disturbances* – The disturbances contain randomly generated initial delays (see also section 4.3). Together with the original timetable, they feed the initial traffic state (which is in reality measured and predicted).

### 3.1.2 Timetable generation module

As it is not possible to use the same timetables for all layouts (due to differences in typology), for each layout and predefined operational characteristics, the timetables are generated separately per layout in the timetable generation module. This self-developed tool enables comparing the performance of an RTRM on different layouts, but with the same operational characteristics (e.g.

comparing two different layouts, both with a homogeneous traffic pattern and with the same running time supplement and infrastructure occupation rate). This module uses the minimum blocking and running times from the microscopic event-based simulator plus the operational characteristics (traffic pattern, running time supplement and infrastructure occupation rate) to generate conflict-free timetables.

The running time supplement is processed by extending the minimum technical running times by a multiplication factor. This results in a running time supplement that is evenly distributed over the entire ride. Note that this is an approximation, as in practice the running time supplement is not evenly distributed over the ride (more concentrated to the last part of a ride, due to coasting). At intermediate stops, the same multiplication factor is used for the dwell time supplement.

The timetable cycle time (the interval between the start of two subsequent timetable cycles) is computed based on the traffic pattern, running time supplement and predefined infrastructure occupation rate. The first step is computing the minimum technical cycle time based on the blocking times of the trains. Subsequently, the timetable cycle time (in seconds) is computed by dividing the minimum technical cycle time by the infrastructure occupation rate (in percentage).

The timetables are formulated through a plan with scheduled arrival times (at the location trains enter the considered dispatching area), scheduled departure times (at intermediate stations) and scheduled arrival times (at the location trains leave the considered dispatching area). The intermediate stations are expressed by block sections where trains should call.

### 3.1.3 Microscopic event-based railway simulator

To compute the minimal technical blocking and running times for the different infrastructure layouts and traffic patterns, an existing microscopic event-based railway simulator is used. This simulator uses as input the infrastructure layout (expressed in block sections with their lengths and switches) and the traffic patterns (expressed by routes, stopping patterns and speeds of trains in one timetable cycle). For the purpose of this research, trains are simulated separately resulting in realistic minimum technical blocking and running times.

The simulator uses the equations of motion, with a constant acceleration and deceleration rate (which is the same for all trains). It does not include track gradients. Trains have a length of 160 meters, which corresponds with the length of a train with 6 coaches (like VIRM-6 or SLT-10 in the Netherlands).

At intermediate stops, trains stop 10 meters in front of the signal of the next block section. The default (minimum) dwell time at a stop is 60 seconds, which is sufficient for intermediate stops of regional or commuter trains.

The approach time is computed by using the braking curve of the train to determine how many block sections are required to be unoccupied to realize a green signal. The signalling system in the simulator makes use of block signalling and is comparable with ERTMS level 1 or 2.

The setup time (the time it takes before the infrastructure is ready) is set to 1 second, while for block sections containing switches and the block sections where trains enter the dispatching area it is set to 6 seconds. The sight and reaction time is set to 10 seconds. The release time (the time to unlock the system for the next train) is set to 2 seconds.

The minimal technical blocking and running times found for each train plus the running time supplements are used in generating the conflict-free timetables and are used in the RTRM (to generate a conflict-free RTTP).

Any discrepancies between the values found from the simulator and reality are supposed to be irrelevant for this research (since it is focused on the assessment of the RTRM).

### 3.1.4 Simple dispatching rules (SDRs)

To be able to show the effectiveness of an RTRM, also SDRs are used to compare the performance with. The relative difference between the KPIs obtained from the SDRs versus the RTRM is a measure of the 'benefit' of using this RTRM. As stated in the literature review, it should be noted that an SDR is not the same as a dispatcher in the real world. These are rules of thumb, which could be used by dispatchers (D'Ariano, 2007a) or are executed if the dispatchers do not intervene (like maintaining the original order). They can be used as a means of expressing the benefits of RTRM (subject to it being only an approximation of how dispatchers operate).

Next to in the literature commonly used SDRs 'Timetable order' and FCFS, priority rules are also applied. These rules are prioritizing intercity trains, on-time trains and delayed trains. The FLFS rule is not considered because it is more difficult to model and the results are roughly comparable to prioritizing intercity trains (as intercity trains are often the first to leave a common route).

A consideration of how these dispatching rules are used in the literature can be found in section 2.2.5. Below for each SDR, it is briefly described why this SDR is used and how it is modelled.

*First come first served (FCFS)* – This SDR prioritises trains that approach first at a shared block section. With this rule, sequence changes can take place if a train is late, so that trains as little as possible have to wait for other (delayed) trains. Because FCFS does not require trains to wait for other trains (at the decision point), FCFS may already provide the best-performing solution for a high amount of scenarios.

The rule is modelled by first computing the earliest possible entry times at the block sections for all the trains subject to timetable and initial delay constraints. Accordingly, with the conflict detection module potential conflicts are identified. The conflict that occurs at first is resolved by delaying the train which approaches the block section last. The earliest possible block entry times of this train are adapted accordingly (by using the minimum running times from the simulation). This process of detecting and resolving conflicts continues until the timetable is conflict-free.

*Timetable order* – This SDR forces trains to run according to the order of the timetable so reordering is forbidden (it only considers retiming). In fact, this dispatching rule is equivalent to 'no intervention'. For that reason, this SDR is interesting to consider when comparing the performance of an RTRM in relation to the 'no intervention scenario'. An advantage of this approach is that a deadlock situation cannot arise (the situation where trains cannot continue due to the chosen sequence) because the order of the timetable never results in a deadlock.

For this rule, the same model and mathematical formulation are used as the optimization model, but the sequence of trains is fixed so that the original order of the timetable is maintained and only retiming is allowed. The optimization model minimizes scheduled event times at all timetable points.

*Prioritise intercity trains* – This SDR prioritises trains with a higher priority if a conflict occurs. For trains from the same category, FCFS is applied. This rule should perform especially well in the situation of delayed intercity trains in comparison to FCFS: FCFS might prioritise the on-time regional train, resulting in the intercity train running behind the regional train building up additional delays.

The computation procedure works the same as FCFS, however, in the case of a conflict between trains from a different category, the train from the lowest category is delayed. An exception to this rule is the situation where both trains have the same origin and the infrastructure does not provide room for overtaking yet. Then still FCFS is applied so that no sequence changes are forced outside of the considered dispatching area.

*Prioritise on-time trains* – This SDR prioritises on-time trains over delayed trains if a conflict occurs. This approach minimizes the spillback from delays on other trains, so that trains that enter the considered dispatching area on-time, should remain punctual when they leave the area.

The approach of this rule works the same as the prioritise intercity trains rule, but now on-time trains are prioritised. Trains are regarded as on-time if the initial delay is smaller than 3 minutes (which is also the threshold value for the punctuality KPI). Note that with this approach trains that are entering the dispatching area on-time, are considered as 'on-time' the entire ride, also if they are delayed somewhere during the ride (the same holds for the prioritise delayed trains rule).

*Prioritise delayed trains* – This SDR prioritises delayed trains over on-time trains if a conflict occurs. This rule makes optimal use of the available running time supplement because it usually only delays on-time trains, which still have some buffer time available (and can therefore make up for this additional delay).

The approach of this rule works the same as the prioritise intercity trains rule, but now delayed trains are prioritised. Trains are regarded as delayed if their initial delay is larger than 3 minutes, like the prioritise on-time trains rule.

### 3.1.5 Evaluation with KPIs

The RTTPs obtained from the RTRM (and from the SDRs) are evaluated by making use of KPIs. The used KPIs are the sum consecutive delay, the weighted sum of consecutive delay, the sum final delay, the maximum final delay, the relative delay, punctuality and the optimization runtime. The weighted sum of consecutive delays is also used in the objective function of the used RTRM (see section 3.2.2), so for this KPI, the RTRM is expected to perform best. The other KPIs are common in the literature and could help to understand and analyze the results. A consideration of how these KPIs are used in the literature can be found in section 2.2.4. Below for each KPI, it is briefly described why it is used and how it is modelled.

*Sum of consecutive delay* – This KPI is used to express the additional delay that occurs in the considered dispatching area due to hindrances with other trains. For every train, the consecutive delay is determined by subtracting the earliest possible arrival time (subject to timetable and initial delay constraints) from the actual arrival time according to the RTTP, at the location where trains leave the considered dispatching area. The consecutive delay is summed over all the trains. In this way, this KPI is a measure of the extent to which the used RTRM (or the used SDR) can limit the propagation of delays in the controlled dispatching area.

*Weighted sum of consecutive delay* or *weighted consecutive delay* – This KPI is computed in the same way as the sum consecutive delay KPI. However, now a train-specific weighting factor is applied, which is the same factor as in the objective function. As the used RTRM minimizes the weighted sum of consecutive delay, this KPI also indicates how well the model performs in achieving its own objective.

*Sum of final delay* – Instead of the previous discussed KPIs, this KPI does include the initial delay. For every train, the final delay is computed by subtracting the planned arrival time according to the schedule from the actual arrival time according to the RTTP at the location where trains leave the considered dispatching area. The final delay is summed over all the trains.

*Maximum final delay* – This KPI has been added to indicate whether one train is disproportionately delayed (to reach the objective). Large delays of a train could cause staff or rolling stock to be late for the next journey, making it undesirable for this train to be delayed so much (note this is not included in the objective of the RTRM). The maximum final delay is computed by taking the maximum of the final delay over all trains.

*Relative delay* – The previously discussed KPIs depend on the size of the initial delay. After all, if there is more initial delay, there will presumably also be more consecutive delay. Therefore, the relative delay is added to the KPIs to investigate this relationship, which is calculated as the factor of the sum of consecutive delay divided by the initial delay.

*Punctuality* – Indicates how many trains leave the considered dispatching area on-time within a margin of 3 minutes.

*Optimization runtime* – This KPI is only used for assessing the RTRM (not the SDRs) and indicates how many seconds it takes the algorithm to generate an RTTP.

### 3.1.6 Limitations framework

This section recalls the limitations and assumptions of the framework. These are motivated and explained in the previous subsections.

*Assumptions in the microscopic event-based simulator* - In the simulator, which is used to compute the minimum technical running times, the following assumptions were made:

- Train properties are fixed: constant acceleration and deceleration rate, trains have a fixed length of 160 meters.
- The setup time is assumed to be 1 second for standard block sections, for block sections containing switches it is assumed to be 6 seconds.
- The sight and reaction time is assumed to be 10 seconds.
- The release time is assumed to be 2 seconds.
- Track gradients are not included
- At intermediate stations, trains stop 10 meters in front of the signal of the next block section. The default (minimum) dwell time at a stop is assumed to be 60 seconds.

*Assumptions speed profile timetable* - In the distribution of the running time supplement, the running time supplement was divided equally over the ride using a multiplication factor. The same multiplication factor was used for intermediate stations, resulting in the dwell time supplement being equal to the running time supplement.

*Assessment from RTTP* – The KPIs sum of consecutive delay, weighted sum of consecutive delay, sum of final delay, maximum final delay, relative delay and punctuality are computed based on the RTTP used. The RTTP is not simulated separately, so it is assumed that the RTTP is fully executable and trains are not affected by stochasticity in dwell and running times.

## 3.2 Selected alternative graph-based RTRM

In this section, the used AG-based model, which is formulated as a MILP, is specified. Section 3.2.1 provides the problem formulation, containing the used sets, constraints, objective function, decision variables and parameters. Section 3.2.2 is used to motivate the used objective function, which is different from the AG model. Section 3.2.3 is a separate section that specifies the various parameters used in the RTRM. In section 3.2.4 the limitations of the observed model are mentioned.

### 3.2.1 Problem formulation

The model used is based on the AG model, which is a commonly applied rescheduling model in the literature and was first described in Mascis and Pacciarelli (2002). In the future, the Dutch infrastructure manager ProRail could use a microscopic model with such a model formulation.

To be able to use the RTRM for different infrastructure and operational scenarios, the AG model has been rewritten and formulated as a MILP. From the AG model, the constraints 'fixed arcs' and 'alternative arcs' have been used. The MILP formulation makes it possible to write the model more generic with trains and block sections as sets, which simplifies the loading of different infrastructure layouts and timetables. In addition, MILP formulation allows trains to run at different speeds (namely at scheduled speed or at maximum technical speed for delayed trains) and allows them to use a different objective function (see section 3.2.2).

In the underlying parts, the sets, parameters, decision variables, objective function and constraints are discussed successively. The computation of the various parameters (such as headways and minimum block entry times) is explained in section 3.2.3. In figure 3.2 a small visualization of the AG model is given for a simplistic case, in which the sets and constraints are visualized.

*Sets:*

| | |
|---|---|
| $T$ | Trains |
| $B$ | Block sections |
| $\forall\, i \in T: B_i \subset B$ | Block sections used by train $i$ |
| $N = \{(i,b) \mid i \in T, b \in B_i\}$ | Nodes |
| $F = \{(i,b,b') \mid i \in T, b \in B_i, b' \in B_i, b' = \sigma(b_i)\}$ | Fixed arcs ($b'$ is block section behind block section $b$) |
| $A = \{(i,j,b) \mid i \in T, j \in T, i \neq j, b \in B_i, b \in B_j, b \neq b_f\}$ | Alternative arcs |

*Definitions:*

$\sigma_i(b)$: Successor block section behind block section $b$ in $B_i$ used by train $i$

$b_f$ : Sink block section which all trains enter when they leave the considered dispatching area

To make the RTRM not layout and operational specific, the AG model is adapted in such a way that its nodes (the operations) are expressed by a train ($i$) that enters a block section ($b$). Sets of trains ($T$), block sections ($B$) and block sections used by train $i$ ($B_i$) are used to generate the nodes. A fictitious block section $b_f$ has been added, which all trains enter when they leave the considered dispatching area. This extra block section is needed to be able to express the event that a train leaves the dispatching area.

$N$ contains all nodes representing all events in which train $i$ enters block section $b$ (in the set $B_i$). $F$ is the set of fixed arcs, which connect the nodes ($N$) of the same train (in the set $B_i$) in the order of how trains pass through the block sections. $A$ is the set of alternative arcs, which connect the different nodes of two trains ($i$ and $j$) which have the same shared block section ($b$), to fix the order of these trains to pass this block section without conflicting operations. See figure 3.2 for a visualization of the nodes (by circles), fixed arcs (by solid arrows) and alternative arcs (by dashed arrows) in an example case.

*Parameters:*

| | | |
|---|---|---|
| $p_{i,b,b'}$ | $\forall\ (i,b,b') \in F$ | Minimum running time train *i* at block section *b* (to next block section *b'*). |
| $a_{i,j,b}$ | $\forall\ (i,j,b) \in A$ | Minimum time between train *i* leaving and train *j* entering block section *b* (sum of clearing and release time train *i* and setup, sight, reaction and approach time train *j*, so headway minus block running time). It represents the arcs between node (*i*, $\sigma_i(b)$) and node (*j*, *b*) and between node (*j*, $\sigma_j(b)$) and node (*i*, *b*). |
| $\tau_{i,b}$ | $\forall\ (i,b) \in N$ | Minimum block entry time train *i* at block section *b* (subject to initial delays and timetable constraints) |
| $\omega_i$ | $\forall\ i \in T$ | Weight factor for train *i* (1 for regional train, 2 for intercity train, see section 3.2.2) |

The minimum running time of trains ($p_{i,b,b'}$) and the headways between two trains ($a_{i,j,b}$) are obtained from the microscopic simulator. The minimal block entry times of trains ($\tau_{i,\mathrm{b}}$) are the earliest possible block entry times of train *i* at the block sections in the set $B_i$, subject to initial delays and timetable constraints. If train *i* has no initial delay, $\tau_{i,b}$ equals the timetable and forces trains to run at the scheduled speed (which includes running time supplements), otherwise $\tau_{i,b}$ is later than the timetable, which allows trains to run at maximum speed (to catch up delays). The computation of $a_{i,j,b}$ and $\tau_{i,b}$ is specified further in section 3.2.3. The weighting factor ($\omega_i$) is part of the objective function, which is described in more detail in section 3.2.2.

*Decision variables:*

| | | |
|---|---|---|
| $t_{i,b}$ | $\forall\ (i,b) \in N$ | Actual block entry time train *i* at block section *b* |
| $\alpha_{i,j,b}$ | $\forall\ (i,j,b) \in A, i < j$ | $\alpha_{i,j,b} = \begin{cases} 0, & \text{if train } i \text{ precedes train } j \text{ at block section } b \\ 1, & \text{if train } j \text{ precedes train } i \text{ at block section } b \end{cases}$ Binary variable defining the order between train *i* and *j* at block section *b* |

The first decision variable $t_{i,b}$ contains the actual block entry times for all nodes. The second decision variable defines the sequence between two trains at a certain shared block section and is binary.

*Objective function and constraints:*

$$Min \sum_{i \in T} \omega_i * (t_{i,b_f} - \tau_{i,b_f}) \tag{1}$$

*Subject to:*

$$t_{i,b'} \geq t_{i,b} + p_{i,b,b'} \qquad \forall\ (i,b,b') \in F \tag{2}$$

$$t_{j,b} \geq t_{i,\sigma_i(b)} + a_{i,j,b} - M * \alpha_{i,j,b} \qquad \forall\ (i,j,b) \in A, i < j \tag{3}$$

$$t_{i,b} \geq t_{j,\sigma_j(b)} + a_{j,i,b} - M * (1 - \alpha_{i,j,b}) \qquad \forall\ (i,j,b) \in A, i < j \tag{4}$$

$$t_{i,b} \geq \tau_{i,b} \qquad \forall\ (i,b) \in N \tag{5}$$

*Definitions:*

$t_{i,b}$ : Decision variable: Actual block entry time train *i* at block section *b*
$\alpha_{i,j,b}$ : Decision variable: Train *i* precedes train *j* at block section *b*

$\tau_{i,b}$ : Minimum block entry time train $i$ at block section $b$ (subject to initial delays and timetable constraints)
$a_{i,j,b}$ : Headway from train $i$ to train $j$ at block section $b$ (sum of clearing and release time train $i$ and setup, sight, reaction and approach time train $j$, see figure 3.3)
$p_{i,b,b'}$ : Minimum running time train $i$ at block section $b$ to successor block section $b' = \sigma_i(\mathrm{b})$
$\omega_i$ : Weight factor for train $i$ (1 for regional train, 2 for intercity train)
$M$ : High number

The objective function (1) minimizes the weighted consecutive delay for all trains at the point where they leave the considered dispatching area (when they enter block section $b_f$). The consecutive delay is calculated per train by subtracting the minimum block entry time ($\tau_{i,b_f}$) from the actual block entry time ($t_{i,b_f}$) for this last block section. A train-specific weighting factor $\omega_i$ ensures that the consecutive delay of intercity trains counts twice. More details about the objective function can be found in section 3.2.3.

The fixed arcs are set by the first constraint (2), which ensures that the block entry time at the next block section is greater than or equal to the block exit time of the previous block section (which is the block entry time of that block section plus the minimum travel time in that block section).

Alternative arcs are set by two constraints (3) and (4), which ensure the order of two trains having a shared block section. Using decision variable $\alpha_{i,j,b}$ constraint (3) or (4) is activated by making use of a high number ($M$). The block entry time of the second train should be equal to or larger than the time the first train leaves the considered block section plus the headway ($a_{i,j,b}$). The time that the first train leaves the block section, equals the time that this train enters the next block section (so that time is used in (3) and (4)). In section 3.2.3 it can be found how $a_{i,j,b}$ is computed.

The last constraint (5) ensures that a train is not running early, before its minimum block entry times ($\tau_{i,b}$).

*Example:*

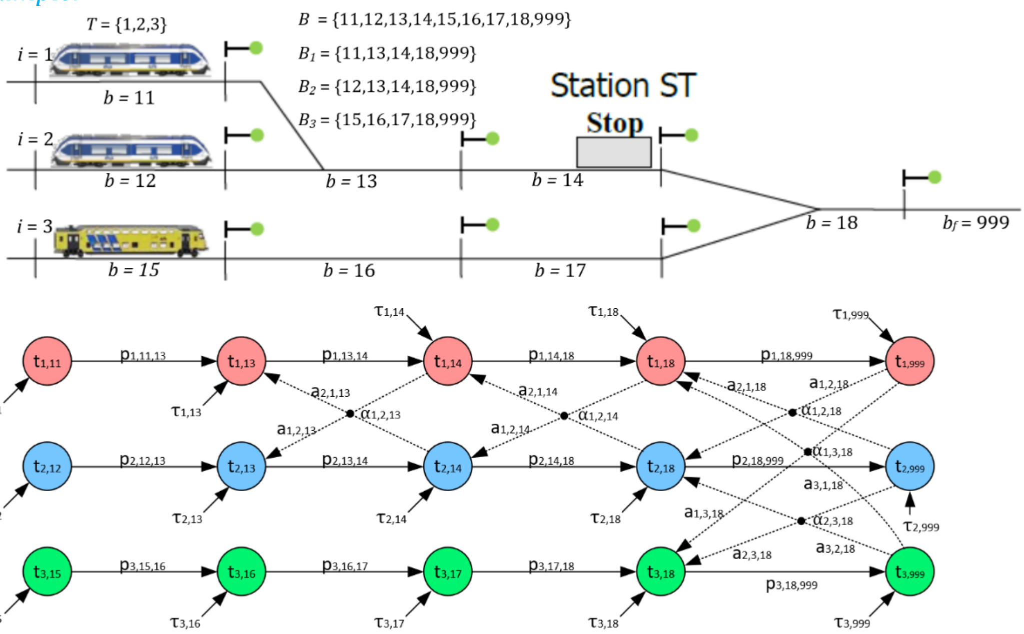



*Figure 3.2. Visualization of used AG model for an example case*

In figure 3.2 the MILP formulation based on the AG model is visualized for a mini-network case with three trains (1,2 and 3) running towards block section $b_f$ (which is called 999). The nodes are given by circles each representing the moment that a train enters a block section. The nodes are connected by solid arrows representing the fixed arcs (2). The alternative arcs are represented by a pair of dashed arcs corresponding to the disjunctive constraints (3) and (4), which is the case for block sections 13, 14 and 18. Solid dots indicate which alternative arcs are paired. The associated decision variable $\alpha_{i,j,b}$ selects one arc in each pair. The times that trains enter the model (scheduled arrival time plus initial delay), the times that trains 1 and 2 are allowed to depart from station ST and running time supplements for on-time trains are fixed using $\tau_{i,b}$ according to (5). In the computation of the objective value $t_{1,999}$, $t_{2,999}$, $t_{3,999}$, $\tau_{1,999}$, $\tau_{2,999}$ and $\tau_{3,999}$ are used.

### 3.2.2 Objective function

As shown in the literature review in chapter 2, different objective functions are applied by the analyzed papers. The formal AG model has the objective function of minimizing the maximum consecutive delay. A disadvantage of this objective is that it does not account for the total consecutive delay: The model can propose an RTTP in which the maximum consecutive delay is low but many individual trains are delayed and therefore the sum of (consecutive) delay is high. Another option could be available where the maximum consecutive delay (of one train) is higher, but the sum of (consecutive) delay is much lower because the rest of the trains can continue without much hindrance. From the passenger's (or customer's) perspective, delays are considered as discomfort and should therefore be limited as much as possible. Therefore, it was decided to deviate from the objective of the AG model, but to use the minimization of the total consecutive delay as the objective, which is also possible with the used model formulation.

The (consecutive) delay can be determined for each station. Because not all trains stop at every station, it is not necessary to sum the (consecutive) delay over all trains over all stations (after all, it does not matter whether an intercity train passes a station with some delay, as long as it is on-time at its next stop). Therefore it has been chosen only to regard the times that each train leaves the considered dispatching area or terminates (so at block section $b_f$).

In most countries, there are several train categories, which are also discussed in section 2.2.7. A common classification is for example regional/commuter trains, intercity/long-distance trains, high-speed/international trains and freight trains. Because these trains vary in speed, the number of passengers (or goods) and ticket prices (or infrastructure charge), it can be stated that certain train categories are more important than other categories. In addition, the delay of a train of a higher category may have larger consequences, such as a delayed international train that has to pass through several countries and may also cause additional delays there. For these reasons, weighting factors are assigned to different train categories in various papers such as Khosravi et al. (2012) and Sama et al. (2015) in their objective function. In Sama et al. (2015) in the objective function, delays from intercity trains are counted twice over delays of commuter and regional trains, while delays of high-speed trains are counted twice over delays of intercity trains. The advantage of applying a factor of 2 over the increasing importance of the train category is that in a trade-off where the delay for both categories is of approximately the same order, the most important category is prioritised, while if the train from the lower category would get much more delay than the higher category (more than a factor of 2), the train from a lower category would be prioritised. The application of a weighting factor should not be confused with the SDR prioritise intercity trains, since this SDR gives priority to the most important train category in all cases (even if it would lead to extremely large delays for the trains from the lower train category).

As in this research only regional and intercity trains are regarded, the same weighting factor is used as in Sama et al. (2015) resulting in the objective function of minimizing the sum of the consecutive delay times a weighting factor (which is 1 for regional and 2 for intercity trains) for all trains leaving the dispatching area. In equation:

$$Min \sum_{i \in T} \omega_i * (t_{i,b_f} - \tau_{i,b_f}) \tag{1}$$

With $t_{i,b_f}$ the actual block entry time, $\tau_{i,b_f}$ the earliest possible block entry time (subject to initial delays and timetable constraints) at the point a train leaves the considered dispatching area and $\omega_i$ a train-specific weighting factor, which is 1 for regional trains and 2 for intercity trains.

### 3.2.3 Computation of parameters

This section describes how the parameters needed to run the RTRM for the case studies in this research are calculated.

The minimum time between train *i* leaving and train *j* entering block section *b* ($a_{i,j,b}$) is used in (3). These are based on the clearing and release time of the train leaving the section and the setup, sight, reaction and approach time of the train entering the section. In figure 3.3 the blocking time and its components, which are needed for the computation of $a_{i,j,b}$, are visualized for one train (train *i*). These are obtained from the microscopic event-based simulator, which is specified in section 3.1.3. The following formula is used to compute $a_{i,j,b}$:

$$a_{i,j,b} = t_{setup_b} + t_{sight} + t_{approach_{j,b}} + t_{clear_{i,b}} + t_{release} \qquad \forall (i,j,b) \in A \tag{6}$$

*Definitions:*

| | | |
|---|---|---|
| $a_{i,j,b}$ | : | Minimum time between train *i* leaving and train *j* entering block section *b* (sum of clearing and release time train *i* and setup, sight, reaction and approach time train *j*, so headway minus block running time) $\forall\ (i,j,b) \in A$ |
| $t_{setup_b}$ | : | *Setup time* block section *b* (block specific, default 1 second, 6 seconds at first block section and block sections containing switches) $\forall\ b \in B$ |
| $t_{sight}$ | : | *Sight and reaction time* (not train or block specific, default 10 seconds) |
| $t_{approach_{j,b}}$ | : | *Approach time* of train *j* at block section *b* $\forall\ (j,b) \in N, b \in B_j, b \neq b_f$ |
| $t_{clear_{i,b}}$ | : | *Clearing time* train *i* at block section *b* (the time it takes before the entire train left the block section) $\forall\ (i,b) \in N, b \in B_i, b \neq b_f$ |
| $t_{release}$ | : | *Release time* (not train or block specific, default 2 seconds) |

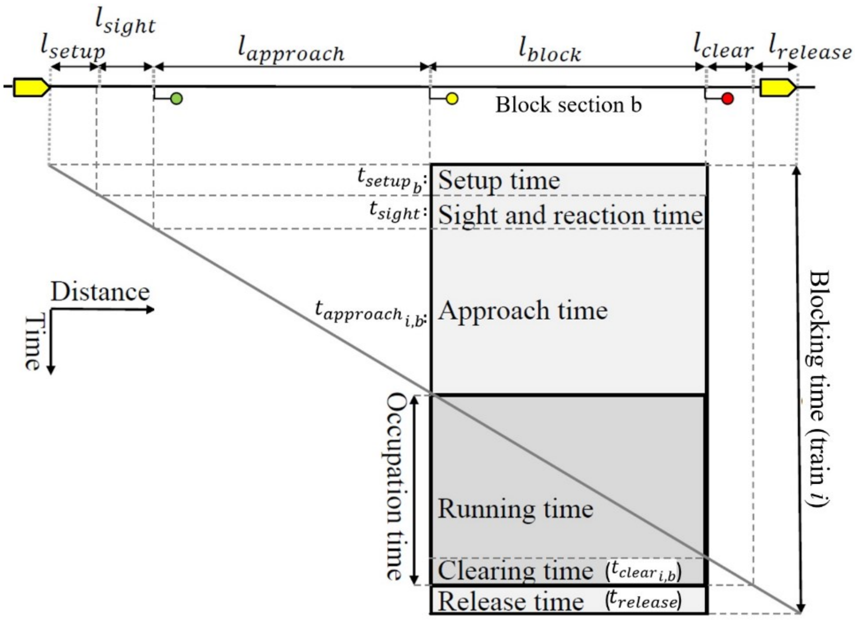



*Figure 3.3. Visualization blocking times of train i (Goverde, 2020)*

The minimum block entry times by the trains at the block sections they pass ($\tau_{i,b}$) are the minimal entry times at the block sections if a train can run without being hindered by other trains, subject to initial delays and timetable constraints. If train *i* has no initial delay $\tau_{i,b}$ equals the timetable and forces trains to run at the scheduled speed (which includes running time supplements), otherwise $\tau_{i,b}$ is larger than the timetable and allows trains to run at maximum speed (to catch up delays).

$\tau_{i,b}$ is used in the objective function to compute the consecutive delay over all the trains at the last block section ($b_f$) and in constraint (5) for all nodes to forbid trains from running early.

$$\tau_{i,\beta(i)} = \rho_{i,\beta(i)} + d_i \qquad \forall\, i \in T \qquad (7)$$

$$\tau_{i,b'} = max\{\tau_{i,b} + p_{i,b,b'}, \rho_{i,b'}\} \qquad \forall\, (i,b,b') \in F \qquad (8)$$

*Definitions:*

| | | | |
|---|---|---|---|
| $\tau_{i,b}$ | $\forall\, (i,b) \in N$ | : | Minimum block entry time train *i* at block section *b* (subject to initial delays and timetable constraints) |
| $\rho_{i,b}$ | $\forall\, (i,b) \in N$ | : | Scheduled block entry times train *i* at block section *b* (including running time supplements, where the running time supplement is equally divided over the entire ride, see section 4.2.3) |
| $p_{i,b,b'}$ | $\forall\, (i,b,b') \in F$ | : | Minimum running time train *i* at block section *b* to successor block section *b′* |
| $d_i$ | $\forall\, i \in T$ | : | Initial delay train *i* |
| $\beta(i)$ | | : | First block section used by train *i* |

Using (7), the block entry time is fixed for block sections where the trains enter the area, which is equal to the scheduled arrival time plus any initial delay. For the other block sections it applies that, using (8), the minimum block entry times are equal to either the block entry time of the previous block section plus the minimum running time ($p_{i,b,b'}$) -if the train is delayed- or equal to the block entry time according to the timetable ($\rho_{i,b}$) -if the train is on-time-. In this way, it is guaranteed that on-time trains run at the scheduled speed, while delayed trains are allowed to run at maximum speed to catch up on their delay (as long as they run behind schedule). $\rho_{i,b}$ also guarantees departure times at intermediate stops. Figure 3.4 provides a graphical overview of the computation of $\tau_{i,b}$, for the same example dispatching area as in figure 3.2.

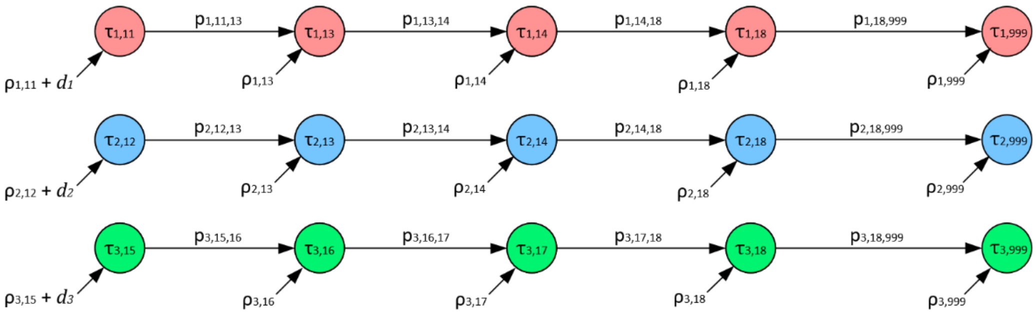


*Figure 3.4. Visualization of computation minimum block entry times at all block sections for simplistic case figure 3.2*

The relationship between $\rho_{i,b}$, $\tau_{i,b}$ and $t_{i,b}$ is visualized in figure 3.5 for a delayed train (train *i*) with a certain initial delay ($d_i$) running from block 0 to block 999. $\rho_{i,b}$ are the scheduled block entry times of the block sections of train *i* according to its schedule, where the scheduled speed (which includes running time supplements) is maintained between the block sections and scheduled departure times at intermediate stations are fixed. $\tau_{i,b}$ are the minimum block entry times of the block sections of this train, subject to initial delays and timetable constraints. Note that $\tau_{i,b}$ uses the minimum technical running time between block 0 and the station in block 4 (according to (8)), while behind this station between block 4 and 999 (where the train could theoretically be on-time again) the scheduled speed is used according to the timetable as $\rho_{i,b} \leq \tau_{i,b}$ (which is also caught in (8)). $t_{i,b}$ are the block entry times of the red train according to a certain control strategy, so that $\rho_{i,b} \leq \tau_{i,b} \leq t_{i,b}$. The control strategy slows down train *i* at block section 2 for some reason, causing the train is driving with minimum technical running time the entire ride, according to (2).

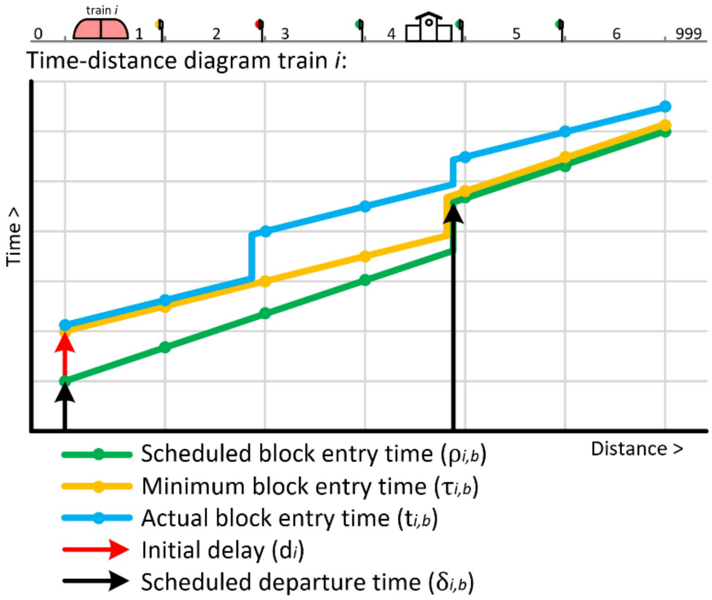


*Figure 3.5. Visualization of parameters for a delayed train*

Note that for this example situation, the consecutive delay equals the total delay, as train *i* could theoretically leave the model on-time, so the unavoidable delay is 0.

Scheduled block entry times by the trains at the block sections they pass ($\rho_{i,b}$), are computed subject to the scheduled departure times at the source block sections and at stations (block section behind a station) and the scheduled running time. The running time supplement is divided equally over the entire ride (the same amount of supplement when trains are accelerating, driving at full speed and breaking), so trains drive at a reduced speed during the entire ride and do not apply coasting.

$$\rho_{i,b} \quad = \delta_{i,b} + r_{i,b} \qquad \forall\ (i,b) \in S \qquad (9)$$

$$\rho_{i,b'} = \rho_{i,b} + p_{i,b} * (1+s) \qquad \forall\ (i,b,b') \in F, (i,b') \notin \mathrm{S} \qquad (10)$$

*Definitions:*

| | | |
|---|---|---|
| $S \subset N$ | : | Set of nodes representing source block sections (where trains enter the considered dispatching area) + block sections behind stations |
| $\rho_{i,b}$ | : | Scheduled block entry times train *i* at block section *b* (including running time supplements) |
| $p_{i,b,b'}$ | : | Minimum running time train *i* block section *b* (to next block section $\sigma(k_i)$ ) |
| $\delta_{i,b}$ | : | Scheduled arrival time at the first block section and scheduled departure time at a station (at the platform) from the previous block section for (*i, b*) at *S*. |
| $r_{i,b}$ | : | Scheduled running time from departure at station train to next block section including running time supplement (at the source block section of every train $r_{i,k} = 0$) |
| $s$ | : | Running time supplement as ratio |

Set *S* is a subset of *N*, which represents the events of trains entering the model (arrive at first block section) and trains leaving a block section after a scheduled stop (arrive at block section behind stations). These events are related to constraints of the timetable, which are the scheduled arrival time and the scheduled departure time at intermediate stations. Note for intermediate stations b in $\delta_{i,b}$ refers to the block section behind the station (so an on-time train departs from the platform in the previous block section at the scheduled departure time $\delta_{i,b}$, and enters block section *b* $r_{i,b}$ seconds later at $\rho_{i,b}$).

In the timetable generation (see section 3.1.2) the scheduled departure times at stations must be developed in such a way that (11) is also obeyed, otherwise the scheduled departure time would be unfeasible.

$$\rho_{i,b} + p_{i,b,b'} * (1+s) \leq \delta_{i,\sigma(b)} + r_{i,\sigma(b)} \qquad \forall\ (i,b) \in N, \big(i, \sigma_i(b)\big) \in S \qquad (11)$$

*Definition:*

$\sigma_i(b)$ : Successor block section behind block section *b* in $B_i$ used by train *i*

Figure 3.6 provides a graphical overview of the computation of $\rho_{i,b}$, for the same example dispatching area as in figure 3.2. The nodes highlighted by red circles are also in the set of *S*, so for these block sections scheduled arrival times ($\delta_{i,b} + r_{i,b}$) are given. Note that also nodes (1,18) and (2,18) representing the node behind a scheduled stop at station ST, also belong to set *S*.

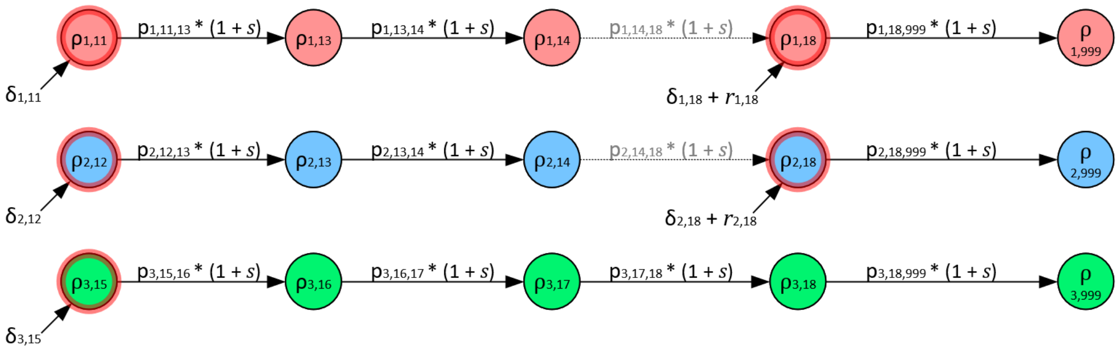


*Figure 3.6. Visualization of computation scheduled arrival times at all block sections for simplistic case figure 3.2*

### 3.2.4 Limitations of the selected RTRM

This section mentions the limitations of the used RTRM.

*Driving styles* – The model assumes certain driving styles of train drivers. If a train is delayed, the train runs as fast as possible to make up for its delay (i.e. using the minimum technical running time). However, once the train is back on-time according to the timetable, the train runs at the scheduled speed (which means an abrupt decrease in speed).

*Minimum headway* – The RTRM generates an RTTP that is conflict-free and would not result in yellow signals. However, this has the consequence that trains have to be slowed down to avoid getting a yellow signal (in case two trains have to follow each other with a minimum headway like an intercity train running behind a regional train). This is possible if there is a driver advisory system available, which advises the driver to slow down timely. If this system is not present, this will result in a small deviation from the RTTP if a driver nevertheless receives a yellow signal and has to slow down and accelerate again when the signal turns green.

## 3.3 Summary

Based on an AG model, an RTRM is implemented in a generic way with MILP formulation, so that it can be evaluated across different infrastructure and operational scenarios. The investigated RTRM optimizes (once for each scenario) the weighted consecutive delay where intercity trains are weighed twice.

A framework has been developed that uses infrastructure layouts, traffic patterns and a set of distribution scenarios as input. In the framework the implemented AG-based RTRM is used to generate an RTTP for each scenario. This RTTP is assessed based on 7 different KPIs (see table 3.1). In addition, 5 SDRs are also used to generate RTTPs, which are also assessed using the same KPIs. In this way the relative improvement of the RTRM compared to the SDRs can be expressed. During the assessment of the results, it can be concluded which infrastructure layout and traffic pattern the RTRM is the most effective.

*Table 3.1. Used RTRM, SDRs and KPIs in the evaluation framework*

| Element | Number | Value |
|---|---|---|
| RTRM | 1 | *Minimizing the weighed sum of consecutive delay* |
| SDR | 5 | Timetable order<br>FCFS<br>Prioritise intercity trains<br>Prioritise delayed trains<br>Prioritise on-time trains |
| KPI | 7 | Sum consecutive delay<br>Weighted consecutive delay<br>Sum final delay<br>Maximum final delay<br>Relative delay<br>Punctuality<br>Optimization runtime |

# 4. Scenarios

This chapter belongs to the third sub-question: 'Which infrastructure, operational and disturbance scenarios are relevant to consider to evaluate an RTRM?'. In this chapter different infrastructure, operational and disturbance scenarios are compiled. First infrastructure and operational characteristics of a railway network are identified, which potentially could influence the performance of an RTRM. This is done based on the results of the literature review (by using the various characteristics of the case studies in the reviewed papers) and in liaison with the Prestatie Analyse Bureau of ProRail, to have a comprehensive set of possible combinations of infrastructure layouts and traffic patterns.

In section 4.1 infrastructure characteristics are identified and infrastructure layouts are developed based on relevant route interactions (ways in which different routes overlap, see section 4.1.2).

In section 4.2 operational characteristics are identified and it is specified which traffic patterns, running time supplements and infrastructure occupation rates are applied in the evaluation of the RTRM.

Section 4.3 contains the regarded disturbance scenarios, which are applied to all regarded infrastructure and operational scenarios.

Section 4.4 provides an overview of the developed infrastructure, operational and disturbance scenarios.

## 4.1 Infrastructure layouts

This section discusses (the development of) the different infrastructure layouts used for the evaluation of the RTRM. In section 4.1.1, different characteristics of infrastructure layouts are identified. Based on these characteristics, 4 layouts have been developed on which only one type of route interaction can take place. 2 layouts are added on which a combination of two route interactions can take place.

### 4.1.1 Identification of infrastructure characteristics

In this section different characteristics of infrastructure layouts are identified. In table 4.1 example layouts are given for different infrastructure types.

As shown in the literature review, a railway network consists of the following infrastructure types namely lines, stations and junctions. Each of these has its own characteristics.

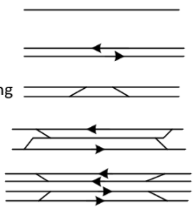
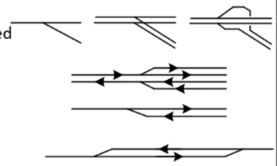
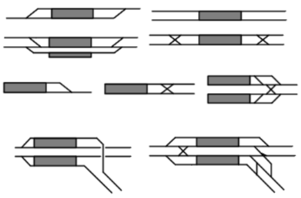
*Lines* – For a (railway) line, the number of tracks, overtaking possibilities and number of switches are variable. A railway line also has a certain maximum speed, a certain signalling system and therefore also a minimum headway between trains. These factors affect the capacity and flexibility of a railway line.

*Junctions* – A (railway) junction connects different railway lines. There are different types of junctions, namely a merge, a diverge or a change in the number of tracks. Some junctions are level junctions with less capacity, others are grade-separated junctions. Often applied junction types are a merge, diverge and a reduction or increase of the number of tracks. Junctions can vary in level- or grade-separated.

*Stations* – For a station, the number of tracks, connected lines and number of switches are variable. These aspects lead to different numbers of possible routes trains can have through the station area. More possible routes lead to higher flexibility.

In table 4.1, for the main infrastructure types, characteristics are specified including example layouts.

*Table 4.1. Characteristics infrastructure layouts with example layouts*

| **Characteristic** | | **Example layout** |
|---|---|---|
| Line | • Nr. of tracks<br>• Nr. of passing possibilities<br>• Nr. of switches (flexibility) | Single track line<br>Dubble track line<br>Dubble track line with diverting and connecting points<br>3 tracks<br>4 tracks (with some swithces)  |
| Junction | • Typology: merge/diverge/triangle/ change nr. of tracks<br>• Characteristics of connected lines | Merge/diverge level/grade-saparated<br>Change # tracks<br>Passing location (on single track line)  |
| Station | • Nr. of tracks<br>• Nr. of lines connected<br>• Terminus / continuing<br>• Nr. of possible routes through the station (local rerouting)<br>• Flexibility (nr. of switches) | Station on one line<br>Terminus<br>More lines  |

A railway network is built up from different elements that have been discussed above. As it is not feasible to consider all possible combinations of types of lines, junctions and stations, in this research a selection has been made of combinations where only one or two route interactions can take place In this way the influence of each type of route interaction (which is linked to the infrastructure layout) on the performance of an RTRM could be investigated. These route interactions are discussed in the next section.

### 4.1.2 Route interactions

In this section, common interactions between routes of trains (ways in which different routes overlap) are considered. These route interactions could potentially lead to conflicts and require different control actions. To distinguish the effects of these different control actions, the infrastructure layouts are developed in such a way that one or two of these route interactions can take place (see section 4.1.3). In figure 4.1 these interactions are visualized.

1. *Cross-over* - These are route interactions of routes with a small overlapping part, only for one block section (e.g. at a railway yard, or at a ground-level junction). The routes have different origins and destinations. If a conflict occurs, dispatchers decide which train is allowed first. The second train has to wait just for a few minutes until the cross-over is cleared.
2. *Merge* - These are route interactions of routes with a longer overlapping part from a certain merging point. The dispatcher decides which train is allowed earlier. The final delay of the second train depends on the length of the overlapping section, the stopping pattern of both trains and the minimum headway between the two trains. It could therefore be larger than a few minutes.
3. *Overtaking* - These are route interactions of overlapping routes (with the same origin and destination), however with a short separated part of the route where overtaking could

take place. Dispatchers here have the choice of whether or not to allow an overtaking to take place, if there is a potential conflict downstream of the overtaking location.

4. *Single track* - These are route interactions of overlapping routes in opposite directions (at a single track section). If a conflict occurs, dispatchers choose which of the trains is allowed to enter the single track section first.

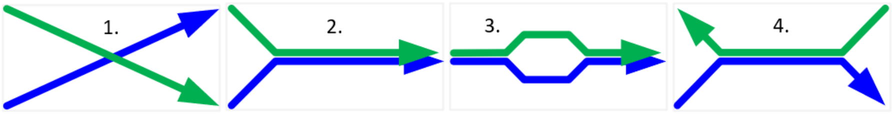


*Figure 4.1. Route interactions which lead to potential conflicts*

Because in practice in a dispatching area several route interactions could occur, in addition to the 4 infrastructure layouts above, two infrastructure layouts are added where combinations of route interactions occur (see also figure 4.2). In this way, the influence of two combined route interactions on the performance of an RTRM can be investigated and compared against one single route interaction.

5. *Cross-over & merge* - At a ground-level junction of two double-track railway lines, more than one route interactions occur, namely the merge for two trains with their routes in the same direction and the cross-over for two trains with their routes in opposite directions that have to cross each other. Note that for this layout only a small share of trains is passing both the cross-over and the merge (the green direction in figure 4.2).
6. *Merge & Overtaking* - Two routes merge at a certain point, while further downstream there is an overtaking location. An example of this combination is a main station where an intercity and a regional train depart from different tracks (merge) while further downstream the line is a small station where an overtaking can take place. Note that all trains pass both the merge and the overtaking location.

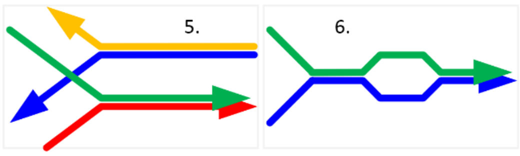


*Figure 4.2. Combinations of route interactions which could lead to conflicts*

### 4.1.3 Considered infrastructure layouts

From the 20 example infrastructure layouts from table 4.1, only a few are selected and combined so that on each layout one of the 6 route interactions from the previous section can take place.

To be able to compare the different layouts under the same conditions, the same dimensions, signalling system, length block sections, minimum headway and maximum speeds are used for all the layouts. For this purpose, a railway area is selected where all these possible interactions can take place, while for each of the 6 described layouts only a part of the tracks of this area is activated (see also table 4.2).

The considered area (with its dimensions, block sections and maximum speeds) is copied from the Utrecht-Ede railway line including the branch towards Veenendaal. In this area, a merge, cross-over and overtaking layout could take place. By adjusting the layout at some points, it can also be used as a single track layout.

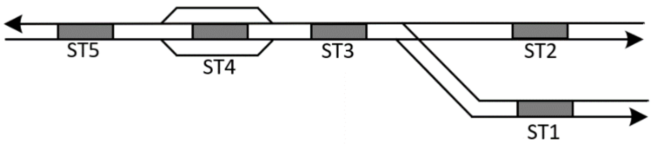
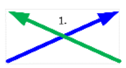
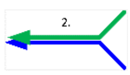
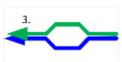
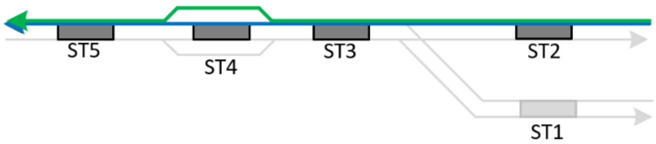
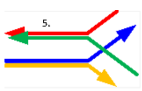
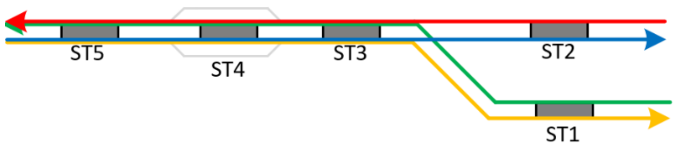
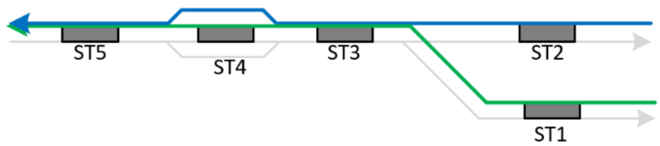


*Figure 4.3. Full considered infrastructure layout with tracks and stations*

[Figure 4.3](#) shows the full considered infrastructure layout with all tracks and stations. Table 4.2 contains the 6 layouts considered for this research. For each layout, only the tracks necessary for the regarded route interaction are used (the other tracks are frozen). A more detailed overview of these layouts containing the block sections and dimensions of the layouts can be found in appendix A.

*Table 4.2. Infrastructure layouts with route interactions and control actions*

<table>
<tr><th>Infrastr. layout</th><th>Route interaction</th><th>Control actions</th><th>Direction(s)</th></tr>
<tr><td>1</td><td>Cross-over</td><td>Change the sequence of trains at cross-over</td><td>Two (conflicting) directions</td></tr>
<tr><td></td><td colspan="3">
</td></tr>
<tr><td>2</td><td>Merge</td><td>Change the sequence of trains at the merge</td><td>One direction, towards ST5</td></tr>
<tr><td></td><td colspan="3">
</td></tr>
<tr><td>3</td><td>Overtaking</td><td>Overtaking at ST4 yes or no</td><td>One direction, no trains at ST1</td></tr>
<tr><td></td><td colspan="3">
</td></tr>
<tr><td>4</td><td>Single track</td><td>Deciding at which station trains running in opposite directions pass</td><td>Two directions with additional switches, no trains at ST1</td></tr>
<tr><td></td><td colspan="3">
</td></tr>
<tr><td>5</td><td>Cross-over & Merge</td><td>Change the sequence of trains at the level junction</td><td>Two directions</td></tr>
<tr><td></td><td colspan="3">
</td></tr>
<tr><td>6</td><td>Merge & Overtaking</td><td>Change the sequence of trains at the merge, overtaking at ST4 yes or no</td><td>One direction, towards ST5</td></tr>
<tr><td></td><td colspan="3">
</td></tr>
</table>

## 4.2 Operational characteristics

This section discusses the different operational characteristics regarded in the evaluation of the RTRM. In section 4.2.1 different operational characteristics are identified, while in the subsequent sections the regarded traffic patterns, running time supplements and infrastructure occupation rates are more specified.

The operational characteristics are one of the main inputs of the evaluation framework proposed in section 3.1. It is used by the module timetable generation module (see section 3.1.2) where timetables are created. More details about the generated timetables can be found in appendix B.

### 4.2.1 Identification of operational characteristics

In this section different operational characteristics are identified. These characteristics are also discussed in the literature review in which various implementations of these characteristics in the literature can be found (see table 2.2). The operational characteristics are based on the characteristics of a timetable (these characteristics are also used in the evaluation framework in the timetable generation module).

One characteristic of a timetable is the traffic pattern. The traffic pattern contains train types (traffic configuration with stopping pattern), routes, frequencies, speeds and orders of trains. According to the literature review, train types vary between (sub-)urban trains (metro), regional trains, intercity trains, high-speed trains and freight trains. Traffic patterns can be heterogeneous or homogeneous. For railway market segments like metro lines or dedicated freight lines, the traffic pattern is mostly homogeneous. Heterogeneous traffic patterns are more common, for example on main lines with a mix of commuter, regional, intercity, international and freight trains.

In the design of a timetable, a running time supplement (or recovery time) is added to the running times of trains, to make the timetable more robust. With the help of this supplement, delayed trains can make up for their delay, while trains that run on-time can use this supplement to drive energy efficiently (for example use this time for coasting).

The traffic pattern also contains the frequency. The literature review shows that for disturbance scenarios with a high frequency, relatively more consecutive delay occurs, especially when the capacity is reached. However, these characteristics cannot be used in a comparison of different infrastructure layouts and traffic patterns, because (due to the different capacity limits of the infrastructure), the same frequency could be for one layout close to its capacity limit, while for other layouts the same frequency is still far from its capacity limit. Therefore the infrastructure occupation rate is used as a characteristic from which (per infrastructure and operational scenario) time-headway and frequency are derived. The infrastructure occupation rate is defined as the minimum technical cycle time divided by the timetable cycle time (Goverde and Hansen, 2013). The minimum technical cycle time is the time needed to run one timetable cycle (which depends on both the infrastructure layout, traffic pattern and running time supplement).

The following operational characteristics are regarded, which are clarified in the next subsections:

- Traffic pattern (homogeneous/heterogeneous operations, homogeneous/heterogeneous routes, sequence of trains, with or without overtaking)
- Running time supplement (0%, 5% or 10%)
- Infrastructure occupation rate (50%, 75% or 90%)

### 4.2.2 Traffic patterns

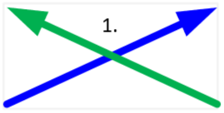
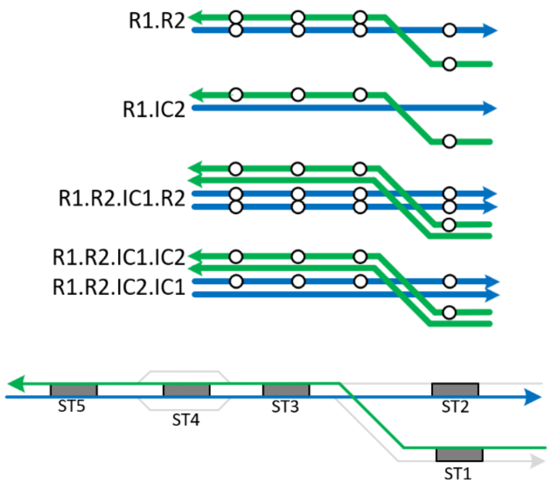
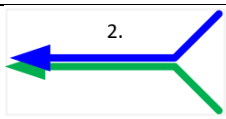
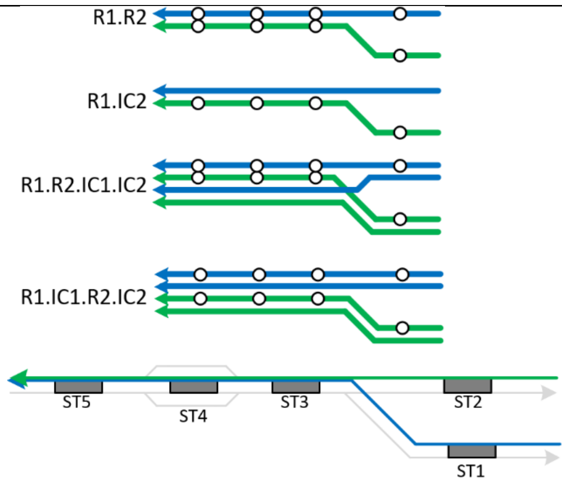
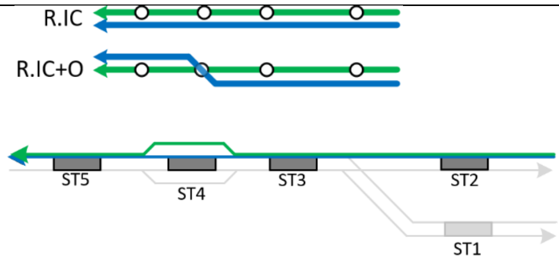
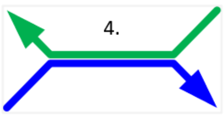
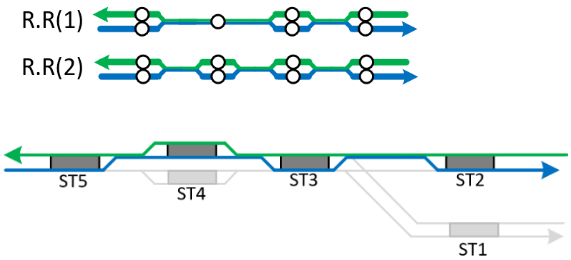
The traffic pattern contains the train types, with routes, stopping patterns and speeds, and the sequence of trains in one timetable cycle (pattern repeating at a certain interval in a cyclic timetable). The traffic patterns can be distinguished in the following way:

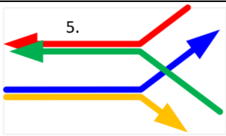
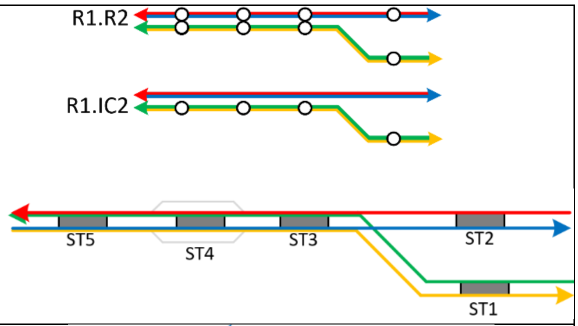
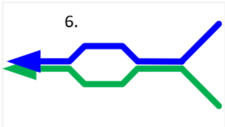
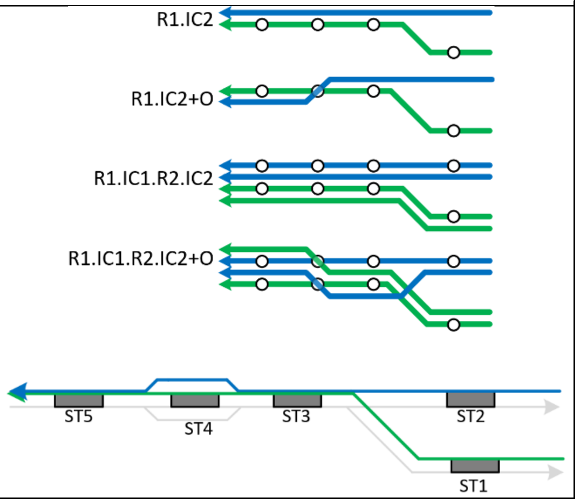
- A distinction can be made between heterogeneous and homogeneous traffic patterns. For homogeneous traffic patterns, all trains have the same stopping pattern and speeds, while for heterogeneous traffic patterns these aspects differ over the trains.
- For the heterogeneous traffic patterns, a distinction can be made between homogeneous and heterogeneous operations on the regarded routes. A heterogeneous traffic pattern with homogeneous routes means that trains with different stopping patterns and speeds are regarded, but trains on one route have the same stopping pattern and speeds.
- For heterogeneous traffic patterns with heterogeneous routes, the sequence of trains can be varied, i.e. bundling trains from the same train category (trains with the same stopping pattern and speeds) or bundling trains with the same route.
- For the overtaking layout, in the traffic pattern it is specified whether an overtaking is scheduled (so a scheduled change of sequence at ST4).
- For the single track layout, in the traffic pattern it is specified which intermediate stations (ST3 or ST4) trains from opposite directions pass each other.

The homogeneous traffic patterns considered in this research only contain regional trains with the same characteristics. These regional trains stop at all intermediate stations. A homogeneous traffic pattern with only intercity trains is not regarded, as it is expected this structure would lead to similar results (with the only difference that the headways between trains may be different). The heterogeneous traffic patterns considered in this research contain only intercity and regional trains. Intercity trains only stop at main stations and therefore do not stop anywhere in the considered layouts because there are no main stations there. The regional trains stop at all intermediate stations. Both intercity and regional trains have a maximum speed of 140 km/h.

The considered traffic patterns for each infrastructure layout are discussed in table 4.3. Note that not all possible traffic patterns are applied to all layouts, as not every pattern is relevant or feasible per layout. In the table, the traffic patterns (including routes, stopping patterns and sequence of the trains) are visualized in the right column for one timetable cycle. Depending on the traffic pattern 2 or 4 trains run per timetable cycle. The traffic patterns are expressed in codes that indicate what kind of trains run in one timetable cycle and how they alternate. R stands for regional train and IC for intercity train. Addition 1 stands for the route via ST1 and addition 2 stands for the route via ST2. Addition '+O' stands for 'overtaking', which applies to traffic patterns for which an overtaking is scheduled. For the single track layout, a (1) or a (2) is added to the code indicating the number of intermediate stations where trains running in opposite direction pass.

*Table 4.3. Considered traffic patterns with stopping patterns infrastructure layout*

| Infrastructure layout | Stopping pattern (per timetable cycle) + Layout |
|---|---|
|  <br>*Cross-over layout* contains:<br>- A homogeneous traffic pattern (R1.R2) with only regional trains for both routes.<br>- A heterogeneous traffic pattern with homogeneous routes (R1.IC2) with on one route regional and on the other route intercity trains.<br>- A heterogeneous traffic pattern with one homogeneous (only regional trains) and one heterogeneous route (R1.R2.IC1.R2).<br>- A heterogeneous traffic pattern with bunched train categories and alternating routes at the cross-over (R1.R2.IC1.IC2).<br>- A heterogeneous traffic pattern with bunched train categories and bunched routes at the cross-over (R1.R2.IC2.IC1). |   |
|  <br>*Merge layout* contains:<br>- A homogeneous traffic pattern (R1.R2) with only regional trains for both routes.<br>- A heterogeneous traffic pattern with homogeneous routes (R1.IC2) with on one route regional and on the other route intercity trains.<br>- A heterogeneous traffic pattern with bunched train categories (R1.R2.IC1.IC2).<br>- A heterogeneous traffic pattern with bunched routes (R1.IC1.R2.IC2). |   |
|  <br>*Overtaking layout* contains:<br>- A heterogeneous traffic pattern without scheduled overtaking (R.IC)<br>- A heterogeneous traffic pattern with scheduled overtaking at ST4 (R.IC+O) |   |
|  <br>*Single track layout* contains:<br>- A homogeneous traffic pattern in which trains pass each other only at one intermediate station ST3 (R.R(1)). *This gives rail traffic control more freedom to move this passage to another station in case of delays.*<br>- A homogeneous traffic pattern in which trains pass each other at both intermediate stations ST3 and ST4 (R.R(2)). |   |

| | |
|---|---|
| <br>*Cross-over & Merge l.* contains:<br>- A homogeneous traffic pattern (R1.R2) with only regional trains for both routes.<br>- A heterogeneous traffic pattern with homogeneous routes (R1.IC2) with on one route regional and on the other route intercity trains. |  |
| <br>*Merge & Overtaking l.* contains:<br>- Two heterogeneous traffic patterns with homogeneous routes (with on one route regional and on the other route intercity trains) with one pattern without scheduled overtaking (R1.IC2) and the other pattern with scheduled overtaking (R1.IC2+O).<br>- Two heterogeneous traffic patterns with bunched train categories with one pattern without scheduled overtaking (R1.IC1.R2.IC2) and the other pattern with scheduled overtaking (R1.IC1.R2.IC2+O). |  |
| | *IC: intercity trains, R: regional trains*<br>*R1, IC1: trains from route 1 via ST1*<br>*R2, IC2: trains from route 2 via ST2*<br>*+O: Pattern contains scheduled overtaking* |

Note that for the overtaking and merge & overtaking layouts, only heterogeneous patterns are regarded. For these layouts, homogeneous traffic patterns are not interesting to consider, as for trains with the same stopping pattern and speed an overtaking seldom occurs.

Note that for the single track layout no heterogeneous traffic pattern is regarded, while in practice heterogeneous traffic patterns do occur on single lines. However, the feasibility of a heterogeneous traffic pattern on a single track line depends very much on the dimensions of the line and locations where trains can pass each other. For that reason, this kind of pattern is not included in this research.

Independent of the number of trains per timetable cycle in a traffic pattern, 12 trains are considered per operational scenario (so a total of 3 or 6 timetable cycles per scenario). More details of the generated timetables can be found in appendix B, which also includes time-block diagrams of the corresponding conflict-free timetables.

### 4.2.3 Running time supplement

One of the operational characteristics considered in this research is the running time supplement. In the generation of a timetable, a running time supplement is added to the running times to cope with stochasticity in process times (such as a too-long stop, a temporary speed limit or waiting for other trains). Therefore, a higher running time supplement leads to a more robust timetable as delays can be partially compensated for by the running time supplement. On-time trains can use the running time supplement to save energy (e.g. by coasting), while delayed trains use the running time supplement to make up for the delay.

An RTRM can possibly also contribute to the robustness of a timetable because an RTRM can reduce the accumulation of delay. Therefore, less running time supplement may be needed to create the same robustness in case an RTRM is applied. The typical running time supplement applied by European railways is between 3% and 7% (Hansen and Pachl, 2008). In the evaluated scenarios in this research, running time supplement is varied between 0%, 5% and 10%. This running time supplement is processed in the entry times at block sections in the timetable.

### 4.2.4 Infrastructure occupation rate

One of the operational characteristics considered in this research is the infrastructure occupation rate. It is the share of time a given traffic pattern occupies a given infrastructure in a given time period in percentage.

$$infrastructure\ occupation\ rate = \frac{minimum\ technical\ cycle\ time}{timetable\ cycle\ time} * 100\% \tag{12}$$

For the layouts and traffic patterns, timetables are developed with different (average) headways between the trains, resulting in different infrastructure occupation rates. To determine the headway and timetable cycle time, first the minimum technical cycle time is found (which is the minimum time needed to run one timetable cycle, which depends on both the infrastructure layout, traffic pattern and running time supplement). Accordingly, the timetable cycle time is chosen -by using the formula above- in such a way that the infrastructure occupation rate of the timetable equals the desired infrastructure occupation rate.

UIC (International Union of Railways) guidelines advise a maximum infrastructure occupation rate of 75% during rush hour and 60% during the day for heterogeneous traffic, while for suburban this number may be higher (Goverde and Hansen, 2013).

It is investigated what the impact is on the performance of the RTRM when the infrastructure occupation rate is higher than the UIC guideline (an infrastructure occupation rate of 90%, so very close to the effective capacity of the infrastructure. In addition, a low infrastructure occupation rate (of 50%) is investigated, to show the effectiveness of an RTRM on relatively quiet (regional) lines.

## 4.3 Disturbances

This section contains the regarded disturbance scenarios, which are applied to all regarded infrastructure layouts and traffic patterns.

The literature review shows that there are three forms of disturbances, namely initial delays, dwell time extensions and travel time extensions (see section 2.2.8). Because in this research only one RTTP is generated 'in advance' according to the open-loop approach, only the initial delay is included. The stochastic dwell time extensions and travel time extensions are not yet known at the time of computation. A simulation of the RTTP is necessary to include these aspects.

To gain insight into the effects on the magnitude of delay, three magnitudes of delay are analyzed. These consists of small delays (2 to 6 minutes), medium delays (6 to 10 minutes) and large delays (10 to 15 minutes). Larger delays than 15 minutes are not regarded, because the control actions considered in this research are often no longer adequate, and other control actions may be implemented such as cancelling trains or skipping intermediate stations.

Table 4.4 provides an overview of all regarded delay scenarios. For each of the three sizes of delays, 32 scenarios are generated in which 1 train (8 scenarios) or 2 trains (24 scenarios) are given a random initial delay according to an uniform distribution (small delay: 2-6 minutes, medium delay: 6 to 10 minutes, large delay: 10 to 15 minutes). An uniform distribution is used as it is often applied in the literature and strict boundaries can be set between different magnitudes of delay.

For disturbance scenarios with one train initially delayed, one train from the first timetable cycle is selected to be delayed. For disturbance scenarios with two trains initially delayed, the 1st delayed train is selected from the first timetable cycle, while the 2nd delayed train is the 1st, 2nd or 3rd train following the 1st delayed train. Selecting the 4th or 5th train behind the 1st delayed train is no longer interesting because there is (for most operational conditions) too much time between these delayed trains, which in most cases results in two different delay problems.

*Table 4.4. Example of disturbance scenarios for timetable cycles of 2 and 4 trains*

| Magnitude of delay | Scenarios (1 train delayed) | Scenarios (2 trains delayed) |
|---|---|---|
| **Small delays**<br>*Total 32 scenarios* | 8 scenarios:<br>One train from first timetable cycle<br>delayed by 2 to 6 minutes (uniform distribution) | 24 scenarios:<br>One train from first timetable cycle plus the 1st, 2nd or 3rd following train delayed by 2 to 6 minutes (uniform distribution) |
| **Medium delays**<br>*Total 32 scenarios* | 8 scenarios:<br>One train from first timetable cycle<br>delayed by 6 to 10 minutes (uniform distribution) | 24 scenarios:<br>One train from first timetable cycle plus the 1st, 2nd or 3rd following train delayed by 6 to 10 minutes (uniform distribution) |
| **Large delays**<br>*Total 32 scenarios* | 8 scenarios:<br>One train from first timetable cycle<br>delayed by 10 to 15 minutes (uniform distribution) | 24 scenarios:<br>One train from first timetable cycle plus the 1st, 2nd or 3rd following train delayed by 10 to 15 minutes (uniform distribution) |

Note that before running the model, it is checked that no sequence changes occur outside the model due to the initial delay of one of the trains. If this is the case, the train originally running behind a delayed train is also delayed so that it enters the model at block distance behind the initially delayed train, so that no sequence changes take place outside the model.

## 4.4 Summary

In this chapter, the different infrastructure and operational characteristics are determined to evaluate the considered RTRM. In addition, different disturbance scenarios are developed, which are applied to each infrastructure and operational scenario.

6 types of infrastructure layouts are regarded. Four represent typical interactions of routes namely a cross-over, merge, overtaking and single track section. Two represent common combinations of route interactions namely and cross-over & merge (which is common in a level junction with two merging double-track lines) and merge & overtaking (common on main lines).

Regarding operational characteristics, the traffic pattern, running time supplement and infrastructure occupation rate are regarded. The considered traffic patterns differ in homogeneous or heterogeneous operations, homogeneous or heterogeneous routes (for heterogeneous operations), with or without scheduled overtaking/passage of trains (for single track and overtaking layouts) and in the sequence of trains (for heterogeneous operations). Three different sizes are considered for both the running time supplement (0%, 5% and 10%) and for the infrastructure occupation rate (50%, 75% and 90%).

Regarding disturbances three magnitudes of delays are used, where for each magnitude 32 disturbance scenarios are generated in which 1 or 2 trains are delayed (initial delay) according to an uniform distribution.

In table 4.5 an overview is given of the infrastructure, operational and disturbance scenarios. 19 (5+4+2+2+2+4) combinations of infrastructure layout and traffic patterns are regarded (see table 4.3). Note that for each layout not the same number of traffic patterns is applied, as not all traffic patterns are relevant for each layout. For the 19 combinations of infrastructure layouts and traffic patterns, 3 different sizes of running time supplement and 3 infrastructure occupation rates are applied, resulting in a total of 171 infrastructure and operational scenarios. For each of these scenarios, 96 (32 * 3) disturbance scenarios are applied. This results in a total number of 16416 scenarios.

*Table 4.5. Overview of infrastructure, operational and disturbance scenarios*

| Scenario | Characteristic | Number | Value |
|---|---|---|---|
| Infrastructure scenarios: | Infrastructure layouts | 6 | Cross-over,<br>Merge,<br>Overtaking,<br>Single track,<br>Cross-over & Merge,<br>Merge & Overtaking |
| Operational scenarios: | Traffic pattern | 19:*<br>5 + 4 + 2 +<br>2 + 2 + 4 | Homog./heterog. operation,<br>Homog./heterog. routes,<br>Sequence of trains,<br>With/without scheduled overtaking<br>Location of train passages |
| | Running time supplement | 3 | 0%, 5%, 10% |
| | Infra. occupation rate | 3 | 50%, 75%, 90% |
| **Total infrastructure and operational scenarios:** | | **171** | **Scenarios** |
| Disturbance scenarios: | Initial delay | 96 | Small (32), Medium (32), Large (32) |
| **Total scenarios:** | | **16416** | **Scenarios** |

**19 combinations of infrastructure layouts and traffic patterns. The number of traffic patterns considered per layout is not the same for each layout (so 5 traffic patterns for the cross-over layout, 4 traffic patterns for the merge layout, etc.).*

# 5. Assessment of the alternative graph-based RTRM

This chapter refers to the fourth sub-question: 'How sensitive is the performance of an RTRM to different infrastructure layouts and traffic patterns?'. Here results are reported obtained from the application of the observed AG-based RTRM to the different scenarios.

In section 5.1 the results of the conflict detection module are discussed. This is an indication of how complex the generated scenarios are, which could support understanding the results.

Section 5.2 discusses the performance of the RTRM versus the performance of the SDRs by using 6 different KPIs. Two indicators are introduced namely the relative improvement and the percentage scenarios the RTRM outperforms an SDR (for a certain KPI). It concludes which KPIs and SDRs are useful in the assessment of an RTRM.

In section 5.3 RTRM is evaluated across different layouts and traffic patterns, by mainly using the weighted consecutive delay KPI and the relative improvement indicator (η).

In sections 5.4, 5.5 and 5.6 the impact of infrastructure occupation rate, running time supplement and size of initial delay on the performance of the RTRM and SDRs are discussed based on the weighted consecutive delay KPI. Section 5.6 also contains the results of the relative delay KPI for the RTRM.

Section 5.7 elaborates on the optimization runtime KPI.

Section 5.8 is added to show the impact of the train-specific weighting factor in the objective function. It contains a sensitivity analysis of the weighting factor, in which the solutions obtained by the RTRM (with weighting factor) are compared with solutions from the same RTRM for which the weighting factor is set to 1.

Section 5.9 provides a summary of this chapter, addressing different aspects that are discussed in this chapter.

## 5.1 Analysis of train conflicts

To have an overview of what the impact of a set of disturbance scenarios is on the considered infrastructure layouts and traffic patterns, in this section the results of the conflict detection module are discussed. The conflict detection module counts the number of pairs of trains that have conflicting routes (which are resolved by the RTRM or by SDRs). This number is also an indication of the problem complexity for the underlying scenarios.

Figure 5.1 shows the average number of conflicts over the scenarios for the investigated layouts and traffic patterns. A distinction is made for scenarios with a timetable cycle time resulting in an infrastructure occupation rate of 50%, 75% and 90%.

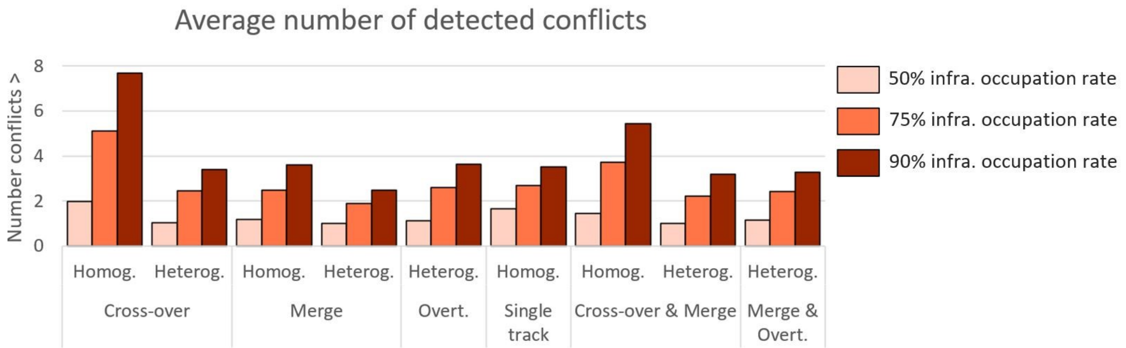



*Figure 5.1. Average number of detected conflicts for different infrastructure layouts and traffic patterns*

This figure shows that most conflicts are detected for scenarios with a small timetable cycle time, with an infrastructure occupation rate of 90%. It also shows that most conflicts arise for homogeneous traffic patterns. This is because for these traffic patterns the timetable cycle time is shorter compared to heterogeneous traffic patterns with the same infrastructure occupation rate (see appendix B for the timetable cycle times).

Table 5.1 gives the average number of conflicts for the different layouts over the different infrastructure occupation rates, running time supplements and sizes of delay (small, medium or large initial delay). Conditional formatting is used to highlight the scenarios where on average many conflicts occur.

*Table 5.1. The average number of detected conflicts*

| **Average number of conflicts** | | **Infrastr. occupation rate** | | | **Running time suppl.** | | | **Size initial delay** | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Layout** | **All sce.** | **50%** | **75%** | **90%** | **0%** | **5%** | **10%** | **Small** | **Med.** | **Large** |
| Cross-over | 3.3 | 1.4 | 3.5 | 5.1 | 3.5 | 3.3 | 3.2 | 2.2 | 3.3 | 4.5 |
| Merge | 1.9 | 1.0 | 2.0 | 2.8 | 2.0 | 2.0 | 1.9 | 1.3 | 2.0 | 2.6 |
| Overtaking | 2.5 | 1.1 | 2.6 | 3.6 | 2.5 | 2.5 | 2.4 | 1.7 | 2.3 | 3.3 |
| Single track | 2.6 | 1.6 | 2.7 | 3.5 | 2.6 | 2.6 | 2.5 | 2.2 | 2.7 | 2.9 |
| Cross-over & Merge | 2.8 | 1.2 | 3.0 | 4.3 | 3.0 | 2.8 | 2.7 | 1.5 | 2.8 | 4.2 |
| Merge & Overtaking | 2.3 | 1.2 | 2.4 | 3.3 | 2.4 | 2.3 | 2.2 | 1.7 | 2.2 | 3.0 |
| **All layouts** | **2.6** | **1.3** | **2.7** | **3.8** | **2.7** | **2.6** | **2.5** | **1.8** | **2.6** | **3.5** |

This table shows that the size of the initial delay also influences the timetable cycle time, as on average over the scenarios more conflicts arise with large initial delays (10 to 15 minutes). For the single track layout, the influence of the size of the initial delay on the average number of conflicts is the smallest because for this layout most conflicts arise between oncoming trains, while a small delay (2 to 5 minutes) also quickly leads to a conflict.

The running time supplement has a limited effect on the number of conflicts. Due to the available supplement, the delays are slightly reduced and there is less chance of a conflict with the next train, which results in a slight decrease in the average number of conflicts for a larger percentage of running time supplements.

Table C.1 in appendix C contains the average number of conflicts for the different investigated running time supplements and sizes of initial delay, subdivided over the different traffic patterns including the sequence of trains and differences in operational manoeuvres (with/without scheduled overtaking and locations were trains pass). For the 'overtaking' and 'merge & overtaking' layouts, it is notable that most conflicts arise for timetables where an overtaking is scheduled. This is because in most cases delay does lead to a conflict because of the timing around the overtaking location.

*Conflict free scenarios*

For several scenarios, the initial delay is such that no conflicts were detected. Table 5.2 gives the percentage of scenarios for which no conflicts are detected for the different layouts against the infrastructure occupation rate, running time supplement and size of initial delay. It highlights percentages larger than 5%.

*Table 5.2. Percentage conflict-free scenarios*

| % conflict-free scenarios | | Infrastr. occupation rate | | | Running time suppl. | | | Size of initial delay | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Layout** | **All sce.** | **50%** | **75%** | **90%** | **0%** | **5%** | **10%** | **Small** | **Med.** | **Large** |
| Cross-over | 7% | 18% | 1% | 0% | 5% | 6% | 8% | 16% | 3% | 2% |
| Merge | 10% | 28% | 2% | 0% | 8% | 10% | 12% | 23% | 4% | 3% |
| Overtaking | 10% | 28% | 2% | 0% | 10% | 10% | 11% | 19% | 10% | 1% |
| Single track | 2% | 3% | 2% | 0% | 2% | 2% | 2% | 3% | 1% | 2% |
| Cross-over & Merge | 12% | 34% | 2% | 0% | 10% | 12% | 14% | 30% | 6% | 0% |
| Merge & Overtaking | 10% | 28% | 1% | 0% | 9% | 10% | 11% | 18% | 8% | 5% |
| **All layouts** | **9%** | **24%** | **1%** | **0%** | **8%** | **9%** | **10%** | **19%** | **5%** | **2%** |

The table shows that for almost all scenarios belonging to the single track layouts, conflicts are detected. The same holds for all scenarios with smaller timetable cycle times with an infrastructure occupation rate of 75% or 90% and for scenarios with large initial delays. The running time supplement does not have much impact on the share of conflict-free scenarios. As expected cross-over and single track layouts are mostly affected by conflicts.

Because the RTRM cannot do anything to reduce the delay in conflict-free scenarios (trains can run their conflict-free path and no consecutive delay should arise), these scenarios are not included in the computation of the KPIs in the next results sections.

## 5.2 Key performance indicators and simple dispatching rules

To assess the RTRM over different infrastructures and operational conditions, 7 different KPIs were used. In this section, 6 KPIs are discussed that can be related to SDRs to express the relative benefit. For this purpose two indicators are introduced:

1. the relative improvement by the RTRM over the SDRs ($\eta$), which is computed for each SDR using the following formula:

   $$\eta = \frac{\kappa_{SDR} - \kappa_{RTRM}}{\kappa_{RTRM}} * 100\% \tag{13}$$

   In this formula, $\eta$ is the relative improvement by the RTRM over the SDR, $\kappa_{RTRM}$ is the average value of the KPI by the RTRM over the considered scenarios and $\kappa_{SDR}$ is the average value of the KPI by the SDR over the considered scenarios. Note that for the punctuality KPI, the highest $\kappa_{.}$ the better. Therefore in the formula, the numerator is changed to $(\kappa_{RTRM} - \kappa_{SDR})$ in order to obtain positive values in case the RTRM performs better than the SDR.
2. the percentage of scenarios for which the RTRM outperforms the SDR (in short '% scenarios RTRM better'). A margin of 10 seconds (and for the punctuality KPI 1%) is used to cover rounding errors. This indicator can highlight SDRs for which the $\eta$ is high for a certain layout due to some outliers, but the '% scenarios RTRM better' be low meaning
3. that in most cases this SDR is performing as well (or better) than the RTRM.

Figure 5.2 shows the first indicator, the relative improvement (η), for 6 KPIs for the 6 considered infrastructure layouts. The bars represent for a specific layout and traffic pattern only the best performing SDR (i.e. with the most favourable value for the KPI). The color of the bar indicates which SDR performs best and is used for the calculation of η. So on average over all cross-over layout scenarios the FCFS performs best of all SDRs for the weighted consecutive delay KPI (however the weighted consecutive delay for FCFS is still 19% higher than for the RTRM).

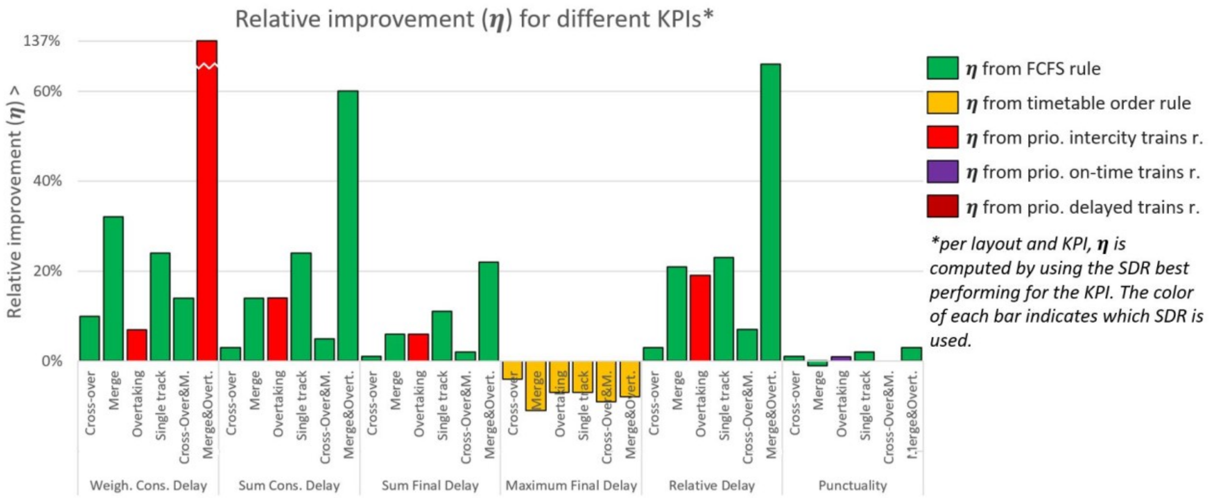



*Figure 5.2. Relative improvement (η) for different infrastructure layouts and KPIs*

This figure shows that the η of the RTRM over an SDR, varies over the different layouts but also over the different used KPIs. Since the RTRM minimizes the weighted consecutive delay, it is to be expected that for these KPIs the highest η's are obtained. For the punctuality and the maximum final delay KPI, the investigated RTRM appeared to be less suitable and another objective function should be chosen to minimize these KPIs. For the maximum final delay, the values of η for the timetable order rule are even negative for all layouts, which means that timetable order SDR outperforms the considered RTRM for this KPI.

A comparison between the different SDRs and the RTRM for the different KPIs and layouts is shown in table 5.3. This table gives the average values of the 6 different KPIs for the RTRM over the different infrastructure layouts. It also gives the values of the KPIs for the SDRs. The table includes the η and the '% scenarios RTRM better' only for the best performing SDR per row. The color of the cell indicates which SDR performs best and is used for the computation of this indicator. These colors are the same as the colors used in the histograms and for the average KPI value (so green is FCFS, yellow timetable order, etc.).

For the single track and the merge & overtaking layout, some SDRs result in deadlock situations for several scenarios, with the result that extremely high values are found for the delay-related KPIs for these SDRs. For this reason, these scenarios have been omitted in the computation of the average value of the KPI and of the *η* for the delay-related KPIs. If more than 5% of the scenarios result in deadlock situations, this SDR is not usable for that specific layout and is marked grey. The '% scenarios RTRM better' indicator still includes scenarios that result in deadlock situations (and of course for these scenarios, the RTRM performs better).

*Table 5.3. Average values for KPIs and SDRs per infrastructure layout*

| KPI + Layout | Average KPI value | | | | | | Relative im-provement by RTRM ($\eta$)** | % scenarios RTRM performs better** |
|---|---|---|---|---|---|---|---|---|
| | RTRM | FCFS | Timetable order | Pr. intercity trains | Pr. on-time trains | Pr. delayed trains | | |
| **Weigh. Cons. Del.(s)** | **674** | ***957** | **1356** | ***1072** | ***1344** | ***1140** | ***44%** | **46%** |
| Cross-over | 784 | 859 | 1695 | 1129 | 1368 | 1254 | 10% | 30% |
| Merge | 689 | 909 | 1161 | 1358 | 1470 | 1015 | 32% | 36% |
| Overtaking | 764 | 1355 | 1001 | 818 | 1043 | 1331 | 7% | 25% |
| Single track | 576 | *596 | 1054 | *596 | *1467 | *764 | *24% | 27% |
| Cross-over & M. | 733 | 835 | 1217 | 962 | 1013 | 944 | 14% | 26% |
| Merge & Overt. | 496 | 1181 | 1524 | *1144 | *1463 | *1313 | *137% | 68% |
| **Sum Cons. Delay (s)** | **508** | ***603** | **987** | ***922** | ***978** | ***765** | ***21%** | **40%** |
| Cross-over | 555 | 572 | 1179 | 894 | 987 | 840 | 3% | 21% |
| Merge | 501 | 569 | 867 | 1136 | 1060 | 730 | 14% | 28% |
| Overtaking | 489 | 701 | 638 | 560 | 605 | 710 | 14% | 25% |
| Single track | 576 | *596 | 1054 | *596 | *1467 | *764 | *24% | 27% |
| Cross-over & M. | 596 | 629 | 986 | 866 | 817 | 745 | 5% | 21% |
| Merge & Overt. | 385 | 617 | 998 | *1127 | *894 | *740 | 60% | 68% |
| **Sum Final Delay (s)** | **1274** | ***1367** | **1753** | ***1684** | ***1745** | ***1530** | **8%** | **40%** |
| Cross-over | 1467 | 1484 | 2091 | 1805 | 1899 | 1752 | 1% | 21% |
| Merge | 1236 | 1305 | 1602 | 1872 | 1795 | 1465 | 6% | 28% |
| Overtaking | 1284 | 1496 | 1432 | 1355 | 1399 | 1505 | 6% | 25% |
| Single track | 1126 | *1125 | 1604 | *1125 | *1990 | *1301 | *11% | 27% |
| Cross-over & M. | 1428 | 1461 | 1818 | 1698 | 1649 | 1577 | 2% | 21% |
| Merge & Overt. | 1060 | 1292 | 1673 | *1788 | *1556 | *1415 | 22% | 68% |
| **Max. Final Delay (s)** | **492** | ***556** | **455** | ***568** | ***711** | ***501** | **-8%** | **6%** |
| Cross-over | 475 | 483 | 453 | 528 | 590 | 487 | -4% | 4% |
| Merge | 514 | 612 | 459 | 621 | 798 | 491 | -11% | 0% |
| Overtaking | 494 | 587 | 460 | 514 | 586 | 580 | -7% | 0% |
| Single track | 461 | *504 | 429 | *504 | *911 | *429 | -7% | 16% |
| Cross-over & M. | 511 | 537 | 464 | 612 | 681 | 472 | -9% | 0% |
| Merge & Overt. | 500 | 616 | 459 | *605 | *771 | *542 | -8% | 15% |
| **Relative Delay (-)** | **0.55** | ***0.68** | **0.97** | ***1.15** | ***1.15** | ***0.81** | ***26%** | **41%** |
| Cross-over | 0.49 | 0.51 | 0.99 | 0.89 | 0.87 | 0.71 | 3% | 21% |
| Merge | 0.58 | 0.70 | 0.91 | 1.56 | 1.26 | 0.81 | 21% | 28% |
| Overtaking | 0.50 | 0.73 | 0.62 | 0.59 | 0.63 | 0.74 | 19% | 25% |
| Single track | 0.75 | *0.84 | 1.26 | *0.84 | *2.43 | *0.97 | *23% | 27% |
| Cross-over & M. | 0.57 | 0.61 | 0.88 | 0.94 | 0.88 | 0.71 | 7% | 21% |
| Merge & Overt. | 0.48 | 0.80 | 1.07 | *1.61 | *1.17 | *0.92 | 66% | 68% |
| **Punctuality (%)** | **79** | **78** | **68** | **73** | **74** | **73** | **1%** | **18%** |
| Cross-over | 75 | 75 | 62 | 71 | 72 | 70 | 1% | 9% |
| Merge | 80 | 80 | 71 | 74 | 79 | 73 | -1% | 10% |
| Overtaking | 78 | 77 | 75 | 77 | 78 | 76 | 1% | 17% |
| Single track | 80 | 79 | 71 | 79 | 70 | 75 | 2% | 11% |
| Cross-over & M. | 77 | 77 | 67 | 74 | 76 | 72 | 0% | 8% |
| Merge & Overt. | 83 | 80 | 70 | 71 | 70 | 76 | 3% | 35% |

**Scenarios resulting in deadlocks excluded*

***The cell color indicates which SDR performs best and is used for the η and '% scenarios RTRM better'*

*Grey cells: Invalid as more than 5% of scenarios are excluded due to deadlocks*

To these results from table 5.3, it should first be noted that the same operational conditions and disturbance scenarios were applied for all layouts, however the (consecutive) delay that occurs is different per layout due to the divergent topologies and available infrastructure which could prevent the accumulation of delays. In addition, the extent to which the RTRM reduces the delay also differs compared to the SDRs. It should be noted that the best performing SDR for a layout and KPI, not always is the SDR with the least '% scenarios RTRM better', like for example for the merge & overtaking layout for the sum consecutive delay KPI. However, the values of these KPIs are often close to each other.

The results from figure 5.2 and table 5.3 are discussed separately for the KPIs and SDRs.

*Key performance indicators (KPIs)*
The most interesting KPI is the weighted consecutive delay as this KPI is also the objective of the RTRM. For this KPI also most improvement can be gained by the RTRM versus the SDRs (an η of 44% over all scenarios). In addition, the RTRM shows improvement for the sum consecutive delay KPI (an η of 21% over all scenarios) and sum final delay KPIs (an η of 8% over all scenarios). For the punctuality and the maximum final delay KPIs, the η is much lower, so the objective function used is not very suitable for improving these KPIs. Note that de SDRs for no scenario outperform the RTRM for the weighted consecutive delay KPI, as the RTRM is optimizing for this KPI. In addition, the '% scenarios RTRM better' is for all SDRs and layouts the highest for the weighted consecutive delay.

Comparing the KPIs weighted consecutive delay and the sum of consecutive delay (without weighting factor), it appears that for all layouts and most SDRs the $\eta$ is lower for the sum of consecutive delay. This is because the RTRM is train specific with its weighting factor, while most SDRs do not account for different train categories (see also section 5.8).

As the sum final delay KPI also includes initial delays (which are the same for all dispatching strategies) the $\eta$ are reduced in comparison to the sum consecutive delay KPI. This reduction is by approximately the same amount namely by 60% for all layouts and SDRs. Regarding the '% scenarios RTRM better', exactly the same percentages are found. From this it can be concluded that this KPI is not very relevant for the purpose of comparing RTRMs with SDRs.

The relative delay indicates how much consecutive delay arises in relation to the initial delay. Averaged over all scenarios, it is 0.55 for the RTRM. For the single track layout, an initial delay results in the most consecutive delay with the highest relative delay of 0.75 over all single track scenarios for the RTRM. Less relevant is the comparison with the SDRs, as the initial delays for an RTRM as an SDR are the same anyway. For this reason, the η and the '% scenarios RTRM better' are roughly equivalent to the sum final delay KPI.

The maximum final delay KPI is an indicator of how often one specific train is delayed (for the sake of other trains). It appears that the rescheduling model performs relatively better than most SDRs. An exception is the timetable order rule, which performs for almost all layouts on average better than the RTRM. This is because when maintaining the original order, never one train is delayed extremely long. The maximum delay is therefore never larger than the highest initial delay.

Regarding the punctuality KPI, for most SDRs, the $\eta$ is positive, which means that the RTRM results in higher punctuality in comparison to the SDRs. This is not the case for every scenario, as it regularly happens that the RTRM delays a train somewhat (so it falls outside the punctuality margin) if this benefits the intended objective. This can be seen back in the results where the η is negative for the FCFS rule for the merge layout. In figure 5.3, an example can be found (for the merge layout with the R1.IC2 traffic pattern), with a scenario where an intercity train (IC201) has an initial delay of 6 minutes. For this scenario, the FCFS results in higher punctuality as the regional train (R101) which should originally run behind the (delayed) intercity train is prioritised and arrives punctual at the destination. On the contrary, the RTRM proposes the regional train (R101) to wait for the intercity train (IC201) so that the delay of the intercity train is limited, however now also the regional train (R101) falls outside the punctuality margin.

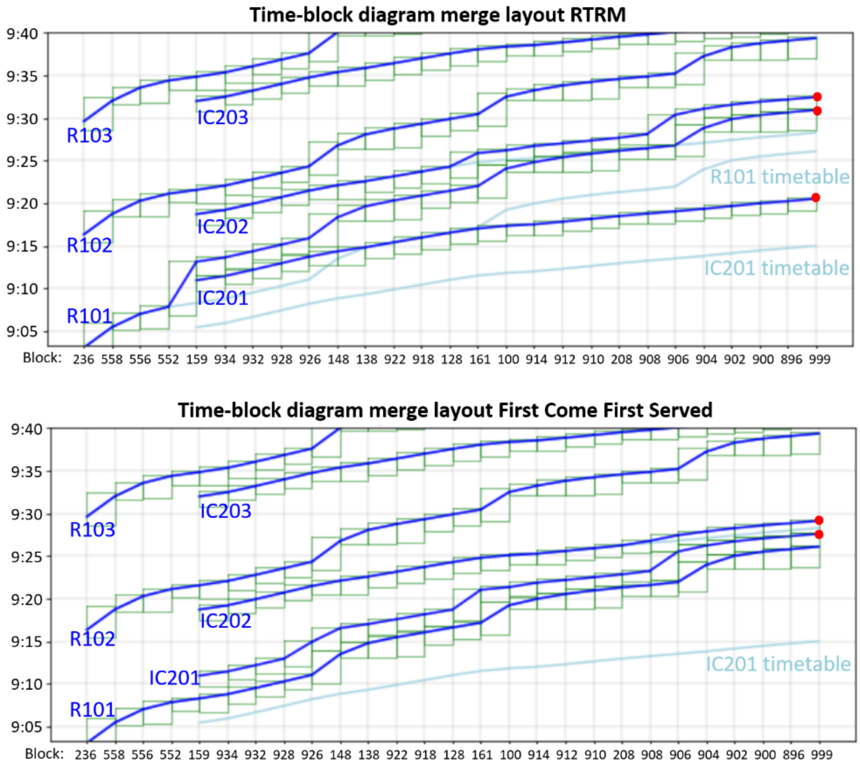



*Figure 5.3. Time-block diagram for example scenario with RTRM and FCFS solutions*

For this KPI it is expected the prioritise on-time trains rule to perform best, as it prioritises on-time trains which should remain punctual. However, this cannot be seen back in the results (over all scenarios it results in a punctuality of 74%, while the RTRM and the FCFS rule result in 79% and 78%). This is due to some trivial and myopic choices (like delayed trains blocking the tracks resulting in more delayed trains), which lower the punctuality.

*Simple dispatching rules (SDRs)*

From the considered SDRs, the FCFS rule appeared to perform best in most scenarios and for most KPIs. This is especially true for the cross-over layout, where the η is also very low (10% for the weighted consecutive delay KPI), but also for the merge, single track and cross-over & merge layout.

For overtaking and merge & overtaking, the prioritise intercity trains rule was often found to have the best performance of the SDRs (with also a low η of 7% for the weighted consecutive delay KPI for the overtaking layout). The FCFS rule will never suggest overtaking there because the regional train can always leave before the next intercity train. For the merge & overtaking layout, the difference between the prioritise intercity trains and the FCFS rule is very small though (137% and 138%) with the big difference that no deadlock situations arise with the FCFS rule for this layout.

The timetable order was found to have the best performance of the RTRMs, especially for small delays or timetables with small infrastructure occupation rates. In addition, this SDR appeared to be the most strategic for the maximum final delay KPI, where it improved the RTRM. This rule also has the advantage that it cannot lead to deadlock situations in any scenario. This is because no sequence changes take place and the scheduled order never leads to deadlock situations if all goes well.

The other considered SDRs rarely appeared to be the most strategic SDR, often partly due to myopic and trivial choices (which the timetable order rule and the prioritise intercity trains rule also suffer from).

## 5.3 Layouts and traffic patterns

This section contains evaluation results of the RTRM across different layouts and traffic patterns. For this purpose, the RTRM is compared against SDRs using the indicators 'relative improvement by RTRM' (η) and '% scenarios RTRM better'. Mostly only the weighted consecutive delay KPI is used for this, as this is the best indicator of how the RTRM reaches its objective (as stated in section 5.2). The underlying subsections go more into depth about the behaviour of the RTRM and the SDRs and elaborate more on the different traffic patterns (including the sequence of trains and differences in operational manoeuvres) regarded for the layouts.

Figure 5.4 shows the η for the different layouts and traffic patterns (aggregated over homogeneous and heterogeneous traffic patterns). The bars only represent the best performing SDR. The color of the bar indicates which SDR performs best and is used for the calculation of η.

Note that for the cross-over layout the R1.IC2 pattern (with on one route only intercity trains and on the other route only regional trains) is regarded as a homogeneous traffic pattern, as it shows very similar behaviour to the R1.R2 pattern (with only regional trains), which is further explained in section 5.3.1.

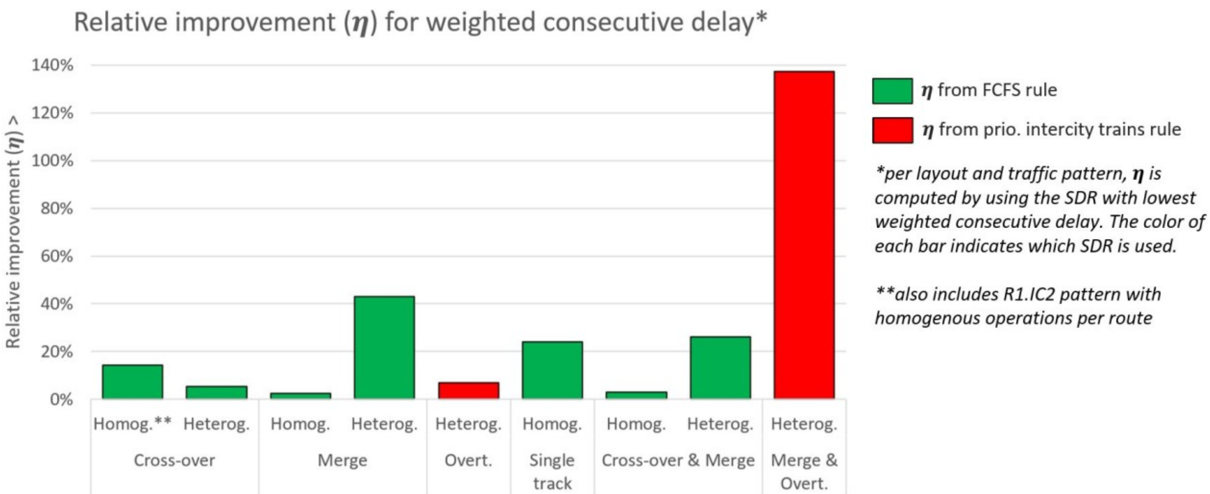



*Figure 5.4. Relative improvement (η) for different infrastructure layouts and traffic patterns*

In table 5.4 the weighted consecutive delay is given for the different layouts subdivided into homogeneous and heterogeneous traffic patterns for the RTRM and for the best performing SDR (with the lowest weighted consecutive delay). Furthermore, the table gives per SDR the η and the '% scenarios RTRM better' for the weighted consecutive delay. For these indicators, the best performing SDRs (with the lowest percentages) are underlined.

*Table 5.4. Weighted consecutive delay, η and '% scenarios RTRM better' over different layouts for the SDRs.*

| | Weighted cons. delay (s) | | Relative improvement by RTRM (η) | | | | | % scenarios RTRM better | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Layout + Traffic pattern** | **RTRM** | **Best perf. SDR**** | **FCFS** | **Timetable order** | **Pr. intercity trains** | **Pr. on-time trains** | **Pr. delayed trains** | **FCFS** | **Timetable order** | **Pr. intercity trains** | **Pr. on-time trains** | **Pr. delayed trains** |
| **Cross-over** | **784** | **859** | **10%** | **116%** | **44%** | **75%** | **60%** | **30%** | **72%** | **52%** | **66%** | **53%** |
| Homogeneous*** | 886 | 1012 | 14% | 139% | 57% | 99% | 100% | 40% | 78% | 61% | 73% | 68% |
| Heterogeneous | 710 | 748 | 5% | 96% | 32% | 52% | 23% | 22% | 67% | 46% | 61% | 42% |
| **Merge** | **689** | **909** | **32%** | **68%** | **97%** | **113%** | **47%** | **36%** | **43%** | **41%** | **68%** | **40%** |
| Homogeneous | 727 | 744 | 2% | 102% | *2%* | 131% | 43% | 10% | 56% | *10%* | 69% | 42% |
| Heterogeneous | 676 | 967 | 43% | 56% | 132% | 107% | 49% | 46% | 39% | 52% | 68% | 39% |
| **Overtaking** (Het.) | **764** | **818** | **77%** | **31%** | **7%** | **37%** | **74%** | **81%** | **51%** | **25%** | **50%** | **79%** |
| **Single track** (Hom.) | **576** | ***596** | ***24%** | **83%** | ****24%*** | *204% | ***51%** | **27%** | **59%** | ***27%*** | **80%** | **48%** |
| **Cross-over & Merge** | **733** | **835** | **14%** | **66%** | **31%** | **38%** | **29%** | **26%** | **50%** | **35%** | **54%** | **39%** |
| Homogeneous | 748 | 769 | 3% | 70% | *3%* | 33% | 23% | 18% | 57% | *18%* | 57% | 42% |
| Heterogeneous | 718 | 905 | 26% | 62% | 63% | 44% | 35% | 34% | 43% | 52% | 51% | 35% |
| **Merge & Overtaking** (Het). | **496** | **1144** | **138%** | **207%** | ***137%** | *237% | ***166%** | **81%** | **79%** | **68%** | **80%** | **77%** |

**Scenarios resulting in deadlocks excluded*
***The cell color indicates which SDR is best performing for a traffic pattern*
****Also includes the R1.IC2 pattern with homogeneous operations per route*
*Grey cells: Invalid if more than 5% of scenarios are excluded due to deadlocks*

From figure 5.4 and table 5.4 it can be concluded that the benefits of an RTRM expressed in terms of relative improvement on SDRs not only differs per layout but this is also influenced by the (homogeneous or heterogeneous) traffic pattern.

For most traffic patterns with homogeneous operation, the weighted consecutive delay for the FCFS rule is almost equal to that for the RTRM. For the merge and the cross-over & merge layout the η is very low for a homogeneous operation, namely 2% and 3%. This means that the implementation of an RTRM is not very effective for these infrastructure and traffic configurations

For the cross-over layout, it is the other way around, where the RTRM provides an η of 14% for homogeneous operation, whereas for heterogeneous operation this improvement is only 5%. The main reason for this difference is that the timetable cycle time of the homogeneous timetable is much smaller than the timetable cycle time for a heterogeneous timetable (for an equal infrastructure occupation rate). This results in more trains passing the cross-over in a heterogeneous timetable, which causes more conflicts (this can be seen in section 5.1 and figure 5.1).

For the single track layout with homogeneous operation, the RTRM only offers a reduction of the weighted consecutive delay of 24% compared to FCFS. However, for this layout, the occurrence of deadlock situations must be taken into account when using the FCFS rule, which occurs in 5% of the cases (see more about this in section 5.3.4).

For the overtaking layout with a heterogeneous timetable, the prioritise intercity trains rule performs best of the SDRs. The RTRM offers here a 7% reduction of the average weighted consecutive delay.

According to the results, the merge, cross-over & merge and merge & overtaking layouts are the layouts where the considered RTRM most effective in reducing the weighted consecutive delay are with the merge, cross-over & merge and merge & overtaking layout with heterogeneous operations. For the merge and the cross-over & merge layout, the weighted consecutive delay is for the FCFS rule 43% and 27% higher than the RTRM. For the merge & overtaking layout, the prioritise intercity trains rule performs best of the SDRs, however, the RTRM can reduce this value much stronger, namely with an η of 137% (this is 138% for the FCFS rule). This shows that with increasing complexity, i.e. a merge and a subsequent overtaking location, the simple dispatching rules are less suitable for delay reduction, whereas the RTRM can provide a large reduction of delay in this situation.

### 5.3.1 Cross-over layout

In this section, the performance of an RTRM on a cross-over layout is discussed. This section also regards the different traffic patterns belonging to this layout including the differences in the sequence of trains.

Figure 5.4 and table 5.4 showed that for this layout, the FCFS rule performs best of the SDRs. This is also plausible since by prioritizing the train that approaches the cross-over first, the waiting time of trains in front of the cross-over is minimal. Nevertheless, the RTRM can still offer improvement (η of 10% and a '% scenarios RTRM better' of 30%). In four situations the RTRM offers a different solution than the FCFS rule.

- If two trains of a different category approach the cross-over (intercity and regional train), while the train of the lower category approaches the cross-over first. With the FCFS rule, this train would have priority. However, the RTRM can make other choices here if the sum of the weighted consecutive delay is lower by prioritizing the train from the higher category.
- Even if no weighting factor is applied (as for example in the homogeneous timetable with regional trains on both routes (R1.R2 pattern)), the RTRM can make a different choice in case two trains approach the merge just at the same time. Due to differences in blocking times of the trains (e.g. due to differences in speeds of the trains and due to different locations of the signals and block sections). For that specific cases, the RTRM makes different choices if the consecutive delay of prioritizing the second train is smaller (note that this difference is very small).
- If an on-time train and a delayed train approach the cross-over. Since the delayed train has no more running time supplement available, it may be more strategic to prioritise this train, even if it approaches the cross-over later than the on-time train.
- If the FCFS rule results in the situation that the train that approaches the cross-over last, causes further down the line delay by a third train.
  This situation is illustrated by the following example (of one of the scenarios) with a homogeneous traffic pattern. Trains cross in shared block section 159. The train with identity number 201 is delayed, causing train 101 to approach the block section first. Originally train 201 would pass the cross-over first. Figure 5.5b shows a schematic representation of the situation.

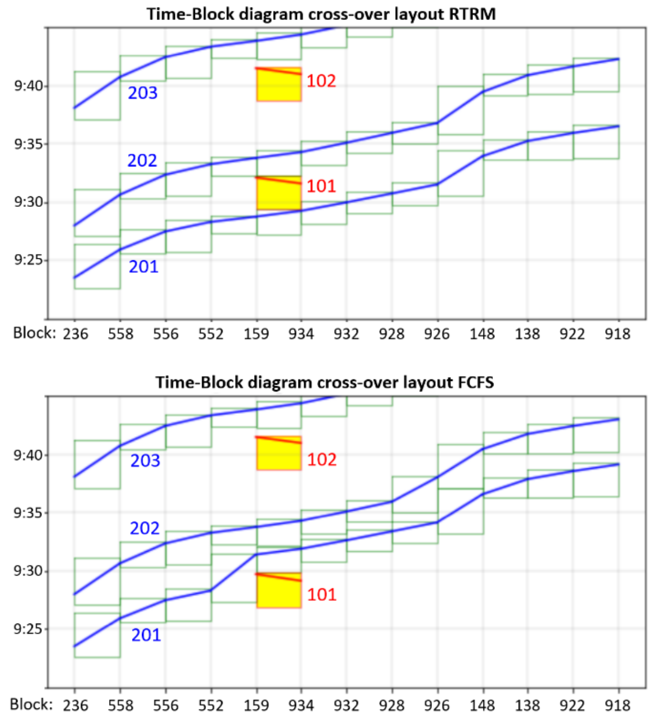



*Figure 5.5a. Time-block diagram for example scenario with RTRM and FCFS solutions.*

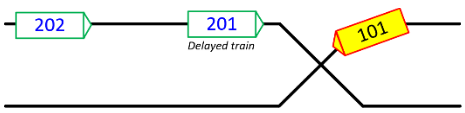



*Figure 5.5b. Schematic representation example situation*

With the FCFS rule, a change of sequence is implemented, letting train 101 pass the cross-over at first. This minimizes delays at the cross-over location itself. However, due to the additional delay of train 201 (received at the cross-over), trains 201 and 202 are running with a minimum headway behind the cross-over. This causes problems in block section 926 where train 201 has a scheduled stop, causing an additional delay for train 202. In the RTRM, train 101 waits a bit longer and uses the available space between trains 201 and 202, causing only train 101 to be delayed. In many of these cases, the RTTP of the RTRM results in alternating the different directions (instead of always rigidly letting the first approaching train go first, as in FCFS).

*Traffic patterns (including sequence of trains)*

Different traffic patterns have been considered for the cross-over layout, with different stopping patterns and different orders of trains passing through the cross-over (see section 4.2.2). In table 5.5 the weighted consecutive delay is given for the different traffic patterns for the RTRM and for the best performing SDR (with the lowest weighted consecutive delay). Furthermore, the table gives per SDR the η and the '% scenarios RTRM better' for the weighted consecutive delay. For these indicators, the best performing SDRs (with the lowest percentages) are underlined.

*Table 5.5. Weighted consecutive delay, η and '% scenarios RTRM better' for traffic patterns from cross-over layout*

| | Weighted cons. delay (s) | | Relative improvement by RTRM (η) | | | | | % scenarios RTRM better | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Traffic pattern** | **RTRM** | **FCFS*** | **FCFS** | **Timetable order** | **Pr. intercity trains** | **Pr. on-time trains** | **Pr. delayed trains** | **FCFS** | **Timetable order** | **Pr. intercity trains** | **Pr. on-time trains** | **Pr. delayed trains** |
| **Homogeneous** | **886** | 1012 | **14%** | **139%** | **57%** | **99%** | **100%** | **40%** | **78%** | **61%** | **73%** | **68%** |
| R1.R2 | 764 | 852 | 12% | 111% | *12%* | 117% | 87% | 39% | 72% | *39%* | 77% | 65% |
| R1.IC2 | 1007 | 1171 | 16% | 160% | 92% | 85% | 111% | 41% | 83% | 84% | 70% | 71% |
| **Heterogeneous** | **710** | 748 | **5%** | **96%** | **32%** | **52%** | **23%** | **22%** | **67%** | **46%** | **61%** | **42%** |
| R1.R2.IC1.R2 | 574 | 613 | 7% | 108% | 38% | 66% | 33% | 23% | 65% | 46% | 65% | 44% |
| R1.R2.IC1.IC2 | 769 | 814 | 6% | 92% | 35% | 41% | 18% | 25% | 68% | 51% | 60% | 41% |
| R1.R2.IC2.IC1 | 783 | 813 | 4% | 90% | 25% | 54% | 22% | 18% | 69% | 39% | 58% | 42% |

**FCFS is for all traffic patterns the best performing SDR*

For the homogeneous patterns, a distinction is made between a pattern with all trains from the same train category (R1.R2) and a pattern with trains on each route from the same train category, but different categories over the routes (R1.IC2). This difference has limited influence on the results, since the η (12% and 16%) and the '% performs RTRM better' (39% and 41%) for the FCFS rule are comparable. This is because, for both traffic patterns, the traffic on each route is homogeneous. The only place where trains from different routes come together is the cross-over, but this location is so small that the effects of different train categories at that point have limited influence on the performance of a control strategy. For that reason the R1.IC2 pattern is regarded as a homogeneous traffic pattern.

For the heterogeneous patterns, 3 different traffic patterns were regarded. For the traffic pattern with homogeneous operation on one route and heterogeneous operation on the other route (R1.R2.IC1.R2), the absolute weighted consecutive delay by the RTRM is the smallest (574s in comparison to 769s and 783s for the other patterns). However, this is due to a different valuation, as only 1 out of 4 trains is an intercity train, limiting the weighted consecutive delay. The differences with the other heterogeneous traffic patterns are small, and for all patterns, the best FCFS can be used from the SDRs. Also, the sequence of trains (where in the R1.R2.IC1.IC2 pattern the directions alternate, while in the R1.R2.IC2.IC1 pattern the directions are bunched) does not appear to have any influence on the performance of the RTRM.

The other considered SDRs are no relevant control strategies for the cross-over layouts. For the timetable order rule, trains remain to wait until it is their turn according to the schedule, while an order change could have led to no (or very low) consecutive delay. The priority-based rules are also often less strategic, especially if the train that has priority is already approaching the cross-over last, causing the train from the other direction to have to wait for a few minutes, resulting in more consecutive delay. For the prioritise intercity trains rule, it occurs in some scenarios that a queue of waiting regional trains is formed in front of the cross-over. This is mainly the case for the R1.IC2 traffic pattern (where the η is also very high for this SDR namely 92%).

### 5.3.2 Merge layout

In this section, the performance of an RTRM on a merge layout, where trains from two different directions use a common piece of infrastructure from a certain point, is discussed. It also discusses the influence of different traffic patterns (the differences in homogeneous and heterogeneous operations, homogeneous and heterogeneous routes and sequence of trains).

Figure 5.4 and table 5.4 showed that for this layout a homogeneous traffic pattern (R1.R2) results in a very low η for the weighted consecutive delay for the FCFS rule, namely 2% (which is to be expected so that trains have to wait as little as possible). Nevertheless, in 10% of the scenarios, the RTRM offers a better solution than the FCFS regarding the consecutive delay. This occurs in two cases namely:

- Scenarios where two trains approach the merge at about the same time. This is because the blocking times of different directions are not equal (e.g. due to speed restrictions of the diverging direction and the locations of the signals and block sections), which could result that the train that approaches the cross-over first being prioritised by the FCFS rule, while this train occupies the block section of the cross-over for a longer time. This results in a slightly more consecutive delay than in case the other train is prioritised (which occupies the bloc section of the cross-over for a shorter time).
- Scenarios where an on-time train approaches the merge just earlier than a delayed train from the other direction. Because the last approaching train is already delayed, it is driving at maximum technical speed to catch up on its delay. However, with the FCFS rule, the on-time train is prioritised. As this on-time train is running at the scheduled speed, the delayed train is slowed down even more. In this case, it would be more beneficial to prioritise the delayed train (so that it can maintain running at maximum technical speed).

For the heterogeneous timetables, the FCFS rule turns out to score the best of the SDRs with an η of 43% for the weighted consecutive delay. This improvement is mainly caused by conflicts between trains from a different category, where the slower regional train is approaching the merge first and therefore served first. As a result, the intercity train is slowed down the entire stretch resulting in high consecutive delays. Although the η is lowest for the FCFS rule, the timetable order and the prioritise delayed trains rules have fewer scenarios the RTRM performs better (which is for the FCFS rule 46%, and for the timetable order and prioritise delayed trains rules 39%). These rules perform also well, especially by preventing a delayed intercity train from running behind a (punctual) regional train.

It is noticeable that the prioritise intercity trains rule performs low (for heterogeneous scenarios) with a weighted consecutive delay 132% higher in comparison to the RTRM. This is mainly due to scenarios in which conflicts arise far downstream of the merge. For that scenarios the prioritise intercity trains rule results in the regional train having to wait a long time in front of the merge, so that the intercity train can drive the entire stretch without delay. There are also scenarios (mainly with high infrastructure occupation rates) where this control strategy results in regional trains even having to wait for multiple intercity trains.

*Traffic patterns (including sequence of trains)*

For this layout, homogeneous and heterogeneous traffic patterns are regarded (see section 4.2.2). For the heterogeneous traffic patterns, it is possible to distinguish whether the different merging routes are served homogeneously or heterogeneously and whether trains are bunched per direction or per train category. The R1.IC2 traffic pattern is heterogeneous downstream of the merge, but the two connecting routes are homogeneous. The R1.R2.IC1.IC2 and the R1.IC1.R2.IC2 patterns also have heterogeneous operations over both routes, but differ in order. The first has the train categories bunched (and alternating routes) while the second has the routes bunched (with alternating train categories).

In table 5.6 the weighted consecutive delay is given for the different traffic patterns for the RTRM and for the best performing SDR (with the lowest weighted consecutive delay). Furthermore, the table gives per SDR the η and the '% scenarios RTRM better' for the weighted consecutive delay. For these indicators, the best performing SDRs (with the lowest percentages) are underlined.

*Table 5.6. Weighted consecutive delay, η and '% scenarios RTRM better' for traffic patterns from merge layout*

| | Weighted cons. delay (s) | | Relative improvement by RTRM (η) | | | | | % scenarios RTRM better | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Traffic pattern** | **RTRM** | **Best perf. SDR*** | **FCFS** | **Timetable order** | **Pr. intercity trains** | **Pr. on-time trains** | **Pr. delayed trains** | **FCFS** | **Timetable order** | **Pr. intercity trains** | **Pr. on-time trains** | **Pr. delayed trains** |
| **Homogeneous** R1.R2 | **727** | **744** | **2%** | **102%** | ***2%*** | **131%** | **43%** | **10%** | **56%** | ***10%*** | **69%** | **42%** |
| **Heterogeneous** | **676** | **967** | **43%** | **56%** | **132%** | **107%** | **49%** | **46%** | **39%** | **52%** | **68%** | **39%** |
| R1.IC2 | 501 | 870 | 74% | 86% | 290% | 136% | 83% | 54% | 48% | 75% | 67% | 45% |
| R1.R2.IC1.IC2 | 768 | 956 | 24% | 66% | 143% | 123% | 49% | 34% | 48% | 63% | 74% | 44% |
| R1.IC1.R2.IC2 | 747 | 939 | 43% | 27% | 26% | 72% | 28% | 49% | 22% | 21% | 62% | 30% |

**The cell color indicates which SDR is best performing for a traffic pattern*

This table shows that for a heterogeneous traffic pattern with homogeneous routes (R1.IC2) the RTRM is the most effective: Compared to the other traffic patterns, the absolute value of the weighted consecutive delay for the RTRM is low (501s) while the η is high (74% for FCFS). For this traffic pattern the η for the prioritise intercity trains rule is extremely high (290%). This is due to a large number of scenarios where a queue arises on one of the branches of the merge of waiting regional trains, waiting for a conflict-free path (without hindering any intercity train).

For timetables with homogeneous routes (R1.R2.IC1.IC2 and R1.IC1.R2.IC2), the sequence of trains is not relevant for the performance of the RTRM. On the contrary, various SDRs are sensitive to the sequence of trains. For example, the FCFS rule performs less well when for traffic patterns with alternating train categories (R1.IC2 and R1.IC1.R2.IC2 patterns), because, due to the alternations, more often the situation occurs that an intercity train has to run behind a regional train, building up additional delay. However for the traffic pattern with heterogeneous routes and alternating train categories (R1.IC1.R2.IC2) the prioritise intercity trains rule performs best of the SDRs with only an η of 26%. The difference in the performance of this SDR with the R1.IC2 pattern is because in this traffic pattern no queues occur of waiting regional trains. This is because a regional train (waiting for the merge) can always leave after the intercity train has passed, as this intercity train is always followed by another regional train (which is of the same category as the waiting regional train).

### 5.3.3 Overtaking layout

This section discusses the performance of an RTRM on an overtaking layout where trains use a common piece of infrastructure with a possibility to overtake. For this layout, only heterogeneous traffic patterns have been considered. Control actions for this layout are introducing an overtaking or cancelling an overtaking (in case it was scheduled).

The results show that the weighted consecutive delay is only 7% higher for the prioritise intercity trains rule in comparison to the RTRM. This rule forces an overtaking if a conflict occurs between trains from a different train category. However, the RTRM deviates from this rule in 25% of the scenarios. This happens when there is a conflict (far) downstream of the overtaking location, which results in less weighted consecutive delay when there is no overtaking. For this layout, the FCFS rule scores much lower, because this rule always prioritises the regional train in case of delay. With this approach, the intercity train is slowed down which in most scenarios results in a high amount of consecutive delay.

*Traffic patterns (including with or without scheduled overtaking)*

For this layout, two different heterogeneous traffic patterns were considered, with the same stopping pattern but with differences in operational manoeuvres, namely with or without scheduled overtaking (see section 4.2.2). In table 5.7 the weighted consecutive delay is given for the different traffic patterns for the RTRM and for the best performing SDR (with the lowest weighted consecutive delay). Furthermore, the table gives per SDR the η and the '% scenarios RTRM better' for the weighted consecutive delay. For these indicators, the best performing SDRs (with the lowest percentages) are underlined.

*Table 5.7. Weighted consecutive delay, η and '% scenarios RTRM better' for traffic patterns from overtaking layout*

| | Weighted cons. delay (s) | | Relative improvement by RTRM (η) | | | | | % scenarios RTRM better | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Traffic pattern** | **RTRM** | **Best perf. SDR*** | **FCFS** | **Timetable order** | **Pr. intercity trains** | **Pr. on-time trains** | **Pr. delayed trains** | **FCFS** | **Timetable order** | **Pr. intercity trains** | **Pr. on-time trains** | **Pr. delayed trains** |
| **Heterogeneous** | **764** | **818** | **77%** | **31%** | **<u>7%</u>** | **37%** | **74%** | **81%** | **51%** | **<u>25%</u>** | **50%** | **79%** |
| R.IC | 349 | 396 | 87% | 87% | 22% | <u>13%</u> | 87% | 66% | 66% | 35% | <u>23%</u> | 66% |
| R.IC+O | 1101 | 1136 | 75% | 16% | <u>3%</u> | 42% | 71% | 93% | 40% | <u>17%</u> | 72% | 90% |

**The cell color indicates which SDR is best performing for a traffic pattern*

Considering these results, it appears that the weighted consecutive delay is significantly lower for the pattern without scheduled overtaking (349s versus 1101s). This is due to the larger timetable cycle time (for the same infrastructure occupation rate), resulting in fewer conflicts, and the larger scope for dealing with conflicts (i.e. introducing an overtaking). Cancelling a scheduled overtaking (in the traffic pattern with scheduled overtaking) costs capacity and, especially for scenarios with high infrastructure occupation rates, leads to delays of trains in the next timetable cycle.

Although the performance of the RTRM in terms of (weighted) consecutive delay over the different traffic patterns is different, the relative improvement is comparable. The most benefit however can be gained for a timetable without scheduled overtaking, with an η of 13% for the prioritise on-time trains rule. Note that for this traffic pattern, this SDR proposes in most cases the same solution as the prioritise intercity trains rule (both control strategies add an overtaking in case a regional train is delayed). However, a regional train may be slightly delayed by trains from an earlier timetable cycle (but still considered to be on-time), having a conflict with the next intercity train far downstream of the overtaking location. In this case, the prioritise intercity trains rule will also introduce an overtaking, while the prioritise on-time trains rule will not, which results in less consecutive delay.

### 5.3.4 Single track layout

In this section, the performance of an RTRM on a single track layout with two intermediate stations where trains can pass each other is considered. For these layouts, only homogeneous timetables were considered with trains having a scheduled stop at each intermediate station.

Figure 5.4 showed that for this layout the FCFS rule is the best performing SDR (with a weighted consecutive delay 24% higher in comparison to the RTRM). However, it should be noted that the FCFS can also lead to deadlock situations. These deadlocks occur when trains are sent to a station while there is no empty track available. This can result in a deadlock situation where all trains are waiting for each other, as visualized in figure 5.6.

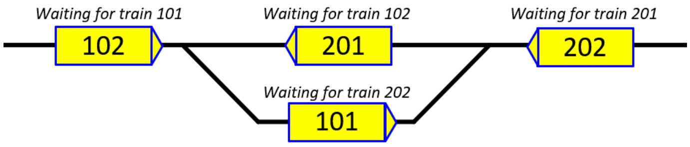



*Figure 5.6. Example deadlock situation single track layout*

In the calculation of the average weighted consecutive delay and the η for the SDRs, the scenarios resulting in deadlock situations are deducted. If this leads to more than 5% of the scenarios not being included, the result is declared invalid as the proportion is then too large.

*Traffic patterns (including the location of train passages)*

For this layout, two different homogeneous traffic patterns were considered, one in which trains pass each other at one intermediate station (R.R(1)), and the other in which trains pass each other at both intermediate stations (R.R(2)). The first one offers more freedom of control by moving the passing of trains to the other intermediate station, while the other one does not have this freedom but can only drop passages on the single track section and let trains pass each other on the still double track section at the edges of the layout (see table 4.3). Since in the R.R(1) pattern trains pass each other less, the minimum timetable cycle time to perform this traffic pattern is larger, resulting in a larger timetable cycle time and lower frequency (for the same infrastructure occupation rate) compared to the R.R(2) pattern (see also appendix B).

In table 5.8 the weighted consecutive delay is given for the different traffic patterns for the RTRM and for the best performing SDR (with the lowest weighted consecutive delay). Furthermore, the table gives per SDR the η and the '% scenarios RTRM better' for the weighted consecutive delay. For these indicators, the best performing SDRs (with the lowest percentages) are underlined. In addition, the table provides the percentage scenarios that result in deadlock situations if using the RTRM or an SDR. Percentages larger than 5% are highlighted. Note that the prioritise intercity trains rule is missing in the table as only homogeneous traffic patterns are considered without intercity trains (so this rule acts like the FCFS rule, see section 3.1.4).

*Table 5.8. Weighted consecutive delay, η and '% scenarios RTRM better' for traffic patterns from single track layout*

| | Weigh. cons. delay (s) | | Relative improvement by RTRM (η) | | | | % scenarios RTRM better | | | | % Deadlock situations | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Traffic pattern** | **RTRM** | **Best perf. SDR**** | **FCFS** | **Timetable order** | **Pr. on-time trains** | **Pr. delayed trains** | **FCFS** | **Timetable order** | **Pr. on-time trains** | **Pr. delayed trains** | **RTRM** | **FCFS** | **Timetable order** | **Pr. on-time trains** | **Pr. delayed trains** |
| **Homogeneous** | **576** | ***596** | ***24%** | **83%** | *204% | ***51%** | **27%** | **59%** | **80%** | **48%** | **0%** | **5%** | **0%** | **9%** | **4%** |
| R.R(1) | 320 | 336 | 5% | 164% | *229% | 62% | 12% | 54% | 73% | 45% | 0% | 0% | 0% | 1% | 0% |
| R.R(2) | 823 | 1256 | *34% | 53% | *190% | *45% | 41% | 63% | 86% | 50% | 0% | 9% | 0% | 18% | 8% |

*Scenarios resulting in deadlocks excluded

**The cell color indicates which SDR is best performing for a traffic pattern

This table shows that the two different homogeneous traffic patterns show differences in how much delay occurs when the RTRM is used. For the traffic pattern where trains pass at only one intermediate station (R.R(1)), the RTRM can reduce the consecutive delay to 320s, whereas for the traffic pattern where trains pass both intermediate stations, the consecutive delay can be reduced to 832s.

Since deadlock situations occur frequently, especially for the R.R(2) layout, it is not possible to make statements based on η for which traffic pattern the RTRM offers the most improvement versus the SDRs. The timetable order rule is an exception because it maintains the original order, which will never lead to deadlock situations. Compared to this rule, much can be gained by the RTRM with an η of 83%. Note that although deadlock occurs in 5% of the scenarios with FCFS, the RTRM performs better than FCFS in only 23% of the scenarios. The RTRM however, can also be used for deadlock prevention, as it never results in deadlock situations (thanks to the AG constraints in the RTRM), which can also be seen as an additional benefit of implementing an RTRM for this layout.

### 5.3.5 Cross-over & merge layout

This section discusses the performance of an RTRM in the considered cross-over & merge layout where trains in opposite directions can cross each other and trains in equal directions can merge (such as in a ground-level junction of two double-track railway lines). For this layout, only one homogeneous and one heterogeneous traffic pattern are regarded (see section 4.2.2).

Although this layout is a combination of the cross-over & merge layout, the performance of this layout is very similar to the merge layout:

- Like the merge layout, the η for a homogeneous traffic pattern for the cross-over & merge layout is low (see table 5.4). The FCFS rule turns out to be as effective as the RTRM, so the implementation of this rule would be sufficient instead of using an advanced algorithm: In only 18% of the scenarios, the RTRM could make a marginal improvement.
- With a heterogeneous traffic pattern, just as for the merge layout, the FCFS rule performs best of the SDRs, and here too it does not appear useful to give intercity trains full priority. The weighted consecutive delay is 26% higher for the FCFS rule compared to the RTRM.

Although this layout, like the merge & overtaking layout, is a combination of two layouts, it does not achieve as much improvement as the merge & overtaking layout (η of 14% versus 137%, see table 5.4). This is because in this layout there is less complexity, as there is only one decision point where the order in which trains pass the merge and cross-over is determined. In addition, only a quarter of the trains considered have a route via both the cross-over and the merge (while in the merge & overtaking layout all trains pass through both the merge and the overtaking location, see also figure 4.2). In addition, besides the merge, there is also a diverging direction where trains turn off and which cannot and does not need to be regulated by a control system.

### 5.3.6 Merge & overtaking layout

This section discusses the performance of an RTRM on the combined merge & overtaking layout where two lines merge, with an overtaking location downstream of the merge. It also distinguishes between the different regarded heterogeneous traffic patterns, namely whether the different (merging) routes are served homogeneously or heterogeneously, and whether or not an overtaking is scheduled.

In figure 5.4, it is noticeable that the η found for the merge & overtaking layout (an η of 137% for FCFS) is much higher than for the other layouts. This difference is because this observed layout has many more degrees of freedom than the other layouts. At the merge, it can be decided which trains to go first, while at the overtaking location, it can be decided to have an overtaking or not.

To illustrate this, in the case of a delayed regional train, (1) the original order can be maintained, (2) an overtaking can be introduced, or (3) a change in order can take place at the merge. Although the delay-related KPIs are low for the RTRM with this layout, the SDRs do score badly for these KPIs (much consecutive delay occurs if using an SDR):

- The FCFS rule performs best of the SDRs on the merge layout (η of 43% with a heterogeneous timetable), however, with the FCFS rule never an overtaking is introduced (see section 5.3.3). Therefore this SDR is much more limited on the merge & overtaking layout.
- The prioritise intercity trains rule together with the prioritise on-time trains rule performs well on the overtaking layout. However, on the merge layout, these priority-based SDRs show poor performance because at the slightest conflict, trains with the lowest priority wait (long) for the merge section, which in many cases increases the weighted consecutive delay (see section 5.3.3). Therefore, on this combined merge & overtaking, they show worse performance.

The RTRM, on the other hand, is very capable of reducing the weighted consecutive delay by making good use of the available control options. This can also be seen in the absolute values of the weighted consecutive delay in table 5.3, where (with the same set of delays on layouts of the same dimension) the weighted consecutive delay for this layout is 496s, while for the merge layout and overtaking layout these are 689s and 764s.

*Deadlocks*

Like the single track layout, for this considered layout deadlock situations could occur if using the (priority-based) SDRs. These deadlock situations are caused by choices made at the merge location, which could lead to an infeasible situation at the overtaking location. This can be illustrated with the following example with 2 regional trains (identity number R101 and R202) and one intercity train (identity number IC203) as shown in figure 5.7. Originally train R202 would pass the merge at first, followed by train R101. According to the schedule, train IC203 passes the merge last and will overtake train R101 later at the overtaking. Suppose train R202 is late. The prioritise intercity trains rule (which applies FCFS for trains from the same category) forces an order change prioritizing R101, which is now the first train passing the merge. However, the prioritise intercity trains rule will still maintain the overtaking as IC203 is prioritised over train R101. However this overtaking is infeasible now as train R202 keeps waiting until R101 has left the station.

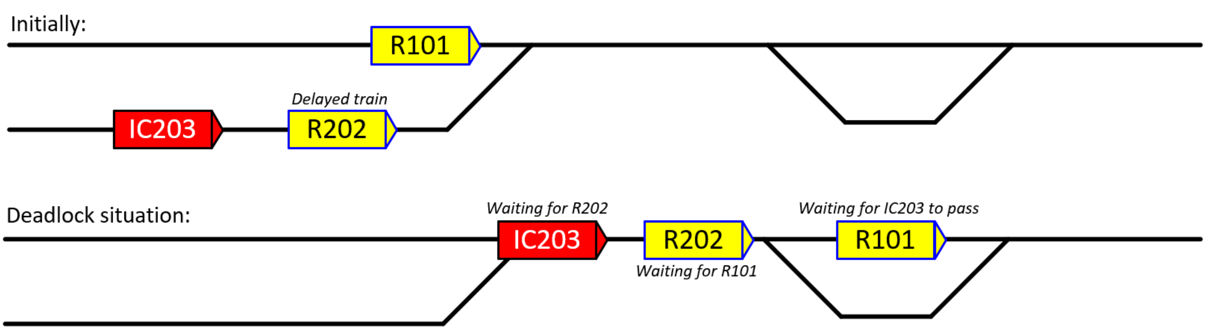



*Figure 5.7. Example deadlock situation merge & overtaking layout*

*Traffic patterns (including with or without scheduled overtaking)*

For this layout, only heterogeneous traffic patterns have been observed, since a homogeneous traffic pattern (with only trains with the same stopping pattern) would seldom result in an overtaking. The considered homogeneous traffic patterns are distinguished into homogeneous operation on the different routes (R1.IC2) and heterogeneous operation on the different routes

(R1.IC1.R2.IC2) and a distinction can be made between with or without a scheduled overtaking (see section 4.2.2).

Table 5.9 shows the number of scenarios resulting in deadlock situations per control strategy and per traffic pattern.

*Table 5.9. Number of deadlock situations per traffic pattern from merge & overtaking layout*

| Percentage deadlock situations | RTRM | FCFS | Timet. order | Pr. inter-city trains | Pr. on-time trains | Pr. delayed trains |
|---|---|---|---|---|---|---|
| **Heterogeneous** | **0%** | **0%** | **0%** | **2%** | **17%** | **0%** |
| R1.IC2 | 0% | 0% | 0% | 0% | 18% | 0% |
| R1.IC2+O | 0% | 0% | 0% | 0% | 30% | 1% |
| R1.IC1.R2.IC2 | 0% | 0% | 0% | 2% | 0% | 0% |
| R1.IC1.R2.IC2+O | 0% | 0% | 0% | 8% | 21% | 0% |

In table 5.10 the weighted consecutive delay is given for the different traffic patterns for the RTRM and for the best performing SDR (with the lowest weighted consecutive delay). Furthermore, the table gives per SDR the η and the '% scenarios RTRM better' for the weighted consecutive delay. For these indicators, the best performing SDRs (with the lowest percentages) are underlined.

*Table 5.10. Weighted consecutive delay, η and '% scenarios RTRM better' for traffic patterns from merge & overtaking layout*

| | **Weighted cons. delay (s)** | | **Relative improvement by RTRM (η)** | | | | | **% scenarios RTRM better** | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Traffic pattern** | **RTRM** | **Best perf. SDR**** | **FCFS** | **Timetable order** | **Pr. intercity trains** | **Pr. on-time trains** | **Pr. delayed trains** | **FCFS** | **Timet. order** | **Pr. iintercity trains** | **Pr. on-time trains** | **Pr. delayed trains** |
| **Heterogeneous** | **496** | **1144** | **<u>138%</u>** | **207%** | **<u>*137%</u>** | ***237%** | ***166%** | **81%** | **79%** | **<u>67%</u>** | **75%** | **77%** |
| R1.IC2 | 314 | 525 | 178% | 197% | <u>67%</u> | *216% | 135% | 76% | 72% | <u>65%</u> | 73% | 67% |
| R1.IC2+O | 819 | 1818 | <u>122%</u> | 212% | 193% | *187% | *191% | 89% | 84% | <u>81%</u> | 87% | 90% |
| R1.IC1.R2.IC2 | 420 | *530 | 143% | 125% | <u>*34%</u> | 166% | 90% | 81% | 73% | <u>55%</u> | 74% | 68% |
| R1.IC1.R2.IC2+O | 390 | 934 | <u>139%</u> | 283% | *163% | *462% | 211% | 74% | 87% | <u>66%</u> | <u>66%</u> | 82% |

**Scenarios resulting in deadlocks excluded*
***The cell color indicates which SDR is best performing for a traffic pattern*
*Grey cells: Invalid if more than 5% of scenarios are excluded due to deadlocks*

The weighted consecutive delay for the RTRM and for the SDRs is the highest for the traffic pattern with homogeneous routes and scheduled overtaking (R1.IC2+O) since for this layout the headways are shortest with low timetable cycle time (see appendix B) and it has the most detected conflicts (see table C.3 in appendix C).

The performance of the SDRs is strongly dependent on the traffic pattern. For traffic patterns, where no overtaking is scheduled (with larger timetable cycle times, where an overtaking can be introduced), the prioritise intercity trains rule scores best of the SDRs, and the η for these traffic patterns (67% and 36%) is relatively low in comparison to the traffic patterns with scheduled overtaking. In addition, not many deadlock situations occur for these traffic patterns. For the traffic patterns with scheduled overtaking, the FCFS rule proves to be the best of the SDRs. However, the η in these situations is much higher (122% and 139%) and the RTRM can strongly reduce the weighted consecutive delay compared to these SDRs.

The influence of whether the different routes are served homogeneously or heterogeneously (which resulted in differences for the merge layout) is limited for this layout. However, it can be seen that, just like in the merge layout, the prioritise intercity trains rule in the R1.IC1.R2.IC2 traffic pattern performs relatively well (with an η of 36%).

## 5.4 Infrastructure occupation rate

This section discusses the impact of different timetable cycle times (expressed by the infrastructure occupation rate) on the performance of the RTRM for all layouts and traffic patterns for the weighted consecutive delay KPI.

In the previous sections, different timetables with different infrastructure occupation rates were aggregated for the different layouts and traffic patterns. In this section, this distinction is made to show the difference in performance between timetables close to the capacity limit and quieter timetables with an infrastructure occupation rate of 50%. In figure 5.8, the relative improvement (η) is shown for each layout, for the traffic patterns (aggregated over homogeneous and heterogeneous traffic patterns), and for the different infrastructure occupation rates. The bars only represent the best performing SDR. The color of the bar indicates which SDR performs best and is used for the calculation of η.

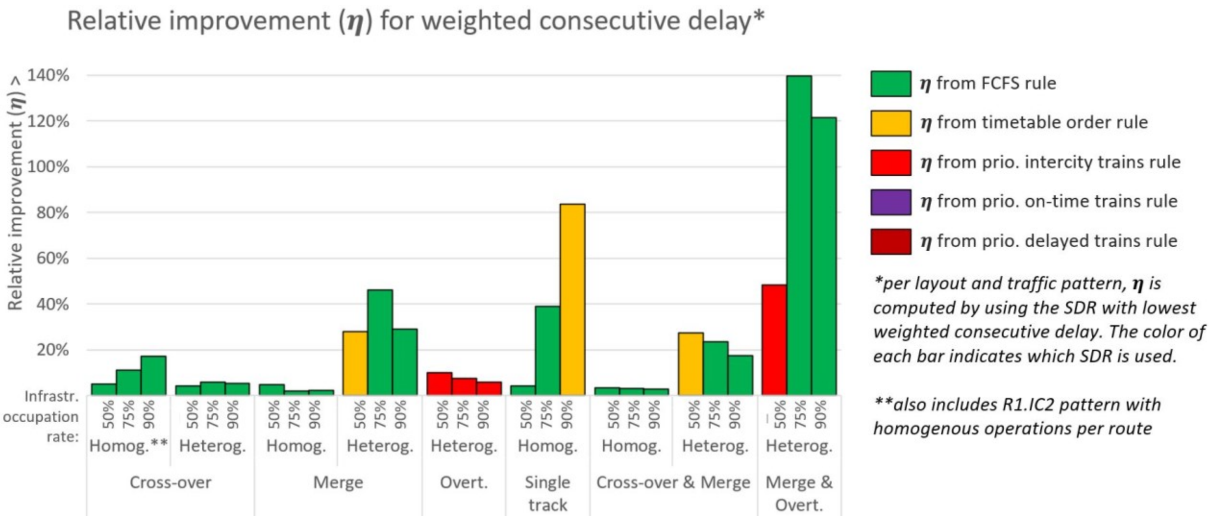



*Figure 5.8. Relative improvement (η) for different layouts, traffic patterns and infrastructure occupation rates*

From these results it can be concluded that for most layouts the η for high infrastructure occupation rates (75% or 90%) is higher than for small infrastructure occupation rate (50%), so the effectiveness of the RTRM is higher for timetables which are close to the capacity limit. With a low infrastructure occupation rate, enough capacity of the infrastructure is available to catch up for delayed trains and in these circumstances for most layouts (cross-over, merge (homogeneous traffic pattern), single track, cross-over & merge (homogeneous traffic pattern) the FCFS rule would be sufficient. Note that for some layouts the η is always low, independent of the infrastructure occupation rate (see section 5.3 and figure 5.4).

For the cross-over layout (homogeneous traffic pattern) and the single track layout, the RTRM is the most effective with an infrastructure occupation rate of 90% (so close to the effective capacity). However, this cannot be observed for the merge, cross-over & merge and merge & overtaking layout, where the best performance is visible for a lower timetable cycle time with an infrastructure occupation rate of 50% or 75%.

- This decrease in η as the infrastructure occupation rate increases is primarily due to the behaviour of the FCFS rule applied to layouts with a merge and with a homogeneous traffic pattern: The rule gets closer to the RTRM as timetable cycle time decreases and the capacity limit is reached. This can also be seen in table 5.11 where the η for the FCFS rule decreases with a higher infrastructure occupation rate for the merge (88% versus 29%), cross-over & merge (88% versus 17%) and the merge & overtaking layout (211% versus 121%). Therefore, for low infrastructure occupation rates, other SDRs may perform better than the FCFS rule, such as maintaining the timetable order rule (for the merge and cross-over & merge layout) or prioritizing intercity trains rule (for the merge & overtaking layout). For these SDRs, the η increases with a higher infrastructure occupation rate.

- In addition, the absolute values of the weighted consecutive delay also differ significantly as the infrastructure occupation rate increases. This can be seen in table 5.11, which also includes these values for the RTRM. For example, for the merge layout, the average consecutive delay for the scenarios varies between 310s to 1095s (with an infrastructure occupation rate of 50% and 90%). For the timetables with an infrastructure occupation rate of 90% more consecutive delay occurs that cannot be avoided (due to the topology of the layout) and less remaining capacity available to handle these delayed trains. This results in a low η (while the consecutive delay for both the RTRM and the SDR are both high), while the RTRM may have reached a larger reduction of consecutive delay in absolute terms in comparison to lower infrastructure occupation rates.
  Figure 5.9 shows the '% scenarios RTRM better' for all layouts for the various infrastructure occupation rates. It shows indeed that as the infrastructure occupation rate increases the share of scenarios for which the RTRM performs better increases. This means that, although in relative terms the RTRM is less effective for an infrastructure occupation rate of 90%, still in most scenarios it offers a better RTTP in comparison to the SDRs.

So for timetables with high infrastructure occupation rates, the relative difference between the RTRM and FCFS rule often becomes smaller because the amount of consecutive delays that occurs is high in all cases, due to less available capacity to handle delayed trains. However, the relative improvement for scenarios with an infrastructure occupation rate of 90% is still high enough that the implementation of an RTRM is beneficial (for the merge -heterogeneous traffic pattern-, single track, cross-over & merge -heterogeneous traffic pattern- and merge & overtaking layout).

Table 5.11 provides the weighted consecutive delay for the RTRM over the different layouts, traffic patterns (homogeneous or heterogeneous) and infrastructure occupation rates. In addition, the table provides per SDR the η for the weighted consecutive delay KPI.

*Table 5.11. Weighted consecutive delay and η for different infrastructure occupation rates*

| Layout + Traffic Pattern | Weighted cons. delay (s) | | | Relative improvement by RTRM (η) | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | RTRM | | | FCFS | | | Timetable order | | | Prio. intercity tr. | | | Prio. on-time trains | | | Prio. delayed trains | | |
| | 50% | 75% | 90% | 50% | 75% | 90% | 50% | 75% | 90% | 50% | 75% | 90% | 50% | 75% | 90% | 50% | 75% | 90% |
| **Cross-over** | **200** | **703** | **1342** | **4%** | **8%** | **11%** | **189%** | **126%** | **102%** | **39%** | **59%** | **37%** | **97%** | **84%** | **67%** | **37%** | **61%** | **63%** |
| Hom.** | 173 | 792 | 1656 | 5% | 11% | 17% | 285% | 164% | 113% | 47% | 95% | 40% | 115% | 130% | 82% | 52% | 108% | 102% |
| Het. | 223 | 643 | 1131 | 4% | 6% | 5% | 125% | 95% | 92% | 33% | 29% | 33% | 85% | 46% | 52% | 26% | 21% | 24% |
| **Merge** | **310** | **556** | **1095** | **78%** | **37%** | **20%** | **44%** | **78%** | **69%** | **32%** | **55%** | **131%** | **166%** | **102%** | **108%** | **36%** | **52%** | **47%** |
| Hom. | 135 | 466 | 1460 | 5% | 2% | 2% | 160% | 144% | 85% | *5%* | *2%* | *2%* | 162% | 140% | 126% | 99% | 48% | 37% |
| Het. | 377 | 587 | 974 | 88% | 46% | 29% | 28% | 60% | 61% | 36% | 69% | 196% | 166% | 92% | 99% | 28% | 52% | 52% |
| **Overt.** (Het.) | **457** | **673** | **1076** | **83%** | **80%** | **74%** | **37%** | **33%** | **28%** | **10%** | **8%** | **6%** | **43%** | **37%** | **35%** | **78%** | **76%** | **72%** |
| **Single.** (Ho.)* | **244** | **498** | **974** | **4%** | **39%** | **21%** | **124%** | **62%** | **84%** | ***4%*** | ***39%*** | ***21%*** | **204%** | **183%** | **202%** | **51%** | **49%** | **46%** |

| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Cross-over & Merge** | **247** | **666** | **1119** | **47%** | **13%** | **10%** | **53%** | **67%** | **67%** | **19%** | **29%** | **35%** | **122%** | **36%** | **27%** | **32%** | **30%** | **28%** |
| Hom. | 211 | 696 | 1192 | 3% | 3% | 3% | 82% | 74% | 66% | *3%* | *3%* | *3%* | 79% | 29% | 29% | 37% | 22% | 22% |
| Het. | 291 | 636 | 1047 | 88% | 24% | 17% | 27% | 59% | 69% | 33% | 57% | 71% | 161% | 44% | 25% | 27% | 38% | 34% |
| **Merge & Over.** (Het.)* | **226** | **417** | **769** | **211%** | **140%** | **121%** | **239%** | **224%** | **191%** | **48%** | **186%** | **129%** | **234%** | **209%** | **259%** | **198%** | **166%** | **159%** |

**Scenarios resulting in deadlocks excluded in the computation of $\eta$*
***Also includes the R1.IC2 pattern with homogeneous operations per route*

Figure 5.9 provides per layout, traffic pattern (aggregated over homogeneous and heterogeneous traffic patterns and infrastructure occupation rate the '% scenarios RTRM better'. The bars only represent the best performing SDR. The color of the bar indicates which SDR performs best and is used for the calculation of η.

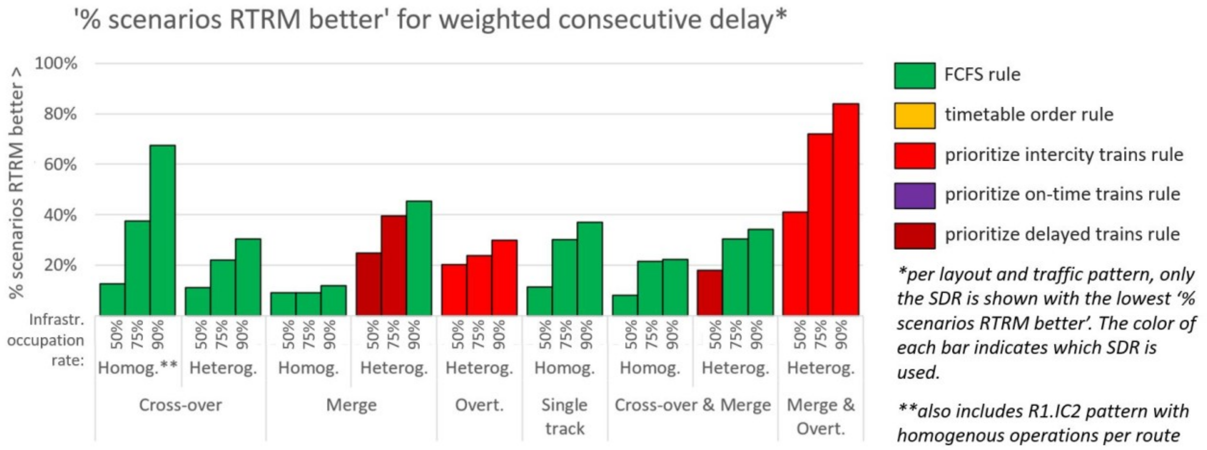



*Figure 5.9. % scenarios RTRM performs better than SDRs for different layouts, traffic patterns and infrastructure occupation rates*

This graph shows that the proportion of scenarios in which the SDRs score as well as the RTRM, decreases as the infrastructure occupation rate increases. This is in contrast with figure 5.8, where the η decreases with increasing infrastructure occupation rate for some SDRs.

## 5.5 Running time supplement

This section discusses the impact of the running time supplements on the performance of the RTRM for all layouts and traffic patterns for the weighted consecutive delay KPI. As described in section 4.2.3, different running time supplements are investigated. Timetables were generated containing no, 5% and 10% running time supplements. In the first part of this section, the (relative) improvement of the RTRM versus SDRs is discussed for the different running time supplements. The second part of this section contains an analysis of whether the improvement of an RTRM can compensate for a potential reduction of the running time supplement.

Since the consecutive delay for both the RTRM and the SDR decreases with more running time supplement, the η increases if more running time supplement is available. Therefore, this indicator is not representative. The indicator '% scenarios RTRM better' therefore gives a better indication of how much better the RTRM performs with or without running time supplement. This is shown in figure 5.10, where the '% scenarios RTRM better' is given for the different layouts, traffic patterns (aggregated over homogeneous and heterogeneous traffic patterns) and different running time supplements.

The bars only represent the SDR with the smallest amount of scenarios the RTRM performs better for the weighted consecutive delay. The color of the bar indicates which SDR is used.

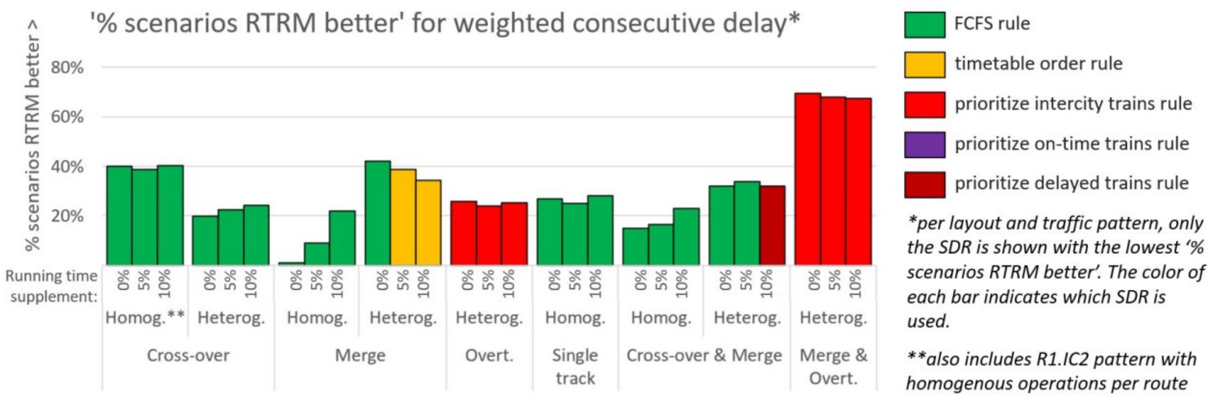



*Figure 5.10. % scenarios RTRM performs better than SDRs for different layouts, traffic patterns and running time supplements*

These results show that for some layouts the '% scenarios RTRM better' increases as there is more available running time supplement. This can be observed for the cross-over, merge (homogeneous traffic pattern), single track and cross-over & merge layout. This increase is because the FCFS rule does not take into account the available running time supplement: It could allow an on-time train to run before delayed trains, resulting in the delayed train (which runs at the minimum technical running time to make up for its delay) being slowed down by the on-time train (which runs at the scheduled running time). The RTRM does take this into account and will earlier slow down on-time trains to make optimal use of their available running time supplement. This can also be observed for the timetable order rule and the prioritise delayed trains rule, which are, with a high amount of running time supplement, more often the best performing SDRs (see figure 5.10 for the merge and cross-over and merge layout).

At the merge (heterogeneous), overtaking and merge & overtaking layout, the timetable order and prioritise intercity trains rules perform best. These rules mainly slow down on-time trains, which benefits these rules when more running time supplement is available (however still the RTRM provides enough improvement for that layout).

*Performance RTRM versus reduction of running time supplement*

The running time supplement primarily reduces the final delay (initial delays can be reduced during the ride resulting in a lower final delay), but it also reduces the occurrence of consecutive delay. This holds for trains running on-time, which are obstructed and delayed by another train. Thanks to the available running time supplement, the incurred delay can be reduced resulting in a reduction of the consecutive delay. This can be seen in figure 5.11 below, where the weighted consecutive delay and the total final delay are given for the regarded running time supplements, for the various layouts, for the RTRM and for the SDR which performs best (per layout).

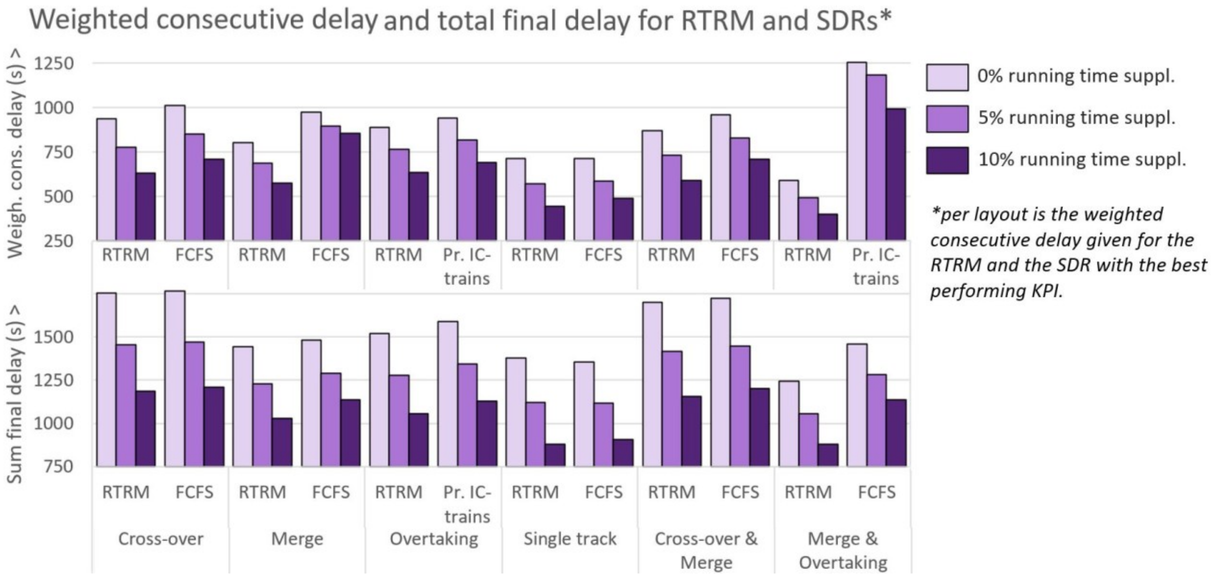


*Figure 5.11. Weighted consecutive delay and total final delay for different running time supplements*

This figure shows that the improvement of an RTRM compared to the SDRs for the weighted consecutive delay can compensate for a reduction in the running time supplement (for some layouts). For example, for the merge layout with the FCFS rule with a 10% running time supplement, there is more weighted consecutive delay than for the RTRM with a 5% running time supplement. However, looking at the total final delay KPI, which is primarily influenced by the running time supplement, this reduction by the RTRM is much less because this also includes the primary delay (which is the same for the RTRM and the SDRs). The steps between the different running time supplements are actually too large to properly see where the reduction of the total final delay by the RTRM may allow having a smaller running time supplement.

In general, it can be concluded that the advantage an RTRM has over the SDRs is very limited to compensate for a possible reduction in the running time supplement in terms of the sum of final delay. In addition, for a large number of layouts (where the FCFS is the best performing SDR), the RTRM is less effective if less running time supplement is available.

## 5.6 Initial delay

This section discusses the impact of the size of initial delay on the performance of the RTRM for all layouts and traffic patterns for the weighted consecutive delay. The scenarios considered can be divided into scenarios with small initial delays (2 to 6 minutes), medium initial delays (6 to 10 minutes) and large initial delays (10 to 15 minutes), see also section 4.3.

In figure 5.12, the relative improvement (η) for the weighted consecutive delay KPI is shown for the layouts and traffic patterns (aggregated over homogeneous and heterogeneous traffic patterns) and different sizes of initial delays. The bars only represent the best performing SDR. The color of the bar indicates which SDR performs best and is used for the calculation of η.

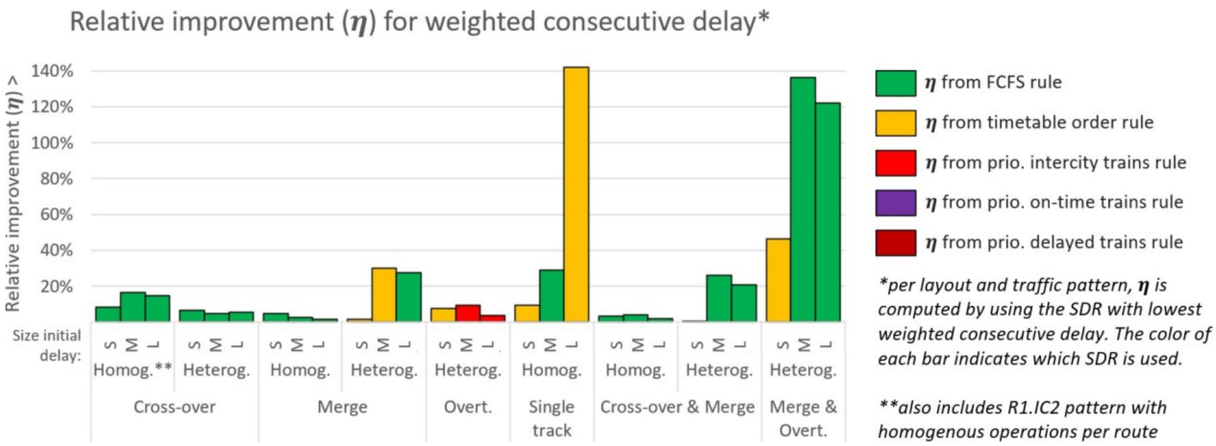



*Figure 5.12. Relative improvement (η) for different layouts, traffic patterns and sizes of initial delay*

For almost all layouts, the η for medium and large delays is higher than for small delays. (Exceptions are the layouts and traffic patterns that lead to low η for all disturbance scenarios). It also appears that for all homogeneous timetables (except for the cross-over layout) at a small delay, the timetable order rule performs best of the simple dispatching rules. (This can also be seen in table C.4 of appendix C where it can be seen that this rule performs very well at low delays).

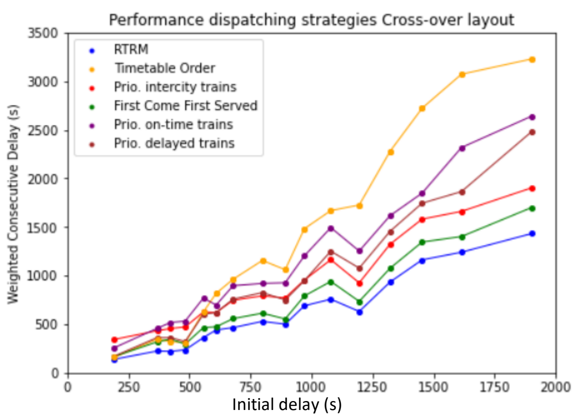
For the merge (heterogeneous traffic pattern), single track and cross-over & merge (heterogeneous traffic pattern) layouts, where aggregated all disturbance scenarios the RTRM offers a reasonable relative improvement (see figure 5.4), it turns out that for small initial delays (2 to 6 minutes) hardly any improvement can be achieved by the RTRM versus the timetable order rule (which is sufficient here also for these layouts).

For most layouts, there is not much difference in η between medium and large delays. In these cases, the situation is equally disrupted, while the RTRM manages to reduce the weighted consecutive delay by about the same percentage. However, it should be noted that there is also more consecutive delay with large initial delays, so in absolute terms, the RTRM reduces a larger amount of consecutive delay with large initial delays.

The single track layout, however, shows a large difference between medium and large delays. This is because, in case of large delays, the FCFS rule results in more than 5% of the scenarios in deadlock situations so the timetable order rule is used as 'best performing SDR'.

*Relation initial delay and consecutive delay*

In the figures below, for the cross-over layout, merge layout, overtaking layout and single track layout, the initial delays are plotted against the weighted consecutive delay for the RTRM and the various SDRs. In these figures, each dot represents 200 scenarios that fall in the same range of initial delay, which is averaged over the scenarios.



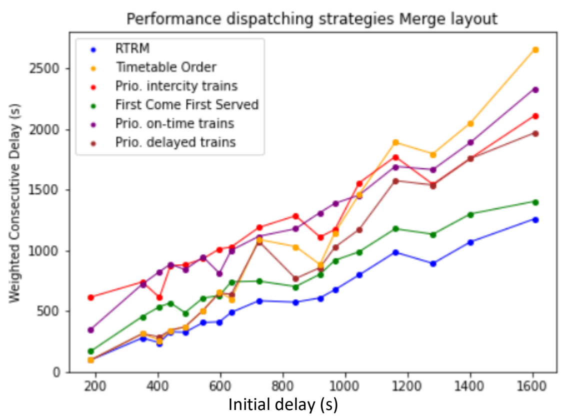



*Figure 5.13a. Performance dispatching strategies over the initial delays for cross-over layout*

*Figure 5.13b. Performance dispatching strategies over the initial delays for merge layout*

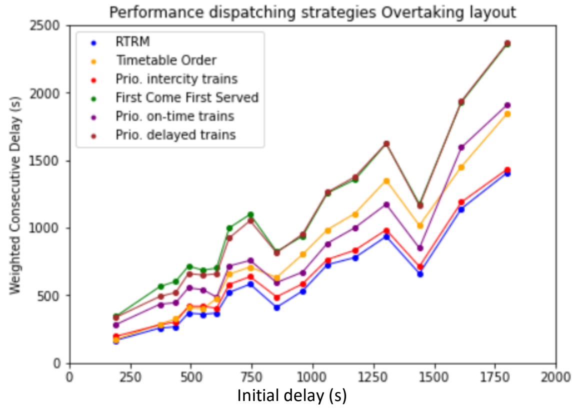



*Figure 5.13c. Performance dispatching strategies over the initial delays for overtaking layout*

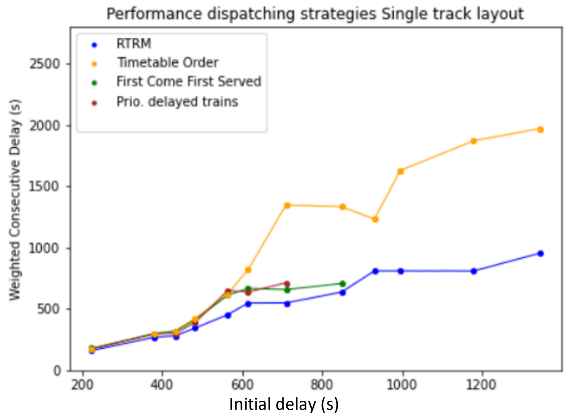



*Figure 5.13d. Performance dispatching strategies over the initial delays for single track layout*

The figures show for all layouts that the timetable order rule performs relatively well for smaller initial delays, while it performs less well as the initial delay is larger. The SDRs do not perform differently relative to each other at different initial delays. For the single track section (figure 5.13d), a large part of the SDRs has been removed for initial delays that lead to deadlock situations in more than 5% of the scenarios. As can also be seen in figure 5.12, for large initial delays, only the timetable order rule is usable there, resulting in a large relative improvement by the RTRM.

Table 5.12 shows the relative delay for the different layouts and traffic patterns (aggregated over homogeneous and heterogeneous traffic patterns) divided over the scenarios with small, medium and large initial delays. The relative delay is only included for the RTRM. Conditional formatting is used to highlight the differences in relative delay over the scenarios. This table does not show relative improvement (η) as this indicator is not relevant for this KPI (see section 5.2).

*Table 5.12. Relative delays for different disturbances scenarios*

| Relative delay | Disturbance scenario | | | |
|---|---|---|---|---|
| **Layout + Traffic Pat.** | **Small** | **Medium** | **Large** | **All sce.** |
| **Cross-over** | **0.52** | **0.48** | **0.47** | **0.49** |
| Homogeneous* | 0.70 | 0.64 | 0.52 | 0.62 |
| Heterogeneous | 0.37 | 0.37 | 0.44 | 0.40 |
| **Merge** | **0.59** | **0.61** | **0.53** | **0.58** |
| Homogeneous | 0.83 | 0.76 | 0.74 | 0.77 |
| Heterogeneous | 0.50 | 0.56 | 0.46 | 0.51 |
| **Overtaking** (Het.) | **0.61** | **0.48** | **0.42** | **0.50** |
| **Single track** (Hom) | **0.61** | **0.91** | **0.75** | **0.75** |
| **Cross-over & Me.** | **0.55** | **0.64** | **0.53** | **0.57** |
| Homogeneous | 0.70 | 0.77 | 0.60 | 0.69 |
| Heterogeneous | 0.37 | 0.51 | 0.45 | 0.45 |
| **Merge & Overt.** (Het) | **0.72** | **0.37** | **0.39** | **0.48** |
| **All scenarios** | **0.60** | **0.55** | **0.50** | **0.55** |

**Also includes the R1.IC2 pattern with homogeneous operations per route*

The relative delay is a good indicator of the accumulation of delay (consecutive delay) that occurs given a certain initial delay. These results show that the relative delay is the smallest for heterogeneous traffic patterns. This can be explained by the differences in timetable cycle time and average headway of these layouts. These are a lot smaller than the homogeneous traffic patterns (see also appendix B), which means that there is less room to catch up on delays and delays often passed on to (several) subsequent timetable cycles.

In addition, for most layouts and traffic patterns, the relative delay is largest for small initial delays. So, relatively speaking, more consecutive delays arise for small delays, also for the RTRM.

## 5.7 Optimization runtime RTRM

A seventh KPI is the optimization runtime of the RTRM solver. Gurobi was used as a solver and the computations were done on a laptop with an Intel Core i7 processor with 2.4 GHz.

This section discusses the influence of the infrastructure occupation rate, running time supplement, size of initial delay, layouts and traffic patterns on the average optimization runtime of the RTRM over the scenarios. In addition, the number of conflicts is also related to the optimization runtime.

In table 5.13, the different optimization runtimes are included for each layout and traffic pattern (aggregated over homogeneous and heterogeneous traffic patterns), averaged over the different infrastructure occupation rates, running time supplements and sizes of initial delays.

*Table 5.13 Optimization runtime over infrastructure layouts and operational scenarios*

| Optimization runt. RTRM (s) | | Infrastr.occupation rate | | | Running time suppl. | | | Size of initial delay | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **Layout + Traffic pattern** | **All scenarios** | **50%** | **75%** | **90%** | **0%** | **5%** | **10%** | **Small** | **Med.** | **Large** |
| **Cross-over** | **0.25** | **0.11** | **0.22** | **0.40** | **0.27** | **0.26** | **0.23** | **0.14** | **0.23** | **0.37** |
| Homogeneous* | 0.34 | 0.11 | 0.27 | 0.59 | 0.36 | 0.32 | 0.29 | 0.15 | 0.31 | 0.51 |
| Heterogeneous | 0.24 | 0.12 | 0.19 | 0.27 | 0.21 | 0.21 | 0.19 | 0.13 | 0.18 | 0.28 |
| **Merge** | **0.41** | **0.20** | **0.29** | **0.68** | **0.45** | **0.42** | **0.36** | **0.21** | **0.37** | **0.60** |
| Homogeneous | 0.61 | 0.17 | 0.26 | 1.32 | 0.71 | 0.63 | 0.48 | 0.21 | 0.45 | 1.10 |
| Heterogeneous | 0.34 | 0.21 | 0.30 | 0.47 | 0.36 | 0.35 | 0.31 | 0.21 | 0.34 | 0.43 |
| **Overtaking** (Het.) | **0.41** | **0.27** | **0.35** | **0.58** | **0.45** | **0.40** | **0.39** | **0.29** | **0.38** | **0.55** |
| **Single track** (Hom) | **0.07** | **0.05** | **0.06** | **0.10** | **0.08** | **0.07** | **0.07** | **0.06** | **0.07** | **0.09** |
| **Cross-over & Merge** | **0.18** | **0.09** | **0.16** | **0.27** | **0.20** | **0.17** | **0.18** | **0.10** | **0.19** | **0.24** |
| Homogeneous | 0.19 | 0.08 | 0.16 | 0.30 | 0.22 | 0.18 | 0.18 | 0.10 | 0.19 | 0.26 |
| Heterogeneous | 0.17 | 0.10 | 0.16 | 0.23 | 0.18 | 0.17 | 0.18 | 0.10 | 0.18 | 0.22 |
| **Merge & Overt.** (Het) | **0.37** | **0.20** | **0.24** | **0.61** | **0.41** | **0.36** | **0.33** | **0.25** | **0.24** | **0.58** |
| **All layouts** | **0.30** | **0.15** | **0.23** | **0.48** | **0.33** | **0.30** | **0.27** | **0.18** | **0.26** | **0.44** |

**Also includes the R1.IC2 pattern with homogeneous operations per route*

These results show that as the infrastructure occupation rate increases (and thus the timetable cycle time decreases), the computation time increases. The same applies to the size of the initial delay, where the scenarios with large initial delays (10 - 15 minutes) lead to the largest computation time.

These scenarios (with a high infrastructure occupation rate and with large initial delays) also cause the highest number of conflicts (see section 5.1 and table 5.1). This relationship between the infrastructure occupation rate, size of initial delay, average number of detected conflicts and average optimization runtime is visualized in figure 5.14, where it is shown that with increasing infrastructure occupation rate and size of initial delay the average number of detected conflicts and also optimization runtime increases.

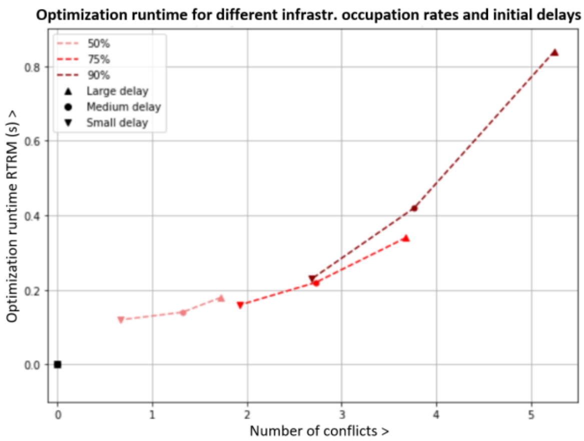



*Figure 5.14. Optimization runtime and number of conflicts for different infrastructure occupation rates and initial delays*

The running time supplement variable shows much less correlation with the optimization runtime. However, for each layout, the absence of a running time supplement results in a slightly larger optimization runtime. This is due to the increasing complexity caused by a larger number of detected conflicts (see section 5.1). The effect that with a larger running time supplement, the model has more 'freedom' to 'shift' with on-time running trains (see section 5.5) appears to be subordinate to this.

In figure 5.15 a visualization is made of the optimization runtime per layout in relation to the number of detected conflicts. Scenarios are averaged over the different sizes of initial delay.

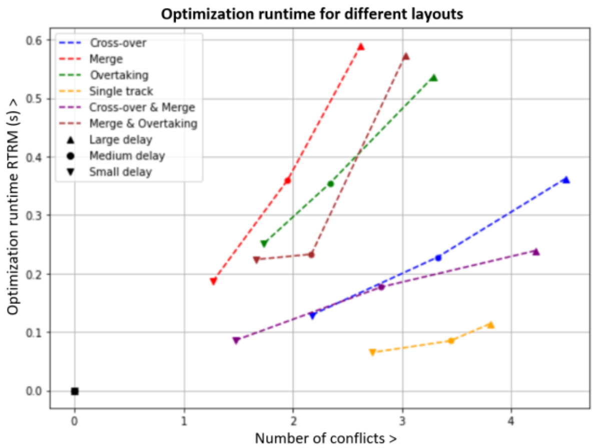


*Figure 5.15. Optimization runtime and number of conflicts for different layouts*

This figure shows that with various layouts such as the single track, cross-over & merge and merge & overtaking layouts, relatively many conflicts arise, however the optimization runtime is low. For the single track, this can be explained by the low number of block sections in this layout, which is much lower than the other layouts, resulting in a lower number of constraints, making it relatively light for the solution algorithm of the RTRM to come up with an optimal RTTP. For the combined layouts, the low number of conflicts can be achieved by finding a solution more quickly because of more control options.

## 5.8 Weighting factor objective function

In the RTRM used, the weighted consecutive delay is minimized (see section 3.2.2). A weighting factor of 2 is applied for intercity trains, which means that consecutive delays of intercity trains are more heavily weighted in the objective. To have insight into the influence of this weighting factor on the final results, all scenarios with heterogeneous timetables, with both intercity and regional trains, are run again with the RTRM optimizing for the sum consecutive delay without weighting factor (so equal weights for all trains). In this section, results from both RTRMs are compared.

Table 5.14 shows the average values over the scenarios for all layouts, averaged over the heterogeneous traffic pattern. Scenarios with traffic patterns with homogeneous timetables (where the weighting factor has no influence) and scenarios without conflicts are excluded from these results. The second column shows per traffic pattern the percentage of the scenarios the same RTTP is found by the different RTRMs. The table also shows the average values for the weighted consecutive delay KPI (which the RTRM with weighting factor optimizes for) and the sum consecutive delay (which the RTRM with equal weights optimizes for) for both the RTRM with and without weighting factor.

*Table 5.14. Comparing weighting factor RTRM objective*

| Layout | % equal RTTP | Weighted consecutive delay (s) | | | Sum consecutive delay (s) | | |
|---|---|---|---|---|---|---|---|
| | | RTRM | RTRM (Eq. W) | Relative difference | RTRM | RTRM (Eq. W) | Relative difference |
| Cross-over | 84% | 789 | 823 | 4.3% | 500 | 472 | -5.5% |
| Merge | 87% | 676 | 697 | 3.1% | 422 | 407 | -3.5% |
| Overtaking | 88% | 764 | 778 | 1.8% | 489 | 482 | -1.6% |
| Cross-over & Merge | 87% | 718 | 741 | 3.2% | 435 | 418 | -3.9% |
| Merge & Overtaking | 75% | 496 | 526 | 5.9% | 385 | 365 | -5.3% |
| **All scenarios** | **83%** | **673** | **699** | **3.9%** | **445** | **425** | **-4.3%** |

These results show that in 83% of all scenarios the RTRMs with and without a weighting factor generate the same RTTP. This share differs per layout.

The largest differences between the RTTPs are observed for the merge & overtaking layout (only 75% of scenarios result in equal RTTPs), the layout with two decision points in a row and the most freedom to apply control actions (see also section 5.3.6). For the overtaking layout, the proportion of overlapping RTTPs is highest (88%) and the KPIs do not differ much either. For this layout, it is therefore less relevant whether a weighting factor is applied in the RTRM.

Observing the weighted consecutive delay KPI and the sum consecutive delay KPI, it appears that the RTRM with a weighting factor scores best for the first KPI, while the RTRM without a weighting factor scores best for the second KPI. This is also obvious because the RTRMs also optimize for these KPIs. Also for the KPIs, the relative difference appears to be largest for the merge & overtaking layout.

## 5.9 Summary

This section contains a summary of the results of the assessment of the AG-based RTRM discussed in this chapter. The 4th sub-question 'How sensitive is the performance of an RTRM to different infrastructure layouts and traffic patterns?' is answered below for the different infrastructure layouts, traffic patterns, infrastructure occupation rates, running time supplements and sizes of initial delay. The last two paragraphs also give a short evaluation of the different KPIs and SDRs used to assess an RTRM.

*Infrastructure layout* – The performance of the observed RTRM can vary significantly over the different layouts under equal operational characteristics and delay scenarios. This is shown in table 5.3, where the performance of the RTRM is compared against SDRs for different KPIs. It showed that for some simplistic layouts like the cross-over layout and the overtaking layout (with limited control options) in most scenarios, the FCFS rule or the prioritise intercity trains rule is sufficient and the RTRM is not very effective in reducing the weighted consecutive delay in comparison to these rules. In contrast, as more control options are available, the RTRM does offer a larger reduction compared to the SDRs, which especially holds for the merge & overtaking layout.

*Traffic pattern* – The results showed a large contrast of the benefits obtained by the RTRM in relation to the SDRs for heterogeneous and homogeneous traffic patterns (see figure 5.4). Although for the homogeneous traffic patterns most conflicts were detected (see section 5.1), consecutive delay occurred (see section 5.3) and the relative delay is high (see section 5.6), the relative improvement for most layouts was smallest for homogeneous traffic patterns. For the merge, overtaking and cross-over & merge layout, the FCFS rule proved to be sufficient for homogeneous traffic patterns.

Also traffic patterns are considered that differ in the sequence of trains and differ in scheduled operational manoeuvres such as overtaking (which only holds for the overtaking layouts). Differences in the sequence of trains showed limited effects on the performance of the RTRM. However, these differences did affect some SDRs, so the relative benefit of the RTRM can for some traffic patterns differ. For the overtaking layout, the RTRM showed a better performance for traffic patterns without scheduled overtaking, because the RTRM can respond better to the control freedom of introducing an overtaking compared to the SDRs, rather than cancelling an overtaking.

*Infrastructure occupation rate* – The influence of different infrastructure occupation rates of the timetables on the benefits of the RTRM, showed different results for the considered layout: For some layouts, like the cross-over and the single track layout, the RTRM showed the most relative improvement for a high infrastructure occupation rate of 90% (close to the capacity limit of the infrastructure). However, for other layouts such as the merge and the merge & overtaking layout, an infrastructure occupation rate of 75% showed the most improvement. This is because at a higher infrastructure occupation rate of 90%, due to a lack of remaining capacity to process delayed trains, also advanced control solutions (e.g. by making trains wait for each other) result in high (consecutive) delays. This results in the relative improvement being slightly lower for an infrastructure occupation rate of 90% versus 75%. In general, for most layouts, the relative improvement at a low infrastructure occupation rate of 50% is small and the application of an SDR is sufficient.

*Running time supplement* – The results show that differences in the amount of running time supplement processed in the timetable have little effect on the performance on the RTRM. For most layouts, the RTRM shows a slightly better performance for scenarios with more available running time supplement. This is achieved by preferably slowing down on-time trains (instead of delayed trains) and therefore making optimal use of the running time supplement available. The results also show that a reduction of the sum of final delay due to the RTRM (compared to the SDRs) can barely offset the increase in final delay that would occur if the running time supplement is reduced.

*Size of initial delay* – The different sizes of initial delay influences the performance of the RTRM. Especially with very small disturbances (with initial delays of 2 to 6 minutes) minutes, it was found that for most layouts the timetable order rule scored very similarly to the RTRM (e.g. for the merge layout an $\eta$ of 4%). The influence of the distinction between medium (6 to 10 minutes) and large (10 to 15 minutes) initial delays on the relative improvement by the RTRM, is limited.

*Key performance indicators (KPIs)* – Because the RTRM optimizes for the weighted consecutive delay, this KPI is the most indicative of how well the RTRM can achieve its objective. In comparison with the other SDRs, the RTRM provides the largest relative improvement for this KPI (for the FCFS rule over all scenarios 44% improvement, as can be seen in table 5.3). Although the relative improvement is less for the other KPIs, still the RTRM offers relatively high improvements for the KPIs sum of consecutive delay and sum of final delay (especially for the merge & overtaking layout with 60% relative improvement for the sum of consecutive delay KPI). Regarding the KPIs punctuality and maximum final delay, according to the results, the effectiveness of the RTRM is much less, whereas SDRs perform just as well (for example the maximum final delay KPI shows -8% relative improvement for the timetable order rule, which means that this SDR performs better for this KPI in comparison to the RTRM). For minimizing these KPIs another objective function should be used.

The KPIs relative delay and optimization runtime were useful to understand the performance of the RTRM in different scenarios with different difficulty levels, however they were not useful for expressing the benefits of the RTRM.

*Simple dispatching rule (SDRs)* – From the considered SDRs, the FCFS rule appeared to perform best in most scenarios (see table 5.3 and table 5.4). This is especially true for the cross-over layout, where the η is also very low (10% for the weighted consecutive delay KPI). This also holds for the merge, single track and cross-over & merge layout. For the overtaking and merge & overtaking layouts, the prioritise intercity trains rule was often found to have the best performance of the SDRs (with also a low η of 7% for the weighted consecutive delay KPI for the overtaking layout). The timetable order rule was found to have the best performance of the RTRMs, especially for small delays or timetables with small infrastructure occupation rates. The other considered SDRs rarely show to be the most strategic SDR, often partly due to myopic and trivial choices (which the timetable order rule and the prioritise intercity trains rule also suffer from). In addition, most SDRs at the single track and merge & overtaking layout lead in some scenarios to deadlock situations. The timetable order rule instead, never leads to deadlocks.

# 6. Conclusion

This research into the influence of infrastructure layouts and traffic patterns on the performance of alternative graph-based Rail Traffic Rescheduling Models (RTRMs) has been carried out to investigate whether the performance of an RTRM is influenced by different infrastructure and operational characteristics and to find a methodology to assess an RTRM on these aspects. This was done by answering the following research question: "How are the benefits provided by an alternative graph-based RTRM influenced by infrastructure layouts and traffic patterns?".

In section 6.1 the 4 sub-questions are answered. In section 6.2 an answer to the main research question is formulated. Section 6.3 contains recommendations for further research and recommendations to ProRail.

## 6.1 Sub-questions

In this section, the 4 research questions are answered subsequently, based on findings from this research.

1. *Which types of RTRMs exist and how are these evaluated in the literature?*

According to the reviewed literature, there are different kinds of RTRMs, which, depending on the case study, are developed for mitigating delays, solving conflicts, improving punctuality, minimizing energy consumption or for other objectives. These RTRMs differ in infrastructure granularity, model formulation, solution approach, rescheduling actions, objective functions and control loops.

In most reviewed papers, developed RTRMs are evaluated by a case study in which de RTRM is used to generate Real-Time Traffic Plans (RTTPs) for a set of disturbance scenarios. From these computation results and by simulation, values for different Key Performance Indicators (KPIs), which indicate how an RTRM performs, are found. Much research compares an RTRM with simple dispatching rules (SDRs, which are rules of thumbs which can be used by dispatchers (D'Ariano, 2007a)) to show the benefits of the considered RTRM in reducing the propagation of delays and improving punctuality. Most research is restricted to one case study (one infrastructure layout with one timetable) on which an RTRM is implemented and evaluated. Although in the literature the impact of different RTRM approaches on different case studies has been investigated, there is still lacking knowledge about how the effectiveness of an RTRM is affected by different infrastructure layouts and traffic patterns.

2. *How can an RTRM be implemented and evaluated over different infrastructure layouts and traffic patterns?*

An evaluation framework has been developed to assess an RTRM over different infrastructure layouts and traffic patterns. It uses generic inputs, capturing the infrastructure layout, operational characteristics and a set of disturbance scenarios. A microscopic event-based railway simulator and a timetable generation module are used to generate conflict-free timetables based on the infrastructure and operational characteristics. In the framework, the to-be-evaluated RTRM generates for each infrastructure, operational and disturbance scenario an RTTP. These RTTPs are assessed using 7 KPIs, which are derived from the literature review. 5 SDRs are used to compare the performance of the RTRM with. The relative improvement by the RTRM over these SDRs can be used to show how effective an RTRM is versus these SDRs in reducing delays and improving punctuality (and other KPIs) for the different investigated infrastructure layouts and operational scenarios.

The RTRM that is implemented and evaluated in the framework is based on the microscopic AG model. This model is suitable for retiming and reordering. Possibly ProRail could use a microscopic model with such a formulation in the future. From this model, the constraints 'fixed arcs' (which model sequence of fixed train operations) and 'alternative arcs' (which model the sequence of trains approaching the same block section) were used. The AG model has been reformulated as a MILP, to make the model generic, so that different infrastructure layouts and traffic patterns can be implemented. Due to the MILP, the objective function can be adjusted and it is possible to assign the running time supplement to trains that run on-time. The objective function of the considered RTRM is minimizing the weighted sum of consecutive delay. Trains from a higher train category are weighted more heavily, because in general, these trains carry more passengers, have higher ticket pricing and the consequences of delay of these trains are larger as they have a longer distance to cover.

3. *Which infrastructure, operational and disturbance scenarios are relevant to consider to evaluate an RTRM?*

6 different infrastructure layouts and several operational characteristics are applied as input to the evaluation framework. These network characteristics could influence the performance and effectiveness of an RTRM. They were identified based on the results of the literature review (by using the characteristics of the case studies in the reviewed papers) and in liaison with the Prestatie Analyse Bureau of ProRail. The number of infrastructure layouts was reduced to a small number of layouts in which only one form of route interaction (ways in which different routes of trains overlap) can take place. Two layouts are added in which (common) combinations of route interactions can take place. All these layouts have the same dimensions, but different topologies. The operational characteristics are based on the characteristics of a timetable, namely traffic pattern (which includes train types with stopping patterns and the sequence of trains), running time supplement (running time extensions to catch up on delays) and infrastructure occupation rate (which is related to the timetable cycle time and frequency). Due to the evaluation method, only disturbance scenarios are regarded with initial delays assigned to one or two trains per scenario. The total of infrastructure, operational and disturbance scenarios resulted in a total of 16416 scenarios.

*Table 6.1. Overview parameters used in the evaluation of an RTRM over different infrastructure layouts and traffic patterns*

| **Scenarios:** | **Characteristic:** | **Value:** |
|---|---|---|
| Infrastructure scenarios: | Infrastructure layouts | Cross-over, merge, overtaking, single track, cross-over & merge, merge & overtaking |
| Operational scenarios: | Traffic pattern | Homogeneous/heterogeneous operation,<br>homogeneous/heterogeneous routes,<br>sequence of trains,<br>with/without scheduled overtaking (overtaking layouts)<br>location of scheduled train passages (single track layout) |
| | Running time supplement | 0%, 5%, 10% |
| | Infrastructure occupation rate | 50%, 75%, 90%<br>*Related to timetable cycle time and frequency* |
| Disturbance scenarios | Initial delay | Small (2-6 min initial delay), medium (6-10 min initial delay), large (10-15 min initial delay) |
| **Assessing an RTRM:** | | **Value:** |
| Key Performance Indicators (KPIs) | | Weighted consecutive delay, sum consecutive delay, sum final delay, maximum final delay, relative delay, punctuality, optimization runtime |
| Simple dispatching rules (SDRs) | | FCFS, timetable order, prioritise intercity trains, prioritise on-time trains, prioritise delayed trains |

4. *How sensitive is the performance of an RTRM to different infrastructure layouts and traffic patterns?*

The results, as an output of the evaluation framework, show that the performance of the AG-based RTRM differs per layout and traffic pattern. Also, the relative improvement, comparing the RTRM with SDRs, shows that per layout and traffic pattern the effectiveness of the RTRM varies. This is illustrated in figure 6.1, where for each considered layout, the relative improvement (η) for the weighted sum of consecutive delay KPI is shown. This figure only includes the η for the SDRs that perform best (so the most representative), which is indicated by the color of the bar.

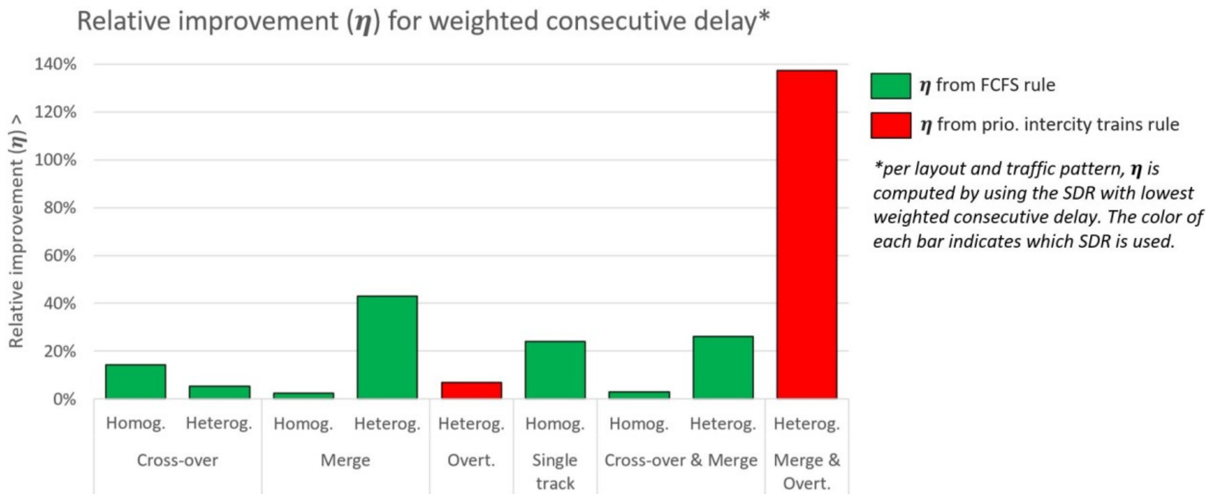



*Figure 6.1. Relative improvement (η) for different infrastructure layouts and traffic patterns*

From these results, it can be concluded that most improvement regarding the weighted sum of consecutive delay can be obtained for the merge & overtaking layout. For this layout, this KPI is 137% higher for the prioritise intercity trains rule in comparison to the RTRM. As the merge & overtaking layout has two decision points in a row, the freedom to apply control actions increases. These results show that the RTRM is also effective for merge and the cross-over & merge layout with a heterogeneous operation, with a relative improvement of 42% and 26% against the FCFS rule. Another layouts specific benefit of the RTRM over the SDRs are the occurrence of deadlock situation, which is the case for the single track and the merge & overtaking layout. Instead, the considered RTRM never results in a deadlock (due to the used AG constraints in the RTRM).

On the other hand, for the cross-over layout with heterogeneous operation, for the merge layout with homogeneous operation and for the cross-over & merge layout with homogeneous operation, these results argue that an FCFS rule is sufficient: The RTRM would reduce the weighted sum of consecutive delay in only a few specific cases, resulting in an η of 5%, 2% and 3%, respectively. The same holds for the overtaking layout, the η is only 7% against the prioritise intercity trains rule, which means that in most cases prioritizing intercity trains at an overtaking location (i.e. introducing an overtaking) is the best control strategy.

Besides that the performance of the RTRM differs per layout and for homogeneous or heterogeneous traffic patterns (see figure 6.1), the degree to which the capacity of the infrastructure is utilized (which is expressed by the infrastructure occupation rate) also influences the performance of the RTRM. This is visible in figure 6.2, where the relative improvement (η) is shown for the different layouts, traffic patterns (aggregated over homogeneous and heterogeneous traffic patterns) and applied infrastructure occupation rates (50%, 75% or 90%).

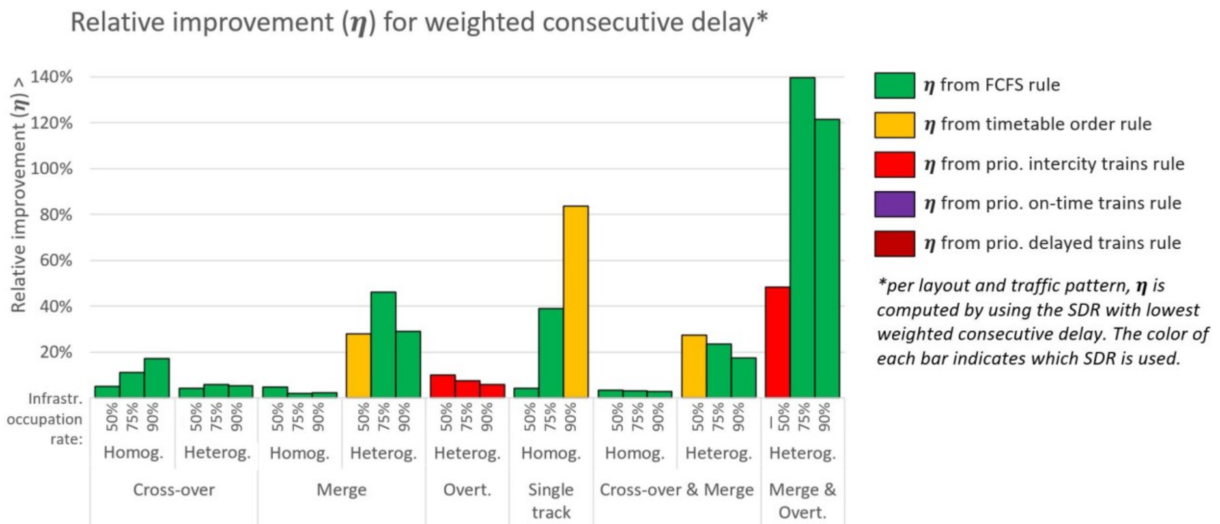



*Figure 6.2. Relative improvement (η) for different infrastructure layouts and traffic patterns*

From these results it can be concluded for a part of the layouts like the cross-over and single track layout, the relative improvement by the RTRM would be larger for more complex operational scenarios with high infrastructure occupation rates of 90% (so closer to the capacity limit of the infrastructure). However, this cannot be concluded for the merge, cross-over & merge and merge & overtaking layout, where the best relative improvement is achieved for a lower timetable cycle time with an infrastructure occupation rate of 50% or 75%. This decrease is due to the behaviour of the FCFS rule at these layouts, which performs better in relation to the RTRM as the infrastructure occupation rate is higher. In these traffic configurations where the capacity limit is almost reached, the difference (in terms of consecutive delay) between an FCFS solution and an advanced control solution (where trains wait for each other) becomes smaller: Making trains wait for each other often results in additional delays of trains in the next timetable cycle, causing also high amount of delays for the RTTP from the RTRM. However, the relative improvement for these scenarios, is still high enough that the implementation of an RTRM could be beneficial (for the merge -heterogeneous traffic pattern-, single track, cross-over & merge -heterogeneous traffic pattern- and merge & overtaking layout).

For timetables with a low infrastructure occupation rate of 50% is the relative improvement low for most layouts, however for some layouts (the merge, cross-over & merge and merge & overtaking) with heterogeneous traffic patterns still high enough to state that can be argued that the implementation of an RTRM is beneficial.

The observed RTRM reached the most improvement for the weighted consecutive delay KPI, which is also included in the objective of the RTRM. For other KPIs, infrastructural and operational characteristics also appear to influence the performance of the RTRM in comparison with the SDRs. However, it appears that for punctuality and maximum delay KPI the considered RTRM does not have much added value (aggregated over all scenarios 1% relative improvement for the punctuality KPI (versus FCFS rule) and -8% relative improvement for the maximum final delay KPI the (versus timetable order rule), which means the RTRM performs worse than this SDR). Another RTRM or at least another objective will have to be used to satisfy these KPIs.

## 6.2 Main research question

In this section, the main research question is answered.

> *How are the benefits provided by an alternative graph-based RTRM influenced by infrastructure layouts and traffic patterns?*

According to the results of different experiments on 6 different infrastructure layouts and different traffic patterns, it appears that the benefits provided by an AG-based RTRM, compared to 5 SDRs, expressed in relative improvement, are strongly dependent on the type of infrastructure layout and traffic pattern.

For some layouts, the benefit of the considered RTRM is very small compared to the FCFS rule, like the cross-over layout with heterogeneous traffic pattern and the merge layout with homogeneous traffic pattern. The same applies to the overtaking layout where the benefit of the RTRM is small in comparison to the prioritise intercity trains rule. For these layouts, the weighted consecutive delay for the SDRs was only 5%, 2% and 7% higher in relation to the RTRM, so it could be argued that these simple heuristics are sufficient.

For other layouts and traffic patterns, the RTRM seems beneficial compared to the SDRs. This is especially true for heterogeneous traffic patterns for the merge, cross-over & merge and merge & overtaking layout where a relative improvement of the weighted consecutive delay is realized of 43%, 26% and 137% respectively versus the FCFS or prioritise intercity trains rule. For the latter layout (with very high relative improvement), trains pass through more decision points, creating more control options and thus giving the RTRM more freedom to apply advanced control solutions to reduce delays. For the single track and merge & overtaking layout the RTRM provides an additional benefit of never creating deadlock situations, whereas multiple SDRs can.

For most layouts, it can be concluded that the benefit of the RTRM is smallest for timetables with low frequencies with an infrastructure occupation rate of 50%. The benefit for the RTRM with an infrastructure occupation rate of 75% and 90% is mostly larger, though for most layouts the relative improvement of the weighted consecutive delay KPI is greatest with an infrastructure occupation rate of 75% (while 90% would be expected). This is caused by the little remaining capacity available for high infrastructure occupation rates. As a result the difference in the amount of consecutive delay, which could be reduced by an advanced control approach, becomes smaller compared to applying the FCFS rule (both approaches lead to high amounts of delay).

## 6.3 Recommendations

In this section, recommendations are made for future research and the use of the evaluation framework (section 6.3.1) and for ProRail (section 6.3.2).

### 6.3.1 Future research

This section contains recommendations for future research and for improvements to the evaluation framework.

*Infrastructure characteristics*

In this research, the characteristics of the considered infrastructure layouts (such as dimensions, signalling system, length block sections, minimum headway and maximum speed) were all fixed. In this way, a comparative analysis between the layouts was possible, as all layouts had the same properties. However, in practice, these infrastructure characteristics are different, which could potentially also affect the effectiveness of an RTRM. Therefore for future research, it is recommended to add these infrastructure characteristics to the evaluation framework. Infrastructure characteristics that could be varied are signalling system, length block sections, minimum headway and maximum speed. Specifically for the considered infrastructure layouts, the following characteristics can be varied:

- *Cross-over layout* – In the considered layout, the cross-over is located at a junction and trains pass the cross-over at maximum speeds in opposite directions. However, there are also cross-overs for example at a railway yard where trains pass through the cross-over at a low speed in the same or opposite direction (for example, after departure or before arrival from a station). These aspects also result in different minimum headways at the cross-over, which could affect the performance of an RTRM.

- *Merge layout* – For the merge layout, the length of the common part of the tracks of the two merging routes (i.e. downstream of the merge) can be varied. Also, the speed of different train categories can be varied, making the operation less or more heterogeneous, which could affect the performance of an RTRM.
- *Overtaking layout* – For the overtaking layout, the dimensions of the track considered upstream and downstream of the overtaking can be varied. In addition, layouts with multiple overtaking locations, layouts with overtaking locations where more than one train can be overtaken simultaneously (more tracks available), layouts with an overtaking location outside a station (where trains that are overtaken have to stop additionally) or layouts with an overtaking location at a main station (where all train categories have to stop) could be investigated.
- *Single track layout* – For the single track layout, the length of the single track section and the number of locations where trains can pass can be varied. In addition, passing locations where trains pass each other without stopping (a small section of double track where trains pass each other while driving) or passing locations outside stations (where trains do have to stop additionally to pass each other) could be investigated. In addition, a heterogeneous traffic pattern could be investigated for the single track layout (due to the dependency of the traffic pattern from the dimensions and locations where trains can pass each other).

*Larger network layouts*

This research was limited to only 6 infrastructure layouts where only one or two route interactions could take place. In this way, the influence of certain route interactions on the performance of an RTRM could be investigated. However, for real infrastructure layouts, many more route interactions can occur, creating many more control options. The effect of multiple layouts can be seen with the merge & overtaking layout where, due to a combination of a merge and an overtaking, the RTRM has many more options and proved to be more effective to reduce the consecutive delay. Therefore, the considered network layouts in this research are a limited representation of RTRM performance. It is recommended for future research to investigate larger (parts of) networks or dispatching areas where more route interactions take place.

- This could be done with networks with the same dimensions however a varying number of overtaking locations, a varying number of single track sections and a varying number of cross-overs (which can be replaced by fly-overs). For these layouts, main stations or terminal stations of trains can be included.
- Another approach is comparing layouts based on real case studies (like comparing a regional network with mainly single track lines and low connectivity, with a network with high connectivity and mainly double track lines) and to interpret the characteristics of these layouts.

*Timetable cycle time and infrastructure occupation rate*

In this research different traffic patterns are compared under the same conditions with the same infrastructure occupation rate. In this way, a comparative analysis could be done between different layouts under the same operational conditions.

A disadvantage of fixing the infrastructure occupation rate in the comparison over the traffic patterns is that the timetable cycle time and average headway is different for each traffic pattern. This results in relatively small timetable cycle times for homogeneous and in relatively large timetable cycle times for heterogeneous traffic patterns. As a result, more conflicts are detected (see section 5.1), more consecutive delay occurs (see section 5.3) and the relative delay is higher (see section 5.6) for homogeneous traffic patterns, so it can be said that the problem complexity is greater for these traffic patterns.

- In future research, when comparing different traffic patterns, in addition to the used approach (with fixed infrastructure occupation rates), also a comparison can be done with fixed timetable cycle times.
- Another approach is adding new (relative) KPIs like the ratio 'sum of consecutive delay divided by average headway' or the ratio 'sum of consecutive delay divided by the number of detected conflicts', to incorporate the differences in problem complexity over the traffic patterns into the KPIs.

*Stochasticity in processing times*

In the evaluation framework used, only disturbances with initial delays are regarded. Running time and dwell time extensions are not taken into account (as these are not yet known at the moment when an RTRM runs). However, especially for the scenarios in which the running time supplement is set to 0%, there is a large chance that due to stochasticity in running and dwell times deviations occur. This makes the proposed RTTP no longer feasible, resulting in an additional (consecutive) delay. In addition, in this research, a certain speed profile was assumed (depending on whether or not a train is running on-time), which in practice could differ per train driver. In future research, the evaluation framework could be adapted so that the generated RTTPs (from an RTRM and SDRs) are simulated again where stochasticity in running and dwell times could be investigated. In this way, it can also be tested how feasible the RTTPs generated by the RTRM are. The KPIs should be obtained from the results from the simulation (instead of directly from the RTTP).

*Simple Dispatching Rules (SDRs)*

In the evaluation framework, SDRs were used as comparison material to compare an RTRM with. They make it possible to express a relative improvement compared to an RTRM. However, these rules are limited and do not represent the practice of manual railway dispatching: In some cases, SDRs come up with solutions that are trivial and myopic and would never be executed by a dispatcher. Therefore in future research, some SDRs could be adapted a bit so that the RTTPs they propose are more realistic, which makes the comparison with an RTRM more fair.

- For future research, it is recommended to modify the priority-based SDRs (like the prioritise intercity trains rule), so that it accepts small delays of the prioritised train (e.g. up to 3 minutes). In this research, these SDRs are so strictly tuned that they do not accept any delay from a prioritised train (caused by a non-prioritised train). This results in situations (according to the results) of a non-prioritised train being quite delayed to prevent the prioritised train to have just a few seconds delay. For this case, prioritizing the non-prioritised train is a much more realistic solution. For this reason, the prioritised related SDRs score poorly, making it seem that an RTRM performs well against these SDRs, while the SDRs themselves come up with solutions that are trivial and myopic and will never be executed by a dispatcher. Therefore, to make these priority rules more realistic, a margin of, for example, 3 minutes (within the punctuality limit) could be added.
- For the single track layout, many SDRs have resulted in deadlock situations. As a result, in the analysis of these results, only the timetable order rule was valid to use as reference material. In future research, SDRs resulting in deadlock situations could be adapted with a deadlock prevention, so that in case it produces a deadlock situation, it automatically deviates to timetable order rule. In this way, the results, obtained from SDRs that lead to deadlock situations in some scenarios, can still be used in the comparison with an RTRM (under the notion that deadlock situations could have occurred).

In addition, if larger networks are being surveyed (with for example multiple overtaking and merge locations), it is recommended to use, in addition to the regular SDRs, a 'hybrid SDR' which uses different SDRs for different parts of the network. To illustrate, for the investigated merge & overtaking layout, none of the SDRs now appeared to perform well, because they were applied to both the merge and the overtaking. This new 'hybrid SDR' would for example control the overtaking locations by the prioritise intercity trains rule (which performed best of the SDR at an overtaking) and control the merge locations by the FCFS rule (which performed best of the SDR at a merge). Possibly this new SDR could come closer to reality than applying the same SDR at all locations in the considered area.

### 6.3.2 Recommendations ProRail

As described in section 1.2, ProRail was interested in the extent the performance of an alternative graph-based RTRM is sensitive to differences in infrastructure and operational characteristics of a dispatching area.

In this section, recommendations are made to ProRail for an assessment methodology for investigating the effectiveness of an RTRM and, based on the results of this research with the experiments carried out, in which situation the implementation of the considered RTRM is or is not beneficial in relation to the SDRs.

*Recommendations assessment methodology RTRM*

First of all, this research showed that the performance of an RTRM is different per infrastructure layout and with different operational characteristics. Therefore is recommended when testing an RTRM, not to investigate only one case study, but at least to apply some variation between different timetables (for example by comparing peak timetables with off-peak or weekend timetables), to at least have some insight into how the evaluated RTRM performs in different operational conditions.

In addition, it must be realized that the results of a research into one RTRM for a certain case study, may not be a good representation of the observed RTRM in another area with possibly completely different infrastructural or operational characteristics. To illustrate this, the RTRM studied, showed considerable differences in performance between a homogeneous and heterogeneous traffic pattern. Also, the presence of more decision points in a network (such as merges, overtaking locations, level crossings and stretches of single track, which results in more control options) may influence the performance of an RTRM.

*KPIs* – In this research, a wide range of KPIs were used to test the performance of an RTRM. However, it turned out that the considered RTRM mainly scores well on the KPIs it optimizes for, while other KPIs that are not related to the objective function, turned out to have a poor performance (even with SDRs performing better than the observed RTRM like for the maximum weighted consecutive delay KPI). Therefore it is recommended to use at least those KPIs that are related to the objective function and related to the purpose for which an RTRM would be implemented

*SDRs* – When using simple dispatching rules, it is recommended to use at least the FCFS rule, the prioritise intercity trains rule and the timetable order rule as reference material. The other SDRs considered were found to overlap with the RTRM in far fewer scenarios and did not often prove to be a good reference to compare the RTRM with. In addition, it is recommended to modify the prioritise intercity trains rule so that is tuned softer allowing some delays of the prioritised trains to obtain more realistic traffic plans (see recommendations for future research, section 6.3.1).

*Recommendations implementation RTRM*

Note that these recommendations are based on the AG-based RTRM described in 3.2. They may be invalid for any other RTRM with other modelling approaches and objectives.

*Layouts* - Regarding the infrastructure layouts, it turned out that the observed RTRM was better able to reduce delays for the layouts with more control options available (in particular the merge & overtaking layout where trains pass two decision points in a row, where the RTRM realized a relative improvement of 137% for the weighted consecutive delay KPI). In a layout, where there are just a few control options, an RTRM is - just like a dispatcher - less capable of preventing mitigating delays than in a layout with more control options. To illustrate this, in the results the RTRM showed a limited improvement versus the FCFS rule for the cross-over layout (relative improvement of 10% for the weighted consecutive delay KPI), where the only control option is to change the sequence of trains. The FCFS rule also proved to be very capable of doing this. For this reason, it can be stated that the implementation of an RTRM is most successful on layouts with the most freedom to apply control actions.

*Traffic patterns* – Regarding timetables, it turned out that the benefit of the RTRM is limited to homogeneous timetables where all trains have the same characteristics and stopping pattern. For these traffic conditions, an FCFS rule is often the best control rule (see figure 6.1). (Note that this does not apply to single track layouts, due to possible deadlock situations.)

In addition, the benefit of the RTRM also differs at different rail traffic intensities (expressed by the infrastructure occupation rate). At low frequencies (half of the available capacity of the infrastructure is used, with an infrastructure occupation rate of 50%), the benefit of the RTRM is relatively small, because conflicts do not arise as quickly and the conflicts are relatively easy to resolve by the SDRs. An exception to this are infrastructure layouts with a merge with heterogeneous operation: even at low infrastructure occupation rates, SDRs are not able to always make the right trade-off of which train to leave ahead at the merge.

At higher traffic intensities (infrastructure occupation rate of 75 or 90%), there are more layouts for which the RTRM is found to be effective, and the relative benefit is then often greater (see table x). However, there are a few layouts such as the merge and the merge & overtaking layouts where the relative benefit compared to FCFS decreases with a high infrastructure occupation rate. This is caused by the little remaining capacity available for high infrastructure occupation rates. As a result, the difference in the amount of consecutive delay, which could be reduced by an advanced control approach becomes smaller compared to applying the FCFS rule (both approaches lead to high amounts of delay).

*Running time supplement* – The running time supplement does not appear to be very relevant to the implementation of an RTRM. The RTRM appeared to be slightly more effective due to the presence of more running time supplement, as the RTRM can make optimal use of the available running time supplement (by rather prioritizing delayed trains over on-time trains).

Based on the results it is not recommended to reduce the running time supplement and implement an RTRM to compensate for the -additional- potential delay that could occur. The results show that the benefits obtained by implementing an RTRM in reducing the sum of final delay (in comparison with SDRs), can barely offset the increase in final delay that would occur if the running time supplement is reduced.

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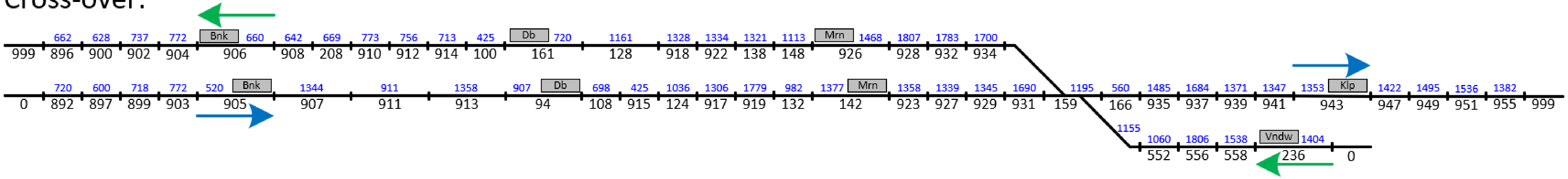
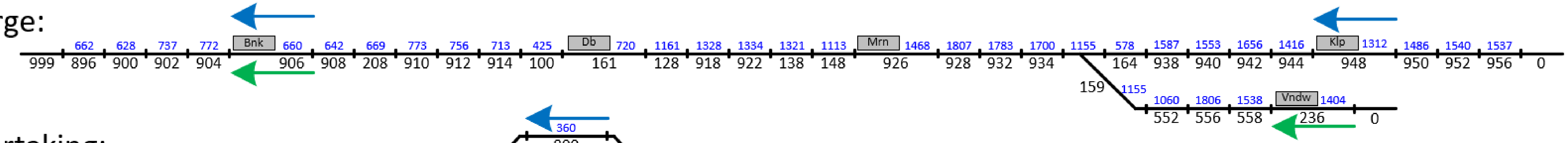
## Appendix A: Infrastructure layouts including dimensions

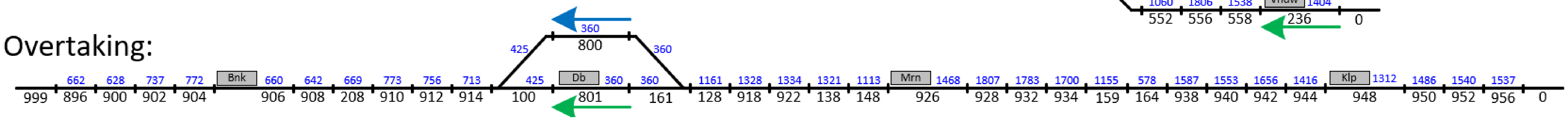
### Cross-over:



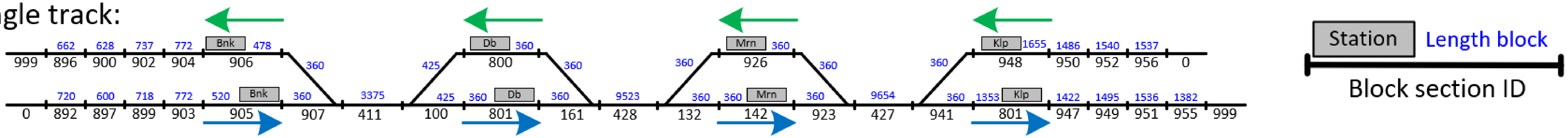
### Merge:



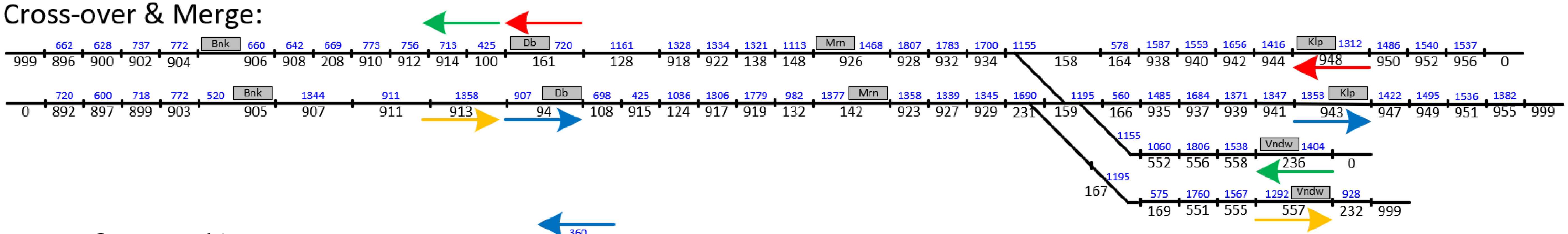
### Overtaking:



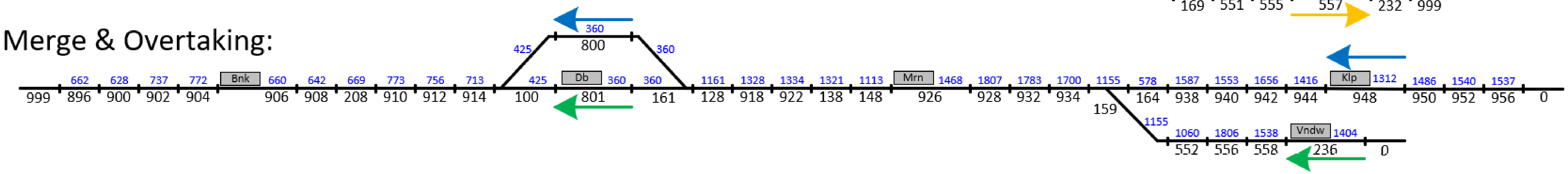
### Single track:




### Cross-over & Merge:



### Merge & Overtaking:

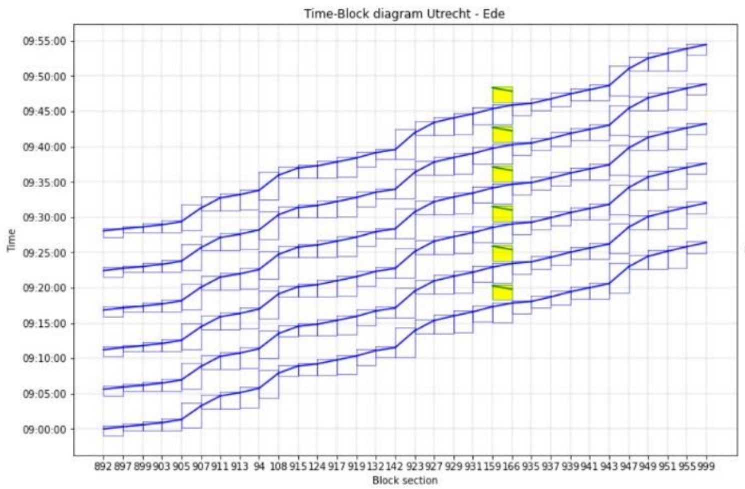
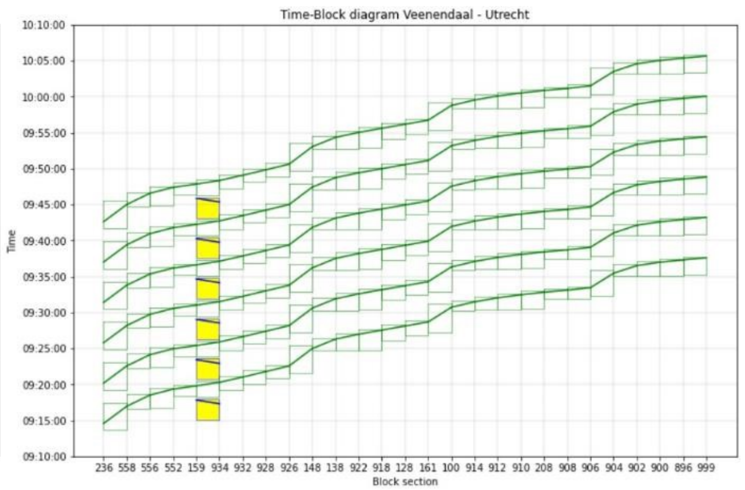
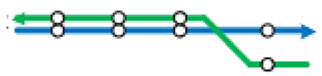
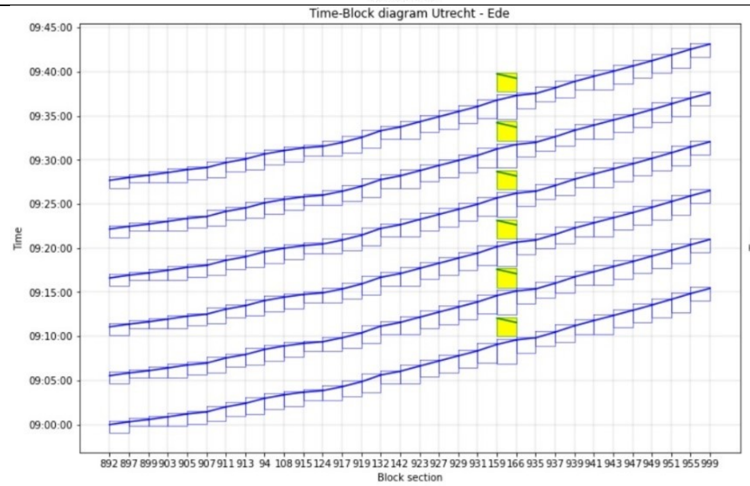
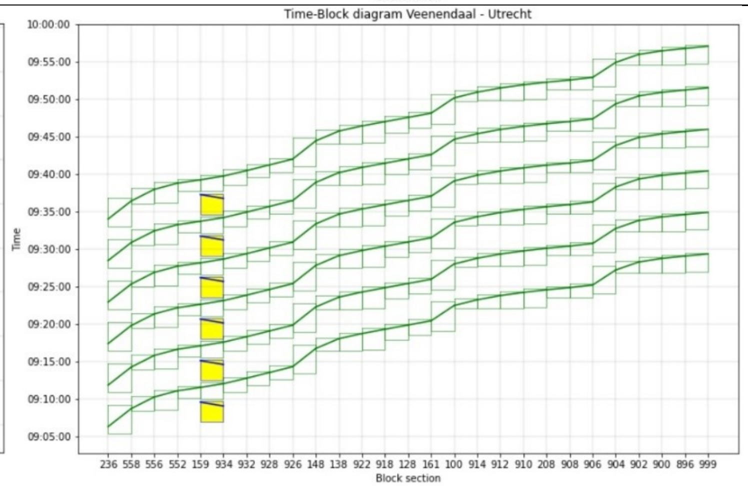
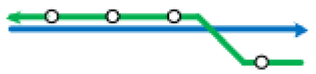


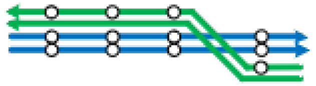
# Appendix B. Timetables

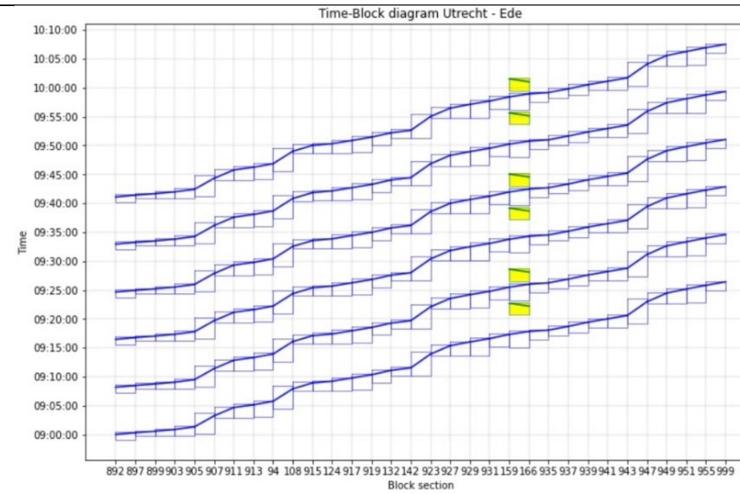
This appendix contains more details of the regarded timetables (which are the output of the timetable generation module from section 3.1.2). For all layouts 20 to 50 different timetables were generated, with different traffic structures, infrastructure occupation rate and running time supplement. The timetables with 100% infrastructure occupation rate and 0% running time supplement are generated with as goal to determine the timetable with the shortest possible timetable cycle time (without conflicts). The minimum timetable cycle time is used to compute the timetable cycle time of the other timetables. In the analysis of the RTRM the timetable with 100% infrastructure occupation rate and 0% running time supplement are not used.

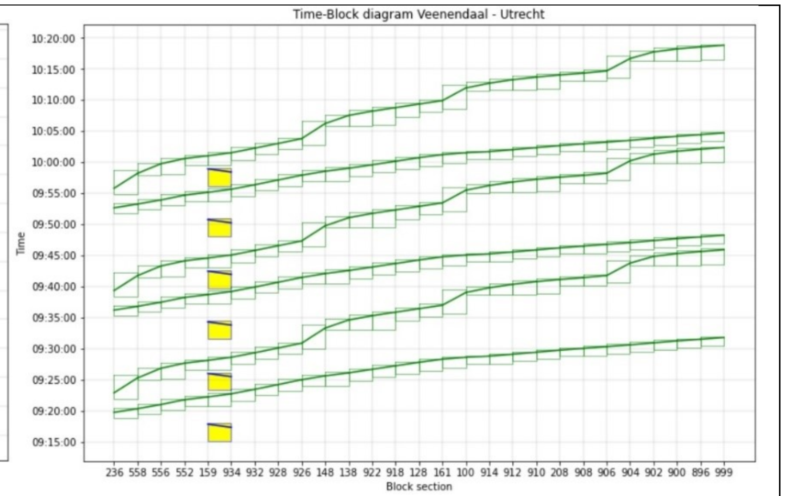
Tables B.1 to B.6 show the generated timetables for the 6 different infrastructure layouts. Each row of the table is one timetable with 10 timetables belonging to one traffic structure (shown in the first column). Furthermore it gives per timetable the infrastructure occupation rate, running time supplement, timetable cycle time (time at which the stopping pattern repeats), the total running time per train series (R stands for regional, IC for intercity train, 100 series is first direction, 200 series is second direction), number of trains in timetable, number of timetable cycles in the timetable, average headway of trains (timetable cycle time divided by number of trains) and duration (time between the first train entering and the last train leaving the network). Per traffic structure one example time-blocking diagram is given with 90% infrastructure occupation rate and 0% running time supplement.

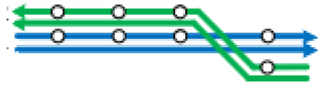
*Table B.1. Overview timetables cross-over layout with timetable characteristics*

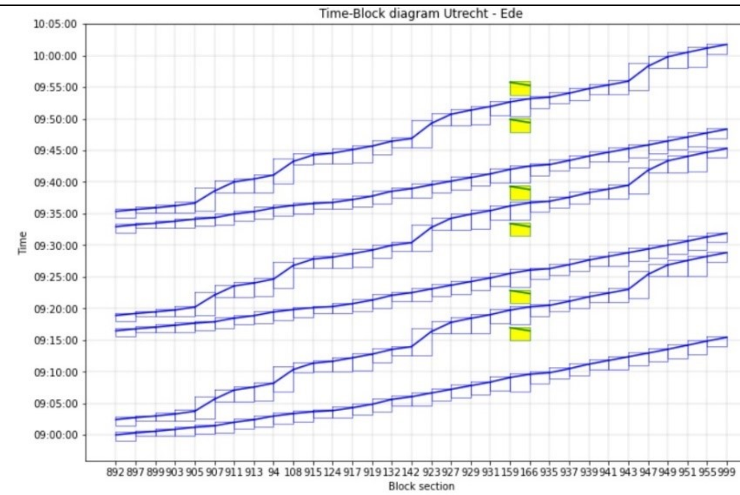
| Layout: Cross-over<br>Traffic structure | Infra. occ. r | Running time s. | Cycle-time(s) | Total running time (timet.) (s)<br>R100< | <br>IC100< | <br>R200> | <br>IC200> | Nr. trains | Nr. cycles | Avg.Head-way (s) | Dur-ation | Time-block diagram<br>90% infrastructure occupation rate, 0% running time supplement |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 100% | 0% | 5:03 | 23:02 | | 26:25 | | 12 | 6 | 2:31 | 1:02:34 | |
| | 50% | 0% | 10:06 | 23:02 | | 26:25 | | 12 | 6 | 5:03 | 1:30:21 |   |
| | 50% | 5% | 10:06 | 24:11 | | 27:44 | | 12 | 6 | 5:03 | 1:31:55 | |
| | 50% | 10% | 10:06 | 25:21 | | 29:03 | | 12 | 6 | 5:03 | 1:33:44 | |
| R1.R2 | 75% | 0% | 6:44 | 23:02 | | 26:25 | | 12 | 6 | 3:22 | 1:11:50 | |
| | 75% | 5% | 6:44 | 24:11 | | 27:44 | | 12 | 6 | 3:22 | 1:13:24 | |
|  | 75% | 10% | 6:44 | 25:21 | | 29:03 | | 12 | 6 | 3:22 | 1:15:13 | |
| | 90% | 0% | 5:37 | 23:02 | | 26:25 | | 12 | 6 | 2:48 | 1:05:39 | |
| | 90% | 5% | 5:37 | 24:11 | | 27:44 | | 12 | 6 | 2:48 | 1:07:14 | |
| | 90% | 10% | 5:37 | 25:21 | | 29:03 | | 12 | 6 | 2:48 | 1:09:03 | |
| | 100% | 0% | 4:59 | 23:02 | | | 15:26 | 12 | 6 | 2:30 | 0:54:00 |   |
| | 50% | 0% | 9:58 | 23:02 | | | 15:26 | 12 | 6 | 4:59 | 1:21:25 | |
| | 50% | 5% | 9:58 | 24:11 | | | 16:12 | 12 | 6 | 4:59 | 1:22:34 | |
| | 50% | 10% | 9:58 | 25:21 | | | 16:59 | 12 | 6 | 4:59 | 1:24:07 | |
| | 75% | 0% | 6:39 | 23:02 | | | 15:26 | 12 | 6 | 3:19 | 1:03:08 | |
| | 75% | 5% | 6:39 | 24:11 | | | 16:12 | 12 | 6 | 3:19 | 1:04:18 | |
| | 75% | 10% | 6:39 | 25:21 | | | 16:59 | 12 | 6 | 3:19 | 1:05:51 | |
| R1.IC2 | 90% | 0% | 5:32 | 23:02 | | | 15:26 | 12 | 6 | 2:46 | 0:57:03 | |
| | 90% | 5% | 5:32 | 24:11 | | | 16:12 | 12 | 6 | 2:46 | 0:58:12 | |
|  | 90% | 10% | 5:32 | 25:21 | | | 16:59 | 12 | 6 | 2:46 | 0:59:45 | |

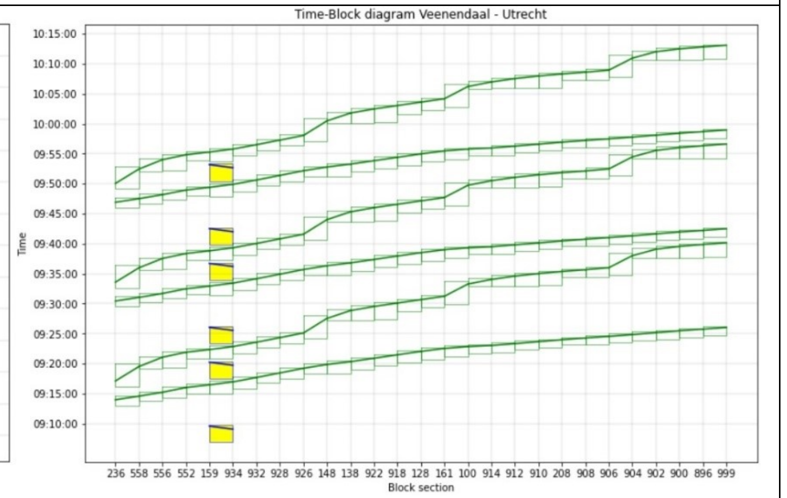
| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| R1.R2.IC1.R2  | 100% | 0% | 14:49 | 23:02 | 12:03 | 26:25 | | 12 | 3 | 3:42 | 1:14:18 |
| | 50% | 0% | 29:38 | 23:02 | 12:03 | 26:25 | | 12 | 3 | 7:24 | 1:55:03 |
| | 50% | 5% | 29:38 | 24:11 | 12:40 | 27:44 | | 12 | 3 | 7:24 | 1:56:52 |
| | 50% | 10% | 29:38 | 25:21 | 13:16 | 29:03 | | 12 | 3 | 7:24 | 1:58:16 |
| | 75% | 0% | 19:45 | 23:02 | 12:03 | 26:25 | | 12 | 3 | 4:56 | 1:27:53 |
| | 75% | 5% | 19:45 | 24:11 | 12:40 | 27:44 | | 12 | 3 | 4:56 | 1:29:42 |
| | 75% | 10% | 19:45 | 25:21 | 13:16 | 29:03 | | 12 | 3 | 4:56 | 1:31:06 |
| | 90% | 0% | 16:28 | 23:02 | 12:03 | 26:25 | | 12 | 3 | 4:07 | 1:18:50 |
| | 90% | 5% | 16:28 | 24:11 | 12:40 | 27:44 | | 12 | 3 | 4:07 | 1:20:39 |
| | 90% | 10% | 16:28 | 25:21 | 13:16 | 29:03 | | 12 | 3 | 4:07 | 1:22:03 |

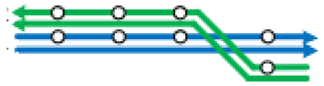


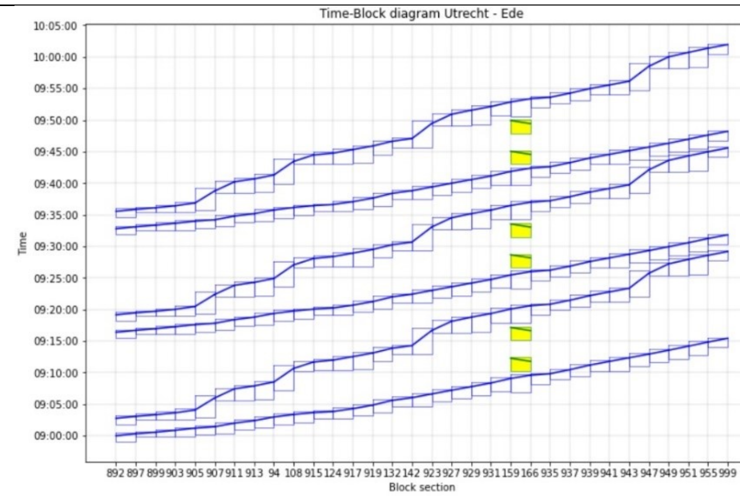




| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| R1.R2.IC1.IC2  | 100% | 0% | 14:49 | 23:02 | 12:03 | 26:25 | 15:26 | 12 | 3 | 3:42 | 1:08:33 |
| | 50% | 0% | 29:38 | 23:02 | 12:03 | 26:25 | 15:26 | 12 | 3 | 7:24 | 1:49:18 |
| | 50% | 5% | 29:38 | 24:11 | 12:40 | 27:44 | 16:12 | 12 | 3 | 7:24 | 1:50:42 |
| | 50% | 10% | 29:38 | 25:21 | 13:16 | 29:03 | 16:59 | 12 | 3 | 7:24 | 1:51:42 |
| | 75% | 0% | 19:45 | 23:02 | 12:03 | 26:25 | 15:26 | 12 | 3 | 4:56 | 1:22:08 |
| | 75% | 5% | 19:45 | 24:11 | 12:40 | 27:44 | 16:12 | 12 | 3 | 4:56 | 1:23:32 |
| | 75% | 10% | 19:45 | 25:21 | 13:16 | 29:03 | 16:59 | 12 | 3 | 4:56 | 1:24:32 |
| | 90% | 0% | 16:28 | 23:02 | 12:03 | 26:25 | 15:26 | 12 | 3 | 4:07 | 1:13:05 |
| | 90% | 5% | 16:28 | 24:11 | 12:40 | 27:44 | 16:12 | 12 | 3 | 4:07 | 1:14:29 |
| | 90% | 10% | 16:28 | 25:21 | 13:16 | 29:03 | 16:59 | 12 | 3 | 4:07 | 1:15:29 |




| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| R1.R2.IC2.IC1  | 100% | 0% | 14:45 | 23:02 | 12:03 | 26:25 | 15:26 | 12 | 3 | 3:41 | 1:03:08 |
| | 50% | 0% | 29:30 | 23:02 | 12:03 | 26:25 | 15:26 | 12 | 3 | 7:23 | 1:40:01 |
| | 50% | 5% | 29:30 | 24:11 | 12:40 | 27:44 | 16:12 | 12 | 3 | 7:23 | 1:41:10 |
| | 50% | 10% | 29:30 | 25:21 | 13:16 | 29:03 | 16:59 | 12 | 3 | 7:23 | 1:42:28 |
| | 75% | 0% | 19:40 | 23:02 | 12:03 | 26:25 | 15:26 | 12 | 3 | 4:55 | 1:15:26 |
| | 75% | 5% | 19:40 | 24:11 | 12:40 | 27:44 | 16:12 | 12 | 3 | 4:55 | 1:16:35 |
| | 75% | 10% | 19:40 | 25:21 | 13:16 | 29:03 | 16:59 | 12 | 3 | 4:55 | 1:17:53 |
| | 90% | 0% | 16:23 | 23:02 | 12:03 | 26:25 | 15:26 | 12 | 3 | 4:06 | 1:07:14 |
| | 90% | 5% | 16:23 | 24:11 | 12:40 | 27:44 | 16:12 | 12 | 3 | 4:06 | 1:08:23 |
| | 90% | 10% | 16:23 | 25:21 | 13:16 | 29:03 | 16:59 | 12 | 3 | 4:06 | 1:09:41 |



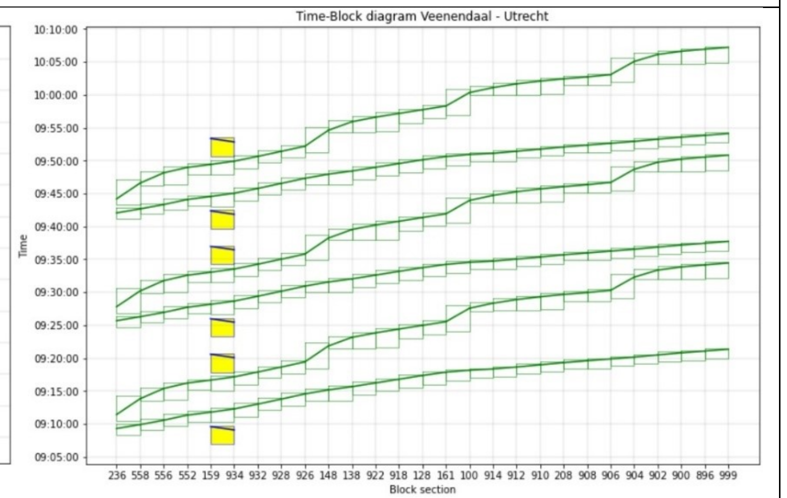
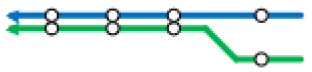
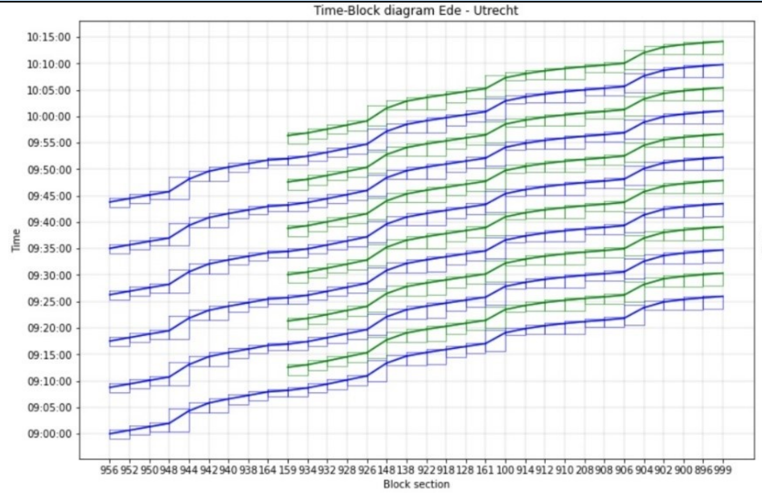
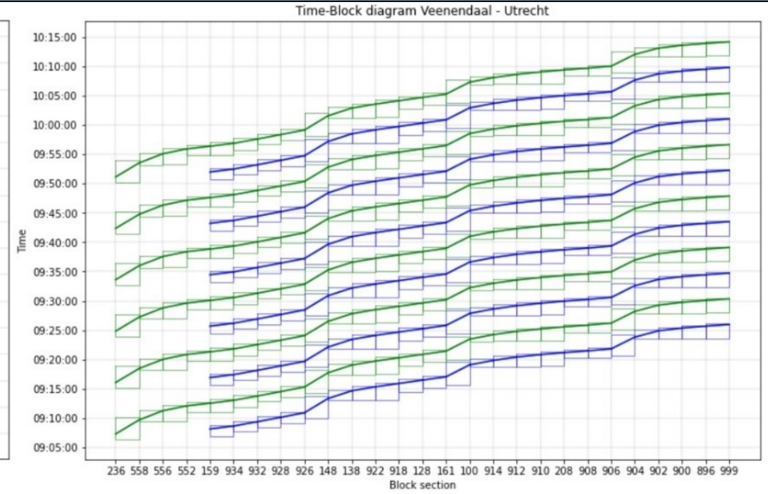
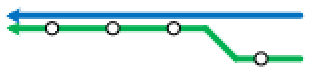
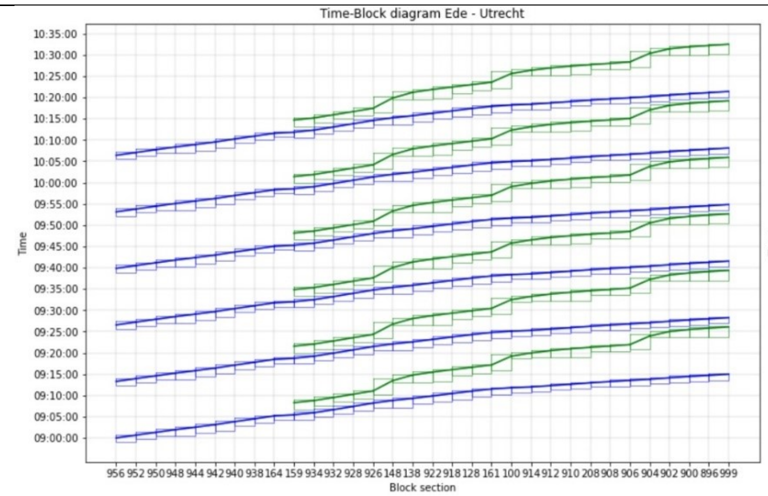
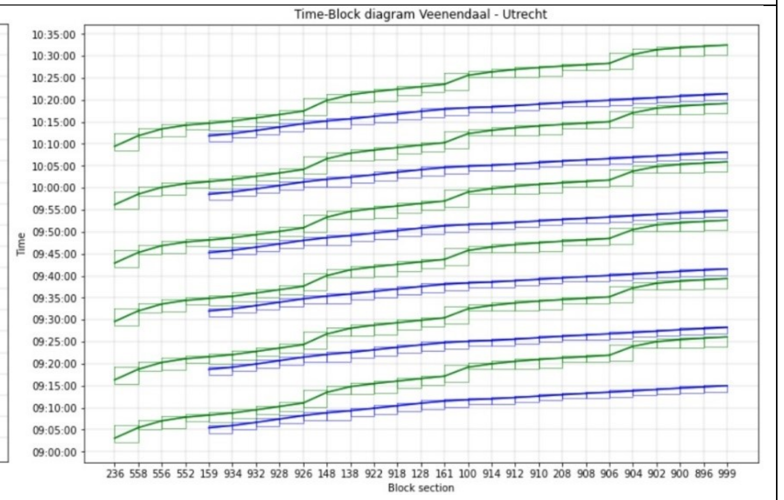
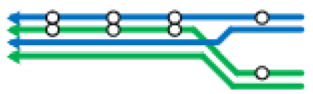
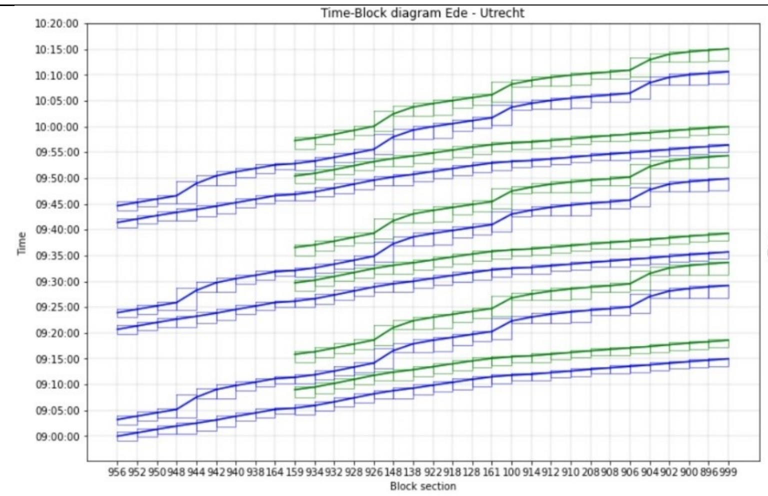
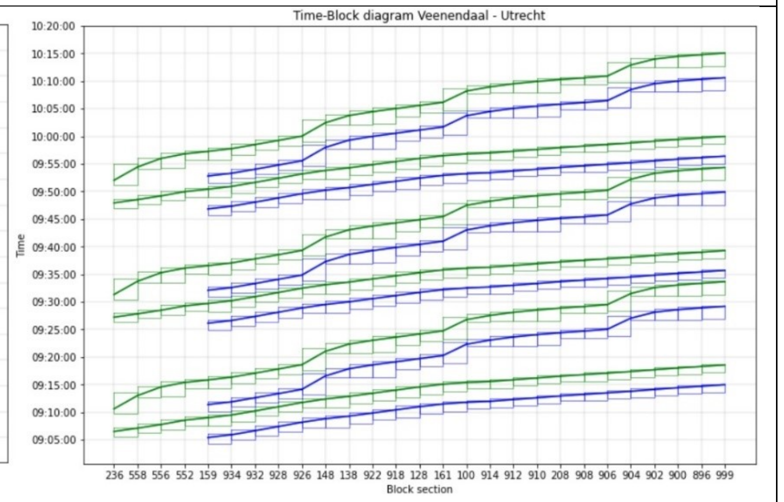



*Table B.2. Overview timetables merge layout with timetable characteristics*

| Layout: Merge<br>Traffic structure | Infra. occ. r | Running time s. | Cycle-time(s) | Total running time (timet.) (s)<br>R100< | IC100< | R200< | IC200< | Nr. trains | Nr. cycles | Avg.Head-way (s) | Dur-ation | Time-block diagram<br>90% infrastructure occupation rate, 0% running time supplement |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| R1.R2  | 100% | 0% | 7:53 | 23:02 | | 25:59 | | 12 | 6 | 3:57 | 1:09:20 |     |
| | 50% | 0% | 15:46 | 23:02 | | 25:59 | | 12 | 6 | 7:53 | 1:52:42 | |
| | 50% | 5% | 15:46 | 24:11 | | 27:17 | | 12 | 6 | 7:53 | 1:53:51 | |
| | 50% | 10% | 15:46 | 25:21 | | 28:34 | | 12 | 6 | 7:53 | 1:55:00 | |
| | 75% | 0% | 10:31 | 23:02 | | 25:59 | | 12 | 6 | 5:15 | 1:23:47 | |
| | 75% | 5% | 10:31 | 24:11 | | 27:17 | | 12 | 6 | 5:15 | 1:24:57 | |
| | 75% | 10% | 10:31 | 25:21 | | 28:34 | | 12 | 6 | 5:15 | 1:26:06 | |
| | 90% | 0% | 8:46 | 23:02 | | 25:59 | | 12 | 6 | 4:23 | 1:14:09 | |
| | 90% | 5% | 8:46 | 24:11 | | 27:17 | | 12 | 6 | 4:23 | 1:15:18 | |
| | 90% | 10% | 8:46 | 25:21 | | 28:34 | | 12 | 6 | 4:23 | 1:16:48 | |
| R1.IC2  | 100% | 0% | 11:57 | 23:02 | | | 15:00 | 12 | 6 | 5:58 | 1:25:10 |     |
| | 50% | 0% | 23:54 | 23:02 | | | 15:00 | 12 | 6 | 11:57 | 2:30:54 | |
| | 50% | 5% | 23:54 | 24:11 | | | 15:45 | 12 | 6 | 11:57 | 2:32:03 | |
| | 50% | 10% | 23:54 | 25:21 | | | 16:30 | 12 | 6 | 11:57 | 2:32:52 | |
| | 75% | 0% | 15:56 | 23:02 | | | 15:00 | 12 | 6 | 7:58 | 1:47:05 | |
| | 75% | 5% | 15:56 | 24:11 | | | 15:45 | 12 | 6 | 7:58 | 1:48:14 | |
| | 75% | 10% | 15:56 | 25:21 | | | 16:30 | 12 | 6 | 7:58 | 1:49:03 | |
| | 90% | 0% | 13:17 | 23:02 | | | 15:00 | 12 | 6 | 6:38 | 1:32:28 | |
| | 90% | 5% | 13:17 | 24:11 | | | 15:45 | 12 | 6 | 6:38 | 1:33:38 | |
| | 90% | 10% | 13:17 | 25:21 | | | 16:30 | 12 | 6 | 6:38 | 1:34:27 | |
| R1.R2.IC1.IC2  | 100% | 0% | 18:38 | 23:02 | 12:03 | 25:59 | 15:00 | 12 | 3 | 4:40 | 1:09:22 |     |
| | 50% | 0% | 37:16 | 23:02 | 12:03 | 25:59 | 15:00 | 12 | 3 | 9:19 | 2:00:37 | |
| | 50% | 5% | 37:16 | 24:11 | 12:40 | 27:17 | 15:45 | 12 | 3 | 9:19 | 2:01:46 | |
| | 50% | 10% | 37:16 | 25:21 | 13:16 | 28:34 | 16:30 | 12 | 3 | 9:19 | 2:02:25 | |
| | 75% | 0% | 24:51 | 23:02 | 12:03 | 25:59 | 15:00 | 12 | 3 | 6:13 | 1:26:27 | |
| | 75% | 5% | 24:51 | 24:11 | 12:40 | 27:17 | 15:45 | 12 | 3 | 6:13 | 1:27:36 | |
| | 75% | 10% | 24:51 | 25:21 | 13:16 | 28:34 | 16:30 | 12 | 3 | 6:13 | 1:28:15 | |
| | 90% | 0% | 20:42 | 23:02 | 12:03 | 25:59 | 15:00 | 12 | 3 | 5:11 | 1:15:04 | |
| | 90% | 5% | 20:42 | 24:11 | 12:40 | 27:17 | 15:45 | 12 | 3 | 5:11 | 1:16:13 | |
| | 90% | 10% | 20:42 | 25:21 | 13:16 | 28:34 | 16:30 | 12 | 3 | 5:11 | 1:16:52 | |

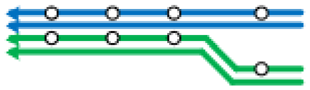
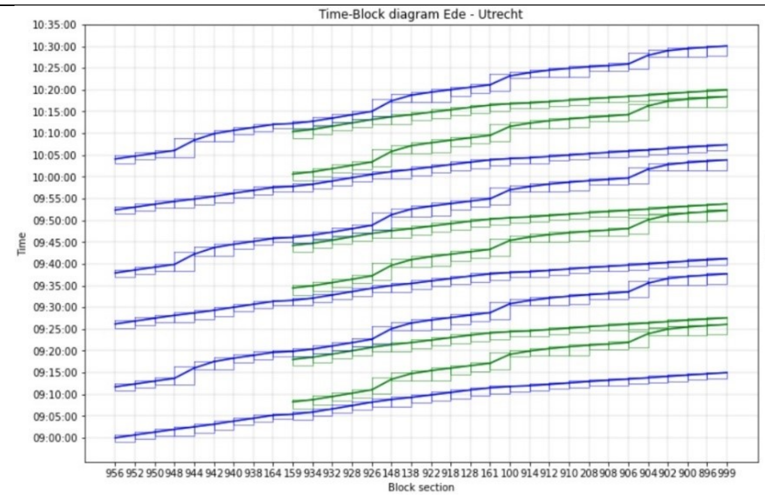
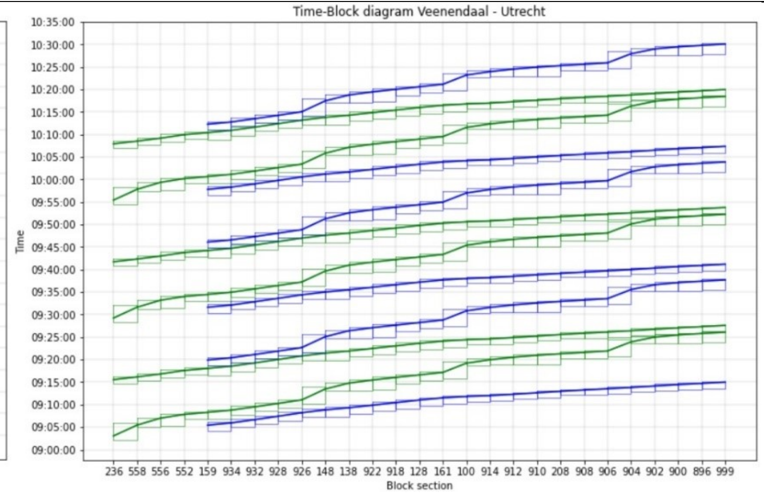
| | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| R1.IC1.R2.IC2  | 100% | 0% | 23:34 | 23:02 | 12:03 | 25:59 | 15:00 | 12 | 3 | 5:53 | 1:24:11 |     |
| | 50% | 0% | 47:08 | 23:02 | 12:03 | 25:59 | 15:00 | 12 | 3 | 11:47 | 2:17:12 | |
| | 50% | 5% | 47:08 | 24:11 | 12:40 | 27:17 | 15:45 | 12 | 3 | 11:47 | 2:18:50 | |
| | 50% | 10% | 47:08 | 25:21 | 13:16 | 28:34 | 16:30 | 12 | 3 | 11:47 | 2:20:22 | |
| | 75% | 0% | 31:25 | 23:02 | 12:03 | 25:59 | 15:00 | 12 | 3 | 7:51 | 1:41:51 | |
| | 75% | 5% | 31:25 | 24:11 | 12:40 | 27:17 | 15:45 | 12 | 3 | 7:51 | 1:43:29 | |
| | 75% | 10% | 31:25 | 25:21 | 13:16 | 28:34 | 16:30 | 12 | 3 | 7:51 | 1:45:01 | |
| | 90% | 0% | 26:11 | 23:02 | 12:03 | 25:59 | 15:00 | 12 | 3 | 6:33 | 1:30:04 | |
| | 90% | 5% | 26:11 | 24:11 | 12:40 | 27:17 | 15:45 | 12 | 3 | 6:33 | 1:31:42 | |
| | 90% | 10% | 26:11 | 25:21 | 13:16 | 28:34 | 16:30 | 12 | 3 | 6:33 | 1:33:14 | |

*Table B.3. Overview timetables overtaking layout with timetable characteristics*

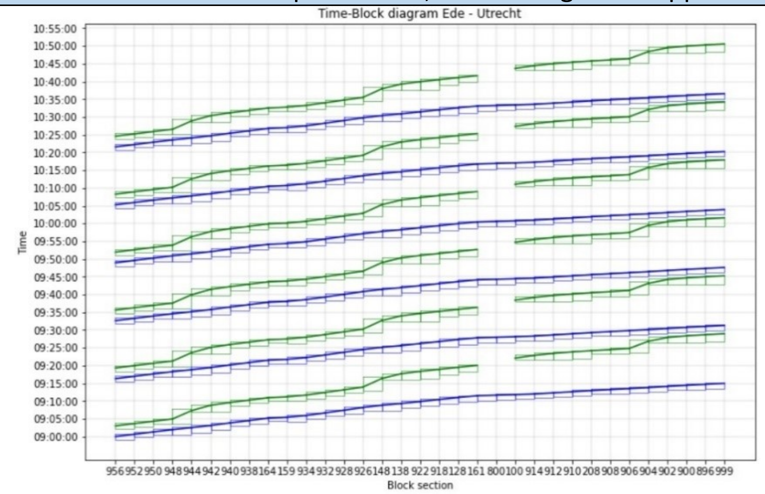
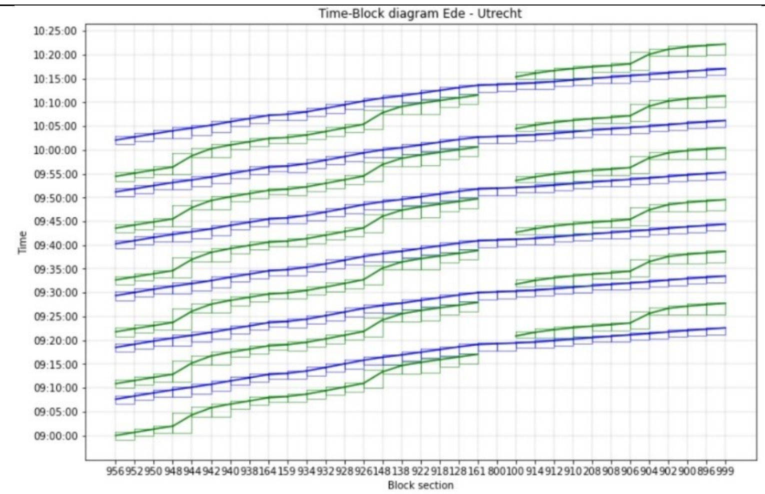
| Layout: Overtaking | Infra. | Running | Cycle- | Total running time (timet.) (s) | | | Nr. | Nr. | Avg.Head- | Dur- | Time-block diagram |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Traffic structure | occ. r | time s. | time(s) | | R200< | IC200< | trains | cycles | way (s) | ation | 90% infrastructure occupation rate, 0% running time supplement |
| R.IC  | 100% | 0% | 14:41 | | 25:59 | 15:00 | 12 | 6 | 7:20 | 1:39:24 |   |
| | 50% | 0% | 29:22 | | 25:59 | 15:00 | 12 | 6 | 14:41 | 2:52:49 | |
| | 50% | 5% | 29:22 | | 27:17 | 15:45 | 12 | 6 | 14:41 | 3:09:51 | |
| | 50% | 10% | 29:22 | | 28:34 | 16:30 | 12 | 6 | 14:41 | 3:11:54 | |
| | 75% | 0% | 19:35 | | 25:59 | 15:00 | 12 | 6 | 9:47 | 2:08:30 | |
| | 75% | 5% | 19:35 | | 27:17 | 15:45 | 12 | 6 | 9:47 | 2:09:48 | |
| | 75% | 10% | 19:35 | | 28:34 | 16:30 | 12 | 6 | 9:47 | 2:10:24 | |
| | 90% | 0% | 16:19 | | 25:59 | 15:00 | 12 | 6 | 8:09 | 1:50:33 | |
| | 90% | 5% | 16:19 | | 27:17 | 15:45 | 12 | 6 | 8:09 | 1:51:51 | |
| | 90% | 10% | 16:19 | | 28:34 | 16:30 | 12 | 6 | 8:09 | 1:52:27 | |
| R.IC+O  | 100% | 0% | 9:48 | | 27:47 | 15:00 | 12 | 6 | 4:54 | 1:16:47 |   |
| | 50% | 0% | 19:36 | | 27:47 | 15:00 | 12 | 6 | 9:48 | 2:05:47 | |
| | 50% | 5% | 19:36 | | 29:10 | 15:45 | 12 | 6 | 9:48 | 2:07:10 | |
| | 50% | 10% | 19:36 | | 30:33 | 16:30 | 12 | 6 | 9:48 | 2:08:33 | |
| | 75% | 0% | 13:04 | | 27:47 | 15:00 | 12 | 6 | 6:32 | 1:33:07 | |
| | 75% | 5% | 13:04 | | 29:10 | 15:45 | 12 | 6 | 6:32 | 1:34:30 | |
| | 75% | 10% | 13:04 | | 30:33 | 16:30 | 12 | 6 | 6:32 | 1:35:53 | |
| | 90% | 0% | 10:53 | | 27:47 | 15:00 | 12 | 6 | 5:27 | 1:22:13 | |
| | 90% | 5% | 10:53 | | 29:10 | 15:45 | 12 | 6 | 5:27 | 1:23:37 | |
| | 90% | 10% | 10:53 | | 30:33 | 16:30 | 12 | 6 | 5:27 | 1:25:00 | |

*Table B.4. Overview timetables single track layout with timetable characteristics*

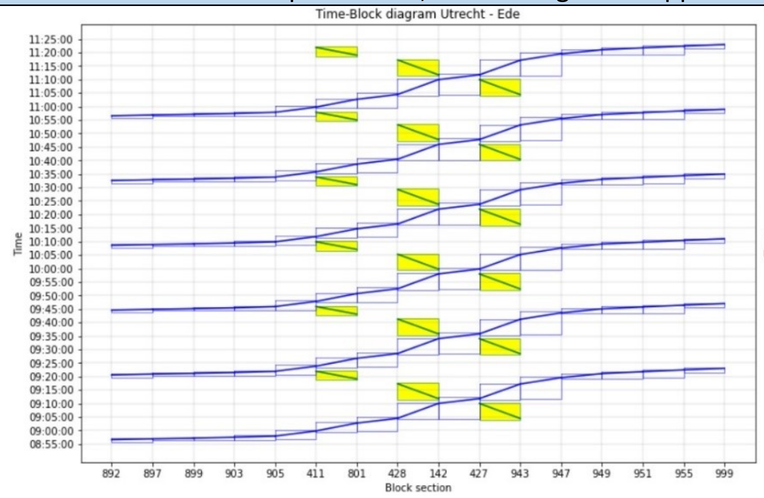
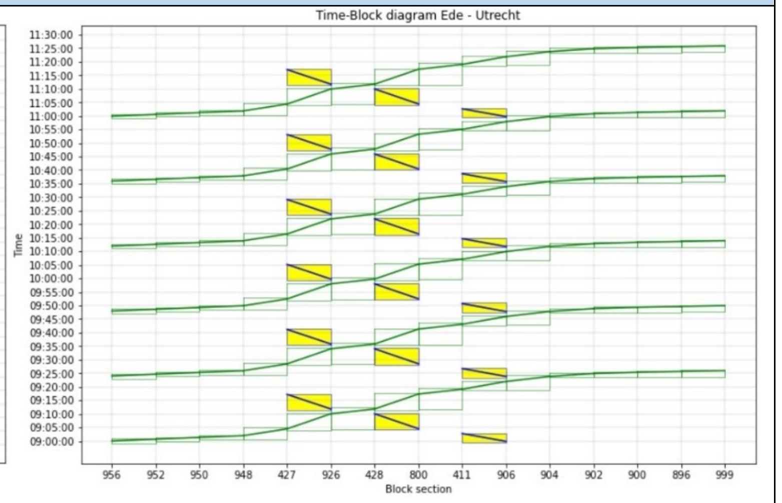
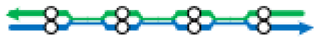
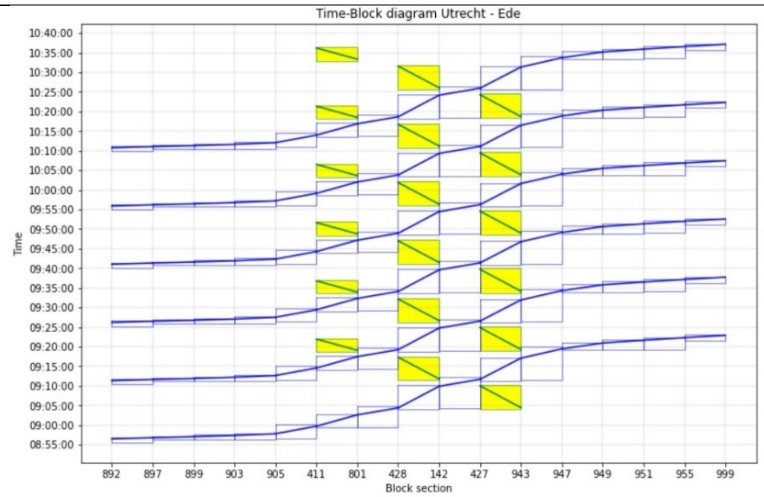
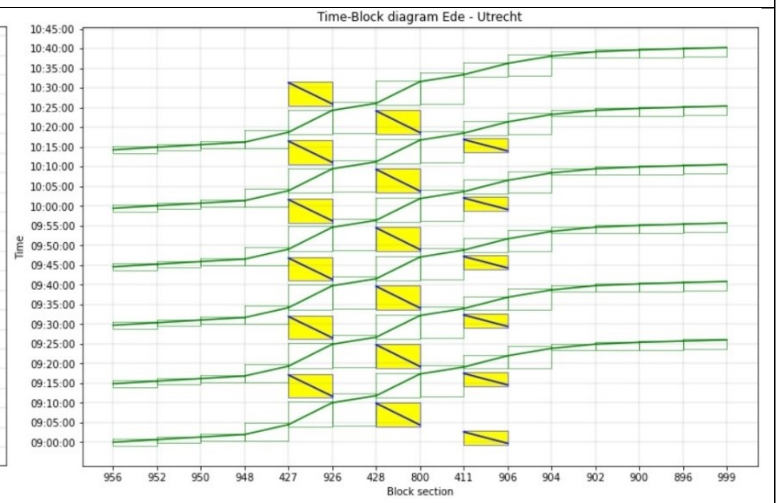
| Layout: Single track<br>Traffic structure | Infra. occ. r | Running time s. | Cycle-time(s) | Total running time (timet.) (s) | R200< | R200> | Nr. trains | Nr. cycles | Avg.Head-way (s) | Dur-ation | Time-block diagram<br>90% infrastructure occupation rate, 0% running time supplement |
|---|---|---|---|---|---|---|---|---|---|---|---|
| R.R(1)  | 100% | 0% | 21:35 | | 25:59 | 26:25 | 12 | 6 | 10:47 | 2:13:54 |     |
| | 50% | 0% | 43:10 | | 25:59 | 26:25 | 12 | 6 | 21:35 | 4:01:49 | |
| | 50% | 5% | 43:10 | | 27:17 | 27:44 | 12 | 6 | 21:35 | 4:03:07 | |
| | 50% | 10% | 43:10 | | 28:34 | 29:03 | 12 | 6 | 21:35 | 4:04:24 | |
| | 75% | 0% | 28:47 | | 25:59 | 26:25 | 12 | 6 | 14:23 | 2:49:52 | |
| | 75% | 5% | 28:47 | | 27:17 | 27:44 | 12 | 6 | 14:23 | 2:51:10 | |
| | 75% | 10% | 28:47 | | 28:34 | 29:03 | 12 | 6 | 14:23 | 2:52:28 | |
| | 90% | 0% | 23:59 | | 25:59 | 26:25 | 12 | 6 | 11:59 | 2:25:53 | |
| | 90% | 5% | 23:59 | | 27:17 | 27:44 | 12 | 6 | 11:59 | 2:27:11 | |
| | 90% | 10% | 23:59 | | 28:34 | 29:03 | 12 | 6 | 11:59 | 2:28:29 | |
| R.R(2)  | 100% | 0% | 13:22 | | 25:59 | 26:25 | 12 | 6 | 6:41 | 1:32:49 |     |
| | 50% | 0% | 26:44 | | 30:56 | 31:22 | 12 | 6 | 13:22 | 2:44:36 | |
| | 50% | 5% | 26:44 | | 31:48 | 32:15 | 12 | 6 | 13:22 | 2:45:28 | |
| | 50% | 10% | 26:44 | | 32:39 | 33:08 | 12 | 6 | 13:22 | 2:46:19 | |
| | 75% | 0% | 17:49 | | 26:28 | 26:54 | 12 | 6 | 8:55 | 1:55:34 | |
| | 75% | 5% | 17:49 | | 27:20 | 27:47 | 12 | 6 | 8:55 | 1:56:26 | |
| | 75% | 10% | 17:49 | | 28:34 | 29:03 | 12 | 6 | 8:55 | 1:57:41 | |
| | 90% | 0% | 14:51 | | 25:59 | 26:25 | 12 | 6 | 7:26 | 1:40:14 | |
| | 90% | 5% | 14:51 | | 27:17 | 27:44 | 12 | 6 | 7:26 | 1:41:32 | |
| | 90% | 10% | 14:51 | | 28:34 | 29:03 | 12 | 6 | 7:26 | 1:42:50 | |

*Table B.5. Overview timetables cross-over & merge layout with timetable characteristics*

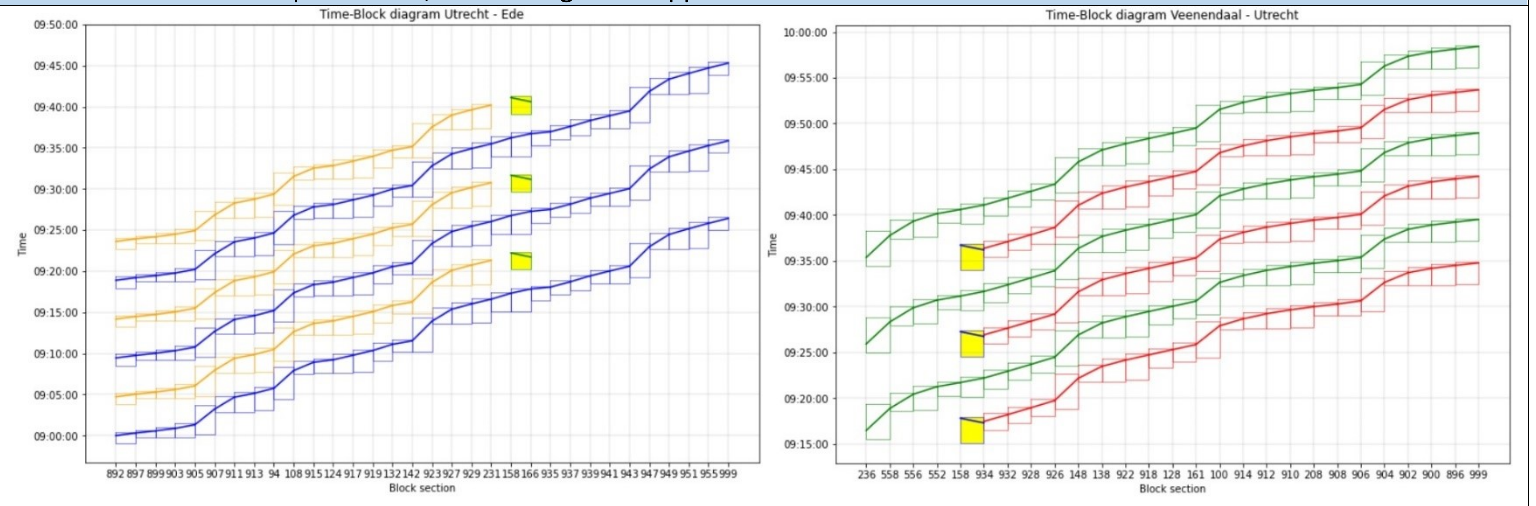
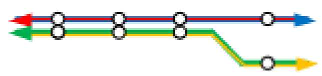
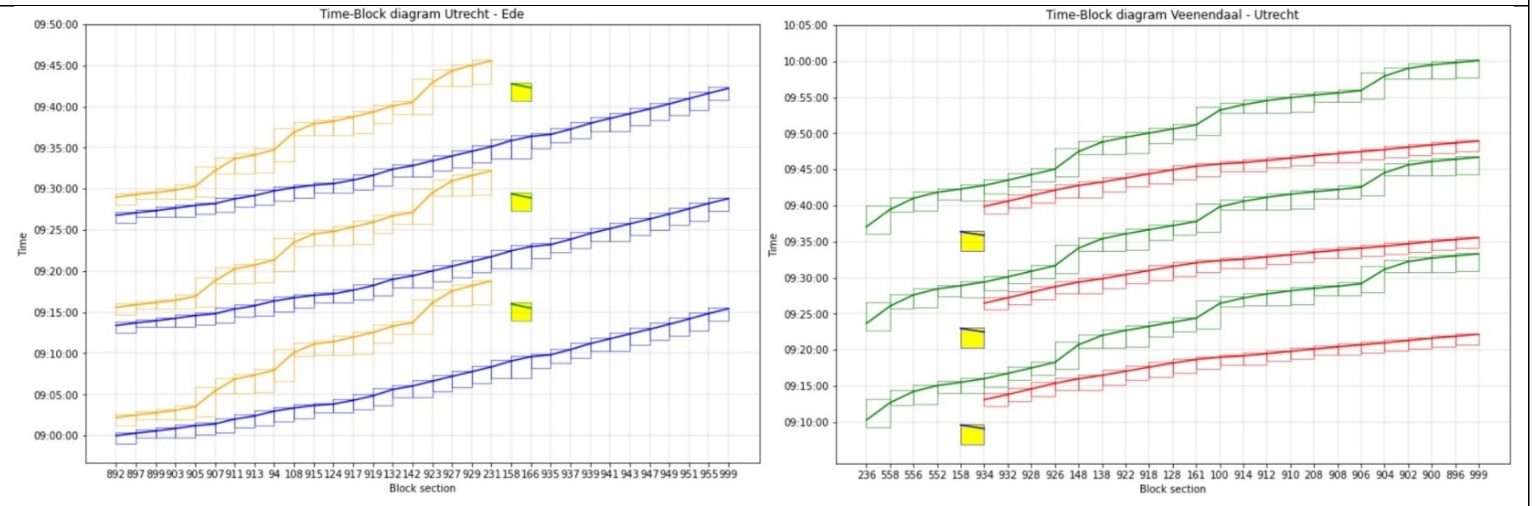
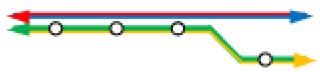
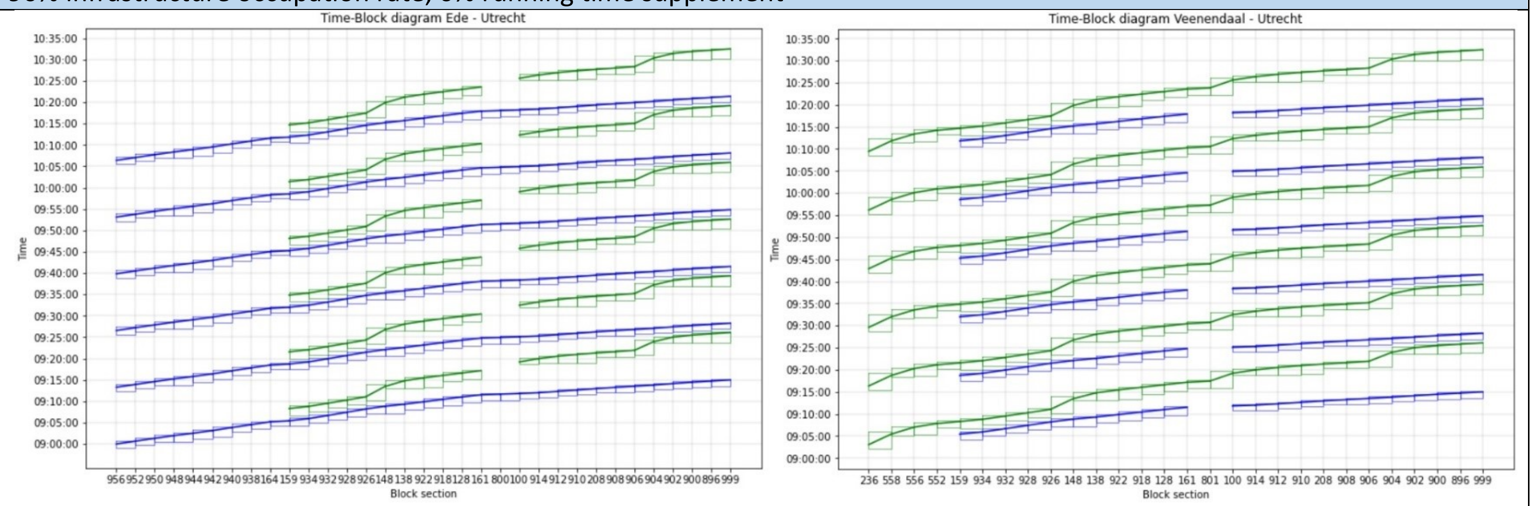
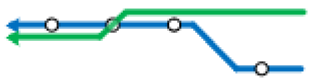
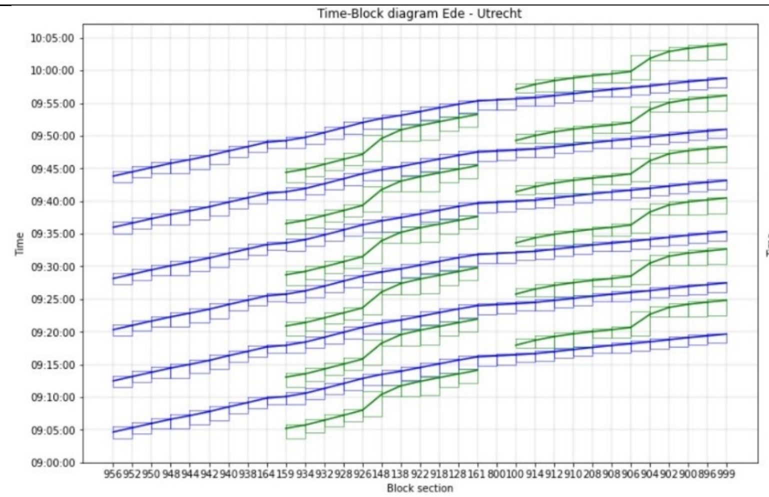
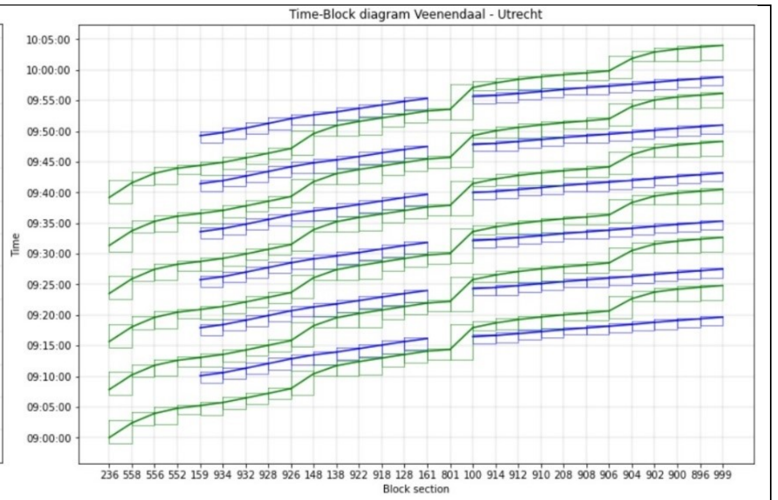
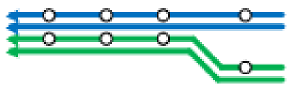
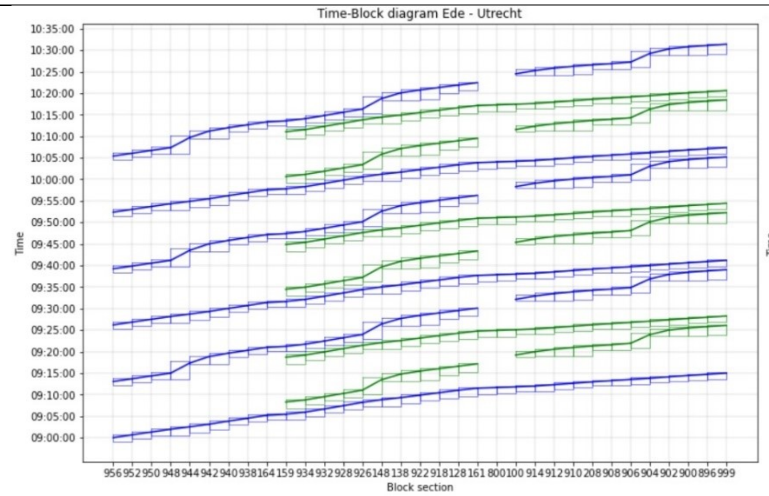
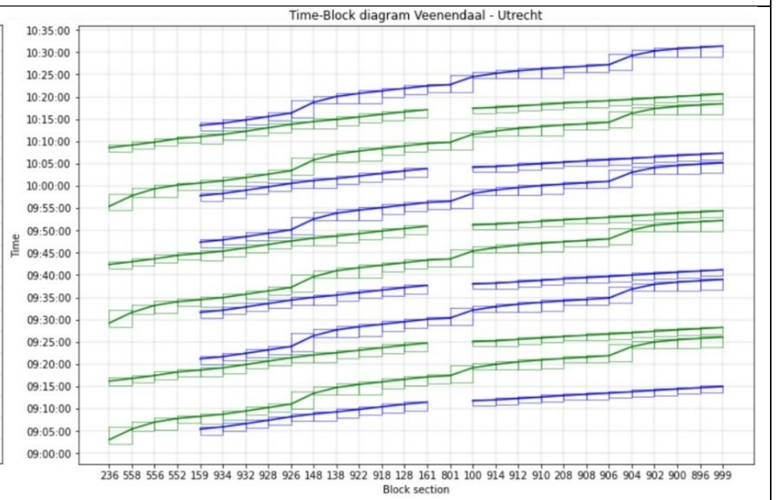
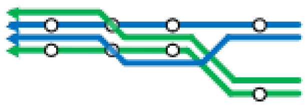
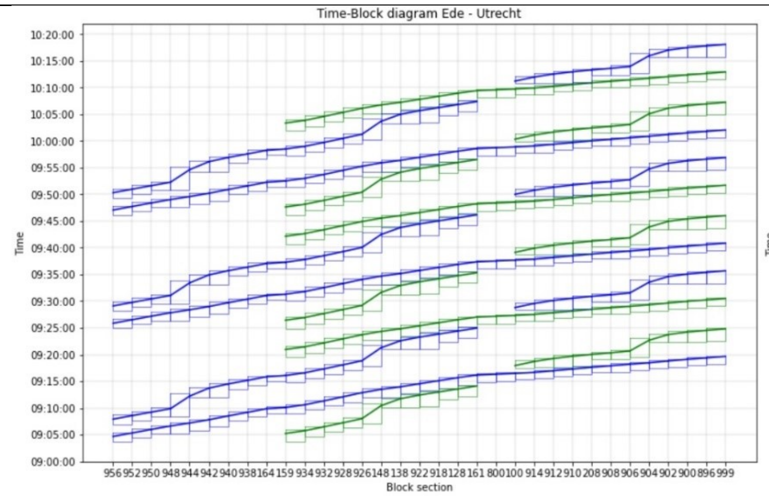
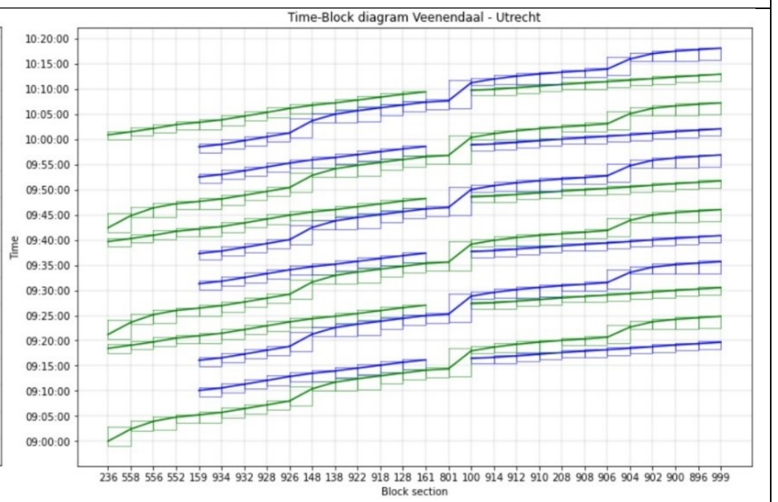
| Layout: Cross-over & M.<br>Traffic structure | Infra. occ. r | Running time s. | Cycle-time(s) | Total running time (timet.) (s)<br>R100< | <br>R100> | <br>R200< | <br>R200> | Nr. trains | Nr. cycles | Avg.Head-way (s) | Dur-ation | Time-block diagram<br>90% infrastructure occupation rate, 0% running time supplement |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 100% | 0% | 8:30 | 23:02 | 23:02 | 25:59 | 26:25 | 12 | 3 | 4:15 | 0:56:03 |  |
| | 50% | 0% | 17:00 | 23:02 | 23:02 | 25:59 | 26:25 | 12 | 3 | 8:30 | 1:17:18 | |
| | 50% | 5% | 17:00 | 24:11 | 24:11 | 27:17 | 27:44 | 12 | 3 | 8:30 | 1:18:57 | |
| | 50% | 10% | 17:00 | 25:21 | 25:20 | 28:34 | 29:03 | 12 | 3 | 8:30 | 1:20:37 | |
| R1.R2 | 75% | 0% | 11:20 | 23:02 | 23:02 | 25:59 | 26:25 | 12 | 3 | 5:40 | 1:03:08 | |
|  | 75% | 5% | 11:20 | 24:11 | 24:11 | 27:17 | 27:44 | 12 | 3 | 5:40 | 1:04:47 | |
| | 75% | 10% | 11:20 | 25:21 | 25:20 | 28:34 | 29:03 | 12 | 3 | 5:40 | 1:06:27 | |
| | 90% | 0% | 09:27 | 23:02 | 23:02 | 25:59 | 26:25 | 12 | 3 | 4:43 | 0:58:25 | |
| | 90% | 5% | 09:27 | 24:11 | 24:11 | 27:17 | 27:44 | 12 | 3 | 4:43 | 1:00:04 | |
| | 90% | 10% | 09:27 | 25:21 | 25:20 | 28:34 | 29:03 | 12 | 3 | 4:43 | 1:01:43 | |
| | | | | R100< | R100> | IC200< | IC200> | | | | | |
| | 100% | 0% | 12:03 | 23:02 | 23:02 | 15:00 | 15:26 | 12 | 3 | 6:01 | 0:56:44 |  |
| | 50% | 0% | 24:06 | 23:02 | 23:02 | 15:00 | 15:26 | 12 | 3 | 12:03 | 1:26:52 | |
| | 50% | 5% | 24:06 | 24:11 | 24:11 | 15:45 | 16:12 | 12 | 3 | 12:03 | 1:28:31 | |
| | 50% | 10% | 24:06 | 25:21 | 25:20 | 16:30 | 16:59 | 12 | 3 | 12:03 | 1:29:40 | |
| R1.IC2 | 75% | 0% | 16:04 | 23:02 | 23:02 | 15:00 | 15:26 | 12 | 3 | 8:02 | 1:06:47 | |
|  | 75% | 5% | 16:04 | 24:11 | 24:11 | 15:45 | 16:12 | 12 | 3 | 8:02 | 1:08:26 | |
| | 75% | 10% | 16:04 | 25:21 | 25:20 | 16:30 | 16:59 | 12 | 3 | 8:02 | 1:09:35 | |
| | 90% | 0% | 13:23 | 23:02 | 23:02 | 15:00 | 15:26 | 12 | 3 | 6:42 | 1:00:05 | |
| | 90% | 5% | 13:23 | 24:11 | 24:11 | 15:45 | 16:12 | 12 | 3 | 6:42 | 1:01:44 | |
| | 90% | 10% | 13:23 | 25:21 | 25:20 | 16:30 | 16:59 | 12 | 3 | 06:42 | 1:02:53 | |

*Table B.6. Overview timetables merge & overtaking layout with timetable characteristics*

| Layout: Merge & Overt.<br>Traffic structure | Infra. occ. r | Running time s. | Cycle-time(s) | Total running time (timet.) (s)<br>R100< | <br>IC100< | <br>R200< | <br>IC200< | Nr. trains | Nr. cycles | Avg.Head-way (s) | Dur-ation | Time-block diagram<br>90% infrastructure occupation rate, 0% running time supplement |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 100% | 0% | 11:57 | 23:02 | | | 15:00 | 12 | 6 | 5:58 | 1:25:10 |  |
| | 50% | 0% | 23:54 | 23:02 | | | 15:00 | 12 | 6 | 11:57 | 2:30:54 | |
| | 50% | 5% | 23:54 | 24:11 | | | 15:45 | 12 | 6 | 11:57 | 2:32:03 | |
| | 50% | 10% | 23:54 | 25:21 | | | 16:30 | 12 | 6 | 11:57 | 2:32:44 | |
| R1.IC2 | 75% | 0% | 15:56 | 23:02 | | | 15:00 | 12 | 6 | 7:58 | 1:47:05 | |
|  | 75% | 5% | 15:56 | 24:11 | | | 15:45 | 12 | 6 | 7:58 | 1:48:14 | |
| | 75% | 10% | 15:56 | 25:21 | | | 16:30 | 12 | 6 | 7:58 | 1:48:55 | |
| | 90% | 0% | 13:17 | 23:02 | | | 15:00 | 12 | 6 | 6:38 | 1:32:28 | |
| | 90% | 5% | 13:17 | 24:11 | | | 15:45 | 12 | 6 | 6:38 | 1:33:38 | |
| | 90% | 10% | 13:17 | 25:21 | | | 16:30 | 12 | 6 | 6:38 | 1:34:19 | |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| R1.IC2+O  | 100% | 0% | 7:03 | 24:49 | | | 15:00 | 12 | 6 | 3:32 | 1:00:04 |  |  |
| | 50% | 0% | 14:06 | 24:49 | | | 15:00 | 12 | 6 | 7:03 | 1:35:19 | | |
| | 50% | 5% | 14:06 | 26:04 | | | 15:45 | 12 | 6 | 7:03 | 1:36:34 | | |
| | 50% | 10% | 14:06 | 27:18 | | | 16:30 | 12 | 6 | 7:03 | 1:37:39 | | |
| | 75% | 0% | 9:24 | 24:49 | | | 15:00 | 12 | 6 | 4:42 | 1:11:49 | | |
| | 75% | 5% | 9:24 | 26:04 | | | 15:45 | 12 | 6 | 4:42 | 1:13:04 | | |
| | 75% | 10% | 9:24 | 27:18 | | | 16:30 | 12 | 6 | 4:42 | 1:14:09 | | |
| | 90% | 0% | 7:50 | 24:49 | | | 15:00 | 12 | 6 | 3:55 | 1:03:59 | | |
| | 90% | 5% | 7:50 | 26:04 | | | 15:45 | 12 | 6 | 3:55 | 1:05:14 | | |
| | 90% | 10% | 7:50 | 27:18 | | | 16:30 | 12 | 6 | 3:55 | 1:06:19 | | |
| R1.IC1.R2.IC2  | 100% | 0% | 23:34 | 23:02 | 12:03 | 25:59 | 15:00 | 12 | 3 | 5:53 | 1:24:11 |  |  |
| | 50% | 0% | 47:08 | 23:02 | 12:03 | 25:59 | 15:00 | 12 | 3 | 11:47 | 2:28:59 | | |
| | 50% | 5% | 47:08 | 24:11 | 12:40 | 27:17 | 15:45 | 12 | 3 | 11:47 | 2:30:17 | | |
| | 50% | 10% | 47:08 | 25:21 | 13:16 | 28:34 | 16:30 | 12 | 3 | 11:47 | 2:30:57 | | |
| | 75% | 0% | 31:25 | 23:02 | 12:03 | 25:59 | 15:00 | 12 | 3 | 7:51 | 1:45:47 | | |
| | 75% | 5% | 31:25 | 24:11 | 12:40 | 27:17 | 15:45 | 12 | 3 | 7:51 | 1:47:05 | | |
| | 75% | 10% | 31:25 | 25:21 | 13:16 | 28:34 | 16:30 | 12 | 3 | 7:51 | 1:47:45 | | |
| | 90% | 0% | 26:11 | 23:02 | 12:03 | 25:59 | 15:00 | 12 | 3 | 6:33 | 1:31:23 | | |
| | 90% | 5% | 26:11 | 24:11 | 12:40 | 27:17 | 15:45 | 12 | 3 | 6:33 | 1:32:41 | | |
| | 90% | 10% | 26:11 | 25:21 | 13:16 | 28:34 | 16:30 | 12 | 3 | 6:33 | 1:33:21 | | |
| R1.IC1.R2.IC2+O  | 100% | 0% | 19:05 | 24:49 | 12:03 | 27:47 | 15:00 | 12 | 3 | 4:46 | 1:16:47 |  |  |
| | 50% | 0% | 38:10 | 24:49 | 12:03 | 27:47 | 15:00 | 12 | 3 | 9:33 | 2:05:47 | | |
| | 50% | 5% | 38:10 | 26:04 | 12:40 | 29:10 | 15:45 | 12 | 3 | 9:33 | 2:07:10 | | |
| | 50% | 10% | 38:10 | 27:18 | 13:16 | 30:33 | 16:30 | 12 | 3 | 9:33 | 2:08:33 | | |
| | 75% | 0% | 25:27 | 24:49 | 12:03 | 27:47 | 15:00 | 12 | 3 | 6:22 | 1:33:07 | | |
| | 75% | 5% | 25:27 | 26:04 | 12:40 | 29:10 | 15:45 | 12 | 3 | 6:22 | 1:34:30 | | |
| | 75% | 10% | 25:27 | 27:18 | 13:16 | 30:33 | 16:30 | 12 | 3 | 6:22 | 1:35:53 | | |
| | 90% | 0% | 21:12 | 24:49 | 12:03 | 27:47 | 15:00 | 12 | 3 | 5:18 | 1:22:13 | | |
| | 90% | 5% | 21:12 | 26:04 | 12:40 | 29:10 | 15:45 | 12 | 3 | 5:18 | 1:23:37 | | |
| | 90% | 10% | 21:12 | 27:18 | 13:16 | 30:33 | 16:30 | 12 | 3 | 5:18 | 1:25:00 | | |

# Appendix C. Tables and histograms

This appendix contains histograms and tables with the results for all considered infrastructure layouts and traffic patterns.

Table C.1 contains the average number of detected conflicts for all the considered layouts and traffic patterns. A subdivision is made between timetables with different running time supplements and different delay scenarios. More about the results of the conflict detection module can be found in section 5.1.

*Table C.1. Average number of detected conflicts per layout over for different timetable characteristics and delay scenarios*

| **Avg. number of detected conflicts** | | **Infrastr. occupation rate** | | | **Running time supplement** | | | **Size initial delay** | | | ***Average* headway (s)*** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Layout + Traffic Pattern** | **All scenarios** | **50%** | **75%** | **90%** | **0%** | **5%** | **10%** | **Small** | **Medium** | **Large** | |
| **Cross-over** | **3.3** | **1.4** | **3.5** | **5.1** | **3.5** | **3.3** | **3.2** | **2.2** | **3.3** | **4.5** | ***286*** |
| R1.R2 | 5.0 | 2.0 | 5.2 | 7.8 | 5.3 | 5.0 | 4.7 | 2.9 | 4.9 | 7.1 | *224* |
| R1.IC2 | 4.8 | 2.0 | 5.0 | 7.5 | 5.1 | 4.8 | 4.6 | 2.9 | 4.7 | 6.9 | *221* |
| R1.R2.IC1.R2 | 2.0 | 1.0 | 2.1 | 3.0 | 2.2 | 2.0 | 1.9 | 1.3 | 2.1 | 2.7 | *329* |
| R1.R2.IC1.IC2 | 2.5 | 1.2 | 2.7 | 3.6 | 2.6 | 2.5 | 2.4 | 2.1 | 2.5 | 2.9 | *329* |
| R1.R2.IC2.IC1 | 2.4 | 0.9 | 2.6 | 3.6 | 2.5 | 2.3 | 2.2 | 1.7 | 2.4 | 3.0 | *328* |
| **Merge** | **1.9** | **1.0** | **2.0** | **2.8** | **2.0** | **2.0** | **1.9** | **1.3** | **2.0** | **2.6** | ***455*** |
| R1.R2 | 2.4 | 1.2 | 2.5 | 3.6 | 2.5 | 2.4 | 2.3 | 1.4 | 2.5 | 3.4 | *350* |
| R1.IC2 | 1.5 | 0.8 | 1.6 | 2.1 | 1.5 | 1.5 | 1.4 | 1.0 | 1.4 | 2.0 | *531* |
| R1.R2.IC1.IC2 | 2.2 | 1.0 | 2.4 | 3.3 | 2.3 | 2.2 | 2.1 | 1.5 | 2.3 | 2.8 | *524* |
| R1.IC1.R2.IC2 | 1.7 | 1.2 | 1.7 | 2.1 | 1.7 | 1.7 | 1.6 | 1.2 | 1.5 | 2.3 | *414* |
| **Overtaking** | **2.5** | **1.1** | **2.6** | **3.6** | **2.5** | **2.5** | **2.4** | **1.7** | **2.3** | **3.3** | ***544*** |
| R.IC | 1.6 | 0.6 | 1.8 | 2.4 | 1.7 | 1.6 | 1.5 | 1.1 | 1.6 | 2.1 | *653* |
| R.IC+O | 3.3 | 1.7 | 3.4 | 4.9 | 3.4 | 3.3 | 3.3 | 2.4 | 3.1 | 4.5 | *436* |
| **Single track** | **2.6** | **1.6** | **2.7** | **3.5** | **2.6** | **2.6** | **2.5** | **2.2** | **2.7** | **2.9** | ***777*** |
| R.R(1) | 1.9 | 1.5 | 1.9 | 2.3 | 1.9 | 1.9 | 1.8 | 1.7 | 2.0 | 2.0 | *959* |
| R.R(2) | 3.3 | 1.8 | 3.5 | 4.7 | 3.4 | 3.3 | 3.3 | 2.7 | 3.4 | 3.8 | *594* |
| **Cross-over & Merge** | **2.8** | **1.2** | **3.0** | **4.3** | **3.0** | **2.8** | **2.7** | **1.5** | **2.8** | **4.2** | ***457*** |
| R1.R2 | 3.5 | 1.4 | 3.7 | 5.4 | 3.8 | 3.5 | 3.3 | 1.7 | 3.5 | 5.4 | *378* |
| R1.IC2 | 2.1 | 1.0 | 2.2 | 3.2 | 2.2 | 2.2 | 2.0 | 1.3 | 2.1 | 3.1 | *536* |
| **Merge & Overtaking** | **2.3** | **1.2** | **2.4** | **3.3** | **2.4** | **2.3** | **2.2** | **1.7** | **2.2** | **3.0** | ***448*** |
| R1.IC2 | 1.5 | 0.8 | 1.6 | 2.1 | 1.5 | 1.5 | 1.4 | 1.0 | 1.4 | 2.0 | *531* |
| R1.IC2+O | 3.9 | 1.9 | 4.0 | 5.7 | 4.0 | 3.9 | 3.7 | 2.5 | 3.7 | 5.4 | *313* |
| R1.IC1.R2.IC2 | 1.5 | 0.8 | 1.6 | 2.1 | 1.6 | 1.5 | 1.4 | 1.0 | 1.4 | 2.1 | *524* |
| R1.IC1.R2.IC2+O | 2.3 | 1.2 | 2.5 | 3.3 | 2.3 | 2.3 | 2.3 | 2.2 | 2.2 | 2.6 | *424* |
| **All layouts** | **2.6** | **1.3** | **2.7** | **3.8** | **2.7** | **2.6** | **2.5** | **1.8** | **2.6** | **3.5** | ***453*** |

**Averaged over all timetables with (different infrastructure occupation rates, running time supplements and sizes of initial delay)*

Figure C.1 is a histogram, which shows the relative improvement by the (η) for all the regarded layouts and traffic patterns. The bars only represent the best performing SDR. The color of the bar indicates which SDR performs best and is used for the calculation of η. These values can also be found in table C.2, where also the results for the other SDRs are given.

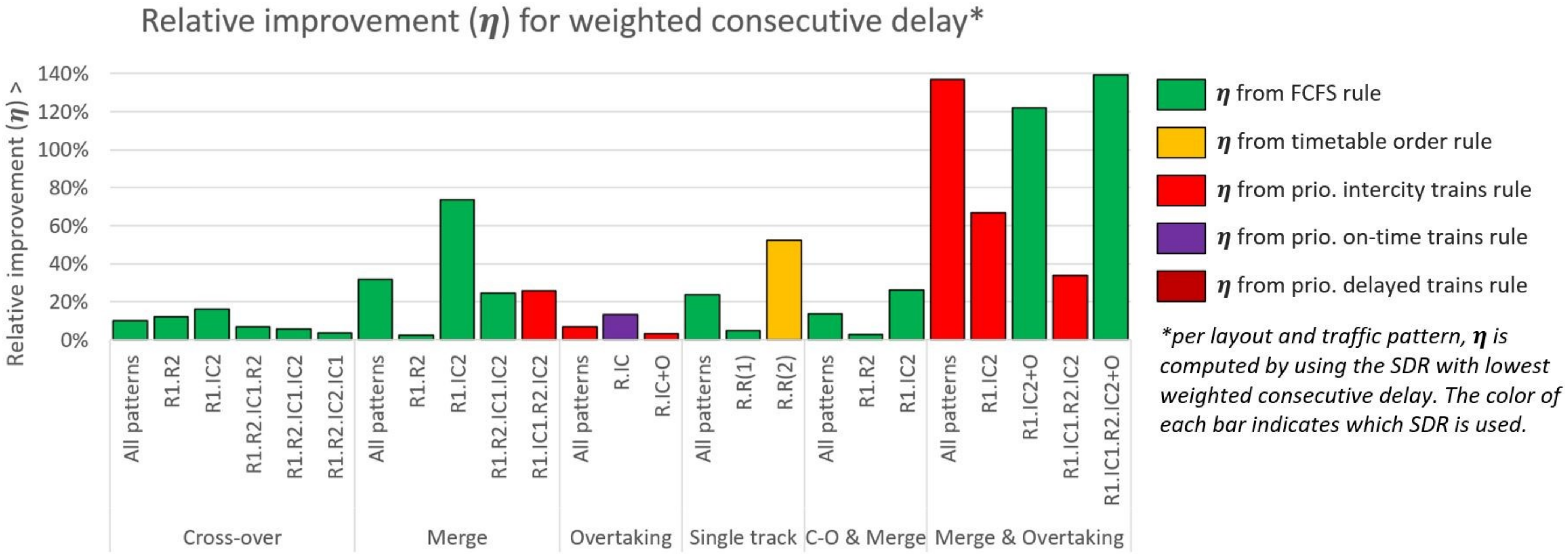



*Figure C.1. Relative improvement (η) for different infrastructure layouts and traffic patterns*

Table C.2 contains results for the weighted consecutive delay for all regarded layouts and traffic patterns. It also provides the relative improvement by the RTRM (η) and the percentage of scenarios that the RTRM outperforms the SDR. For the η and '% scenarios RTRM better' per layout and traffic pattern the RTRM performing best is underlined. More about this results can be found in section 5.3.

*Table C.2. Weighted consecutive delay, η and '% scenarios RTRM better' for all considered layout and traffic patterns*

| | Weighted consecutive delay (s) | | | | | | Relative improvement by RTRM (η) | | | | | % scenarios RTRM outperforms SDR | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Layout + Traffic Pattern | RTRM | FCFS | Timetable order | Prioritize intercity trains | Prioritize on-time trains | Prioritize delayed trains | FCFS | Timetable order | Prioritize intercity trains | Prioritize on-time trains | Prioritize delayed trains | FCFS | Timetable order | Prioritize intercity trains | Prioritize on-time trains | Prioritize delayed trains | *Average* headway (s)* |
| **Cross-over** | **784** | **859** | **1695** | **1129** | **1368** | **1254** | **10%** | **116%** | **44%** | **75%** | **60%** | **30%** | **72%** | **52%** | **66%** | **53%** | ***286*** |
| R1.R2 | 764 | 852 | 1609 | *852* | 1660 | 1426 | 12% | 111% | *12%* | 117% | 87% | 39% | 72% | *39%* | 77% | 65% | *224* |
| R1.IC2 | 1007 | 1171 | 2623 | 1929 | 1865 | 2123 | 16% | 160% | 92% | 85% | 111% | 41% | 83% | 84% | 70% | 71% | *221* |
| R1.R2.IC1.R2 | 574 | 613 | 1196 | 793 | 953 | 761 | 7% | 108% | 38% | 66% | 33% | 23% | 65% | 46% | 65% | 44% | *329* |
| R1.R2.IC1.IC2 | 769 | 814 | 1476 | 1038 | 1086 | 910 | 6% | 92% | 35% | 41% | 18% | 25% | 68% | 51% | 60% | 41% | *329* |
| R1.R2.IC2.IC1 | 783 | 813 | 1487 | 975 | 1206 | 956 | 4% | 90% | 25% | 54% | 22% | 18% | 69% | 39% | 58% | 42% | *328* |
| **Merge** | **689** | **909** | **1161** | **1358** | **1470** | **1015** | **32%** | **68%** | **97%** | **113%** | **47%** | **36%** | **43%** | **41%** | **68%** | **40%** | ***455*** |
| R1.R2 | 727 | 744 | 1469 | *744* | 1678 | 1038 | 2% | 102% | *2%* | 131% | 43% | 10% | 56% | *10%* | 69% | 42% | *350* |
| R1.IC2 | 501 | 870 | 935 | 1955 | 1183 | 917 | 74% | 86% | 290% | 136% | 83% | 54% | 48% | 75% | 67% | 45% | *531* |
| R1.R2.IC1.IC2 | 768 | 956 | 1276 | 1867 | 1717 | 1146 | 24% | 66% | 143% | 123% | 49% | 34% | 48% | 63% | 74% | 44% | *524* |
| R1.IC1.R2.IC2 | 747 | 1065 | 947 | 939 | 1284 | 954 | 43% | 27% | 26% | 72% | 28% | 49% | 22% | 21% | 62% | 30% | *414* |
| **Overtaking** | **764** | **1355** | **1001** | **818** | **1043** | **1331** | **77%** | **31%** | **7%** | **37%** | **74%** | **81%** | **51%** | **25%** | **50%** | **79%** | ***544*** |
| R.IC | 349 | 653 | 653 | 425 | 396 | 653 | 87% | 87% | 22% | 13% | 87% | 66% | 66% | 35% | 23% | 66% | *653* |
| R.IC+O | 1101 | 1923 | 1282 | 1136 | 1567 | 1880 | 75% | 16% | 3% | 42% | 71% | 93% | 40% | 17% | 72% | 90% | *436* |
| **Single track** | **576** | **596*** | **1054** | ***596**** | **1467*** | **764*** | **24%*** | **83%** | ***24%**** | **204%*** | **51%*** | **27%** | **59%** | ***27%*** | **80%** | **48%** | ***777*** |
| R.R(1) | 320 | 336 | 845 | *336* | 1058 | 520 | 5% | 164% | *5%* | 229%* | 62% | 12% | 54% | *12%* | 73% | 45% | *959* |
| R.R(2) | 823 | 874* | 1256 | *874** | 1944* | 1019* | 34%* | 53% | *34%** | 190%* | 45%* | 41% | 63% | *41%* | 86% | 50% | *594* |
| **Cross-over & Merge** | **733** | **835** | **1217** | **962** | **1013** | **944** | **14%** | **66%** | **31%** | **38%** | **29%** | **26%** | **50%** | **35%** | **54%** | **39%** | ***457*** |
| R1.R2 | 748 | 769 | 1270 | 769 | 992 | 920 | 3% | 70% | 3% | 33% | 23% | 18% | 57% | 18% | 57% | 42% | *378* |
| R1.IC2 | 718 | 905 | 1160 | 1168 | 1036 | 968 | 26% | 62% | 63% | 44% | 35% | 34% | 43% | 52% | 51% | 35% | *536* |
| **Merge & Overtaking** | **496** | **1181** | **1524** | **1144*** | **1463*** | **1313*** | **138%** | **207%** | **137%*** | **237%*** | **166%*** | **81%** | **79%** | **68%** | **80%** | **77%** | ***448*** |
| R1.IC2 | 314 | 872 | 933 | 525 | 863* | 738 | 178% | 197% | 67% | 216%* | 135% | 76% | 72% | 65% | 79% | 67% | *531* |
| R1.IC2+O | 819 | 1818 | 2559 | 2400 | 2071* | 2362* | 122% | 212% | 193% | 187%* | 191%* | 89% | 84% | 81% | 91% | 90% | *313* |
| R1.IC1.R2.IC2 | 420 | 1021 | 946 | 530* | 1119 | 797 | 143% | 125% | 34%* | 166% | 90% | 81% | 73% | 56% | 74% | 68% | *524* |
| R1.IC1.R2.IC2+O | 390 | 934 | 1494 | 906* | 1848* | 1213 | 139% | 283% | 163%* | 463%* | 211% | 74% | 87% | 69% | 74% | 82% | *424* |
| **All layouts** | **674** | **957*** | **1356** | **1072*** | **1344*** | **1140*** | **44%*** | **101%** | **62%*** | **103%*** | **71%*** | **46%** | **62%** | **46%** | **68%** | **56%** | ***453*** |

**Scenarios resulting in deadlocks excluded. Cell is marked grey if more than 5% scenarios are excluded*

***Averaged over all timetables with different infrastructure occupation rates, running time supplements and sizes of initial delay*

Table C.3 contains the average weighted consecutive delay (for the observed RTRM) for all the considered layouts and traffic patterns. A subdivision is made between timetables with different running time supplements and different delay scenarios.

*Table C.3. Weighted consecutive delay (for observed RTRM) per layout over for different timetable characteristics and delay scenarios*

| **Weigh. cons. delay RTRM (s)*** | | **Infrastr. occupation rate** | | | **Running time supplement** | | | **Size initial delay** | | | ***Average** headway (s)*** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Layout + Traffic Pattern** | **All scenarios** | **50%** | **75%** | **90%** | **0%** | **5%** | **10%** | **Small** | **Medium** | **Large** | |
| **Cross-over** | **784** | **200** | **703** | **1342** | **938** | **778** | **630** | **361** | **705** | **1224** | ***286*** |
| R1.R2 | 764 | 156 | 690 | 1408 | 948 | 756 | 581 | 362 | 738 | 1165 | *224* |
| R1.IC2 | 1007 | 190 | 893 | 1904 | 1199 | 994 | 824 | 487 | 987 | 1525 | *221* |
| R1.R2.IC1.R2 | 574 | 194 | 517 | 897 | 690 | 578 | 451 | 231 | 481 | 933 | *329* |
| R1.R2.IC1.IC2 | 769 | 221 | 703 | 1272 | 909 | 768 | 626 | 363 | 627 | 1246 | *329* |
| R1.R2.IC2.IC1 | 783 | 253 | 708 | 1223 | 920 | 768 | 651 | 328 | 681 | 1236 | *328* |
| **Merge** | **689** | **310** | **556** | **1095** | **804** | **686** | **575** | **354** | **669** | **975** | ***455*** |
| R1.R2 | 727 | 135 | 466 | 1460 | 892 | 723 | 556 | 360 | 635 | 1118 | *350* |
| R1.IC2 | 501 | 297 | 435 | 681 | 553 | 501 | 448 | 336 | 583 | 535 | *531* |
| R1.R2.IC1.IC2 | 768 | 268 | 643 | 1245 | 889 | 770 | 642 | 368 | 710 | 1118 | *524* |
| R1.IC1.R2.IC2 | 747 | 523 | 686 | 993 | 862 | 738 | 641 | 350 | 741 | 1133 | *414* |
| **Overtaking** | **764** | **457** | **673** | **1076** | **890** | **765** | **635** | **415** | **697** | **1112** | ***544*** |
| R.IC | 349 | 110 | 290 | 517 | 409 | 355 | 280 | 173 | 247 | 547 | *653* |
| R.IC+O | 1101 | 621 | 1042 | 1631 | 1292 | 1098 | 915 | 565 | 1072 | 1664 | *436* |
| **Single track** | **576** | **244** | **498** | **974** | **712** | **570** | **445** | **258** | **656** | **808** | ***777*** |
| R.R(1) | 320 | 272 | 277 | 407 | 393 | 315 | 253 | 194 | 433 | 326 | *959* |
| R.R(2) | 823 | 217 | 709 | 1541 | 1019 | 820 | 630 | 317 | 879 | 1271 | *594* |
| **Cross-over & Merge** | **733** | **247** | **666** | **1119** | **872** | **732** | **590** | **321** | **714** | **1038** | ***457*** |
| R1.R2 | 748 | 211 | 696 | 1192 | 909 | 742 | 585 | 329 | 734 | 1075 | *378* |
| R1.IC2 | 718 | 291 | 636 | 1047 | 832 | 721 | 596 | 312 | 694 | 1001 | *536* |
| **Merge & Overtaking** | **496** | **226** | **417** | **769** | **591** | **495** | **401** | **385** | **395** | **690** | ***448*** |
| R1.IC2 | 314 | 204 | 268 | 421 | 362 | 313 | 265 | 251 | 318 | 352 | *531* |
| R1.IC2+O | 819 | 264 | 701 | 1460 | 992 | 814 | 653 | 579 | 642 | 1238 | *313* |
| R1.IC1.R2.IC2 | 420 | 217 | 371 | 583 | 490 | 424 | 341 | 257 | 330 | 611 | *524* |
| R1.IC1.R2.IC2+O | 390 | 204 | 321 | 609 | 474 | 391 | 310 | 362 | 277 | 541 | *424* |
| **All layouts** | **674** | **263** | **583** | **1079** | **802** | **671** | **546** | **354** | **629** | **986** | ***453*** |

**Scenarios with zero conflicts are excluded*
***Averaged over all timetables (with different infrastructure occupation rates, running time supplements and sizes of initial delay)*

Table C.4 contains the relative difference between the best performing SDR and the RTRM (η). These are included for all the considered layouts and traffic patterns. A subdivision is made between timetables with different running time supplements and different delay scenarios. The color of each cell indicates which SDR is performing best (and is used in the computation of η).

*Table C.4. Relative improvement by RTRM (η) for weighted consecutive delay per layout over for different timetable characteristics and delay scenarios*

| ***η* for weigh. consecutive delay**** | | **Infrastr. occupation rate** | | | **Running time supplement** | | | **Size initial delay** | | | ***Average*** headway (s)*** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Layout + Traffic Pattern** | **All scenarios** | **50%** | **75%** | **90%** | **0%** | **5%** | **10%** | **Small** | **Medium** | **Large** | |
| **Cross-over** | **10%** | **4%** | **8%** | **11%** | **8%** | **9%** | **12%** | **7%** | **11%** | **10%** | ***286*** |
| R1.R2 | 12% | 6% | 9% | 13% | 10% | 11% | 15% | 12% | 13% | 11% | *224* |
| R1.IC2 | 16% | 5% | 13% | 19% | 14% | 16% | 19% | 6% | 19% | 18% | *221* |
| R1.R2.IC1.R2 | 7% | 5% | 7% | 7% | 5% | 6% | 10% | 4% | 5% | 8% | *329* |
| R1.R2.IC1.IC2 | 6% | 6% | 7% | 5% | 4% | 5% | 9% | 10% | 4% | 6% | *329* |
| R1.R2.IC2.IC1 | 4% | 1% | 4% | 4% | 3% | 3% | 5% | 4% | 5% | 3% | *328* |
| **Merge** | **32%** | **32%** | **37%** | **20%** | **21%** | **31%** | **49%** | **4%** | **29%** | **20%** | ***455*** |
| R1.R2 | 2% | 5% | 2% | 2% | 0% | 1% | 8% | 5% | 2% | 2% | *350* |
| R1.IC2 | 74% | 32% | 72% | 59% | 57% | 69% | 75% | 0% | 31% | 73% | *531* |
| R1.R2.IC1.IC2 | 24% | 49% | 30% | 14% | 17% | 24% | 36% | 5% | 25% | 16% | *524* |
| R1.IC1.R2.IC2 | 26% | 9% | 24% | 27% | 24% | 25% | 23% | 0% | 15% | 16% | *414* |
| **Overtaking** | **7%** | **10%** | **8%** | **6%** | **6%** | **7%** | **9%** | **8%** | **9%** | **4%** | ***544*** |
| R.IC | 13% | 47% | 18% | 8% | 10% | 12% | 21% | 33% | 21% | 7% | *653* |
| R.IC+O | 3% | 7% | 3% | 2% | 2% | 3% | 4% | 2% | 6% | 2% | *436* |
| **Single track** | **24%*** | **4%** | **39%** | **84%** | **19%*** | **24%*** | **32%*** | **10%** | **29%*** | **142%** | ***777*** |
| R.R(1) | 5% | 1% | 2% | 10% | 6% | 3% | 6% | 2% | 7% | 4% | *959* |
| R.R(2) | 53% | 8% | 35% | 36% | 52% | 53% | 53% | 12% | 27% | 80% | *594* |
| **Cross-over & M.** | **14%** | **19%** | **13%** | **10%** | **10%** | **13%** | **20%** | **3%** | **14%** | **11%** | ***457*** |
| R1.R2 | 3% | 3% | 3% | 3% | 1% | 3% | 5% | 3% | 4% | 2% | *378* |
| R1.IC2 | 26% | 27% | 24% | 17% | 20% | 25% | 35% | 0% | 26% | 21% | *536* |
| **Merge & Overt.** | **137%*** | **48%** | **140%** | **121%** | **115%** | **137%** | **153%*** | **46%** | **136%** | **122%** | ***448*** |
| R1.IC2 | 67% | 48% | 71% | 70% | 60% | 64% | 81% | 33% | 80% | 59% | *531* |
| R1.IC2+O | 122% | 57% | 118% | 113% | 107% | 122% | 144% | 42% | 103% | 123% | *313* |
| R1.IC1.R2.IC2 | 34%* | 35% | 41% | 94% | 30%* | 30%* | 44%* | 34% | 38% | 93% | *524* |
| R1.IC1.R2.IC2+O | 139% | 46% | 71%* | 117% | 118% | 139% | 170% | 65% | 94% | 114% | *424* |
| **All layouts** | **44%*** | **28%** | **46%*** | **37%*** | **36%*** | **44%*** | **57%*** | **26%** | **42%*** | **37%*** | ***453*** |

**Scenarios resulting in deadlocks excluded*
***Scenarios with zero conflicts are excluded*
****Averaged over all timetables (with different infrastructure occupation rates, running time supplements and sizes of initial delay)*

- ***η*** from FCFS rule
- ***η*** from timetable order rule
- ***η*** from prioritise intercity trains rule
- ***η*** from prioritise on-time trains rule
- ***η*** from prioritise delayed trains rule

Table C.5 contains the percentage of scenarios the RTRM performs better than the best performing SDR ('% scenarios RTRM better'). These are included for all the considered layouts and traffic patterns. A subdivision is made between timetables with different running time supplements and different delay scenarios. The color of each cell indicates which SDR is performing best (and is used).

*Table C.5. % scenarios observed RTRM outperforms SDRs per layout over for different timetable characteristics and delay scenarios*

| % scenarios RTRM better* | | Infrastr. occupation rate | | | Running time supplement | | | Size initial delay | | | *Average** headway (s)* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Layout + Traffic Pattern** | **All scenarios** | **50%** | **75%** | **90%** | **0%** | **5%** | **10%** | **Small** | **Medium** | **Large** | |
| **Cross-over** | **30%** | **12%** | **28%** | **45%** | **28%** | **29%** | **31%** | **19%** | **28%** | **40%** | ***286*** |
| R1.R2 | 39% | 14% | 36% | 65% | 36% | 39% | 42% | 29% | 38% | 49% | *224* |
| R1.IC2 | 41% | 11% | 39% | 70% | 44% | 39% | 38% | 17% | 46% | 58% | *221* |
| R1.R2.IC1.R2 | 23% | 13% | 24% | 28% | 20% | 24% | 24% | 12% | 19% | 34% | *329* |
| R1.R2.IC1.IC2 | 25% | 13% | 24% | 36% | 21% | 26% | 29% | 21% | 18% | 36% | *329* |
| R1.R2.IC2.IC1 | 18% | 7% | 18% | 27% | 19% | 17% | 19% | 13% | 20% | 21% | *328* |
| **Merge** | **36%** | **23%** | **36%** | **37%** | **31%** | **36%** | **37%** | **6%** | **38%** | **38%** | ***455*** |
| R1.R2 | 10% | 9% | 9% | 12% | 1% | 9% | 22% | 7% | 13% | 10% | *350* |
| R1.IC2 | 45% | 30% | 47% | 50% | 49% | 45% | 40% | 1% | 46% | 43% | *531* |
| R1.R2.IC1.IC2 | 34% | 30% | 37% | 32% | 28% | 31% | 42% | 10% | 33% | 39% | *524* |
| R1.IC1.R2.IC2 | 21% | 12% | 21% | 29% | 21% | 21% | 19% | 0% | 21% | 40% | *414* |
| **Overtaking** | **25%** | **20%** | **24%** | **30%** | **26%** | **24%** | **25%** | **19%** | **29%** | **20%** | ***544*** |
| R.IC | 23% | 23% | 28% | 20% | 21% | 22% | 28% | 30% | 24% | 19% | *653* |
| R.IC+O | 17% | 19% | 17% | 15% | 18% | 17% | 16% | 9% | 29% | 13% | *436* |
| **Single track** | **27%** | **11%** | **31%** | **37%** | **27%** | **25%** | **28%** | **13%** | **34%** | **33%** | ***777*** |
| R.R(1) | 12% | 4% | 8% | 23% | 12% | 10% | 13% | 4% | 22% | 8% | *959* |
| R.R(2) | 41% | 18% | 43% | 43% | 41% | 40% | 43% | 21% | 45% | 57% | *594* |
| **Cross-over & Merge** | **26%** | **14%** | **26%** | **28%** | **23%** | **25%** | **30%** | **5%** | **30%** | **31%** | ***457*** |
| R1.R2 | 18% | 8% | 21% | 22% | 15% | 16% | 23% | 7% | 25% | 19% | *378* |
| R1.IC2 | 34% | 18% | 30% | 34% | 32% | 34% | 32% | 2% | 35% | 36% | *536* |
| **Merge & Overtaking** | **68%** | **41%** | **72%** | **84%** | **70%** | **68%** | **67%** | **52%** | **70%** | **70%** | ***448*** |
| R1.IC2 | 65% | 46% | 64% | 75% | 64% | 64% | 61% | 38% | 68% | 63% | *531* |
| R1.IC2+O | 81% | 44% | 83% | 86% | 82% | 81% | 79% | 55% | 82% | 86% | *313* |
| R1.IC1.R2.IC2 | 56% | 35% | 59% | 66% | 58% | 54% | 57% | 38% | 54% | 55% | *524* |
| R1.IC1.R2.IC2+O | 69% | 39% | 66% | 82% | 73% | 70% | 63% | 58% | 49% | 78% | *424* |
| **All layouts** | **46%** | **26%** | **46%** | **55%** | **45%** | **45%** | **46%** | **27%** | **46%** | **49%** | ***453*** |

**Scenarios with zero conflicts are excluded*
***Averaged over all timetables (with different infrastructure occupation rates, running time supplements and sizes of initial delay)*

- from FCFS rule
- from timetable order rule
- from prioritise intercity trains rule
- from prioritise on-time trains rule
- from prioritise delayed trains rule

Table C.6 contains the average optimization runtime of the RTRM for all the considered layouts and traffic patterns. A subdivision is made between timetables with different running time supplements and different delay scenarios. More about the results of the optimization runtime KPI can be found in section 5.7.

*Table C.6. Optimization runtime per layout over for different timetable characteristics and delay scenarios*

| Optimization runtime (s)* | | Infrastr. occupation rate | | | Running time supplement | | | Size initial delay | | | *Average** headway (s)* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Layout + Traffic Pattern** | **All scenarios** | **50%** | **75%** | **90%** | **0%** | **5%** | **10%** | **Small** | **Medium** | **Large** | |
| **Cross-over** | **0.26** | **0.11** | **0.23** | **0.41** | **0.28** | **0.26** | **0.24** | **0.14** | **0.24** | **0.38** | ***286*** |
| R1.R2 | 0.35 | 0.11 | 0.29 | 0.62 | 0.39 | 0.36 | 0.29 | 0.16 | 0.33 | 0.53 | *224* |
| R1.IC2 | 0.33 | 0.11 | 0.26 | 0.62 | 0.36 | 0.33 | 0.31 | 0.16 | 0.34 | 0.49 | *221* |
| R1.R2.IC1.R2 | 0.15 | 0.11 | 0.15 | 0.18 | 0.16 | 0.16 | 0.14 | 0.10 | 0.14 | 0.20 | *329* |
| R1.R2.IC1.IC2 | 0.21 | 0.11 | 0.19 | 0.31 | 0.23 | 0.21 | 0.19 | 0.14 | 0.19 | 0.29 | *329* |
| R1.R2.IC2.IC1 | 0.24 | 0.13 | 0.24 | 0.31 | 0.23 | 0.25 | 0.23 | 0.14 | 0.21 | 0.34 | *328* |
| **Merge** | **0.41** | **0.20** | **0.29** | **0.68** | **0.45** | **0.42** | **0.36** | **0.21** | **0.37** | **0.60** | ***455*** |
| R1.R2 | 0.61 | 0.17 | 0.26 | 1.32 | 0.71 | 0.63 | 0.48 | 0.21 | 0.45 | 1.10 | *350* |
| R1.IC2 | 0.30 | 0.22 | 0.27 | 0.38 | 0.31 | 0.31 | 0.28 | 0.20 | 0.35 | 0.31 | *531* |
| R1.R2.IC1.IC2 | 0.41 | 0.22 | 0.34 | 0.63 | 0.45 | 0.42 | 0.37 | 0.24 | 0.38 | 0.58 | *524* |
| R1.IC1.R2.IC2 | 0.30 | 0.21 | 0.29 | 0.40 | 0.31 | 0.31 | 0.29 | 0.20 | 0.30 | 0.41 | *414* |
| **Overtaking** | **0.41** | **0.27** | **0.35** | **0.58** | **0.45** | **0.40** | **0.39** | **0.29** | **0.38** | **0.55** | ***544*** |
| R.IC | 0.25 | 0.21 | 0.22 | 0.28 | 0.26 | 0.24 | 0.23 | 0.21 | 0.22 | 0.29 | *653* |
| R.IC+O | 0.55 | 0.30 | 0.47 | 0.87 | 0.61 | 0.53 | 0.51 | 0.33 | 0.52 | 0.79 | *436* |
| **Single track** | **0.07** | **0.05** | **0.06** | **0.10** | **0.08** | **0.07** | **0.07** | **0.06** | **0.07** | **0.09** | ***777*** |
| R.R(1) | 0.06 | 0.05 | 0.06 | 0.07 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | 0.06 | *959* |
| R.R(2) | 0.09 | 0.06 | 0.07 | 0.14 | 0.10 | 0.09 | 0.08 | 0.06 | 0.09 | 0.11 | *594* |
| **Cross-over & Merge** | **0.18** | **0.09** | **0.16** | **0.27** | **0.20** | **0.17** | **0.18** | **0.10** | **0.19** | **0.24** | ***457*** |
| R1.R2 | 0.19 | 0.08 | 0.16 | 0.30 | 0.22 | 0.18 | 0.18 | 0.10 | 0.19 | 0.26 | *378* |
| R1.IC2 | 0.17 | 0.10 | 0.16 | 0.23 | 0.18 | 0.17 | 0.18 | 0.10 | 0.18 | 0.22 | *536* |
| **Merge & Overtaking** | **0.37** | **0.20** | **0.24** | **0.61** | **0.41** | **0.36** | **0.33** | **0.25** | **0.24** | **0.58** | ***448*** |
| R1.IC2 | 0.19 | 0.17 | 0.17 | 0.22 | 0.21 | 0.18 | 0.18 | 0.20 | 0.18 | 0.19 | *531* |
| R1.IC2+O | 0.78 | 0.28 | 0.43 | 1.60 | 0.90 | 0.76 | 0.68 | 0.38 | 0.39 | 1.56 | *313* |
| R1.IC1.R2.IC2 | 0.21 | 0.15 | 0.18 | 0.28 | 0.23 | 0.19 | 0.21 | 0.17 | 0.18 | 0.26 | *524* |
| R1.IC1.R2.IC2+O | 0.24 | 0.16 | 0.20 | 0.33 | 0.26 | 0.24 | 0.21 | 0.22 | 0.20 | 0.29 | *424* |
| **All layouts** | **0.30** | **0.15** | **0.23** | **0.48** | **0.33** | **0.30** | **0.27** | **0.18** | **0.26** | **0.44** | ***453*** |

**Scenarios with zero conflicts are excluded*

***Averaged over all timetables (with different infrastructure occupation rates, running time supplements and sizes of initial delay)*

Table C.7 contains the average relative delay KPI for the RTRM for all the considered layouts and traffic patterns. A subdivision is made between timetables with different running time supplements and different delay scenarios. More about the results of the relative KPI can be found in section 5.6.

*Table C.7. Relative delay per layout over for different timetable characteristics and delay scenarios*

| Relative delay (-)* | | Infrastr. occupation rate | | | Running time supplement | | | Size initial delay | | | *Average** headway (s)* |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Layout + Traffic Pattern** | **All scenarios** | **50%** | **75%** | **90%** | **0%** | **5%** | **10%** | **Small** | **Medium** | **Large** | |
| **Cross-over** | **0.49** | **0.16** | **0.44** | **0.81** | **0.64** | **0.48** | **0.35** | **0.52** | **0.48** | **0.47** | ***286*** |
| R1.R2 | 0.61 | 0.17 | 0.56 | 1.09 | 0.85 | 0.59 | 0.39 | 0.70 | 0.62 | 0.52 | *224* |
| R1.IC2 | 0.62 | 0.16 | 0.54 | 1.15 | 0.82 | 0.60 | 0.45 | 0.70 | 0.65 | 0.52 | *221* |
| R1.R2.IC1.R2 | 0.34 | 0.13 | 0.32 | 0.52 | 0.44 | 0.34 | 0.24 | 0.31 | 0.34 | 0.38 | *329* |
| R1.R2.IC1.IC2 | 0.43 | 0.15 | 0.40 | 0.68 | 0.53 | 0.42 | 0.32 | 0.43 | 0.38 | 0.47 | *329* |
| R1.R2.IC2.IC1 | 0.41 | 0.15 | 0.38 | 0.63 | 0.52 | 0.40 | 0.32 | 0.37 | 0.40 | 0.47 | *328* |
| **Merge** | **0.58** | **0.26** | **0.47** | **0.91** | **0.72** | **0.57** | **0.43** | **0.59** | **0.61** | **0.53** | ***455*** |
| R1.R2 | 0.46 | 0.25 | 0.40 | 0.63 | 0.54 | 0.46 | 0.37 | 0.48 | 0.58 | 0.34 | *350* |
| R1.IC2 | 0.77 | 0.16 | 0.52 | 1.52 | 1.02 | 0.76 | 0.53 | 0.83 | 0.76 | 0.74 | *531* |
| R1.R2.IC1.IC2 | 0.50 | 0.19 | 0.44 | 0.77 | 0.61 | 0.49 | 0.38 | 0.48 | 0.51 | 0.51 | *524* |
| R1.IC1.R2.IC2 | 0.57 | 0.43 | 0.52 | 0.73 | 0.70 | 0.56 | 0.44 | 0.53 | 0.61 | 0.55 | *414* |
| **Overtaking** | **0.50** | **0.39** | **0.45** | **0.62** | **0.61** | **0.50** | **0.38** | **0.61** | **0.48** | **0.42** | ***544*** |
| R.IC | 0.25 | 0.09 | 0.21 | 0.36 | 0.30 | 0.26 | 0.19 | 0.25 | 0.21 | 0.27 | *653* |
| R.IC+O | 0.70 | 0.53 | 0.68 | 0.88 | 0.87 | 0.70 | 0.53 | 0.83 | 0.70 | 0.57 | *436* |
| **Single track** | **0.75** | **0.36** | **0.65** | **1.23** | **1.00** | **0.74** | **0.53** | **0.61** | **0.91** | **0.75** | ***777*** |
| R.R(1) | 0.45 | 0.38 | 0.39 | 0.58 | 0.61 | 0.43 | 0.31 | 0.45 | 0.60 | 0.30 | *959* |
| R.R(2) | 1.05 | 0.35 | 0.91 | 1.89 | 1.36 | 1.03 | 0.74 | 0.76 | 1.21 | 1.18 | *594* |
| **Cross-over & Merge** | **0.57** | **0.20** | **0.51** | **0.89** | **0.74** | **0.56** | **0.41** | **0.55** | **0.64** | **0.53** | ***457*** |
| R1.R2 | 0.69 | 0.20 | 0.62 | 1.11 | 0.93 | 0.67 | 0.46 | 0.70 | 0.77 | 0.60 | *378* |
| R1.IC2 | 0.45 | 0.19 | 0.39 | 0.66 | 0.55 | 0.45 | 0.35 | 0.37 | 0.51 | 0.45 | *536* |
| **Merge & Overtaking** | **0.48** | **0.29** | **0.41** | **0.69** | **0.60** | **0.48** | **0.37** | **0.72** | **0.37** | **0.39** | ***448*** |
| R1.IC2 | 0.35 | 0.18 | 0.29 | 0.50 | 0.43 | 0.34 | 0.27 | 0.49 | 0.35 | 0.26 | *531* |
| R1.IC2+O | 0.73 | 0.38 | 0.65 | 1.14 | 0.93 | 0.72 | 0.54 | 1.03 | 0.53 | 0.61 | *313* |
| R1.IC1.R2.IC2 | 0.40 | 0.18 | 0.34 | 0.58 | 0.49 | 0.40 | 0.31 | 0.50 | 0.34 | 0.39 | *524* |
| R1.IC1.R2.IC2+O | 0.42 | 0.35 | 0.38 | 0.53 | 0.52 | 0.43 | 0.32 | 0.70 | 0.24 | 0.31 | *424* |
| **All layouts** | **0.55** | **0.26** | **0.47** | **0.84** | **0.70** | **0.54** | **0.40** | **0.60** | **0.55** | **0.50** | ***453*** |

**Scenarios with zero conflicts are excluded*

***Averaged over all timetables (with different infrastructure occupation rates, running time supplements and sizes of initial delay)*