Benchmark analysis, test and integration of timetable tools

Grant Agreement N°: FP7 – SCP1 – GA – 2011 - 285243

Project Acronym: **ON-TIME**

Project Title: **O**ptimal **N**etworks for **T**rain Integration **M**anagement across **E**urope

Funding scheme: Collaborative Project

Project start: 1 November 2011

Project duration: 3 Years

Work package no.: WP03

Deliverable no.: D3.2

Status/date of document: Final, 30/10/2014

Due date of document: 31/07/2014

Actual submission date: [30/10/2014]

Lead contractor for this document: Delft University of Technology
Delft, The Netherlands

Project website: www.ontime-project.eu

Project co-funded by the European Commission within the Seventh Framework Programme (2007-2013)		
Dissemination Level		
PU	Public	**X**
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

Revision control / involved partners

Following table gives an overview on elaboration and processed changes of the document:

Revision	Date	Name / Company short name	Changes
1	10/07/2014	Goverde / TUDelft	First draft
2	14/08/2014	Nicholson / UoB	Update
3	05/09/2014	Goverde / TUDelft	Update
4	17/10/2014	Sandblad/ UoU	Update
5	17/10/2014	Golightly / UoNott	Update
6	18/10/2014	Goverde / TUDelft	Update
7	24/10/2014	Besinovic / TUDelft	Update
8	25/10/2014	Goverde / TUDelft	Update
9	29/10/2014	Magnus / TV	Section 6.2
10	30/10/2014	Goverde / TU Delft	Update

Following project partners have been involved in the elaboration of this document:

Partner No.	Company short name	Involved experts
6	TV	Magnus Wahlborg
9	UoB	Gemma Nicholson
13	UoNott	David Golightly, David Large
14	TUD	Anne Binder
15	TUDelft	Rob Goverde, Nikola Besinovic
16	UdB	Roberto Roberti
17	UoU	Bengt Sandblad, Peter Hellström

Executive Summary

This document gives the final results of the ON-TIME timetabling approach, with an extensive evaluation of the developed timetabling tools including expert judgment of the developed functionalities, TRL reached, test results of the integrated timetable tools for a complex real-world case study, and a reflection on the achieved contributions to the ON-TIME objectives and innovations.

The timetabling results are evaluated on the KPIs transport volume, journey time, connectivity, resilience, energy consumption and resource usage. The document starts with the objective and general description of the timetabling module (ch. 1), followed by a description of the evaluation procedures (ch. 2) and the evaluation studies performed, including an explanation of the simulation-based quantitative evaluation tool and the considered case study from the Netherlands (ch. 3).

The qualitative evaluation (ch. 4) contains four components. First, it is shown that all KPIs are incorporated in the timetabling approach explicitly. Second, the integration of the timetabling module with the other ON-TIME modules is considered. All modules use a common RailML data exchange format guaranteeing consistency. Furthermore, the timetabling module shares components with other modules from WP5 (disruption management) and WP6 (driver advisory systems). Third, the applicability of the developed performance-based timetabling approach is considered including the step change from TRL 3 to TRL 6. And fourth, the developed timetabling functionalities are positively evaluated in an expert judgment study.

The quantitative evaluation (ch. 5) gives the results from a real-world case study from the Netherlands, with dense heterogeneous traffic and synchronized train services. Several scenarios have been considered including ad-hoc insertion of freight trains into the passenger timetable. Details on the computed timetables and the timetabling process are given, followed by a simulation-based quantitative evaluation using the HERMES simulation tool. The timetables are computed efficiently and outperform the original timetable on most KPIs considered. Journey times are sometimes larger corresponding to the aim of developing robust and energy-efficient timetables. In a simulation study the ON-TIME timetable reduced the average station delays by 0.5 to 3.5 min up to a reduction of 9 min departure delay. Energy consumption can be reduced by 25%-28% using the scheduled energy-efficient speed profiles. Furthermore, the ON-TIME timetables improved connectivity with a decrease of mean transfer time by 2 min at the benchmark connections.

Ch. 6 reflects on the contributions to the project objectives and innovations. In short, the ON-TIME timetabling approach realized the innovation of 'developing improved methods for constructing timetables that are robust to statistical variations in operations and resilient to perturbations', whilst also incorporating customer satisfaction, better capacity consumption and reduced energy consumption. RailML exchange data is used and extended to standardize detailed interoperable timetable information.

Table of contents

Table of figures

Table of abbreviations

Bet	Best (stop in Dutch network)
Btl	Boxtel (station in Dutch network)
Cl	Culemborg (stop in Dutch network)
CN	Connectivity
Ehb	Eindhoven Beukenlaan (stop in Dutch network)
Ehv	Eindhoven (station in Dutch network)
EG	Energy
Gdm	Geldermalsen (station in Dutch network)
Ht	’s-Hertogenbosch (station in Dutch network)
Htda	’s-Hertogenbosch Diezebrug Aansluiting (junction in Dutch network)
Htn	Houten (station in Dutch network)
Htnc	Houten Castellum (station in Dutch network)
Hto	‵s-Hertogenbosch Oost (stop in Dutch network)
JT	Journey Time
Mbrvo	Maasbrug Ravenstein Oostzijde (single-track bridge in Dutch network)
Nm	Nijmegen (station in Dutch network)
Nmd	Nijmegen Dukenburg (stop in Dutch network)
O	Oss (station in Dutch network)
ONT	ONTIME project code on the repository
Ot	Oisterwijk (station in Dutch network)
Ow	Oss West (stop in Dutch network)
PT	Punctuality
Rs	Rosmalen (stop in Dutch network)
RS	Resilience
RU	Resource Usage
Rvs	Ravenstein (stop in Dutch network)
Tb	Tilburg (station in Dutch network)
Tl	Tiel (station in Dutch network)
Tpsw	Tiel Passewaaij (station in Dutch network)
TV	Transport Volume
Ut	Utrecht Centraal (station in Dutch network)
Utl	Utrecht Lunetten (stop in Dutch network)
Vg	Vught (stop in Dutch network)
Vga	Vught Aansluiting (junction in Dutch network)
Wc	Wijchen (stop in Dutch network)
Wnn	Wadenoijen (station in Dutch network)
WP	Work Package
Zbm	Zaltbommel (stop in Dutch network)

1 INTRODUCTION

1.1 Objective of the timetabling module

The overall aim of the ON-TIME project is to improve railway customer satisfaction through increased capacity and decreased delays for passenger and freight. Work Package 3 on 'Development of robust and resilient timetables' is mainly concerned with procedures and algorithms for the annual timetable process and the ad-hoc timetable process producing a multilayer solution for short term (freight) train path requests. The ON-TIME timetabling module aims at contributing to the overall objective by the development of a performance-based timetable design process classified as Timetabling Level 4 in ON-TIME (2013c, 2014) and associated algorithms. This top Timetabling Level is geared towards achieving a stable, feasible, robust and resilient timetable. Moreover, a sustainability dimension of energy-efficiency has been added to enable static driver speed advice for punctual running.

In the ON-TIME Description of Work (ON-TIME, 2011), four objectives were formulated related to the timetabling module:

- Improved management of the flow of traffic through bottlenecks to minimize track occupancy times. This will be addressed through improved timetabling techniques [and real-time traffic management] (Objective 1).
- To reduce overall delays through improved planning techniques that provide robust and resilient timetables capable of coping with normal statistical variations in operations and minor perturbations (Objective 2).
- To better understand, manage and optimize the dependencies between train paths by considering connections, turn-around, passenger transit, shunting, etc. in order to allocate more appropriate recovery allowances, at the locations they are needed, during timetable generation (Objective 7).
- To increase overall transport capacity by demonstrating the benefits of integrating planning and real-time operations, as detailed in Objectives 1-8 (Objective 9).

Overall, the objective of the timetabling module can be summarized as providing high-performance timetables, leading to Innovation 2: The development of improved methods for timetable construction that are robust to statistical variations in operations and resilient to perturbations (ON-TIME, 2011).

To achieve these objectives and this innovation, the WP3 timetabling work package formulated a key objective and several specific objectives to consider (ON-TIME, 2011). They key objective was to reduce overall delays through the use of improved planning techniques to provide timetables that are robust, i.e., capable of coping with normal statistical variations in operations, as well as resilient to minor perturbations. Specific objectives were given as follows:

- Develop common railway timetabling and capacity estimation methods for EU member states that reflect customers' satisfaction and enable interoperability,

more efficient use of capacity, higher punctuality and less energy consumption.
- Further develop methods for robust cross-border timetables and integration of timetables between different regional and national networks improving interoperability and efficient corridor management including standardised approaches for exchanging timetable information between stakeholders.
- Design resilient timetables that can recover or reduce consequences from incidents or disturbances by exploiting feedback of performance data from operations.
- Improve timetable quality, stability, robustness, reliability and effectiveness.
- Validate the developed methods, through benchmarking, using a number of real-world case studies developed in WP2.

This deliverable shows that the objectives have been achieved, using both qualitative and quantitative evaluations.

1.2 General description of the timetabling module

Figure 1 shows the framework of the developed ON-TIME timetabling approach, see D3.1 (ON-TIME, 2014) for a detailed description. The input and output are standardized RailML files. The RailML input data is transformed into an efficient data format that is used internally by the timetabling modules. The timetabling computation is an integrated iterative process on three levels:

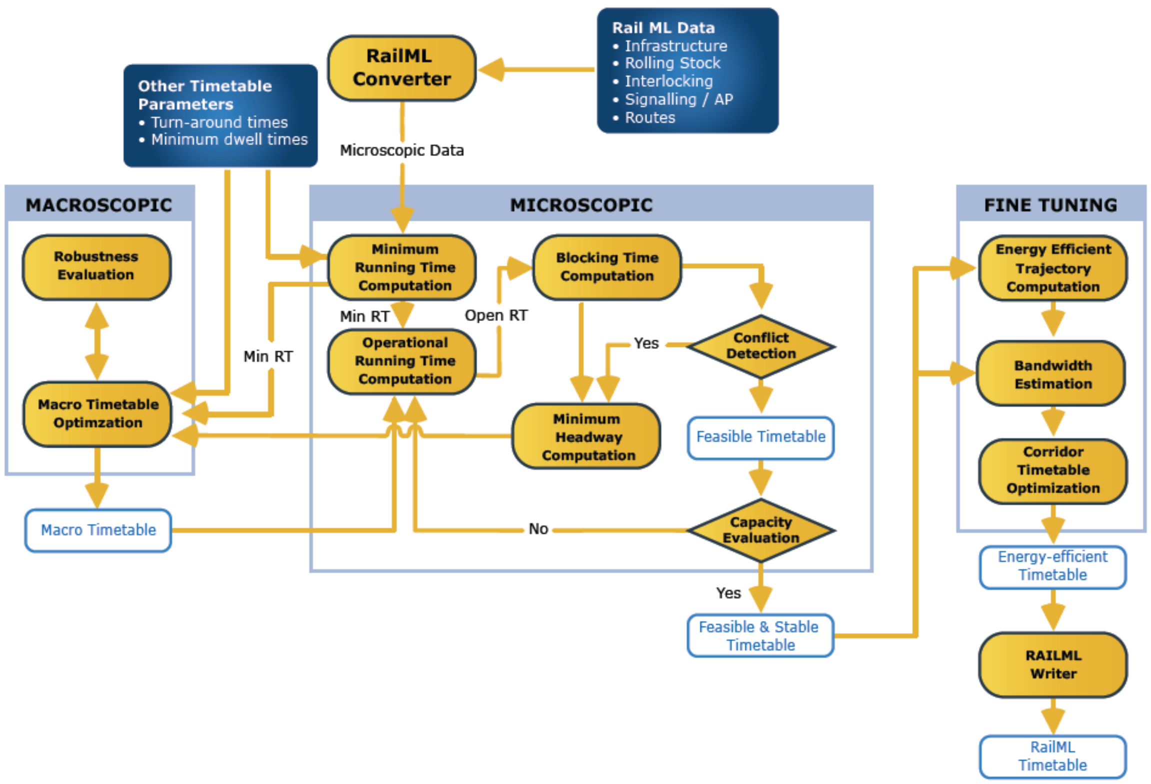

Figure 1. ON-TIME three-level timetabling framework

- A microscopic model for highly detailed local level
- A macroscopic model on aggregated network level
- A fine-tuning model on corridor level.

The input data are standardized RailML files. The microscopic model computes running and blocking times based on detailed realizable operational speed profiles with incorporated running time supplements, and aggregates the results into a macroscopic model that contains only the main macroscopic stations characterized by overtaking opportunities and connections. The macroscopic model then computes a network timetable taking into account network constraints and trying to avoid cancelled train path requests. The macroscopic timetable is transformed back to the microscopic model that fills in the details on microscopic level. These two models work iteratively where the microscopic model is used for conflict detection and evaluating infrastructure occupation and stability, while the macroscopic model optimizes travel times and robustness given the constraints set by the microscopic model. Infrastructure occupation is based on the UIC timetable compression method (UIC, 2013) which also provides norms for acceptable stability. The macroscopic model is an MILP model and includes a simulation model to find the most robust timetable out of several hundred feasible solutions. The overall cost function contains several terms including a robustness cost (average settling time) derived from the simulations. These micro-macro iterations converge to a static traffic plan that is conflict-free, stable and robust.

The third level computes the energy-efficient speed profiles for all trains and optimizes the timetable of short stops on each corridor between main stations while maintaining the scheduled event times at the corridor ends. In this optimization, the stochastic dwell times at the intermediate stops are taken into account and the arrival and departure times at these stops are optimized accordingly. Microscopic models are used for the computation of energy-efficient speed profiles and the bandwidths available for the speed profiles of the local trains within the corridors. A local macroscopic model of each corridor is used to optimize the timetable within the corridor with the associated speed profile. The final result is exported in RailML format extended with the scheduled speed profile information that can be used by the trains for running punctual and energy-efficiently.

This timetabling framework can be used to find optimal cyclic and non-cyclic timetables. Resilience is taken into account with respect to scheduling ad-hoc freight paths. The timetabling algorithms allow inserting additional (freight) train paths whilst sufficient residual capacity must be reserved to guarantee that a stable conflict-free timetable can be found. The freight paths are specified in a multilayer freight path catalogue with various maximum speed paths (e.g. 80/100/120 km/h) on specified corridors. Depending on the maximum speed of a requested freight path, the passenger timetable might have to be adjusted a bit to obtain a conflict-free timetable. This procedure allows a multilayer timetable with a basic passenger timetable and additional freight paths of different speeds to be selected from a catalogue on a first-come-first served basis.

1.3 Document outline

The ON-TIME timetabling approach is evaluated in this document both qualitatively and quantitatively. Chapter 2 explains the evaluation procedure including the qualitative evaluation, the simulation-based quantitative evaluation, the measures used and the evaluation context. Chapter 3 describes the performed evaluation studies, and in particular the Quantitative Evaluation Tool used for the assessment of the simulation results, and the case study and the scenarios applied. Chapter 4 gives the results of the qualitative evaluation, and Chapter 5 provides the quantitative evaluation results. Finally, Chapter 6 gives conclusions about the evaluation results for the timetabling developments, the contributions of the timetabling work package to the ON-TIME project objectives and innovations, and future work.

2 EVALUATION PROCEDURES

2.1 Evaluation methods

2.1.1 Qualitative evaluation

Qualitative evaluation use methods as expert evaluations, observations, interviews, questionnaires etc. The purpose is to evaluate important aspects that cannot be studied using quantitative methods. For the timetabling module the following three important aspects are evaluated:

- **KPI measures**: How well are the KPI measures (see Section 2.2) taken into account by the developed procedures and algorithms?
- **Integration**: How well is the integration with other modules and subsystems of the ON-TIME framework?
- **Applicability**: What is the TRL level and the possibility to apply the algorithms in timetable planning?
- **Expert judgment**: How well do professional timetable planners evaluate the developed procedures and functionalities?

Section 3.1 describes the details of the applied qualitative assessments, while Chapter 4 gives the results.

2.1.2 Quantitative evaluation

The quantitative evaluation uses a set of standard measures to assess the impact of the innovations developed within the ON-TIME project. It results in a set of numerical values that can be used to measure their success against the aims of the project. The ON-TIME key performance indicators (KPIs) were outlined in the Quality of Service (QoS) framework, which was introduced in deliverable D1.2 (ON-TIME, 2012b). Each KPI has one or more key measures, for which numerical values are obtained through the quantitative evaluation process. The QoS framework's KPIs and their key measures are shown in Table 1. Not all of the KPIs are considered within the evaluation of each of the work packages. Depending on the objective of the work package, only the relevant KPIs are evaluated. Section 2.2 lists the KPIs used for the timetabling module (WP3), including their full definitions.

Figure 2 is a schematic of the benchmarking and quantitative evaluation process. The left-hand side of the diagram describes the simulator benchmarking. In this process, the original timetable with baseline scenario (i.e. no service or infrastructure disruptions) is run in the Hermes simulator for the period specified for the given scenario. Inevitably, the simulated reference scenario will show some small differences compared to the timetable. This process allows a comparison between the Hermes simulation and the timetable, in which any differences are quantified. The simulator benchmarking is described in document D2.3 Evaluation and implementation into practice.

Table 1. Key performance indicators and their key measures

KPI	Key measures
TV	Available passenger/cargo tonne km
JT	Average journey time
CN	Average passenger interchange time
PT	Total departure delays of services at departing a station
RS	Time to recover
	Maximum delay
	Delay area
PC	Jerk above EU specified level
EG	Total energy consumption by passenger/freight vehicles
RU	Track usage: number of signal passes per hour
	Rolling stock usage: number of vehicles used during simulation period

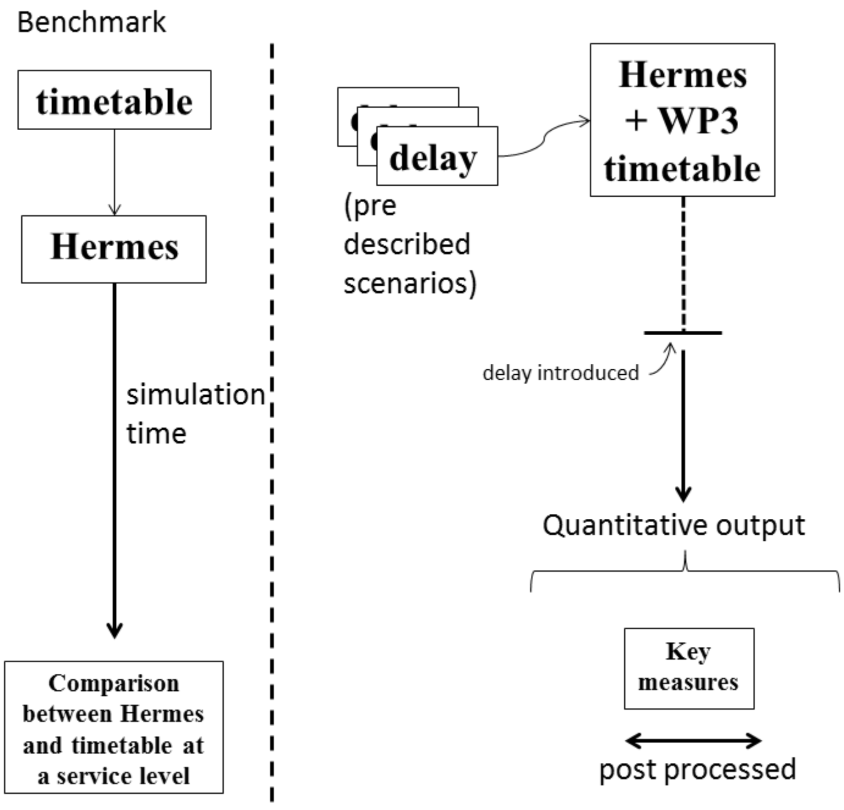

Figure 2. Benchmarking and evaluation in ON-TIME

The benchmarked reference scenario is then taken as the basis against which comparisons are made within the quantitative evaluation process. The quantitative evaluation makes a quantitative comparison between the reference simulation and the following simulations:

- Simulation with no delay using a passenger timetable computed by the WP3 algorithms (*baseline scenario*)
- Simulations with no delay using the timetable computed by the WP3 algorithms and extra freight paths (*freight scenario simulation with new WP3 timetable)*,

as shown on the right-hand side of Figure 2. The extra freight paths may introduce delays. The scenarios for the Dutch network are described in Section Scenarios3.3.3.

The quantitative evaluation is carried out using a Matlab-based tool developed for the project, see Figure 3. Hermes can be configured to produce an observation log file that reports the traffic events that took place in the simulation. The quantitative evaluation requires observation log files from the baseline scenarios and delay scenarios with WP3 timetable simulations as inputs. Together with certain additional information specific to the scenario, the Matlab tool processes the simulation data to produce numerical values for the key measures, which are the outputs of the process. The quantitative evaluation tool is described further in Section 3.2.

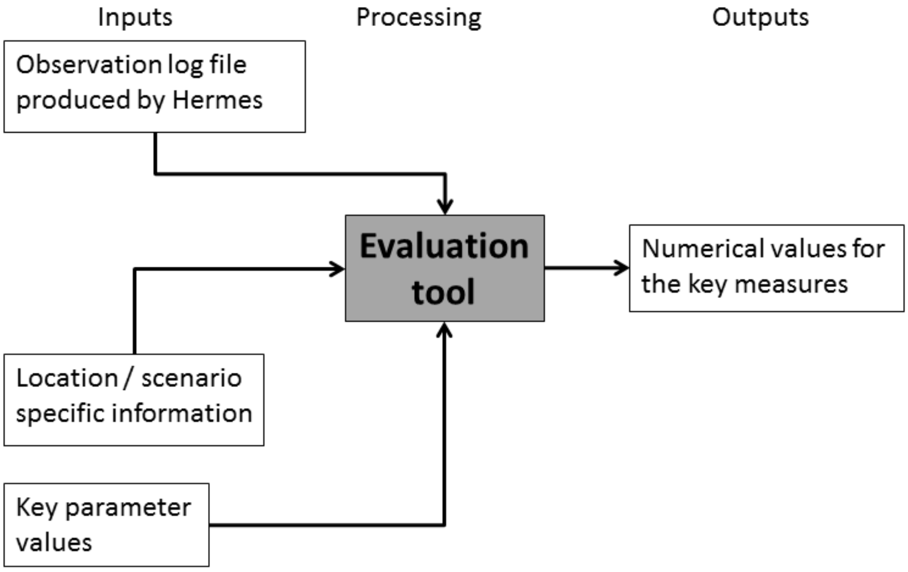

Figure 3. Schematic of input and output of Matlab quantitative evaluation tool

2.2 Measures used

The key performance indicators relevant to WP 3 are transport volume, journey time, connectivity, resilience, energy consumption and resource usage. Their definitions are given in the subsections below. The measures are evaluated for a set of selected conditions depending on the scenario location. For example, a set of origin-destination pairs are selected between which the journey time is evaluated. A list of the key measure parameters for the Dutch network is given in Section 3.4. The key measures are measured for the whole time period T given in the scenario definition.

2.2.1 Transport Volume (TV)

The key measures of transport volume are *total available passenger km* and *total available cargo tonne km*. For a selected origin-destination pair (O-D pair), they measure the total number of passenger seat km and freight tonne km travelled between O and D in time period T (no connection is allowed between O and D), where for each service stopping at O and D,

- passenger seat km = no. of km travelled x no. of seats available on the service
- freight tonne km = no. of km travelled x freight train cargo capacity in tonnes.

The measure is the sum of passenger / freight tonne km travelled by all services departing from O in time period T, considering only complete journeys that both depart O and arrive at D during T.

2.2.2 Journey Time (JT)

For a given O-D pair, the key measure of journey time is the *average journey time* [seconds] of all journeys that make scheduled stops at O and D, in that order, during the simulation time T. No transfer is allowed for a journey to be considered.

2.2.3 Connectivity (CN)

At a given interchange station I, for a service arriving at I from origin O, measure the interchange time to the first service departing for D, as long as the arrival at D also occurs during T and the interchange time is above a specified minimum. The interchange time is the time between arriving at I on a service from O and departing on a service travelling towards D. The *average interchange time* of all interchanges at I for journeys that both depart from O and arrive at D during the simulation time T is given as the key measure of connectivity.

2.2.4 Resilience (RS)

The three measures of the resilience KPI are based on the delay of the system measure shown in the resilience analysis plot, see Figure 4. They are the *maximum deviation* during time period T [s], the *time to recover* [s], and the *delay area* [s^2].

In order to measure the delay of the system, consider all M journeys that run in the simulation area over the simulation time period T, and record the time t_{ij} at which train service i is observed at its jth observation point. An observation point is either a station or a signal, and an observation consists of either a station arrival, a station departure, or a signal passage. For all services, record the deviation L_{ij} of train i at its jth observation point. This is calculated as the time in seconds between the actual time and the time recorded during the simulation of the reference scenario t^s_{ij}, that is, $L_{ij} = t_{ij} - t^s_{ij}$.

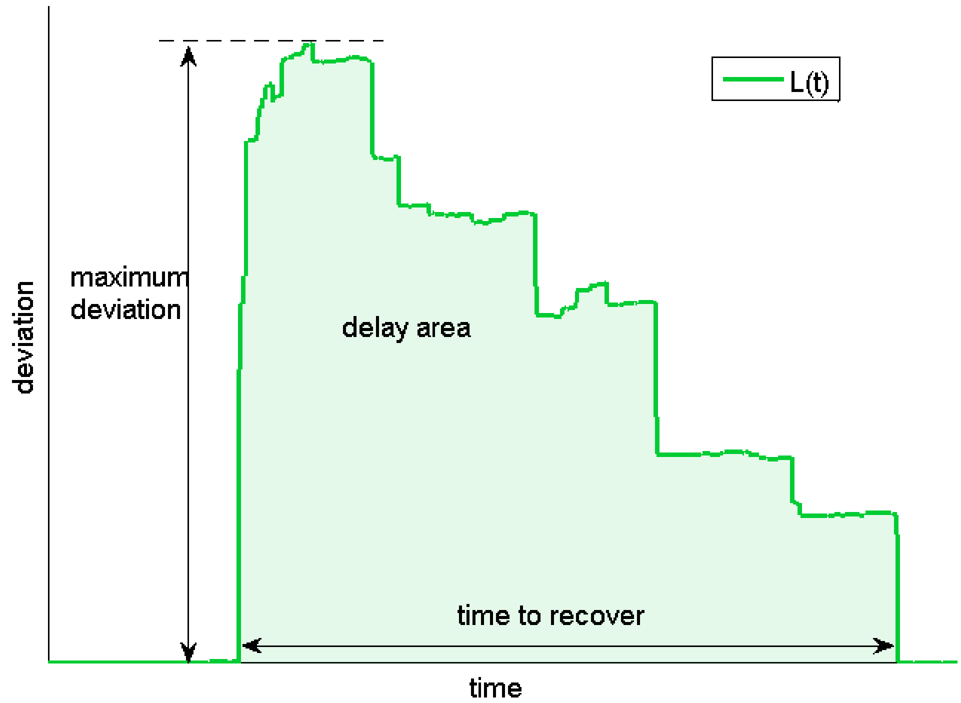

Figure 4. The resilience KPI's key measures

This results in a discrete set of observations of the system. Define a continuous (step) function for each train service, representing the most recent delay recorded by that journey. At the time the k^{th} observation point is passed until the $k+1^{th}$ observation point is reached, the current delay $L^c_i(t)$ is the most recent deviation value recorded. Thus $L^c_i(t) = L_{ik}$ for t such that $t_{ik} \leq t < t_{i,k+1}$.

Then at any time t, the delay of the system is defined for all M trains in the simulation as

$$L(t) = \sum_{i=1}^{M} L_i^c(t).$$

The *time to recover* is defined as the time between the delay of the system increasing above a small threshold value, called the *recovery threshold*, and the return below this threshold. The *maximum deviation* P is the maximum value of the delay of the system,

$$P = \max_t L(t).$$

The *delay area* D is given by the area under the curve L(t) of delay of the system. In practice this may be calculated by placing all *N* observation times t_{ij} in chronological order and redefining them as $[t_1, t_2, \ldots, t_N]$. Then the delay area is:

$$D = \sum_{s=1}^{N-1} (t_{s+1} - t_s) \cdot \frac{(L(t_{s+1}) + L(t_s))}{2}.$$

2.2.5 Energy Consumption (EG)

For a given O-D pair, the *total energy consumed* by all services that both depart from O and arrive at D during time period T is measured for the energy consumption KPI.

2.2.6 Resource Usage (RU)

Resource usage is partitioned in two measures:

- T*rack usage (*RU1*)*: *the average number of trains passing a point per hour* during time period T, where the selected point(s) are signals.
- *Rolling stock (*RU2*)*: *the total number of vehicles in use* during time period T.

2.3 Evaluation context

The quantitative evaluations are done on a case study of the Dutch network. Based on input RailML data of this case study the WP3 timetabling algorithms compute a detailed timetable including running time calculations, network timetable optimization, conflict detection, and consideration of stability, robustness and energy consumption. The results are returned in a RailML Timetable that is imported into HERMES for simulation. The output of HERMES is evaluated using the Quantitative Evaluation Tool.

The evaluation will demonstrate the following:

- Feasibility of a Level 3 timetabling design process, including explicit consideration of conflict detection, UIC 406 infrastructure occupation and stability, and robustness, as well as energy efficiency.
- Feasibility of the WP3 calculations to generate a new timetable for a complex real-life railway network
- Feasibility of a multilayer timetable with the possibility to add freight trains from a multi-speed freight path catalogue, i.e., resilience to ad-hoc freight train requests according to Timetabling Level 4.

3 PERFORMED EVALUATION STUDIES

3.1 Qualitative assessments

The qualitative evaluation consists of four assessments, see Section 2.1.1. The first three assessments cover the technical aspects of KPI measures, integration and applicability, which are assessed by the WP leader with reference to the ON-TIME reports delivered, and in particular the State-of-the-Art document (ON-TIME, 2013a), the Functional Design document (ON-TIME, 2013c), and the Methods and Algorithms Deliverable D3.1 (ON-TIME, 2014). The fourth assessment is the expert judgment. This is done in Sweden and the UK, based on the Integration of Timetabling and Traffic Control document (ON-TIME, 2013b) and additional interviews with stakeholders (timetable planners) at Network Rail. The results of the qualitative assessments are given in Chapter 4.

3.2 Quantitative Evaluation Tool

The quantitative evaluation tool is written in Matlab and works on a post processing basis. It takes as input observation log files produced by Hermes (see Section 2.1.2), and some additional tabulated information required for the computation of certain of the key measures. The observation log file is in comma separated variable format and contains the following fields that are used for the quantitative evaluation

- Observation type (station arrival/station departure/signal passage)
- Train ID
- Station or signal arrived at/departed from/passed
- Time
- Train's first stop station name
- Train's last stop station name
- Unique service ID
- Cumulative energy consumption.

Each time a train either arrives at or departs from a station or passes a signal, a line containing the above fields is written to the observation log. Hermes must be configured to output log files, and given a list of stations and signals at which to produce an observation in the log file. The default used throughout this work is that observations are taken at every station and signal within the simulated network area.

Two tables containing the following are loaded to Matlab and used in the processing:

- A table containing details for all the rolling stock configured for each network, consisting of the train class, type (passenger or freight), number of carriages and seats, or freight tonne capacity,
- A table listing all the stations within the network and to which line they belong, as well as the distances between stations.

The majority of the key measures require configuration to select the stations, signals and journeys at which they are quantified, as follows.

- Transport volume, Journey time, Energy consumption: origin-destination pairs
- Connectivity: two leg journey (origin – connecting station – destination)
- Resource usage (track usage): selected signals.

The key measure parameters for the Dutch network are given in Section 3.4. This information is an input to the quantitative evaluation tool.

The output from the evaluation tool is given by numerical values for each of the key measures for the reference timetable and the new timetables for baseline and delay scenarios. Each KPI is represented in three ways: stored within the Matlab structure KPI, report output in the Matlab console screen, and graphical. The results of the quantitative evaluation are given in Chapter 5.

3.3 Dutch case study

For the quantitative evaluation, the ON-TIME timetabling module is applied to a Dutch case study consisting of a central part of the railway network in the Netherlands. It consists of the railway network bounded by the four main stations Utrecht (Ut) in the North, Eindhoven (Ehv) in the South, Tilburg (Tb) in the West, and Nijmegen (Nm) in the East, with a fifth main station 's-Hertogenbosch (Ht) in the middle and 20 additional smaller stations and stops, see Figure 6. Four corridors connect Ht to the other main stations.

The case study considers the timetable for a workday in 2011 between 7:00 AM and 9:00 AM. There are 36 running trains per hour from eight train lines in both directions, plus ad-hoc freight trains.

3.3.1 Infrastructure

Figure 5 shows a macroscopic view of the infrastructure. On the north side of Ht, there is a double-track bridge with one track for each direction. All trains to/from both Ut and Nm traverse this bridge. At the North site of the bridge, a junction splits the double-track into two double-track lines to/from Ut and Nm, respectively. This junction is referred to as the 's-Hertogenbosch Diezebrug Aansluiting (Htda). On the South side of Ht, a junction splits a triple-track line into two double-track lines to/from Tb and Ehv. This junction is referred to as Vught Aansluiting (Vga). On the corridor to the East between Oss (O) and Nm, there is a single-track bridge (Mbrvo) that is used in two directions. Finally, at the south of station Gdm on the line Ht-Ut there is a branch line with a single-track between Wadenoijen (Wnn) and Tiel (Tl) which contains the stop Tiel Passewaaij (Tpsw).

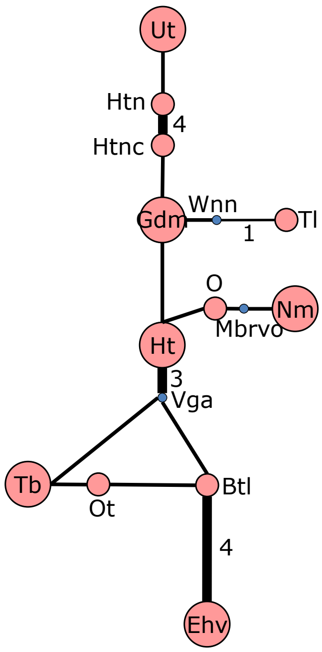

Figure 5. Schematic macro infrastructure layout Dutch case study

The bridge on the north side of Ht is currently one of the bottlenecks in the network. In 2104, the bridge will be replaced by a new one with 4 tracks and a fly-over. This will reduce the number of conflicts between trains running between Ht and Nm/Ut and allow for a timetable that is more robust. In ON-TIME we used the infrastructure situation from 2012.

3.3.2 Line plan

The train line plan in this part of the network is taken from the 2011 timetable. It contains the following ten passenger train lines in both directions, see Figure 6:

1) Intercities
    a. Line 800: Ut – Ht – Ehv, twice per hour
    b. Line 3500: Ut – Ht – Ehv, twice per hour
    c. Line 3600: Nm – Ht – Tb, twice per hour
    d. Line 1900: Tb – Ehv, twice per hour
2) Regional trains
    a. Line 6000: Ut – Gdm – Tl, twice per hour
    b. Line 16000: Ut - Ht, twice per hour
    c. Line 13600: Ht – Tb, twice per hour
    d. Line 4400: Nm – Ht, twice per hour
    e. Line 9600: Ht – Ehv, twice per hour
    f. Line 5200: Tb – Ehv, twice per hour

The intercity lines 800 and 3500 offer a regular 15 min service between Ut and Ehv but have different origin/destinations outside this area. The regional line 13600 from

Tb to Ht continues as the line 16000 from Ht to Ut, and vice versa. The line 9600 from Ehv couples in Ht to the line 4400 to Nm, and vice versa.

Considering both directions the network thus contains 40 running passenger trains per hour.

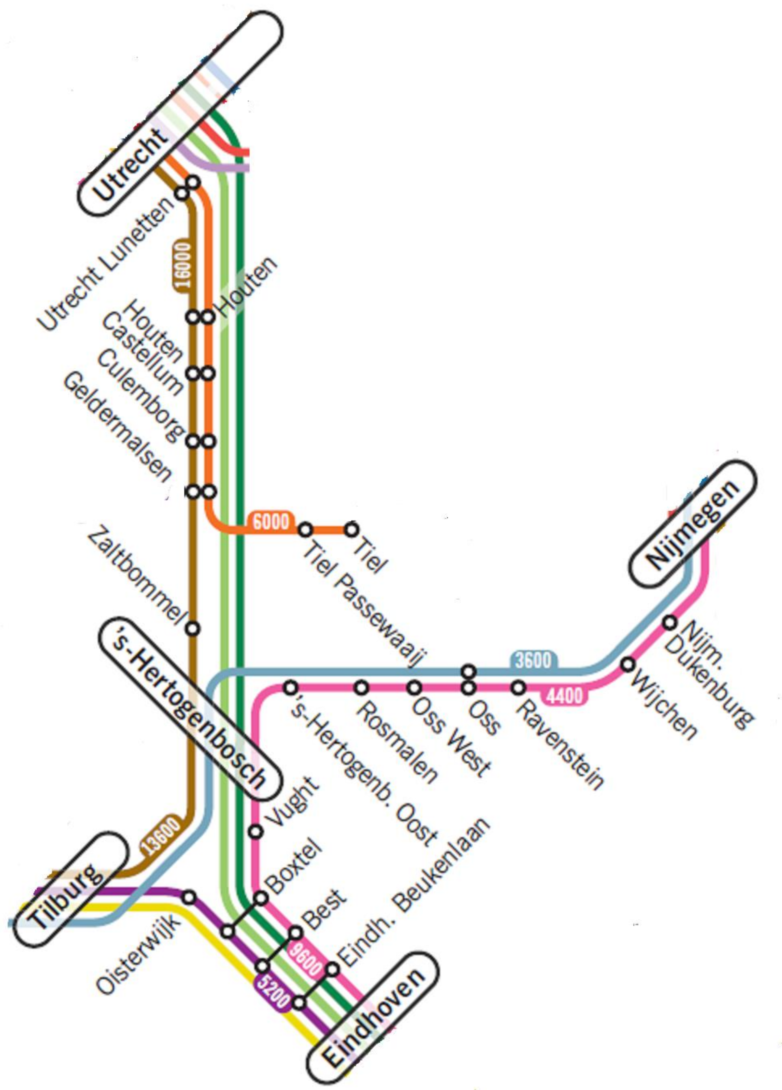

Figure 6. Passenger line plan of the Dutch scenarios

Next to the passenger trains also freight trains use this network. In the Netherlands, basic freight paths are scheduled in the basic hour patterns, which can be requested by freight operators in the ad-hoc timetabling phase. In the considered network the main freight paths (on international corridors) are:

- Utrecht – 's-Hertogenbosch – Eindhoven (and further at both ends)
- Utrecht – Geldermalsen – Meteren – Betuweroute (and further on both ends)
- Tilburg – 's-Hertogenbosch – Nijmegen (and further on both ends)
- Tilburg – Eindhoven (and further on both ends).

According to the Dutch Network Statement (ProRail, 2014), "ProRail, following consultation with the freight transport operators, defines standard paths for various route sections based on an insertion speed of 95 km/h and an average acceleration and deceleration on the basis of BR189 with 2700 tons (E-traction paths)."

3.3.3 Scenarios

Four scenarios are considered:

- Scenario 0 (Reference scenario)
  - Simulation day and time: Workday in 2011, 7:00-9:00 AM.
  - All passenger trains run according to the original timetable from 2011.
  - No freight trains, no infrastructure problems and no perturbations.
- Scenario 1 (Baseline without freight trains)
  - Simulation day and time: Workday in 2011, 7:00-9:00 AM.
  - All passenger trains run according to the new timetable computed by the ON-TIME WP3 algorithms.
  - No freight trains, no infrastructure problems and no perturbations.
- Scenario 2 (Insertion fast freight train)
  - Simulation day and time: Workday in 2011, 7:00-9:00 AM.
  - One freight train Ut-Ehv inserted from the freight path catalogue with maximum speed 120 km/h.
  - All passenger trains run according to the new timetable computed by the ON-TIME WP3 algorithms.
  - No infrastructure problems and no perturbations.
- Scenario 3 (Insertion slow freight train)
  - Simulation day and time: Workday in 2011, 7:00-9:00 AM.
  - One freight train Ut-Ehv inserted from the freight path catalogue with maximum speed 80 km/h.
  - All passenger trains run according to an adapted conflict-free timetable computed by the ON-TIME WP3 algorithms.
  - No infrastructure problems and no perturbations.

3.4 Key measure parameters

The key measures are functions of the simulation parameters, that is, the origin-destination pairs for transport volume, journey time, energy consumption and connectivity, and signals for resource usage. In addition, the connecting station and the minimum allowable connection time for connectivity, and the recovery threshold for resilience must be specified. The parameters for which the quantitative evaluation will be conducted for the WP3 scenarios are provided in the following tables.

Table 2. Parameters for Transport Volume and Journey Time

No.	Origin	Destination
1	Eindhoven	Utrecht Centraal
2	Utrecht Centraal	Eindhoven
3	Nijmegen	's-Hertogenbosch

Table 3. Parameters for Connectivity

Origin	Destination	Transfer station	Minimum transfer time
Utrecht Centraal	Tilburg	's-Hertogenbosch	120 s

Table 4. Parameters for Punctuality

No.	Station in Dutch network
1	Utrecht Centraal
2	's-Hertogenbosch
3	Eindhoven
4	Tilburg
5	Nijmegen

Table 5. Parameter for Resilience

Recovery threshold	60 s

Table 6. Parameters for Resource Usage (Track Usage)

No.	Measure points in Dutch network
1	Signal 528 from Oss West to 's-Hertogenbosch Oost (westbound)
2	Signal 743 from Zaltbommel to 's-Hertogenbosch (southbound)
3	Signal 752 from 's-Hertogenbosch to Zaltbommel (northbound)
4	Signal 711 from Tilburg to Vught Aansluiting (eastbound)

4 QUALITATIVE EVALUATION

4.1 KPI measures

This section gives an assessment on how well the KPI measures (see Section 2.2) are taken into account by the developed procedures and algorithms. This qualitative evaluation is based on an assessment of Deliverable D3.1 that explains the developed timetabling methods and algorithms (ON-TIME, 2014), and additional information from the Functional Design document (ON-TIME, 2013c).

All KPI measures defined in Section 2.2 are explicitly incorporated in the ON-TIME timetabling approach, although the optimization has to deal with trade-offs between the different measures, such as resilience versus minimizing journey times. The outcome of the timetabling process is therefore an optimal balance between the different KPIs. The assessment for each of the relevant KPI measures follows below.

4.1.1 Transport Volume (TV)

The aim of the timetabling module is to schedule all train path requests and therefore to maximize the delivered passenger kilometres over a given time window. Moreover, the improved performance of the timetable in terms of journey times, transfer times and reliability (feasibility and robustness) will lead to a more attractive railway transport that will attract more passengers. This latter is not investigated explicitly in this project.

The timetabling approach takes into account a multi-speed freight path catalogue with the aim to maximize the delivered cargo tonne over a given time window. The catalogue reserves residual capacity for freight according to a realistic amount of freight path requests per time window that may differ from country to country. The innovative multi-speed approach enables fast freight trains to be scheduled easily between the (periodic) passenger trains on a first-come first-served basis, while slow freight trains may lead to small adjustments of passenger trains or a reduced robustness when they are running. In countries with a major share of freight the fast freight paths may enable more freight trains than when they have to fit in slow freight paths. The multi-layer freight path catalogue concept offers a realistic supply of freight paths, while avoiding the scheduling of excessive space to freight paths at the cost of passenger trains, so that overall the combined passenger kilometres and cargo tonne over a given time window is maximized.

4.1.2 Journey Time (JT)

In the microscopic model the running and dwell times are minimised to a certain extent considering that slightly extended process times allow a more robust timetable, and therefore more reliable journey times. First, the microscopic model computes realizable minimum running times based on the infrastructure and rolling stock characteristics. In practice, these characteristics are not fixed but vary for each individual train, e.g., train mass, train length, and wind speed, but also technical parameters such as resistance coefficients and driver behaviour are stochastic, see Besinovic et al. (2013). Therefore, a running time supplement must be taken into account on top of the computed minimum running time. In the microscopic model we added a default minimum of 5% running time supplement, although this percentage is an input parameter that could be different depending on e.g. train type or maximum speed, as discussed in ON-TIME (2013c, Section 3.7). The sum of minimum running time and running time supplement is the nominal running time that is used in all further calculations as the minimal running time to be scheduled. In addition, feasible speed profiles are calculated incorporating the running time supplements to obtain all nominal running times between microscopic points such as signals which are required for blocking time calculations.

The dwell times provided by the microscopic model are just input values depending on rolling stock and station type, but any other calculations could be used, see ON-TIME (2013c). These dwell times are considered as minimum dwell times in the macroscopic and fine-tuning model.

The macroscopic model takes the nominal running times and dwell times as input and computes a feasible solution to the macroscopic timetable constraints optimizing a multi-objective function, which includes a penalty for each time unit exceeding the nominal running times and likewise for the nominal dwell times. The journey times in the final solution may however be larger than the feasible minimal ones, since the optimization must find a balance between minimizing running and dwell times, minimizing transfer times, scheduling all requested train paths, minimizing deviations from the ideal regular interval times (periodicity), and robustness. Hence, within the constraints requested from the IMs the train paths are scheduled with a trade-off between minimal and robust journey times. A parameter sets the maximum running time supplement in percentage of the nominal running times, and another parameter sets a maximum to the total journey time of a train from origin to destination (within the considered area). These parameters thus give additional upper bounds to the total journey times to be scheduled, possibly at the cost of the other cost terms (like periodicity, minimal transfer times, and robustness).

Dwell times are considered in the macroscopic model only at larger stations where synchronization times may be added to the minimum dwell times to enable connections or respect conflicting routes. So the dwell time will be minimized with respect to the other timetabling constraints, and possibly have some additional time to take into account robustness.

The fine-tuning model may reschedule the dwell times at the small stations and short stops at the open track for local trains on corridors between the main (macroscopic) stations to allow more energy-efficient speed profiles for the local trains. This may affect the running times between stops and the dwell times at the stops, and thus also the journey time to the short stops (either positively or negatively) but the journey time over the entire corridor remains unaffected.

4.1.3 Connectivity (CN)

The interchange times between selected services are one of the cost terms to be minimized in the macroscopic timetable optimization model. So the macroscopic model aims at minimizing these transfer times collectively, given the timetable constraints and depending on the other cost terms, as explained for the journey times. The trade-off between the multi objectives can be influenced by choosing different values of the penalties for each cost category. In addition, a maximum transfer time can be defined per connection.

Tight interchange times may lead easily to delay propagation which is evaluated in the macroscopic robustness analysis and reflected in the robustness costs of a timetable solution. Hence, tight transfer times may be penalized leading to a trade-off between small and robust transfer times. In the end this causes less missed connections and thus better overall passenger travel times.

4.1.4 Resilience (RS)

In the timetabling module the operational resilience to minimize delays is incorporated using the concepts of timetable feasibility, timetable stability and timetable robustness. First, the timetabling module will deliver a conflict-free timetable so that if all trains adhere to their schedule then no delays will occur. This includes freight paths for which periodic passenger trains may have been adjusted at critical points to get a conflict-free overall schedule, depending on the maximum speed of the freight trains. Thus the timetabling procedure is also resilient to inserting freight paths from a multi-layer freight path catalogue.

Second, timetable stability is achieved by adding a minimal amount of running time supplement to all computed minimum running times and requiring a minimum total buffer time in each corridor as complement of the infrastructure occupation. These time allowances are inserted and checked at the microscopic level to guarantee that delay propagation stays within acceptable bounds and will settle even without traffic management. For the running time supplements we chose a minimum of 5% everywhere but other options are also possible. The infrastructure capacity (buffer time) reserved for stability follows the UIC guideline, but again other options are possible depending on the experience of specific railways.

Third, timetable robustness is achieved by the actual allocation of running time supplements to train paths and of buffer times between train paths so that delays settle as fast as possible. This is part of the macroscopic level where a delay propagation model is used to compute the settling time for random delays to all trains using Monte Carlo simulation for a large number of delay instances. The implemented algorithm takes 1000 random delay instances per timetable and computes a robustness cost as the mean settling time for each feasible timetable. These robustness costs are added to the objective function of the macroscopic optimization model where it is weighted amongst the other cost terms such as journey times.

Timetable resilience with respect to real-time traffic management has not been explicitly incorporated because of the unpredictability of current largely manual traffic management, but the established conflict-free, stable and robust timetable design will have a positive effect on traffic controllability. This could be tested by simulating real-time traffic management in a case study for both the original timetable and the optimized timetable using the WP3 algorithms.

4.1.5 Energy (EG)

The fine-tuning model computes energy-efficient speed profiles to all trains in two stages while keeping fixed the arrival and departure times optimized in the macroscopic level. The fine-tuning model is applied to the corridors between the macroscopic nodes. In a first step it computes the energy-efficient speed profiles for the intercity trains given the running time supplement resulting from the iterative microscopic/macroscopic level. From the resulting train trajectory of the intercity trains bandwidths are computed for the local trains. Then in the second step the fine-tuning model optimizes the energy-efficient speed profiles of the local trains taking into account the available bandwidths and stochastic dwell time distributions of all intermediate stops. In this step the arrival and departure times of the intermediate stations on the corridor can be shifted to redistribute the running time supplements of the local trains optimally over the corridor to minimize total energy consumption on the corridors.

4.1.6 Resource Usage (RU)

The microscopic model computes the infrastructure occupation using the timetable compression method for each corridor and station. This infrastructure occupation is minimized until it is below an acceptable threshold value depending on circumstances. In this work the UIC Capacity leaflet guidelines are used, but any other norms may be used as well. If the infrastructure occupation exceeds the norm then the timetable solution is not accepted but a new iteration is started with relaxed running time bounds for the critical sections. Solutions below the threshold values are not further considered. The main aim is to schedule all requested train paths. If infrastructure occupation is too high at some corridors then also trains may be cancelled in the macroscopic level, but this is not accepted – assuming that a realistic amount of train paths are requested. So rather than cancelling trains, the trains will be reordered, rerouted, or homogenized to fit the norms. Note that a minimal infrastructure occupation is obtained by homogeneous traffic, but the trade-off with journey times will prevent a too slow speed for intercity and long-distance trains. The timetable is computed with a precision of 5 seconds rather than the customary full minutes to avoid capacity waste.

The timetabling module is based on given train path requests by the RUs, and as such rolling stock circulations are not taken into account. It is assumed that the requested frequencies of the train services fit the traffic demand with an appropriate allocation of rolling stock.

4.2 Integration in the ON-TIME framework

The ON-TIME timetable module is the first step of the ON-TIME framework to achieve increased capacity and decreased delays for passenger and freight. A robust conflict-free timetable as delivered by the ON-TIME timetabling algorithms means less effort for traffic management to monitor and control the train traffic. The timetable properties guarantee conflict-free train runs as long as the trains adhere to their schedule within the allowances of the buffer times between the train paths, the train path envelopes. Hence, structural delays and resulting knock-on delays in dense traffic areas are prevented. Moreover the timetable stability property guarantees that delays will settle by simple retiming of the arrival and departure times. More advanced traffic management measures can be used to settle delays quicker, which is the task of the real-time traffic management modules of WP4, possibly in combination with the driver advice systems of WP6.

In the ON-TIME architecture the timetable module has a moderate role at the beginning of a simulation study only. The timetable module imports the infrastructure, rolling stock, interlocking, and old timetable data from the architecture using the RailML data exchange format. It then computes a new timetable and returns it in timetable RailML format, which is processed by the architecture into the HERMES simulation tool. The WP4 traffic management system then uses this new timetable to compute the initial real-time traffic plan.

Several algorithms within the timetable module are also used in other modules. In particular, the WP5 disruption management module is also based on an iterative micro-macro approach where the microscopic model developed in WP3 is used as well. The WP3 microscopic model is used in the WP5 disruption management module to compute all running times, blocking times and minimum headway times in the disrupted area. Moreover, the micro-macro transformations from WP3 are also applied in WP5 to iterate between the microscopic and macroscopic models, and to set up the macroscopic model. The WP5 macroscopic timetabling model and solution algorithm are however different with a focus on rescheduling. The WP3 and WP5 modules are thus consistent in the microscopic calculations.

The timetable module also shares the algorithm developed in WP6 for computing energy-efficient speed profiles, which is also used in WP4. This algorithm is used in three ways within the fine-tuning model for each corridor, using the timetable RailML as interface. First, the microscopic timetable obtained from the micro-macro iterations is converted into timetable RailML and imported by the WP4/6 algorithm, together with the infrastructure and rolling stock RailML data, to compute the energy-efficient speed profiles for the intercity trains corresponding to the scheduled running times (and thus fixed running time supplements). The resulting speed profiles are returned to the microscopic model which computes the bandwidths available for the local trains on each corridor considered in the fine-tuning. The fine-tuning model then takes this as input and calls the WP4/6 algorithm again to compute the optimal energy consumption for the local trains on each subsection between the intermediate stops within the corridor for varying running time supplements that fit within the bandwidths. These values are used to set up the dynamic programming problem that computes the optimal arrival and departure times at the intermediate stops (and thus the running time supplements per subsection). Finally, the WP6 algorithm is called again with the now locally optimized timetable in RailML to compute the corresponding energy-efficient speed profiles, which is added as an extension to the timetable RailML. The scheduled energy-efficient speed profiles are thus consistent with those computed in WP6 for the Driver Advisory System. Hence, when a train drives on time it can just use the scheduled energy-efficient speed profile and does not need the DAS. Only in case of delays or conflicts the traffic management module will change the real-time traffic plan and a new energy-efficient speed profile has to be computed for the DAS.

4.3 Applicability of the ON-TIME timetabling approach

The applicability of the ON-TIME performance-based timetabling approach can be expressed in terms of Technology Readiness Level. At the beginning of the project the existing TRL for timetable construction was assessed at TRL 3 (Analytical and experimental critical function and/or characteristic proof of concept), while the ON-TIME project was expected to realize a step change to TRL 6 (System/subsystem simulation or prototype demonstration in a railway environment), see ON-TIME (2011). This step change from TRL 3 to TRL 6 corresponds to technology development. This section verifies that the ON-TIME project has indeed realized a step change from TRL 3 to TRL 6 for Improved methods for timetable construction (Innovation 2).

The state-of-the-art of performance-based railway timetabling before the ON-TIME project is assessed at TRL 3. The scientific literature on railway timetabling mainly considered macroscopic optimization models without concern about how to the get accurate input parameters to set up the macroscopic model, while on the other hand, the railway operations literature described microscopic methods for e.g. running time, blocking time and conflict detection calculations (ON-TIME, 2013a). The timetabling practice shows a similar separation, with either macroscopic models to compute network timetables using normative input, or microscopic blocking-time based tools for detailed planning on corridors and stations but without support for network optimization (ON-TIME, 2013ab). Moreover, timetable evaluation on feasibility, stability or robustness is typically applied – if at all – after the timetable construction using simulation tools with unclear procedures how the results are used to improve the timetable design (ON-TIME, 2013ab). The state of affairs at the start of the ON-TIME project is therefore assessed at TRL 3.

The ON-TIME timetable module is based on algorithms from literature which were extended, implemented, and integrated into a timetabling architecture that computes a high-quality timetable using an appropriate internal data structure. In particular, three timetabling levels were defined and integrated in an overall timetabling framework combining microscopic timetabling, macroscopic timetabling, and timetable performance evaluation. This three-level framework explicitly incorporates timetable performance requirements into the timetable computation to achieve stable robust conflict-free timetables with energy-efficient speed profiles. The main railway timetable is computed iteratively between the first two levels of microscopic and macroscopic timetabling. The microscopic level consists of a set of algorithms that computes all nominal running times with minimal running time supplements and corresponding speed profiles at track section level, checks on conflict-free train paths, and evaluates stability using the UIC timetable compression method. The macroscopic level computes a network timetable aiming at optimizing a weighted sum of journey times, transfer times, and robustness, with the latter computed as average settling time in a Monte Carlo simulation of delay propagation for random delays of all trains. Additional constraints and objectives in the macroscopic model are regular intervals for periodic (passenger) trains and minimizing cancelled train path requests. The iterations converge after a conflict-free timetable has been found that satisfies the UIC stability norms. Then in the third level the energy-efficient speed profiles are computed, including optimization of the intermediate stops in corridors with respect to stochastic distributions of the dwell times and the energy consumption of the train runs between the stops. The models of each level have been implemented using an internal data structure and the interaction of the models was implemented with transformations between microscopic and macroscopic network models in both directions to guarantee consistency between the various models. All transformations are taken care of at the microscopic level. This component validation in a laboratory environment led to TRL 4.

TRL 5 was realized by connecting the timetabling models to real railway data using the RailML exchange format. The RailML data formats for infrastructure, rolling stock, and timetable were extended to include the microscopic level of detail required within the ON-TIME project. Moreover, an interlocking RailML format was developed to describe the signalling constraints for the individual trains and their interaction, including characteristic behaviour of automatic train protection and fixed-block systems required for computing blocking times, conflict detection and timetable compression. Conversion algorithms were developed to convert the RailML data into the internal timetabling data structure and the other way around. The functional requirements for the timetable module were translated into contents requirements and extensions to the RailML data format. The internal data structure was further adapted to fit the input data structure from the RailML data. The overall architecture of this timetable module based on RailML input was tested and validated using RailML data of a real-world railway case study from the Netherlands railway network. This component validation in a railway environment led to TRL 5.

TRL 6 was realized by connecting the timetable module via the RailML interface to the ON-TIME architecture (WP7) and the Hermes railway simulation environment. For this an API was developed that takes an extended timetable RailML delivered by the timetable module and replaces the old timetable with the new one. The timetable RailML was extended with the attribute switchingPointsForRunningSection in the trainPart element to provide scheduled speed profile information over the successive track sections partitioned by switching points. The speed profile information is given for each track between two successive track positions with the regime, the starting speed, and the starting tractive or braking effort, with the target speed at the next switchingPoint. The regimes can be FullPower, MaxSpeed (cruising speed), Coast, Brake, and Stop.

This scheduled speed profile information is required for the simulation to know how the running time supplement was allocated to the train route in the timetable construction. Without this information, Hermes aims at running all trains at the maximum speed everywhere, unless the DAS from WP6 is used which provides real-time speed advises to Hermes. For testing the constructed timetable it is important that Hermes knows the scheduled speed profiles, otherwise the trains will run as fast as possible leading to possible conflicts and large energy consumption that were actually solved in the timetable. Finally, the developed timetables for the case study from the Dutch railway network were tested and evaluated using the Hermes simulation tool. The results of this evaluation are provided in Section 5. This integration of the timetable module in the ON-TIME architecture and simulation of the resulting railway operations led to TRL 6.

WP3 also developed a classification of Timetabling Design Levels depending on the explicit incorporation of performance measures in the timetable design process (ON-TIME, 2013c). The developed three-level timetable module demonstrates one path to Timetabling Design Level 3 (stable, conflict-free and robust timetables), and Level 4 with respect to resilience to inserting ad-hoc freight path requests (ON-TIME, 2014). However, the various algorithms within the timetable module may also be replaced by existing tools at various railways to reach the same goal. For instance, railways that rely on normative macroscopic timetabling might integrate a microscopic module to provide more accurate input to the macroscopic approach, and enhancing their functionality with conflict detection and evaluation of infrastructure occupation. Other railways might add macroscopic optimization to their microscopic timetabling approach, and again others might add the fine-tuning module to their timetable process to obtain energy-efficient timetables, all depending on the current functionalities of their timetabling software and the ambition to improve on it.

The developed algorithms can also be applied to other case studies, either directly or after some adaptations to the algorithms. The algorithms were demonstrated on a network of two crossing corridors in the Netherlands. They can also be applied to other corridors, provided that the input data in RailML is available. The size of the network that can be handled by the developed macroscopic model has not been tested. It would be a nice test to check whether the macroscopic model can deal with the national network. The developed micro-macro transformation is particularly powerful in the sense that the macroscopic network model is brought back to its essence as much as possible, with variables only for timetabling decisions on the network. The microscopic and fine-tuning models fill in the details at the corridor level.

The developed algorithms have to be adapted to deal with scenarios of other countries. In particular, the local signalling logic must be included into the microscopic model to compute the appropriate blocking times required for conflict detection and capacity consumption. An 'interlocking' RailML has been developed already that could be used as input to the timetable module describing the signalling and ATP logic. Straightforward multi-aspect fixed-block systems can be implemented easily. Mainly the ATP rules must be considered carefully to obtain an accurate model for the driver behaviour. Another concern is the solution algorithm for the macroscopic model. This algorithm is implemented in C++ and calibrated for the Dutch case study. Different operational characteristics might lead to bad performance of the solution algorithm, which then has to be fine-tuned or even extended for the given characteristics. For example, the dense mixed traffic on mostly multi-track lines in the Netherlands is not at all comparable to the long single-track lines with many long freight trains of the Iron Ore line in Sweden. On the other hand, the macroscopic model may also be solved by existing multi-purpose Mixed-Integer Programming solvers. These solvers are used to solve general MIP problems but generally lead to higher computation times than tailor-made algorithms.

In general, the developed timetable module is a step change into technology development for performance-based timetabling leading to high Timetabling Design Levels. A next step to achieve a timetable system prototype at TRL 7 requires the development of a User Interface to set basic parameters and interact with the solution algorithms to set basic parameters, judge solutions, and guide the solution process with e.g. fixing some train paths, relaxing some running times or connections, cancelling train path requests, changing routes, etc. Also additional features could be implemented that were out of the scope of the ON-TIME project, such as finding the optimal or most robust platform allocation and/or station routes for all train services. The developed Timetable Design Level classification, timetabling architecture, and algorithms, provide a perfect foundation for future research and development towards TRL 7 and higher.

4.4 Expert judgment

The expert judgment studies are performed in Sweden and the UK. This section provides expert views from successively Sweden and the UK on the current timetabling processes and their integration with traffic control, followed by joint recommendations from Sweden and the UK, and a step by step judgment of the experts to the eleven main functionalities of the developed ON-TIME timetabling approach.

4.4.1 Challenges and recommendations from Sweden

Uppsala University has performed an investigation on the integration of timetabling and traffic control as part of WP3, with the following objectives:

- To get a clear understanding about the problems in the integration of timetabling and operational control.
- To describe existing approaches of how to solve the integration problems and improve the railway system.
- To describe innovations and development in these areas.

Here we summarize the findings, conclusions and recommendations from the investigation. For the full report, see ON-TIME (2013b).

Problems related to the integration of timetabling and operational control are important to solve. There are a lot of issues involved in this integration. In our investigation we have focused on the following main issues:

- The time spans in the timetabling process. Shortening the time span of the timetabling process is of vital interest to all operators (RUs) as well as the IMs.
- The rules and regulations. The rules and regulations that have to be obeyed by the IM when scheduling trains of several train operators. They have a significant influence on the time needed to create the 'final' timetable and also its quality.
- The tools used in the creation of the timetable. The time to produce the 'final' timetable is influenced by the tools available within the IM when constructing the timetable and how this construction work is organised. The quality of the timetable is also affected by the models and parameters used in the construction phase. Of course the quality of the data used is also of significant importance.
- The quality of the timetable. How is the quality of the timetable, the production plan, validated? The usability of the timetable in the traffic control process is here one important sub question.
- The feedback process. The feedback, short or long term, from the traffic control process – including experiences and knowledge that are accumulated in traffic controllers and train drivers - back to the planning process is also of greatest importance in order to, in the end, enhance the punctuality.

To conclude, many complicated problems that must be solved in order to have an effective integration of timetabling and operational control processes have been identified. The main findings, mainly related to the situation in Sweden are successively reported.

Rules and regulations

- The timetabling process of today has inconsistent rules for prioritisation between different trains in the planning phase, is by far too long and too rigid, especially compared to the needs of the freight companies, thereby creating problems with overbookings, cancellations, badly adapted train timetables, bookings with the 'wrong' type of train etc.
- Today's timetable, which is based on the yearly timetable, is in a constant state of deterioration due to the rigidity and the lack of appropriate tools of the current timetable process. The yearly process and the ad hoc-process are not coordinated in an optimal way.
- The operational rules concerning the prioritisation are not useful in practice. They do not give an overall effective operational control process.
- The ad hoc-process is not allowing the creation of an optimal daily plan, for example new trains have to be adapted to the timetable without any alterations of the trains already in the planned timetable.

- The so called 'Capacity congestion plans' used in Sweden are too rigid and are 'stealing' useful capacity.
- The cyclic timetables introduced locally are, at least in theory, more capacity consuming than non-cyclic ones and also creates conflicts between the local trains on one hand and the freight and long distance trains on the other. This is a complex problem that has to be solved.

Timetabling and its tools

- The major problem is that the timetable is not planned for every specific day. Trafikverket does not have enough resources and not the appropriate tools for this.
- The timetables are planned with a too low degree of precision – in practice not even working on a 'one minute' level – and therefore creating many problems. For example enhancing the so called 'time in the forest', introducing delays, spreading knock on delays etc. and in the end increasing transport, travel times, and energy consumption and decreasing punctuality.
- The main timetable tool (Trainplan in Sweden) used today has no functions for an appropriate handling of the planning of tracks on larger stations and yards. Furthermore it has no developed functions for dealing with different versions of infrastructure or different versions of the same timetable in an effective way. In Trainplan it is also very time consuming to alter the timetables for trains running long distances.
- The timetable constructors don't specify time supplements in the timetable in a structured and validated way. The timetable construction done in Trainplan are, apart from existing rules and regulations concerning allowances, based on pre specified headway limits and personal experiences.
- The irregular maintenance activities that are needed are not dealt with in the short time planning process in an appropriate way. It is partly due to the 'static structure' of the planning process, and partly because of the tools used.

Quality of the Timetable

- Trafikverket don't have time and resources to check every RU slot request. There are far too many as it is today. The requests for slots in the timetable made by the RUs are often also quite imperfect, i.e. important information is missing.
- The timetables do not contain all information needed by dispatchers and train drivers in the operational process. For example concerning information about train connections and planned handling of freight wagons.
- The construction of the timetable is based on old principles when it comes to so-called buffer times, running time supplements, and other allowances etc. The precision in the planned timetable for individual trains varies a lot. Especially the running times for the freight trains deviates quite often from what is planned in the timetable.

- The planning of track usage on larger stations and yards is not good enough today. The precision in the data and models used as a basis for the calculations of running times and margins is too simplified.
- The running time calculations that are done as a basis for the construction of the timetable have several drawbacks.
- The construction of the timetable is done with Trainplan based on pre calculated running times and a (very) simplified infrastructure model. In the used infrastructure model there is no representation of the signalling system whatsoever which have several effects on the quality of the timetable.
- Another problem with the Swedish timetables is that the planning is done with almost no consideration to the variations of the adhesion. Sweden is a quite large country with very large seasonal variations in temperature, precipitation (snow) etc. and there are also very large variations between different parts of the country.
- The time supplements that are added to trains in the yearly timetable due to planned maintenance work are often based on rough estimations.
- The traffic system of today isn't capable of delivering trains with a 'minute precision'.
- Planning the trains with a low precision creates large punctuality problems, especially in areas with high capacity consumption.
- "Too often the timetable is not used as a timetable but mere as a broad outline for running trains on the tracks".

Operational control and the usability of the timetable

- Temporary speed restrictions are quite frequent and are a source for delays spreading through the traffic system. The timetable is normally not adapted to them and it is left to the dispatchers to handle them in their re-planning procedures.
- Train drivers are normally not informed about changes of the actual timetable (i.e. changes made by dispatchers due to different perturbations or disturbances). Therefore they cannot adapt their driving to the actual timetable.
- The train drivers involved in upcoming train meetings seldom have detailed information enough about to perform them in the best way possible. Train meetings on single track stations are an extremely frequent event in Sweden, whose railway net has only around 20% double track.
- Sometimes there are intentions in the originally planned timetable not known by train drivers and dispatchers. I.e. information that is necessary in order to take correct re-planning actions is lacking in the planned timetable.
- A severe fault is that the trains do not follow their timetable (especially the freight trains). The numbers of freight trains that are carried forward in their timetable channel (plus/minus 5 minutes) are only around 20-30% of the total number of freight trains.

- The times in the time-distance diagram ('train graph') used in operational train are truncated (not rounded). Thereby further decreasing the precision in the operational control of the trains.
- A general and major problem in both the timetabling and operational processes (also in the investment planning process) is the quality of the information structures and also the quality of the data stored in them. There are today a large number of different IT tools and systems involved and a general problem seems to be that the used information and data structures used differs a lot between the systems and for example makes a transfer of data from one system to another quite complicated and difficult to perform. Another effect is also that for example dispatchers must use several different systems in order to obtain the needed data. That goes also for timetable and investment planners.
- A general and major problem in the operational process of today is that the actual timetable (RTTP, Real-Time Traffic Plan) used exists only in the head of the dispatcher or at best also on the 'train graph' in front. The RTTP isn't communicated and almost not possible to communicate to the persons directly involved in the process.

Feedback from operational control

- The accumulated know-how of train dispatchers and train drivers is not fed back to the timetable construction process to any larger extent.
- The punctuality data that is stored in the databases may have some small errors due to a couple of sources of error. One (and the main) source of error is that the automate registration of trains passing, leaving, or arriving at stations is measured when the trains passes selected track circuits and not when the train stops, starts, or passes the station centre. The other source of error is that the time measured isn´t marked with what date it is.
- There are some general problems concerning the feedback reported:
    - When there are badly planned trains in the original timetable - and therefore an urgent need to make appropriate changes – this is not done and the whole process is experienced as quite sluggish.
    - If it is a specific problem every day on a particular line or station, it often takes months before the corrections of the timetable are finalised.
    - There are even trains that, in the same way, year after year are badly planned, without any corrections are being made.
- One passenger RU says that it is difficult to change the timetable for a 'problematic train' because all changes are done as a part of the ad hoc process. If changes are done 'ad hoc' the train get a low priority and the travel time for a fast passenger train could increase with hours. Therefore normally no changes are done during the year!
- The Quality department of the main passenger RU produces a lot of statistics concerning the punctuality. But the ability to produce more in-depth analyses and conclusions is limited. There is a lack of coordination with the IM.

4.4.2 The current state in the UK

A summary of the overview process of UK timetabling is presented in D1.1 (ON-TIME, 2012a). The process is also generally similar to that described in Sweden, with many similar issues. Further details relevant to the expert evaluation of proposed WP3 functions are expanded upon below. This data comes from discussion with subject matter experts on the procedural constraints on train planning in the UK.

Constraints and input

The overall aim is to deliver a robust timetable that meets the needs of all stakeholders. Ideally this should make best use of capacity and reduce the need for 'pathing' wherever possible. Timetabling needs to accommodate both a microscopic and macroscopic level. Microscopic details cover factors such as the infrastructure type, line speed, track occupancy and how that might vary depending on the type of traction. This is also related to factors such as clearance times at junctions. Being able to specify these microscopic constraints, and *manipulate* them according to factors such as rolling stock type, is critical to developing the timetable. The depth, breadth and accuracy of microscopic factors are important.

However, successful microscopic timetabling is linked to macroscopic timetabling. The scope of macroscopic timetabling is critical here, as too limited a view of the geographical area will mean that train paths may be supported in one part of the network, but are not available in other parts of the network for longer routes. Key timing points exist that must be taken as the starting point for any timetabling process. This may not be the major terminating point on the network, but the point where many routes may intersect.

Also, large scale timetable development is driven by operational strategy and goals, but the capacity and capability of the network may change gradually, for example as minor enhancements come along. Also, relatively small changes in infrastructure may have large changes on timetable performance. For example, an increase from 20mph to 30mph line speed on a station approach may have more impact (a 50% increase in speed that will benefit all trains) than an increase in line speed to the fastest parts of the line, which may only benefit a small number of trains.

Freight, in particular, still needs to be considered in a flexible manner, so that train paths can be offered at short notice depending on the requirements of freight RUs. This also should adaptable to the type of freight (including traction) that is being considered.

Finally, a key activity in assessing a new timetable specification or a timetable change is being able to assess it against the current network capability to ensure that improvements have been made, or are appropriate. Therefore, there is an important activity of cross-checking between the current timetable and the proposed timetable.

Process of timetabling in the UK

The process of timetabling in terms of timescales is outlined in D1.3. It is important to emphasise this process is iterative both as a long cycle and as a short cycle.

As a *long-cycle*, a goal will be set for capacity on a given part of the network, based (for example) on major infrastructural change. Early work will take place to understand the general capabilities and constraints of the network, and how those support that goal. Then the formal timetable and its planning base are developed over a year before implementation, with the input of stakeholders (RUs, other IM functions, regulators). The timetable is then developed iteratively to address the needs of users.

As a *short-cycle*, in other words while actually using timetabling and simulation software, the process is also iterative. Different options will be tried out with the timetable to see what might get the best capacity. For example, a timetable may not have sufficient margin with one type of rolling stock, but will provide sufficient margins when a different type of rolling stock is used, such as one with more rapid acceleration and braking profile and/or shorter dwell time.

Both of these have implications for the implementation of simulation and timetabling tools. In order to support the long-cycle process, which involves multiple stakeholders (who may have different constraints and business pressures) it is necessary that any software presents not only the proposed timetabling, but the *reasoning* behind that timetable, so that train planners can justify their decisions, or present options to stakeholders with associated reasons for potential choices.

In order to support the short-cycle iterations on the timetable, it is also important the software support visibility of reasoning in a manner that the planner can interpret to help assess the appropriateness of the proposed solution. Also, it is necessary that the planner has a means of manipulating variables at a microscopic level, such as train model, dwell time, etc., to try and improve the fit with constraints, or to explore the limits of the infrastructure.

Technology, data and feedback

Currently, there are tools in place in the UK to support timetabling. The process of inputting some constraints is often manual in the UK, and this can influence the decision on how to use the tools as it may be more efficient to make an early expert judgment on potential change before inputting data.

The current technology offers many aspects of functionality that are only now being adopted, particularly with regards to microscopic factors.

Currently, there are channels for feeding back experiences of running the timetable. This can be done through assessment of the implemented timetable to see if there are persistent delays, and through direct engagement between planners and current operations staff such as signallers. In some traffic control settings there is a direct feedback link between the control system and planning, by informing planning of when changes are being made to the proposed plan presented through the train graph. For example, the high speed line HS1 between St Pancreas and the Channel Tunnel is the only part of the network that uses interactive train graphs.

4.4.3 Recommendations from Sweden and the UK

Based on what is described above, the future work concerning the integration of timetabling and operational control should be focused on development of the involved models, methods and systems and at the same time raising the quality of used data.

In order to have a modern and efficient railway system, it is important that the involved actors actively work with the main problems described above, and try to achieve the following:

Quality of the Timetable

- Enhance the quality of the models and data used in the timetabling process.
    - The original plans must be in detail, and be realisable.
    - Include detailed track usage: track length, position for and speed through points and lines.
    - Include signalling systems functionality: signal box functionality, position of signals and distant signals, etc.
    - Include functionality of the ATP-systems: distance for route set timing, etc.
    - Calculate minimal (shortest possible) running times as a basis for adding margins for robustness and resilience
- Instate the validation of used data, models, timetables etc. as a standard.
- Introduce structured ways of working with so-called buffer times, running time supplements, and other allowances etc. in the timetabling process.
    - Create algorithms for calculation and fine-tuning of margins – magnitude and allocation - within the scope of timetable objectives.
    - Validation is again of greatest importance.
- Start considering the very large seasonal variations in temperature, precipitation (snow) etc. in the timetabling process.
- The plan as a whole should have specified values for quality measures:
    - capacity utilisation
    - robustness and resilience
    - comfort
    - cost of wear and tear, i.e. maintenance
    - energy consumption

Timetabling and its tools

- Introduce modern and appropriate tools for running time calculations, simulations and "optimisation" of the timetables.
- Work consistently with the introduction of uniform and appropriate information structures in all involved IT systems.

Rules and regulations

- Create operational rules concerning the dynamic prioritisation between trains that supports an overall effective operational control process.
  - Adapt as far as possible rules and regulations to an overall effective operational control process, and of course also the organisation.

Operational control and the usability of the timetable

- Make sure that the timetables do contain all information needed by dispatchers and train drivers in the operational process.
  - Make calculated minimal running times and deadlines - and other requirements by request of the railway undertakers - available in the operational process.
- Force the train operating companies to run the trains according to the plan.
  - And to make necessary updates of the train characteristics relevant for the re-planning process.
- Develop standardised semi-automatic functions for evaluation of accomplishments.

Feedback

- Involve the accumulated proficiency of train dispatchers and train drivers in the timetable construction process.
- Eliminate the existing imprecisions in the measuring of punctuality.
- Make sure that it is possible to analyse the punctuality with the actually used timetables and the actual performance of the trains.

General

- Make sure that all information systems are accessible and usable from a train traffic point of view.
- Avoid 'elephantiasis' when developing and introducing new methods and systems. A stepwise development is recommended.

Software requirements

Overall, it is critical that any timetabling software be developed to

- Anticipate and support iteration and modification of the timetable at a number of timescales – including short-term test/re-test by planners, longer term strategic planning involving all stakeholders, and changes and adaptions to infrastructure.
- Allow input and variation of microscopic variables over short-term iterative cycles of timetable development. Freight is one example of being able to manipulate a microscopic factor to support multiple types of freight performance
- Support alignment between the existing timetable and proposed timetable in order to assess changes
- Support better integration between systems and better exchange of data, ideally so that more data input and output can be standardised

- Present the reasoning to the planners to support both short-term assessment, and justification of the timetable as part of the longer term development process with stakeholders. This could include information regarding options, e.g., "this train would fit if this path or margin could be adjusted".

4.4.4 Expert evaluation of ON-TIME timetabling functionalities

The ON-TIME timetabling approach can be defined as eleven high-level function points. Each of these has been presented to subject matter experts from UK and Sweden for comment. The functions and the judgment are as follows.

Functions and feedback

1. *Microscopic calculation of running and blocking times taking into account all running route details at section level (gradients, speed restrictions, signalling)*
2. *Microscopic conflict detection guaranteeing a conflict-free timetable*
3. *Timetable precision of 10 s, minimizing capacity waste and unrealizable running times*

This kind of functionality was reviewed as highly valuable and an advance on current practice. Precision in the region of 10 seconds is appropriate, though high precision is necessary. Work is in progress in the UK to address the implementation of such functionality, which can be taken as an indication of the relevance of this kind of approach.

With modern computers and good algorithms it is possible to include a simulation model as part of the timetable system. This gives transparency for the timetable constructor. However, the models of the infrastructure must be detailed enough, and must be more detailed than simply running time for a section. There must be accurate train models, including a model for adhesion. Also, consider driver and dispatcher behaviour.

4. *Incorporation of (UIC) infrastructure occupation and stability norms*

It is important to have common standards within the EU. All definitions and norms should be standardized. From the UK perspective, this would require further assessment of rationale and make-up. UIC is not applied in the UK, but the tool would still be effective if it can be configured to reflect local capacity standards.

5. *Macroscopic network optimization with respect to travel times, transfer times, cancelled train path requests and associated cancelled connections*

This function is valuable and would benefit the timetabling process. For the UK, an aim is to remove pathing time in order to optimise the timetable. Network optimization needs to be done at such a scope as to be effective at a corridor / route level, and spare capacity must be managed effectively to offer train paths to freight operators when they require it.

Reflecting this from Sweden, it is important to consider that optimising the timetable needs consideration from all stakeholders including RUs.

6. *Macroscopic robustness analysis using stochastic simulation to include robustness into the macroscopic timetable optimization*

Valuable, particularly if the robustness analysis provides comparison of actual running times with predicted. Feedback on this comparison is likely to support this issue of making the reasoning behind optimisation decisions visible, which is important both for immediate assessment of outputs, and for communicating to the wider stakeholder group. There is a query from the Swedish expert as to whether this is also possible at the microscopic level.

7. *Stochastic optimization of timetables for local trains on corridors between main stations, taking into account stochastic dwell times at short stops on the corridor*

This should increase the quality of the timetable. The optimisation would need to take into account RU access rights and associated commercial factors, and requires further consideration as to how it will be implemented.

8. *Energy-efficient speed profiles computed and incorporated for all trains*

Overall, this would be excellent, if adapted to the properties of the actual train and driver. Desirable for RUs, and would be encouraged by IM / planners provided this can be achieved within the timetable.

9. *Input from standardized RailML files (Infrastructure, Rolling Stock, Interlocking, Timetable/Routes).*

This is useful as it is good to have standards. Potentially useful if cuts down on manual processes and supports integration between systems and functions. The standardized RailML files must be able to incorporate the dynamic properties of the signalling system.

10. *Output provided in standardized RailML Timetable file with scheduled train paths at (track-free detection) section level, extended with energy-efficient speed profile information.*

This is important. Potentially useful if cuts down on manual processes and supports integration between systems and function.

11. *Incorporation of a multi-speed freight path catalogue*

Valuable if it supports being able to optimise and adapt the timetable depending on different types of freight characteristics, and supports flexibility in planning. The weight of the trains is very important when modelling interactions with other trains during the operational process.

Overall

Overall, the developments offered by WP3 are viewed positively. As noted in Section 4.4.2, there are limitations currently with how microscopic detail is incorporated into timetabling, and the need for manual input and output, which WP3 can address.

Comment was raised from the UK SME on ensuring WP3 supports iteration, and presents reasoning, as also discussed in Section 4.4.2. Also comment from both countries is the tool should work *as a whole*, as well as in-terms of individual functions, and further evaluation should be conducted holistically. Also, train planning is a process that involves a wide number of stakeholders. Therefore any tool must support the whole planning process and stakeholder group from both IMs and RUs, and should be relevant to the whole timetabling/planning process.

5 QUANTITATIVE EVALUATION

5.1 Timetabling results

This section considers the computational results and the computed timetables for the various scenarios of the Dutch case study, including the achieved values for the performance measures and plots illustrating the timetables and their performance measures.

5.1.1 Computational results

The computation time depends on the size of the network and the number of train runs. The microscopic network consists of about 1500 track sections and 1000 block sections, which are the number of nodes in the microscopic network (for running time computations) and mesoscopic network (for blocking time computations), respectively, while the macroscopic network contains only 16 nodes due to very efficient micro-macro transformations, see Figure 5. There are 10 passenger train lines, each operating twice per hour and in some scenarios an additional freight path. Table 7 shows the main characteristics of these train lines including the number of stops and legs (runs between successive stops). For both directions of the passenger lines there are in total 82 running times to be computed over all train legs. For an additional freight path 1 more running time must be computed. Note that for the regional trains a running time is computed between all successive stops, while for the intercity and freight trains the running times cover long distances over multiple areas with speed restrictions.

Table 7 Train line characteristics

				Forward			Return	
Line	**Type**	**O-D**	**Stops**	**Legs**	**Freq [/h]**	**Stops**	**Legs**	**Freq [/h]**
800	IC	Ut-Ehv	3	2	2	3	2	2
1900	IC	Ehv-Tb	2	1	2	2	1	2
3500	IC	Ut-Ehv	3	2	2	3	2	2
3600	IC	Tb-Nm	4	3	2	4	3	2
4400	R	Nm-Ht	9	8	2	9	8	2
5200	R	Tb-Ehv	6	5	2	6	5	2
6000	R	Ut-Tl	8	7	2	8	7	2
9600	R	Ht-Ehv	6	5	2	6	5	2
13600	R	Ht-Tb	2	1	2	2	1	2
16000	R	Ut-Ht	8	7	2	8	7	2
9900	Freight	Ut-Ehv	2	1	1	-	-	-

Figure 7 shows the computational results of the micro-macro iterations for Scenario 2 with one fast freight train. After 9 iterations the algorithm converged to a feasible solution which is both microscopically conflict-free and stable and macroscopically optimal. During the iterations a decreasing trend can be observed for the number of conflicts (blue solid line) and the total overlap time of conflicting blocking times (green dashed line), with some iterations leading to an increased number of conflicts and overlap time when the timetable structure (train orders) changes significantly from one iteration to the next in face of the new minimum headway times provided to resolve the conflicts.

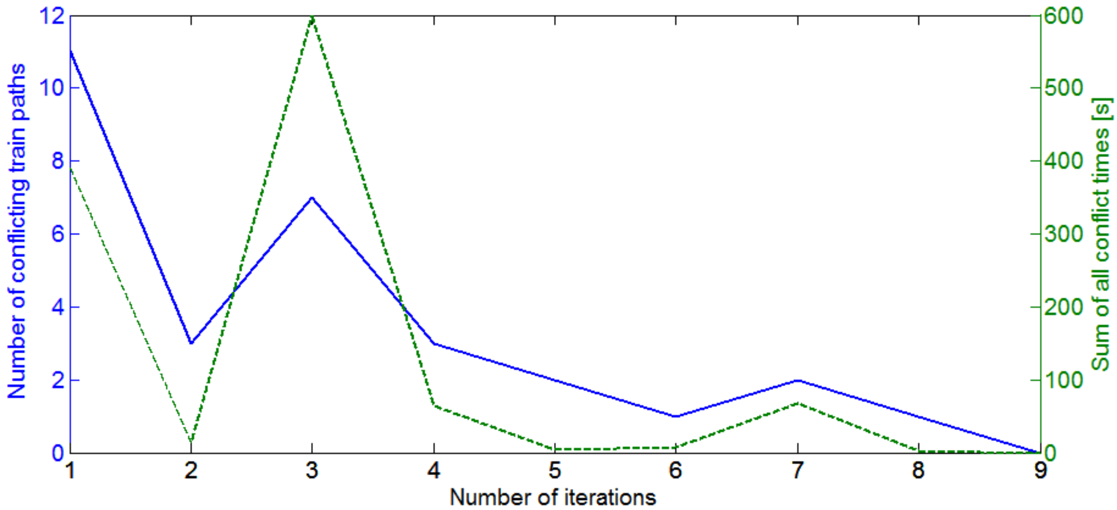

Figure 7. Evolution of the micro-macro interactions

Table 8 shows the detailed computation times. The initial computations to set up the model and compute the speed profiles associated to all minimum running times and the operational running times (with running time supplements) takes 35 s. Then the micro-macro iterations start. Each micro-macro iteration takes on average 2 min with 80 s for the macroscopic model to compute the best out of 1000 solutions, and 40 s for the microscopic model to re-compute the operational speed profiles and blocking times based on the new macroscopic scheduled running times and to set-up the new macroscopic network model with updated minimum headway times. After 9 iterations a solution has been found in 1080 s. Finally, the fine-tuning model starts with 5 s to set up the corridor models, and 210 s to compute all energy-efficient speed profiles. A stable, robust conflict-free and energy-efficient timetable is thus computed in 1330 s (about 22 min). The published timetable will in addition require the stochastic optimization of the short stops of local trains in the corridor which takes more time but this doesn’t chance the static traffic plan. The computation results of the other scenarios are comparable.

Table 8. Timetable computation times

	Iterations	Average [s]	Total [s]
Initial microscopic computations	1	35	35
Micro-macro iterations			1080
Macro (1000 macro iterations)	9	80	
Micro computations	9	40	
Fine-tuning*			215
Micro computations	1	5	
Energy-efficient speed profiles	1	210	
Total			1330

*without stochastic optimization of published timetable for short stops in corridors

5.1.2 Computed timetables

This subsection illustrates the computed timetables by their time-distance diagrams and blocking time diagrams for the three corridors Utrecht-Eindhoven, Tilburg-Nijmegen and Tilburg-Eindhoven for each of the Scenarios 1-3.

Scenario 1 and 2: Baseline (no freight) and fast freight

The timetables computed for scenario 1 and 2 are the same except that scenario 2 includes fast freight paths. This implies that the residual capacity of the passenger timetable can be used directly for fast freight trains without creating conflicts. Figure 8 to Figure 10 show the time-distance diagrams for scenario 2 with the fast freight train path, while the blocking time diagrams for this scenario are given in Figure 11 to Figure 13. The vertical axis shows time in minutes downwards. The horizontal axis shows distance with the station positions indicated. The blue lines are IC trains, the magenta lines are local trains, and the green line is the freight train. The freight train is drawn in a periodic hour pattern although in the simulations we will assume only one freight train in the two hour period. The diagrams for scenario 1 are the same except for the green freight path. Recall that the sections Btl-Ehv and Htn-Htnc have four tracks.

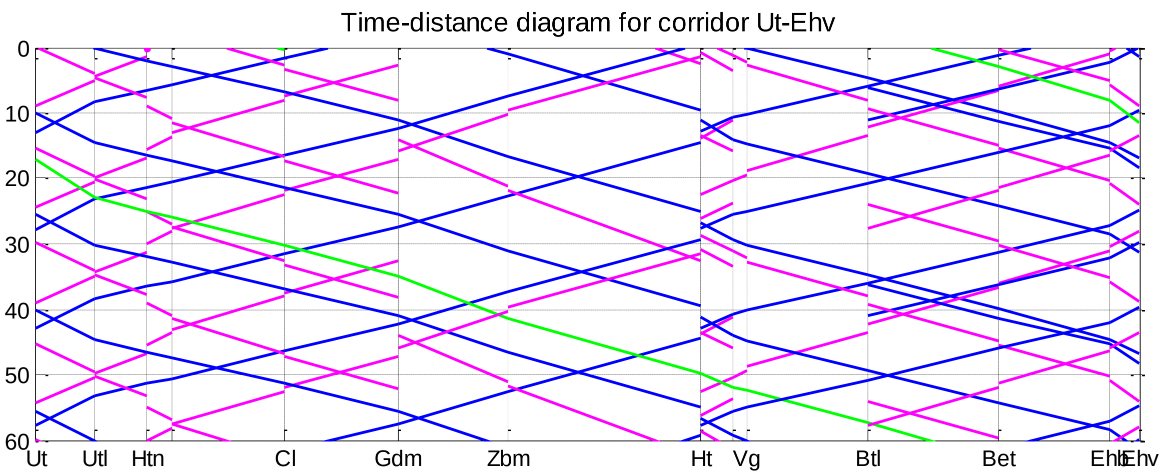

Figure 8. Scenario 2: Time-distance diagram corridor Utrecht – Eindhoven

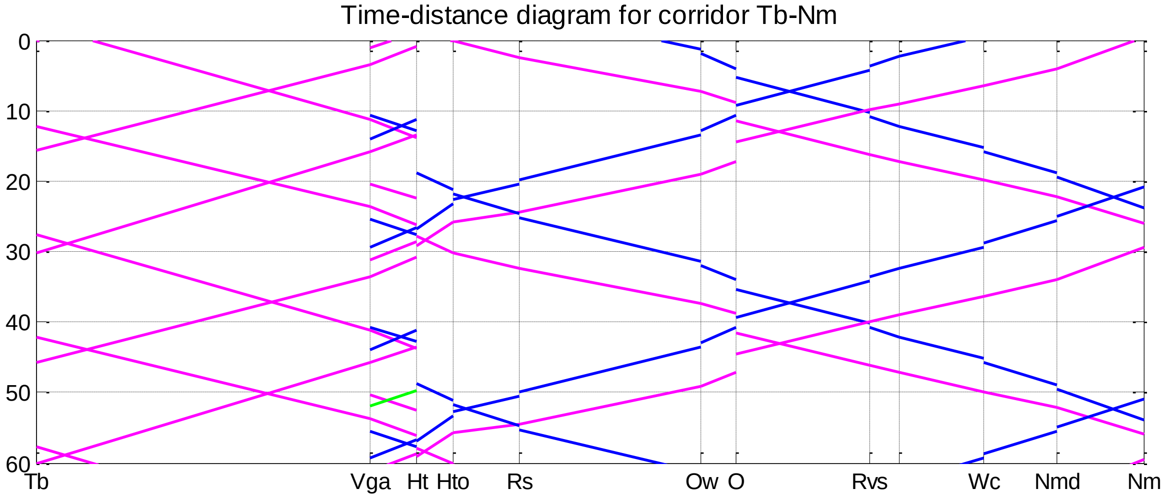

Figure 9. Scenario 2: Time-distance diagram corridor Tilburg – Nijmegen

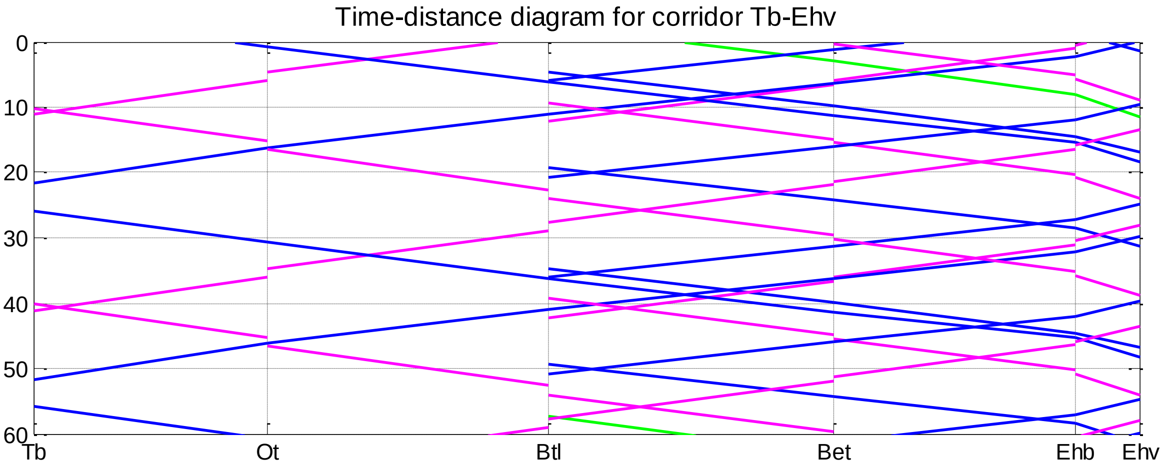

Figure 10. Scenario 2: Time-distance diagram corridor Tilburg – Eindhoven

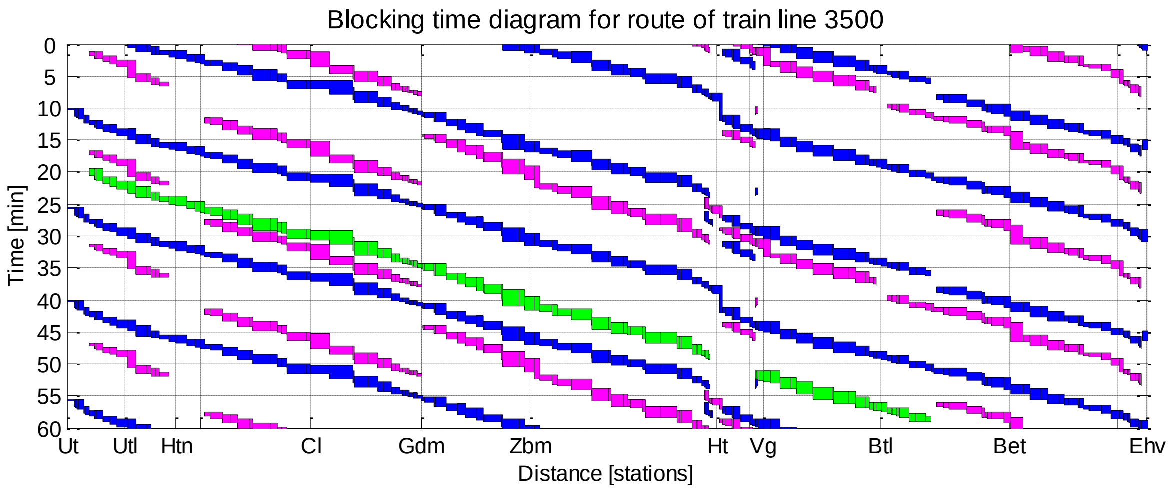

Figure 11. Scenario 2: Blocking time diagram corridor Utrecht – Eindhoven

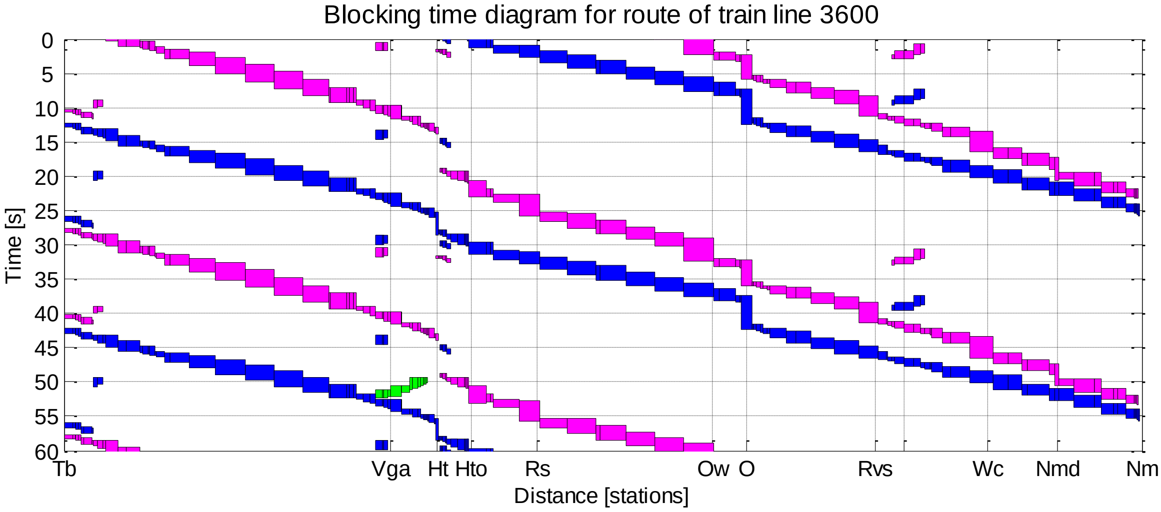

Figure 12. Scenario 2: Blocking time diagram corridor Tilburg – Nijmegen

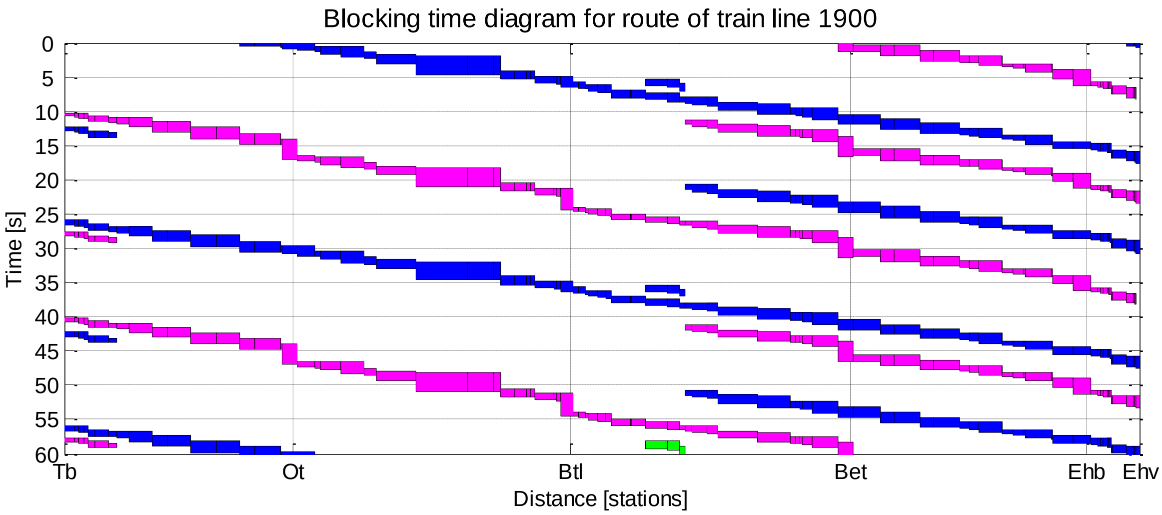

Figure 13. Scenario 2: Blocking time diagram corridor Tilburg – Eindhoven

The optimized timetable shows periodic passenger trains with regular 15 minute services of both IC and local trains where two similar train lines follow the same route. Hence, effectively 15 min train services are realized instead of two separate 30 min train lines. On the main corridor Utrecht-Eindhoven the ICs overtake the local trains at Geldermalsen (Gdm), but not in the return direction. The fast freight train departs after the local train from Utrecht Centraal (Ut) and overtakes this local train at the four-track line around Houten (Htn).

From the blocking time diagram of Figure 11 it can be seen that the freight path has ample buffer time after Geldermalsen to the next IC. Between Houten Castellum (the station just after Htn) and Culemborg (Cl) the freight path and the next local train is tight so that a slight delay of the freight train might propagate to the local train but the buffer time between this local train and the next IC prevents further knock-on delays. In Geldermalsen, the local train also has a longer dwell time that can be used to recover from an arrival delay. In the absence of the freight train the situation is robust, which is the usual case currently with on average 1 freight path per two hour on this corridor. The other corridors show also sufficient white space between the train paths indicating a robust timetable. Only before Nijmegen the IC is close behind the local train which may cause knock-on delays if the local train is delayed.

Scenario 3: Insertion of a slow freight train

Figure 14 to Figure 15 show the time-distance diagrams of the optimized timetable for scenario 3 with the slow freight train path on the corridors Utrecht-Eindhoven and Tilburg-Nijmegen. The slow freight path is so different from the fast freight path that the timetable pattern slightly changed with the slow freight train departing right after the IC from Utrecht before the local train so that overtaking in Houten is no longer applied. As a result the passenger trains are shifted by one to two minutes. This solution is better than a straightforward allocation of the slow freight train in the fast freight path which would result in particular to large (scheduled) delays to the local train after Houten and knock-on delays to the next IC. Hence, the changed train order with respect to the freight path leads to manageable delays and again a robust conflict-free timetable. The resulting scheduled delays for the passenger trains around this freight path are within a two minute punctuality threshold. Note that the resulting timetable is again conflict-free and robust so that if the traffic control system is flexible enough to incorporate the ad-hoc timetable changes to the passenger trains then this solution leads to better operational performance.

This solution might also be found by a real-time conflict detection and resolution (CDR) application such as developed in WP4 but if it is already known that a freight path does not fit in its scheduled freight path it is better to already adjust the timetable beforehand so that the real-time changes to the traffic plan are kept to a minimum. Moreover, an up-to-date timetable is the best solution for railways without advanced real-time CDR functionalities.

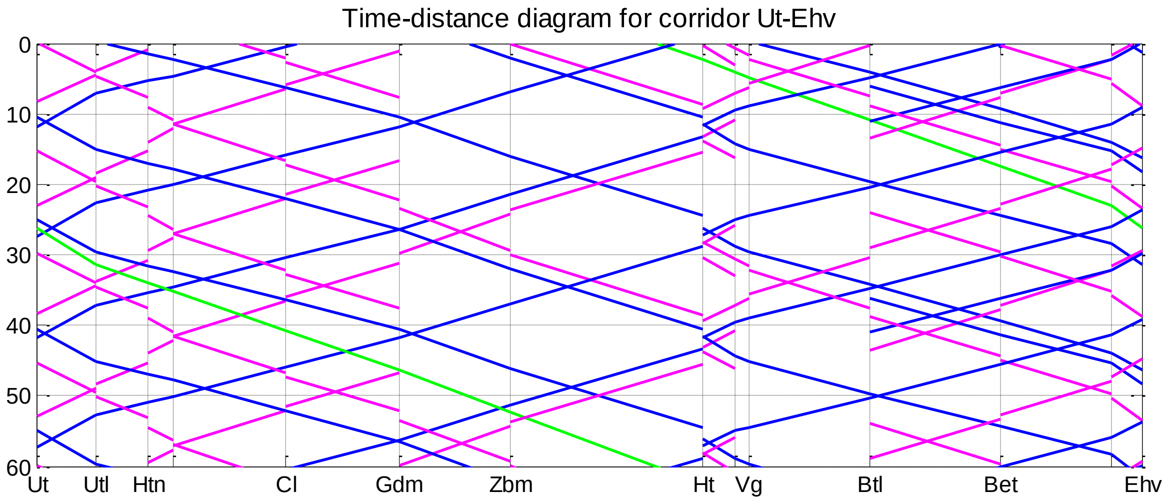

Figure 14. Scenario 3: Time-distance diagram corridor Utrecht – Eindhoven

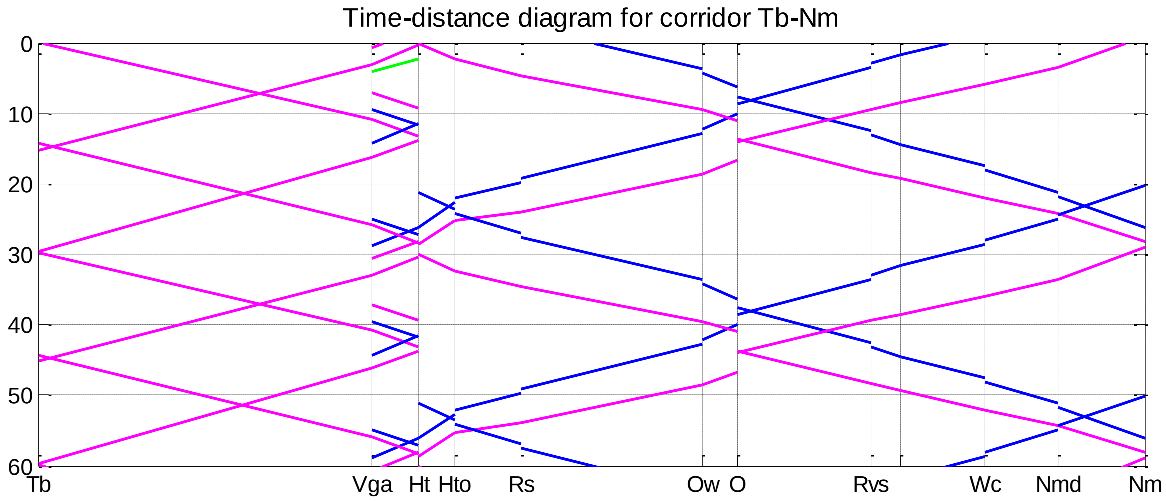

Figure 15. Scenario 3: Time-distance diagram corridor Tilburg – Nijmegen

5.1.3 Capacity assessment

The developed WP3 algorithms efficiently compute the infrastructure occupation at corridors and in stations. Figure 16 and Figure 17 provide examples of compressed blocking time diagrams for the corridor Nijmegen – 's-Hertogenbosch and station Geldermalsen, respectively. The horizontal axis consists of all the track-free detection sections along the corridor or in the station, although their sequence does not follow a topological order as this is not possible for a linear representation of a 2D station layout. The vertical axis represents the infrastructure occupation as obtained from the compressed blocking times of each track-free detection section by the trains. The coloured blocks are the blocking times, with a unique colour for each train. Note that the initial red train is added twice to indicate the first train in each period. The earliest possible departure of a train from the following period is then easily obtained as the difference of the departure times of these two trains. This represents the minimum cycle time of the corridor or station at which a new sequence of trains can start in a periodic pattern.

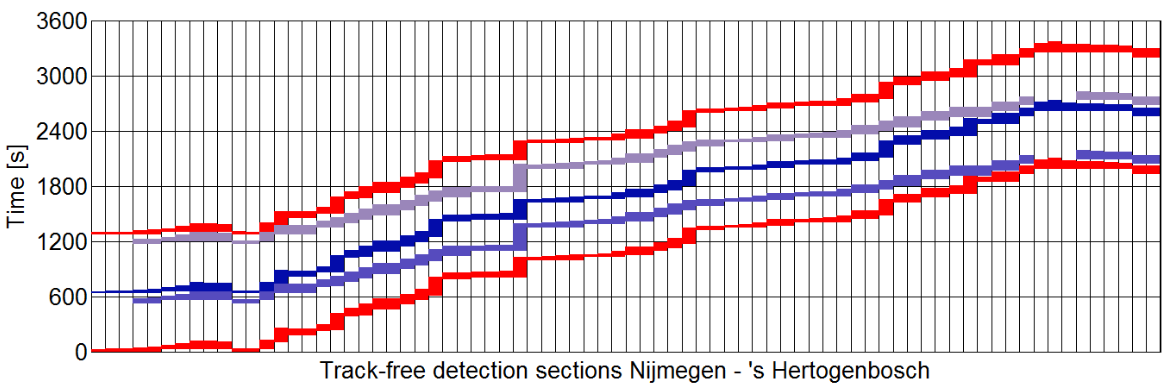

Figure 16. Infrastructure occupation corridor Nijmegen - 's-Hertogenbosch

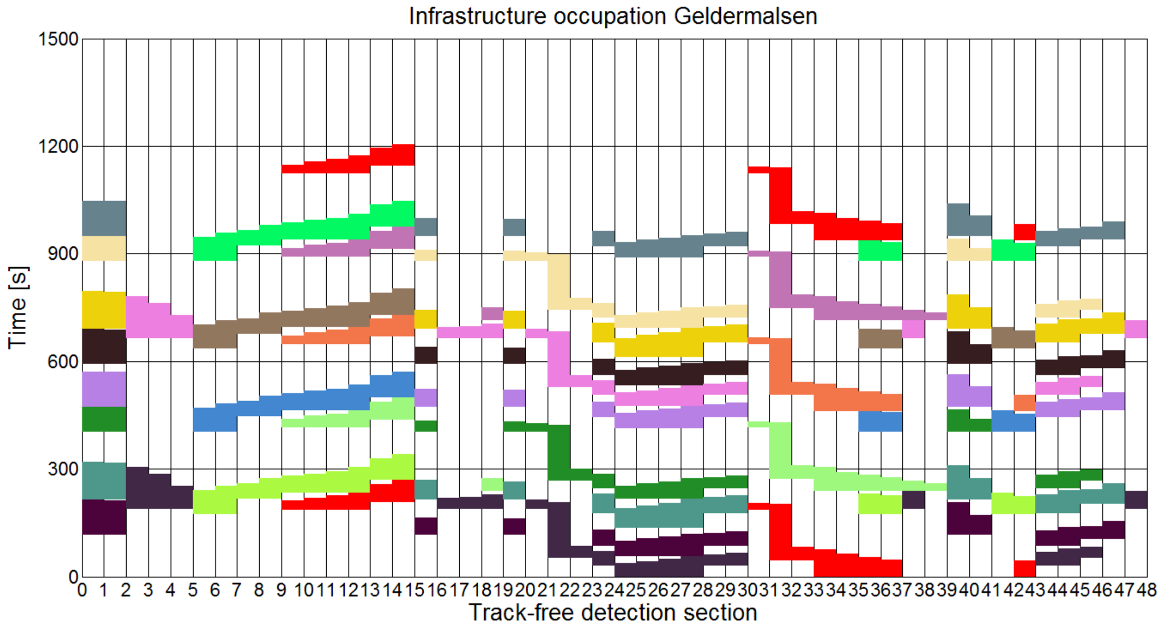

Figure 17. Infrastructure occupation in station Geldermalsen

Table 9 shows the infrastructure occupation of the main corridors for all scenarios. All the infrastructure occupation percentages are below the recommended stability value of 75% defined by the UIC for mixed traffic corridors in the peak hours, which was one of the constraints of the WP3 algorithms. In fact, all timetables are also acceptable throughout the day with values lower than 60%. The two heaviest used corridors in all scenarios are Utrecht-'s-Hertogenbosch and vice versa, with maximum infrastructure occupation percentages of 54.7%, 57.8% and 57.9%, respectively. The other corridors have infrastructure occupation below 41%.

Table 9. Infrastructure occupation at main corridors for all scenarios

Corridor	Scenario 1		Scenario 2 (Fast)		Scenario 3 (Slow)	
	Time [s]	%	Time [s]	%	Time [s]	%
Ut-Ht	1968	54.7	2080	57.8	2003	55.6
Ht-Ut	1924	53.4	1924	53.4	2086	57.9
Ehv-Ht	1320	36.7	1320	36.7	1320	36.7
Ht-Ehv	1338	37.2	1450	40.3	1208	33.6
Ht-Tb	736	20.4	736	20.4	734	20.4
Tb-Ht	680	18.9	680	18.9	516	14.3
Ht-Nm	1270	35.3	1270	35.3	1270	35.3
Nm-Ht	1352	37.6	1352	37.6	1352	37.6

Comparing scenarios 1 and 2, without and with a (fast) freight train, an increment of the infrastructure occupation is observed at Utrecht-'s-Hertogenbosch from 54.7% to 57.8%, and likewise on 's-Hertogenbosch-Eindhoven from 37.2% to 40.3%. These increments of both 3.1% are due to the inserted freight train on Utrecht-Eindhoven. The infrastructure occupation of the other corridors is not affected by this freight train.

In scenario 3 with the slow freight path from Utrecht to Eindhoven the optimized timetable has a slightly different order of trains, due to the bundling of the slow freight path with a local passenger train. As a result, the infrastructure occupation rate between scenarios 2 and 3 at the corridors Ut-Ht is in favour of the latter one. In particular, the slow freight train bundles better with the local passenger trains, without the need for overtaking in Houten.

It can be concluded that a fast freight train does not necessary mean less infrastructure occupation. It depends on the structure of the timetable like the ratio of intercity and local trains as well as the train characteristics. For example, if the timetable is dominantly consisting of fast (IC) trains than the fast freight trains would better fit in such a timetable, i.e., consume less additional capacity. On the other hand, if more slow (local passenger) trains are present the infrastructure occupation rates will be better for slow freight trains.

Table 9 shows that the timetables are very stable, but the blocking time diagrams of Figure 11 and Figure 12 show some train paths with critical block sections that are close, such as from 's-Hertogenbosch to Vught, from Houten to Culemborg when the fast freight train is scheduled, and from Nijmegen Dukenburg to Nijmegen. There is sufficient capacity to make the timetable more robust at these locations by moving more buffer time between the critical train paths. However, there is a trade-off between robustness and customer satisfaction. In particular, small regular intervals are preferred by passengers for predictability and less average waiting time at the start of a trip and at transfer connections. Hence, if the periodicity with 15 min intervals is relaxed, more robust timetables are possible but these are not better from a customer point of view. This is the essential difference between stability and robustness: stability guarantees that there is sufficient buffer time available for reduced delay propagation, but how this buffer time is allocated between the train paths determines how robust the timetable really is. Other factors such as regular intervals and connections also affect where it is optimal to put the buffer times. This trade-off is the main purpose of the macroscopic timetable optimization model.

Table 10 presents the infrastructure occupation in stations and important nodes, such as the single-track bridge Mbrvo. All values are below the UIC capacity norms. The largest infrastructure occupation is observed in station s-Hertogenbosch (Ht) with 58.3% in scenarios 1 and 2, while the smallest is at the junction Wnn and in station Tiel (Tl), with only 7.3% and 7.5%, in all three scenarios.

An increase in infrastructure occupation is observed between scenarios 1 and 2 due to the inserted freight train. This increment is observed in station Boxtel (Btl) with 2.5%, Geldermalsen (Gdm) with 1.3%, Utrecht (Ut) with 3.3%, and the junction Vught aansluiting (Vga) with 3.3%. However, in stations Eindhoven (Ehv) and Den Bosch (Ht) the critical infrastructure occupation is unchanged.

Table 10. Infrastructure occupation in stations for all scenarios

Station	Scenario 1		Scenario 2 (Fast)		Scenario 3 (Slow)	
	Time [s]	%	Time [s]	%	Time [s]	%
Btl	854	23.7	943	26.2	870	24.2
Ehv	940	26.1	940	26.1	930	25.8
Gdm	1015	28.2	1063	29.5	917	25.5
Ht	2100	58.3	2100	58.3	1602	44.5
Htn	900	25.0	900	25.0	900	25.0
Mbrvo	1020	28.3	1020	28.3	1020	28.3
Nm	484	13.4	484	13.4	371	10.3
O	1026	28.5	1026	28.5	1026	28.5
Ot	590	16.4	590	16.4	590	16.4
Tb	466	12.9	466	12.9	446	12.4
Tl	270	7.5	270	7.5	270	7.5
Ut	1134	31.5	1253	34.8	1093	30.4
Vga	916	25.4	1033	28.7	1064	29.6
Wnn	264	7.3	264	7.3	264	7.3

When a slow freight train is inserted in scenario 3, several decreases in infrastructure occupation are observed with even a decrease of 13.8% in station Ht from 58.3% to 44.5% with respect the reference scenario. These results are in line with the conclusions made for the capacity assessment at the corridor level, showing that a slow freight train may be inserted in the timetable more efficiently when speed differences can be kept low by bundling with a similar slow train.

5.2 Evaluation results

The performance of the integrated timetable planning tool developed in WP3 is evaluated by simulating the produced timetables for the Dutch network in HERMES for the three scenarios as defined in Section 3.3.3. This section evaluates the computed timetables with respect to the reference timetable (scenario 0) on the KPIs defined in Section 2.2 for several benchmark situations as defined in Section 3.4.

5.2.1 Transport volume

Table 11 presents the transport volume between three origin-destination pairs. We include both the seat capacity and the number of services between that were realized within the time period 7:00 AM and 9:00 AM. The origin-destination pairs that we consider are Eindhoven–Utrecht (Ehv-Ut), Utrecht–Eindhoven (Ut-Ehv) and Nijmegen – 's-Hertogenbosch (Nm-Ht). The number of services shows the total number of trains that run over the whole OD corridor. The reference and baseline scenarios show passenger trains only, while scenarios 2 and 3 include one freight train from Utrecht to Eindhoven. For all scenarios, the number of passenger trains that complete their entire journey within two hours is equal, with 5 direct trains between Utrecht and Eindhoven, and 4 direct trains for the last corridor. These trains result in a production of 210,749 and 39,528 seat kilometres, respectively. Scenarios 2 and 3 have the same transport volume with an additional 217,890 tonne of freight. The equal values for passenger trains are expected because the same number of services is scheduled in all scenarios.

Table 11. Transport volume benchmark within 7:00 AM – 9:00 AM

TV	O-D	Reference Pass.	Reference F	Scenario 1 Pass.	Scenario 1 F	Scenario 2 & 3 Pass.	Scenario 2 & 3 F
Seat km or tonne km	Eh-Ut	210749	0	210749	0	210749	0
	Ut-Ehv	210749	0	210749	0	210749	217890
	Nm-Ht	39528	0	39528	0	39528	0
Completed services	Ehv-Ut	5	0	5	0	5	0
	Ut-Ehv	5	0	5	0	5	1
	Nm-Ht	4	0	4	0	4	0

5.2.2 Journey Time

Table 12 presents the average time needed to travel from origin to destination for the three benchmark journeys. Here, we take the mean time over all trains that completed the journey from the origin to the destination. The mean journey time from Eindhoven to Utrecht is the same for all scenarios. The mean journey time from Utrecht to Eindhoven for scenario 1 is 1.2 minute less than the reference scenario, while the 1 minute extra of scenario 2 with respect to scenario 1 is due to the freight train on this corridor which is counted as well. The journey time for scenario 3 shows however an increase of the average journey time by 2 minutes (4%) which is due to the slow freight train itself. The passenger trains have the same journey times on this corridor for the ON-TIME timetables.

Table 12. Journey time at benchmark journeys

JT	O-D	Ref.	Scenario 1	Scenario 2	Scenario 3
Mean journey time [min]	Ut-Ehv	49.4	48.2	49.2	51.4
	Ehv-Ut	50.5	50.5	50.5	50.5
	Nm-Ht	30.2	32.5	32.5	32.5

On the corridor Nijmegen-'s-Hertogenbosch the reference scenario is 2.3 minutes (7.6%) faster than all ON-TIME timetables (Scenarios 1-3). Hence, the ON-TIME solution assigned 7.6% more running time supplement for trains at the corridor Nijmegen – 's-Hertogenbosch to provide a conflict-free timetable at the critical area before 's-Hertogenbosch. The extra running time supplement can be used to introduce a more energy-efficient train driving style. The average running times in scenarios 1-3 are the same as the freight paths do not affect the train schedule on this corridor.

5.2.3 Connectivity

Table 13 gives the mean transfer time for the benchmark transfer connection at 's-Hertogenbosch for transferring passengers from Utrecht towards Tilburg. The abbreviation O-C-D stands for Origin-Connection-Destination. All ON-TIME scenarios provide the same mean transfer time which is 2.1 min smaller than the reference scenario. In the computations a minimum transfer time of 2 min was taken into account.

Table 13. Connectivity at benchmark connection

CN	O-C–D	Ref.	Scenario 1	Scenario 2	Scenario 3
Mean transfer time [min]	Ut-Ht–Tb	7.3	5.2	5.2	5.2

The objective function of the macroscopic timetable optimization contained all transfers in 's-Hertogenbosch together with two transfers at Geldermalsen, as well as running times, dwell times and robustness. The optimization is therefore a trade-off between all these processes and was not dedicated to this benchmark transfer.

5.2.4 Resilience

Resilience was in D1.2 (ON-TIME, 2012b) defined as a general term including stability, robustness, and recoverability of operations. In terms of the timetable KPIs this term covers timetable stability, robustness and resilience, and is measured in terms of delays.

The quantitative evaluation tool aimed at a standardized evaluation of all WPs. Section 2.2.4 defined three measures for resilience based on the difference between a simulation of a delayed scenario and a reference scenario without delay. If both scenarios have the same timetable and this timetable is conflict-free then the reference simulation has no delays and therefore the difference between all simulated event times in the two scenarios represent exactly all the primary and knock-on delays of the delayed scenario, which is then summarized into the maximum delay, the settling time of the delays, and the total delay area. If the reference timetable is however not conflict-free then the structural delays caused by the timetable are discarded so that only the additional delays are considered. This approach works for evaluating real-time perturbation management (WP4) and disruption management (WP5). However, when the timetable in both scenarios is different then the offset between the timetables are counted as delays as well, instead of comparing the real delays with respect to the two different timetables. For example, if the new timetable in the 2nd scenario is exactly the same as the reference timetable but for a shift of 5 min everywhere, then each event will cause 5 min delay even if it is on-time according to the new timetable. In WP3 we are interested in comparing the operations according to different timetables and therefore we need to adjust the standard quantitative evaluation to a comparison of the observed delays generated with respect to different timetables.

Table 14. Departure delays at benchmark stations

RS Station	Delay difference Reference - Basline Sum [s]	Mean [s]	Max [s]
's-Hertogenbosch	-874	-35	-116
Eindhoven	-4482	-102	-331
Utrecht Centraal	-8974	-209	-541
Tilburg	-2292	-54	-255
Nijmegen	-1510	-65	-255

In order to evaluate the resilience of the WP3 timetables, we compare the behaviour of the reference and baseline timetables (scenarios 0 and 1) with respect to perturbations. Note that the reference timetable does not contain freight trains so that only a comparison with the baseline scenario without freight trains makes sense. Both scenarios are simulated in HERMES with the same random disturbances and driver behaviour, i.e., driving with the built-in HERMES driving behaviour (maximum speeds) without the energy-efficient speed profiles since these are not available for the reference timetable. Moreover, the simple First-Come First-Served route setting behaviour of HERMES is used rather than simulating the real Automatic Route Setting system ARI.

Table 14 presents the departure delay statistics for all departures at the five benchmark stations realized within the simulation window of 7:00 AM to 9:00 AM. The table shows the difference in observed departure delays for the two simulations, with negative values indicating larger delays for the reference scenario. The results show that the baseline timetable produced fewer delays in each of the benchmark stations with an average (less) delay between 30 s and 3.5 min, and a maximum of 9 min more departure delay from station Utrecht Centraal. Clearly, the ON-TIME timetable is more resilient than the reference one according to the HERMES simulations. Note that this simulation assumes a simple FCFS dispatching strategy instead of the ARS rules and traffic control decisions from real practice. The results are thus only a comparison between two timetables under similar conditions, rather than real-world absolute values.

5.2.5 Energy consumption

Table 15 presents the energy consumption of the simulated scenarios for the two benchmark corridors Eindhoven – Utrecht Centraal and Nijmegen – 's-Hertogenbosch, both in kWh used and in percentage of the reference scenario. The trains running according the ON-TIME timetables have a significant reduction in energy consumption in comparison to the reference timetable, with energy savings between 24.6% up to 28%.

Table 15. Energy consumption for benchmark journeys

EG	Reference		Scenario 1		Scenario 2		Scenario 3	
O-D	kWh	%	kWh	%	kWh	%	kWh	%
Ehv-Ut	32491	100	23470	72.2	23434	72.1	23870	73.5
Nm-Ht	9747	100	7343	75.3	7345	75.4	9228	75.4

The explanation is threefold: First, the journey times in the ON-TIME timetables on these benchmark corridors are either similar or slightly larger than the reference timetable, see Table 12. This means that at some parts more running time supplement is available for energy-efficient running. Second, the reference timetable is not conflict-free so that structural knock-on delays are generated causing braking and re-acceleration where the ON-TIME timetable has optimal energy-efficient running. Third, the ON-TIME timetable satisfies the stability norms and the robustness analysis causes a preference for a robust timetable that have good delay settling behaviour. And fourth, the ON-TIME timetables provide energy-efficient speed profiles that could be used for optimizing driver behaviour in the simulation, while the reference timetable has no indication on how the simulated trains must run other than the static speed profile, by which the trains are simulated with maximum speeds and reduced acceleration and braking which is not optimal for energy consumption.

5.2.6 Resource usage

Table 16 shows the mean track usage per hour over the simulated period between 7:00 AM and 9:00 AM, measured as the mean number of trains passing specified signals on four corridors. The numbers for the reference scenario coincide with the one for the baseline scenario 1, while scenarios 2 and 3 have 0.5 train per hour more on the corridor Utrecht – 's-Hertogenbosch, which corresponds to the inserted freight train in these timetables. The equal values are expected because the same number of passenger trains is scheduled in all scenarios.

Table 16. Track usage at benchmark positions

RU1	Mean number of trains per hour			
Position	**Reference**	**Scenario 1**	**Scenario 2**	**Scenario 3**
Signal 528 Ow-Hto	4.0	4.0	4.0	4.0
Signal 743 Zbm-Ht	6.0	6.0	6.5	6.5
Signal 752 Ht-Zbm	6.0	6.0	6.0	6.0
Signal 711 Tb-Vga	4.0	4.0	4.0	4.0

Table 17 shows the number of trains that are running between 7:00 AM and 9:00 AM. The passenger train count is equal in all scenarios, since the number of the scheduled trains is the same in all scenarios. Scenario 2 and 3 only have another freight train.

Table 17. Rolling stock usage between 7:00 AM-9:00 AM

RU2	Reference		Scenario 1		Scenario 2		Scenario 3	
	Pass.	**Freight**	**Pass.**	**Freight**	**Pass.**	**Freight**	**Pass.**	**Freight**
No. of trains	107	0	107	0	107	1	107	1

6 CONCLUSIONS

6.1 General conclusions

This section gives conclusions from the evaluations with respect to the successive WP3 objectives as mentioned in Chapter 1.

- Reduce overall delays through the use of improved planning techniques to provide timetables that are robust, i.e., capable of coping with normal statistical variations in operations, as well as resilient to minor perturbations.

The ON-TIME timetabling approach reduces overall delays by improved planning techniques that provide conflict-free, stable and robust timetables. Microscopic conflict-free detection and stability tests guarantee that the computed timetable is conflict-free and has sufficient buffer time to prevent or reduce delays. Moreover, the settling time of delays is explicitly incorporated in the timetable optimization in a trade-off with running, dwell and transfer times, to provide robust timetables. At a corridor level the running time supplements of local train legs are optimally allocated over the corridor with respect to normal variations of dwell times to minimize expected delays in a trade-off with minimizing energy consumption. Timetable resilience has been focused on ad-hoc insertion of freight paths of different maximum speeds. The quantitative evaluation shows good results with respect to timetable robustness, and likewise good performance is obtained for inserting a freight path for different speeds resulting in none to small delays.

- Develop common railway timetabling and capacity estimation methods for EU member states that reflect customers' satisfaction and enable interoperability, more efficient use of capacity, higher punctuality and less energy consumption.

A classification of Timetabling Design Levels (TDLs) has been developed that can be used to evaluate and compare the timetabling methods used in all member states and beyond. The higher the TDL, the more advanced tools are used for developing improved timetables. A prototype timetabling framework has been developed and implemented to reach the highest TDL as an example path for IMs and RUs. Capacity consumption is integrated in the timetabling framework using the UIC timetable compression method and guidelines for acceptable infrastructure occupation as rejection norms, with algorithms extended to infrastructure occupation in station layouts. The overall performance-based timetabling approach computes stable, robust conflict-free timetables which reduces both structural primary delays and knock-on delays. This results in a more efficient use of capacity, higher punctuality and increased customers' satisfaction. Moreover, the network timetable is optimized with respect to a trade-off between small running, dwell and transfer times on the one hand and small settling times with respect to delays on the other, which lead to small but reliable travel times. This is the main criterion for customers' satisfaction next to higher punctuality. Energy consumption is explicitly taken into account by including scheduled energy-efficient speed profiles for all trains in the microscopically detailed timetable which can be used by punctual trains even without advanced Driver Advisory Systems. Moreover, on corridors between main stations the timetable is optimized with a trade-off between energy efficiency and robustness to delays due to dwell time variations. The timetabling approach is generic and applies both to periodic and aperiodic timetables with standardized RailML exchange data enabling interoperability.

- Further develop methods for robust cross-border timetables and integration of timetables between different regional and national networks improving interoperability and efficient corridor management including standardised approaches for exchanging timetable information between stakeholders.

The developed timetabling approach is generic and allows scheduling of periodic and aperiodic trains using standardized RailML exchange data which was extended to be able to exchange timetables (or traffic plans) at microscopic detail of track-free detection section or signal level. This allows much more precise traffic monitoring, prediction and management than just scheduled arrival and departure times at selected stations. Moreover, a multilayer timetable approach is proposed to deal with ad-hoc freight path requests using a multi-speed freight path catalogue that can be used for international freight paths.

- Design resilient timetables that can recover or reduce consequences from incidents or disturbances by exploiting feedback of performance data from operations.

Within WP3 a parameter estimation method was developed to derive distributions of characteristic parameters for train dynamics based on track-free detection data. These empirical distributions can be used for validated running time calculations instead of fixed parameters provided by manufacturers. Moreover, the timetable of local trains is optimized with respect to expected delays within corridors and energy consumption using empirical dwell time distributions at short stops.

- Improve timetable quality, stability, robustness, reliability and effectiveness.

The ON-TIME timetabling approach is performance-based with an explicit focus on feasibility, stability, robustness on the one hand and minimizing running, dwell and transfer times on the other. The result is a stable and robust conflict-free timetable of high quality to passengers and effective to Railway Undertakings by enabling reliable operations at minimal rolling stock circulation times. The expert judgments from timetable planners are all positive about the developed functionalities.

- Validate the developed methods, through benchmarking, using a number of real-world case studies developed in WP2.

Chapter 5 contains real-world case studies from the Netherlands as defined in D2.2, with benchmarks of all the key performance indicators defined in D1.2 relative to a reference scenario consisting of the original timetable. The benchmarking was carried out with simulations using the HERMES simulation software. The results show that the computed timetables perform well with the same transport volume, resource usage and number of passenger trains scheduled as in the reference. The journey times are sometimes slightly larger corresponding to the aim of developing robust and energy-efficient timetables. The ON-TIME timetables perform much better to perturbations in running times whereas the reference timetable is also not conflict-free everywhere. In the simulations the ON-TIME timetable reduced the average departure delays by 0.5 to 3.5 minutes at five benchmark stations up to a reduction of a 9 minute departure delay from main station Utrecht. Energy consumption can be reduced by 25%-28% using the provided scheduled energy-efficient speed profiles. Furthermore, the ON-TIME timetables improved connectivity by a decrease of 2 minutes of mean transfer time at the benchmark transfer station 's-Hertogenbosch.

6.2 Contribution to the project objectives and innovations

The timetabling module focused on Innovation 2: The development of improved methods for timetable construction that are robust to statistical variations in operations and resilient to perturbations. The ON-TIME project objectives related to the timetabling module were the following:

- Improved management of the flow of traffic through bottlenecks to minimize track occupancy times. This will be addressed through improved timetabling techniques [and real-time traffic management] (Objective 1).
- To reduce overall delays through improved planning techniques that provide robust and resilient timetables capable of coping with normal statistical variations in operations and minor perturbations (Objective 2).
- To better understand, manage and optimize the dependencies between train paths by considering connections, turn-around, passenger transit, shunting, etc. in order to allocate more appropriate recovery allowances, at the locations they are needed, during timetable generation (Objective 7).
- To increase overall transport capacity by demonstrating the benefits of integrating planning and real-time operations, as detailed in Objectives 1-8 (Objective 9).

WP3 have improved methods for timetable planning and raised TRL from 3 to 6 for the innovation improved methods for timetable planning, as described in Section 4.3. WP3 has fulfilled project objectives 1, 2, 7 and 9. Research results are summarised in Section 6.1.

The main results and contributions for objectives 1, 2, 7 and 9 are the following:

- The ON-TIME timetabling approach reduces overall delays by improved planning techniques that provide conflict-free, stable and robust timetables.
- A classification of Timetabling Design Levels has been developed depending on the explicit incorporation of performance measures in the timetable design process with increasing performance with respect to dealing with delays and disturbances. The Timetabling Design Levels (TDL) go from TDL 0 of low quality timetables to TDL 4 by successively incorporating stability analysis, conflict detection, robustness analysis, and resilience into the timetabling process, resulting in timetables that are more and more robust and resilient.
- A multilayer timetable approach has been proposed to deal with ad-hoc freight

path requests using a multi-speed freight path catalogue that can be used for international freight paths.
- The ON-TIME timetabling approach integrated microscopic and macroscopic timetabling as well as timetable evaluation into one timetabling design process with an explicit focus on timetable performance indicators.
- RailML exchange data was extended to exchange timetables (or traffic plans) at microscopic detail of track-free detection section and signal level.
- The developed methods were validated through benchmarking using a number of real-world case studies developed in WP2.
- The overall performance-based timetabling approach computes stable, robust conflict-free timetables which reduces both structural primary delays and knock-on delays. This results in a more efficient use of capacity, higher punctuality and increased customers' satisfaction.

6.3 Future work

The lessons learnt from the project and future work can be summarized as follows.

- The integration of the extended Timetable RailML developed in WP3 into the HERMES simulator needs further work. A concept was developed to integrate the scheduled speed profiles into the driver behaviour of HERMES but there are still functionality problems.
- There is a need of further simulation evaluations of WP3 timetabling results.
- The WP3 (macroscopic) algorithms need to be checked and possibly adapted for the construction of national timetables.
- The WP3 algorithms need to be verified and possibly adapted for different railways from other countries.
- The WP3 timetabling approach needs to be extended with a model for robust platforming and routing within station layouts.
- The UIC 406 infrastructure occupation calculations need to be evaluated further and in particular the stability parameters and the different options and limits to decrease saturation. Benchmarking calculations between different tools and for different national networks are of interest.
- The UIC 406 infrastructure occupation calculations need to be extended to advanced interlocking constraints such as overlaps and flank protection. This also needs further extension of RailML to include these interlocking characteristics.
- Further study is required into the interaction of timetabling (WP3) and traffic control (WP4) to obtain resilient timetables with respect to perturbations and effective traffic control.
- The ON-TIME timetabling approach to integrate microscopic and macroscopic timetabling is promising but the construction of stable timetables also needs microscopic stochastic simulation and analysis which needs further study.
- The macroscopic optimization model needs a functionality to fixate constraints or train paths to enable an interactive timetable construction by planners.
- The concept of a multilayer timetable with a multi-speed freight path catalogue needs further study to develop an effective freight path catalogue.

7 REFERENCES

[1] N. Besinovic, E. Quaglietta, R.M.P. Goverde (2013). A simulation-based optimization approach for the calibration of dynamic train speed profiles. *Journal of Rail Transport Planning and Management*, 3(4), 126-136.

[2] ON-TIME (2011). *Annex I: Description of Work Part B*, Grant Agreement for Collaborative project, no. 285243.

[3] ON-TIME (2012a). D1.1: Principles, definitions and requirements. Report ONT-WP01-DEL-001.

[4] ON-TIME (2012b). *D1.2: A framework for developing an objective function for evaluating work package solutions (Cost Function)*. Report ONT-WP01-D-UOB-025-01.

[5] ON-TIME (2013a). *Task 3.1: Assessment of State-of-Art of Train Timetabling*. Report ONT-WP03-I-EPF-008-04.

[6] ON-TIME (2013b). *Task 3.3: Problems in the integration of timetabling and traffic control*. Report ONT-WP03-T-UOU-021-01.

[7] ON-TIME (2013c). *Task 3.4: Functional design of Robust and Resilient Timetable models*. Report ONT-WP03-I-UDB-009-03.

[8] ON-TIME (2014). *D3.1: Methods and algorithms for the development of robust and resilient timetables*. Report ONT-WP03-D-TUT-034-01.

[9] ProRail (2014). *Network Statement 2014: Combined Network*, version 1.7 [quote translated from the Dutch version (Netverklaring 2014: gemengde net, versie 1.7) due to inconsistencies between the English and Dutch versions].