

## **ON-TIME**

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## ON-TIME: A Closed-Loop Real-Time Traffic Control Framework in a Realistic Railway Environment

Egidio QUAGLIETTA<sup>1</sup>, Francesco CORMAN<sup>2</sup>, Rob M.P. GOVERDE<sup>3</sup>

### Summary

A wide literature is available on models and tools for the optimal real-time management of railway traffic, but the knowledge of their effects on real operations is still blurry and very limited due to the scarce implementation of these systems in practice. This paper analyses how these tools perform when interfaced in a closed-loop setup with a realistic traffic environment. A framework is developed that couples the rescheduling tool ROMA with the microscopic simulation model EGTRAIN. Railway traffic is managed for different perturbed scenarios using a rolling horizon scheme where optimal plans are periodically computed based on current traffic information and implemented in the simulation model. The closed-loop setup is investigated for different combinations of its parameters relatively to quality and stability of rescheduling plans. A comparison is performed against a typical open-loop approach that implements only the plan computed on the basis of expected train entrance delays. Both the closed-loop and the open-loop approaches are evaluated against the case in which no rescheduling is considered and trains keep on following the original timetable. Results obtained for the Dutch corridor Utrecht-Den Bosch show that the closed-loop always outperforms the open-loop in terms.

**Keywords:** real-time rescheduling, closed-loop model predictive control, stability analysis, quality of dispatching plans

## 1. Introduction

Railway operations are affected by unforeseen disturbances (e.g. extensions of dwell times at stations, unplanned stops at red signals) that induce deviations from the timetable and thereby reducing performances (e.g. punctuality). When time allowances in the timetable are not enough to absorb such deviations it is necessary to reschedule railway traffic in real-time in order to mitigate the delay propagation and keep the capacity levels required by infrastructure managers. Railway dispatchers must therefore solve the so-called rescheduling problem, that is to find a plan (i.e. a combination of control measures like reordering, retiming and/or rerouting trains) that reduces the impact of delays on traffic. Such a plan is therefore called also a „solution” of the rescheduling problem.

In practice the rescheduling problem is currently solved on the basis of rules-of-thumb or the own experience of the dispatcher, with the aim of restoring the original timetable as soon as possible. These plans can be however ineffective or counterproductive due to the limited view that the human dispatcher has on downstream traffic behaviour. Advanced tools could be used instead that mathematically solve the resched-

uling problem, providing to dispatchers plans that minimize the delay propagation on the network. In literature several models have been proposed so far for computing optimal rescheduling plans that guarantee operations free of track conflicts (where a conflict occurs when two trains want to occupy the same block section contemporarily). These approaches use different formulations for the rescheduling problem and adopt diverse objective functions and algorithms to solve it (see e.g. (11), (3), (7)). The most of them are designed to be included within a rolling horizon setup (e.g. (5), (1)) where at regular time intervals (*rescheduling interval RI*) current train information (e.g. measured speeds and positions) is used to predict track conflicts over a time period ahead (*prediction horizon PH*). If conflicts are detected a new conflict-free plan is computed.

Very few works (e.g. (8), (11)) instead evaluate the quality of rescheduling solutions computed in a rolling horizon scheme considering the presence of stochastic traffic disturbances. However, the main shortcoming with such approaches is that no one has ever realized a closed-loop interaction (i.e. a bidirectional communication) between the rescheduling tool and a realistic traffic environment, to reliably evaluate the effects of optimal plans on train services. Practitioners are indeed still

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sceptic about using rescheduling tools into real operation, mainly because their implications on traffic are not investigated and not clear yet. This is also due to the scarcity of installations in practice (e.g. (7), (6)) that prevent from having an extensive overview of their consequences.

This paper wants to clarify these issues by analysing the interaction of an optimal rescheduling tool with realistic traffic settings. We study a closed-loop rolling horizon setup for different configurations of the parameters  $RI$  and  $PH$ , evaluating the computed plans in terms of quality (i.e. effects on several measures of performance) and stability. A plan is defined as stable when it does not change if recomputed at later stages with respect to updated traffic information. A stable plan is therefore insensitive to the dynamic propagation of stochastic disturbances on the network. Stability is an essential requirement for rescheduling tools to prevent nervous behaviours of continuously changing solutions, that is hardly manageable by human dispatchers.

The effects of the closed-loop are then compared with those of a classic open-loop scheme in which the dispatcher only implements the plan computed at the beginning of the observation horizon on the basis of only the estimated train entrance delays. The benefits given by both the closed-loop and the open-loop rescheduling are assessed against the case in which no rescheduling is applied at all and trains continue following the original timetable. The whole study is conducted over multiple disturbed scenarios and limited information on actual train dwell times.

A framework is developed that interfaces the state-of-the-art rescheduling tool ROMA (3) and the microscopic railway simulation tool model EGTRAIN (9), surrogate of the real field. The Dutch railway corridor Utrecht-Den Bosch is used as case-study.

In Section 2 the framework is described while the methodology is reported in Section 3. A practical application is reported in Section 4. Conclusions are supplied in Section 5.

## 2. Approach Description

A closed-loop framework has been developed which connects the rescheduling tool ROMA (Railway Optimization by Means of Alternative Graphs) to a detailed stochastic microscopic model for the simulation of railway traffic, EGTRAIN (Environment for the design and simulation of Railway Networks). EGTRAIN is considered realistic since it is validated by verifying that within undisturbed conditions simulated train running times were congruent with those scheduled in reality. Further research might include validation of the system for the full envelop of disturbed conditions. A detailed description of ROMA and EGTRAIN can be found respectively in (3) and (9).

As shown in Figure 1 both the rescheduling and the simulation models are initialized by specifying input data relative to the infrastructure, the rolling stock, the signaling and Automatic Train Protection (ATP) systems, the original timetable, and the entrance delays. To emulate a realistic traffic setting, random disturbances to dwell times are set only in the simulation model (since it represents the real field) but unknown to the rescheduling tool.

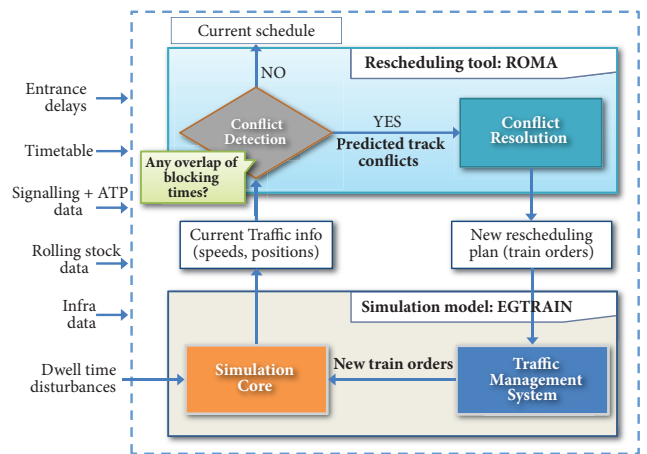


Fig. 1. Architecture of the closed-loop framework

At a given time instant the simulation core of EGTRAIN sends current traffic information (positions and speeds of trains) to the Conflict Detection module of ROMA. Based on this information a deterministic prediction (i.e. train running and dwell times are considered as deterministic) of possible track conflicts is performed over a given period  $PH$ . Conflicts are identified by means of the blocking time theory (4) as overlaps between the blocking times of two trains for a certain block section. If no conflict is detected, the current schedule can still be operated without any modification. Otherwise, the predicted conflicts are sent as input to the Conflict Resolution module, which generates a new conflict-free plan by retiming (i.e. shifting the scheduled departure / arrival / passing times) and reordering (i.e. changing the passage order) trains in order to minimize the delay propagation on the network. This module represents the train scheduling problem as a job-shop model with no-store constraints that is solved by using a truncated version of a Branch and Bound algorithm (2).

Train orders given by the new rescheduling plan at given locations (called checkpoint  $CP$ ) are transferred to the Traffic Management System of EGTRAIN and implemented in the simulation core. Once implemented, the traffic is microscopically simulated (using a time-driven and synchronous approach) respecting the order supplied by the new plan for each specific location.

The interaction between the rescheduling and the simulation models follows a rolling horizon scheme (Figure 2). This means that the entire observation horizon  $H$  is subdivided in  $n$  successive stages, which are partially overlapping and spaced at regular time intervals called rescheduling intervals  $RI$ .

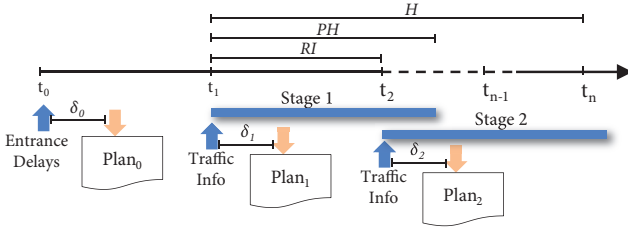


Fig. 2. Rolling horizon scheme with inputs to ROMA (blue arrows) and to EGTRAIN (orange arrows)

At the beginning of each stage ( $t_0, t_1, \dots, t_{n-1}$ ) ROMA receives traffic information (considered not affected by measurements error) from EGTRAIN; predicts track conflicts over a prediction horizon  $PH$  that is constant for all stages, and provides (within the computing time  $\delta_0, \delta_1, \dots, \delta_{n-1}$ ) a new plan ( $Plan_0, Plan_1, \dots, Plan_{n-1}$ ) that is implemented in EGTRAIN. In brief the complete closed-loop depicted in Figure 1 is performed after each  $RI$ . For the sake of simplicity we assume that the time to implement the plans is null, i.e. the simulation is frozen while ROMA computes, and the plans of ROMA are implemented in EGTRAIN as soon as they are computed.

The closed-loop setup has been tested for different combinations of  $RI$  and  $PH$  in order to understand how these parameters affect the performances of computed plans in terms of quality and stability.

A comparison is then performed against an open-loop approach that implements a rescheduling plan computed for the whole observation horizon  $H$ , only on the basis of the expected entrance delays. That is to say that the open-loop only puts into operation  $Plan_0$  calculated by ROMA using a length of  $PH$  equal to the observation horizon ( $PH = H$ ). In this case  $Plan_0$  provides for the entire  $H$ , the solutions to all track conflicts that are expected to happen on the basis of only the entrance delays. This comparison consents us to evaluate which are the benefits given by the closed-loop when constantly updating the rescheduling plans with respect to current traffic conditions. In addition we also report what would happen if no rescheduling was applied at all, and trains operate according to the original timetable. In this way it is possible to understand which advantages the use of optimal rescheduling plans can bring to a situation in which no real-time management is considered.

The whole study is realized over different perturbed scenarios generated in a Monte-Carlo scheme, by ran-

domly sampling: the entrance delays and disturbances to dwell times at stations. These latter are only considered in EGTRAIN and unknown to ROMA.

The metrics used for evaluating the stability of the rescheduling plans are:

*Number of Relative Reordering (NRR)*. This metric describes for a certain location  $CP$  the similarity in terms of ordering between two plans computed at consecutive stages. Considering the plan given at stage  $s$ , we assume that a train is reordered if it is scheduled before some train that was preceding it, in the plan provided at stage  $s-1$ . The value of  $NRR$  is then calculated by counting all reordered trains.

The *average NRR* over all the rescheduling stages gives a measure of how stable in terms of reordering are the optimal plans provided by the rescheduling tool. The lower this average the higher is the plan stability. A condition of full stability is achieved when plans computed at consecutive stages are all the same, i.e. when the average  $NRR$  is zero.

The quality of all the plans (when traffic is rescheduled with the closed and the open loop) and the timetable (when no rescheduling is applied) is calculated with respect to the final station of trains by means of the following metrics:

*Average total arrival delay (AvTotDelay)*. The total arrival delay of a train at a station is intended as the difference between the actual and the arrival time fixed by the original timetable at that station. *AvTotDelay* is the average of the total arrival delay over all delayed trains reaching their final station.

*Average consecutive delay (AvConsDelay)*. For each train the consecutive delay at the final station is obtained by subtracting from its total arrival delay the unavoidable delays (i.e. entrance delays and dwell time disturbances cumulated at the previous stations). *AvConsDelay* is the average of this delay over all delayed trains reaching their final station. This metric gives a measure of how much trains are hindered during their run by the presence of other conflicting trains.

*Max Consecutive Delay (MaxConsDelay)* is the maximum value of the consecutive delay over all trains reaching their final station.

*Punctuality* at the final station with respect to a threshold of 3 ( $P_{3min}$ ) and 5 minutes ( $P_{5min}$ ). These numbers give the percentage of trains whose total arrival delay at the final station is less than 3 and 5 minutes respectively.

### 3. Case Study: The Dutch Corridor Utrecht-Den Bosch

The proposed framework is applied to the railway corridor between Utrecht (Ut) and Den Bosch (Ht) in the Netherlands. This has a length of more than 48 km

with 6 intermediate stations: Lunetten (Ln), Houten (Htn), Houten Castellum (Htnc), Culemborg (Cl), Geldermalsen (Gdm), and Zaltbommel (Zbm). The schematic layout is presented in Figure 3, together with the locations in which trains can overtake each other and a reordering is possible (CP1, CP2, CP3). The network is equipped with a fixed-block signalling system and the traditional Dutch automatic train protection ATB system. The hourly periodic timetable schedules 4 intercity trains (IC) per hour per direction between Ut and Ht without intermediate stops; and 4 regional trains, two of which are limited between Ut and Gdm, while the other two run all the way till Ht. No freight trains are taken into account in the study. For the sake of simplicity, only trains running along the Ut-Ht direction are considered, as in this double-track corridor there is no interaction between trains running in opposite directions. The observation horizon in which the rescheduling is applied is  $H = 120$  min. The closed-loop setup has been tested for 9 different parameter combinations obtained by coupling 3 values of  $RI$ : 30, 60 and 120 s, with 3 lengths of the  $PH$ : 15, 30 and 60 min. The only solution ( $\text{Plan}_0$ ) implemented within the open-loop has been calculated by adopting a  $PH$  equal to the whole observation horizon, i.e.  $PH = 120$  min. The study is performed over 30 different perturbed scenarios obtained by sampling: *i*) entrance delays from a Weibull distribution fitted to real data (3) with scale, shape and shift parameters that are different for ICs and regional trains; *ii*) station dwell times have been considered normally distribution with a lower truncation to the minimum dwell time, the planned duration as mean, and 60% of this latter as standard deviation; this distribution results in a cumulative delay over all stops that is averagely 1.5 to 2 min per train, in accordance to reality.

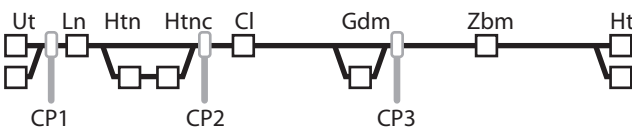


Fig. 3. Schematic layout of the Utrecht – Den Bosch corridor, with the locations (CP1, CP2 and CP3) in which train reordering is considered

### 3.1. Results

The results obtained for all the stability and quality metrics are computed as the average over the 30 disturbed scenarios. Figure 4 shows how the rescheduling plans vary over time in terms of  $NRR$  for different  $RI$ s and  $PH$ s of the closed-loop setup. For a given stage the value of  $NRR$  is aggregated over the three CPs, i.e. it is the sum of their corresponding  $NRR$ . For the first 18 minutes the rescheduling solution is practically stable and equal to  $\text{Plan}_0$ , i.e. the plan computed on the

basis of only expected entrance delays. This is because in this period only two trains have entered the network and stochastic disturbances have not propagated yet. As such disturbances start progressing over the network, the rescheduling plans become unstable and vary over time. The reason of such instability is that the propagation of disturbances induces a deviation between actual and predicted train trajectories, altering from time to time the conflicts detected by ROMA and the corresponding solutions (i.e. the plans). For a fixed  $RI$ , the variation in terms of train reordering  $NRR$  is higher for longer  $PH$ s. For example when fixing  $RI = 30$  (see Figure 4a), this average has a very strong increase of 109% when extending the  $PH$  from 15 to 30 min and then only a slight increment of 11% when further enlarging the  $PH$  to 60 min. The same behaviour is shown for the other tested values of  $RI$  (see Figure 4b–4c). These results suggest that for a fixed  $RI$  the plan stability decreases when enlarging the  $PH$ , until a threshold  $\tau$  (in this case  $\tau = 30$  min) beyond which it remains more or less constant. The motivation is that shorter  $PH$ s are less affected by prediction errors since only the closest future is estimated. Moreover in this case only a limited knowledge is available of traffic evolution and time margins exploitable for reordering. In this myopic situation the rescheduling tool can mostly solve conflicts by retiming (i.e. propagating delays to later trains) rather than reordering, as verified in (10).

This explains why the value of  $NRR$  at a certain stage is generally lower for shorter  $PH$ s. For longer  $PH$ s, conflict predictions are more uncertain (therefore more variable), given that more errors are possible when estimating traffic over a farther future. When progressively enlarging the  $PH$  it will be achieved a threshold length  $\tau$  beyond which computed plans do not consistently differ since traffic predictions (and their errors) are basically the same.

Although the presence of sharper peaks in the value of  $NRR$ , more stable plans (hence more easily manageable by human dispatchers) are obtained for short  $RI$ s. In this case the average  $NRR$  is indeed lower than the one relative to larger  $RI$ s. This is because smaller errors affect the prediction if this latter is updated more frequently on the basis of current train information. For example for  $PH = 30$  min, such average increments of 30% when enlarging  $RI$  from 30 to 60 s. When  $RI$  is widened from 60 to 120 s, a smaller increase of 19% is instead observed.

In Table 1 the effects on traffic are reported in terms of the mentioned quality indices for the timetable, the open-loop and the different configurations of the closed-loop. The last two columns report the total computation time for simulation (by EGTRAIN) and for rescheduling (by ROMA); this latter is in average 1.5 second per stage.



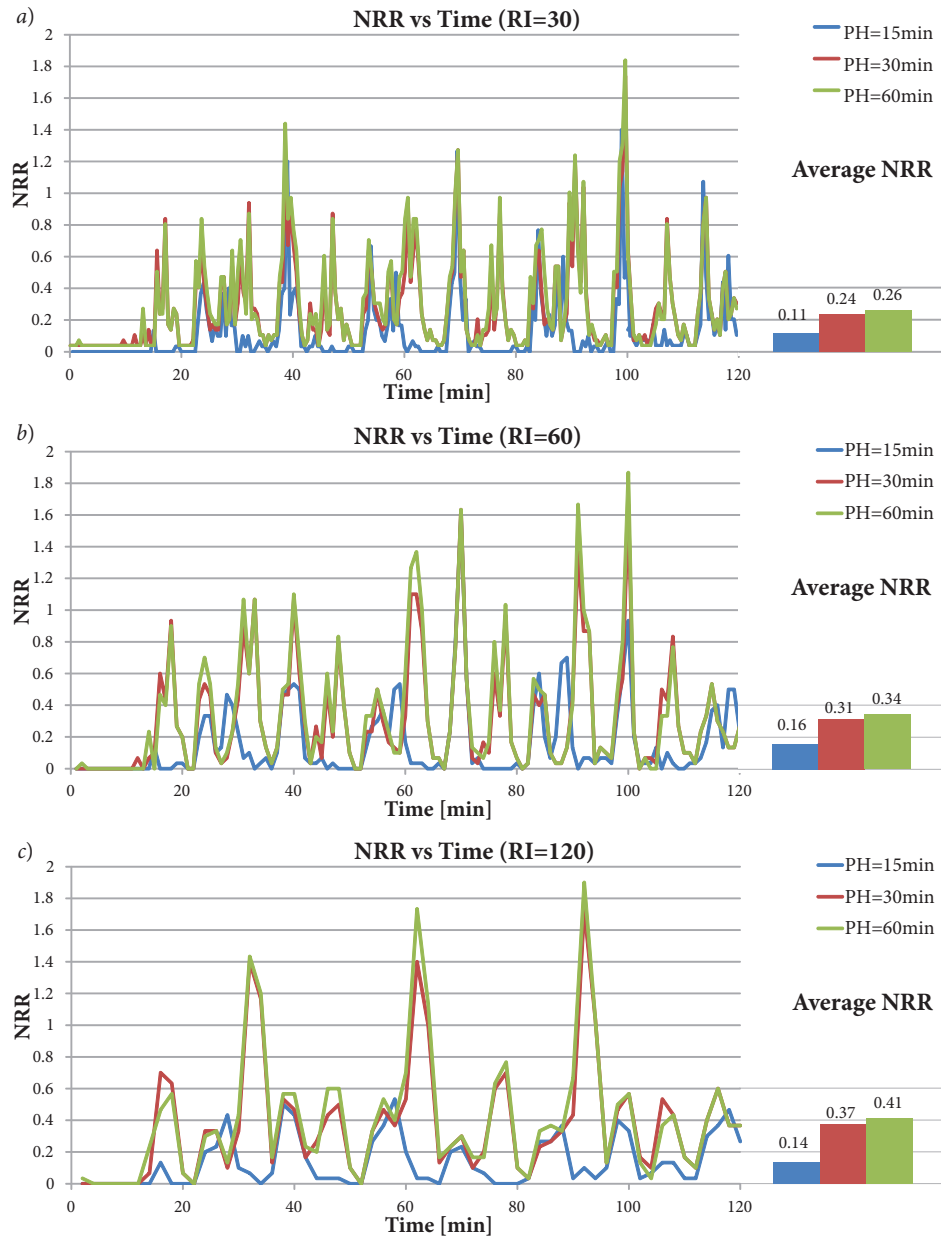


Fig. 4. NRR and average NRR (aggregated for all the CPs) for the different configurations of the closed-loop setup

Table 1

**Quality indices for the different traffic management approaches**

RI [s]	PH [min]	AvTot Delay [s]	AvCons Delay [s]	MaxCons Delay [s]	P3min [%]	P5min [%]	TEGTRAIN [s]	TROMA [s]
Timetable	n/a	118.30	28.31	107.42	87.45	89.52	56.37	n/a
Open-loop	120	106.57	23.52	105.84	90.15	92.79	56.66	1.82
120	15	102.08	22.02	96.64	90.33	93.13	57.50	91.97
	30	100.72	21.41	95.44	90.61	93.24	57.31	92.87
	60	100.72	21.41	95.44	90.61	93.24	58.36	98.37
60	15	99.85	18.02	76.20	90.33	93.96	57.30	178.36
	30	97.51	16.58	71.20	90.78	94.27	57.86	188.07
	60	97.51	16.58	71.20	90.78	94.27	57.91	196.94
30	15	94.36	15.21	77.47	90.61	94.85	57.10	322.75
	30	94.24	15.07	68.65	90.91	94.85	57.57	333.66
	60	91.65	14.52	68.65	91.19	94.85	56.81	357.44

This table clearly highlights the benefits of implementing optimal rescheduling plans instead of leaving traffic operating according to the timetable. A large improvement in traffic performances is already reached when adopting the open-loop approach. In this case we obtain a reduction of *AvTotDelay*, *AvConsDelay* and *MaxConsDelay* that is respectively of 10%, 17% and 1.5% with respect to the timetable. Consistent gains are also achieved in punctuality since the number of punctual trains increases of 21.5% for the threshold of 3 min and 31.2% for the one of 5 min. Larger improvements are achieved when applying the closed-loop rescheduling. Indeed the closed-loop outperforms the open-loop for all tested combinations of its parameters *RI* and *PH*. For instance the closed-loop with *RI* = 120 s and *PH* = 15 min improves the open-loop solution of 4.5%, 6.4%, 8.7% respectively for the three measures of delay while 2% and 4.8% in terms of punctual trains at 3 and 5 min. When the *PH* is enlarged to 30 min these measures of performance are further improved respectively of: 1.3%, 3%, 1.2%, 2.9% and 1.6%. Widening the *PH* up to 60 min no improvement is instead observed. For a fixed value of *RI*, we can say that the quality of rescheduling solutions improves when enlarging the *PH* until the threshold value of 30 min. Beyond this value the improvement seems to be null (as in the case of *RI* = 120 and 60s) or only marginal (when *RI* = 30s). Very short *PH*s (i.e. 15 min) are less effective than larger ones since the rescheduling tool is forced to solve conflicts mainly by retiming rather than reordering. On the other hand, *PH*s larger than the threshold of 30 min can only marginally improve the solution, while certainly increasing the total computation time of the rescheduling tool (reported in the column  $T_{ROMA}$  in Table 1). This conclusion is fully in line with what previously deduced by Törnquist in (11).

The improvement of the solution is much more sensitive to the variation of *RI* than to the one of *PH*. When fixing for example the *PH* to 30 min, the closed-loop with *RI* = 120 s improves the open-loop solution of 6%, 9%, 10%, 4.7% and 6.3%, respectively for *AvTotDelay*, *AvConsDelay*, *MaxConsDelay*, and the amount of punctual trains at 3 and 5 min. When *RI* is reduced to 60 s, such measures of performance are further improved respectively of: 3.2%, 22.5%, 25.4%, 2% and 15%. If *RI* is further reduced to 30 s, these performances are still improved of 3.4%, 9.1%, 8.8% 1.4% and 10%. The closed-loop setup with short *RI* heavily improves the quality of the rescheduling plans with respect to an open-loop approach. In this case the critical point is constituted by the total computation time of the rescheduling tool that practically doubles each time that *RI* is reduced. The total simulation time  $T_{EGTRAIN}$  is instead more or less constant and averagely equal to 57.34 s. The value of *RI* that guaran-

tees the best performances of the closed-loop setup must be chosen on the basis of an optimal trade-off between solution quality and total computation time.

## 4. Conclusions

This paper presents an innovative analysis of a closed-loop rolling horizon approach for the optimal real-time management of railway traffic. A framework has been developed that dynamically integrates the tool for optimal rescheduling ROMA, with the microscopic railway traffic simulation model EGTRAIN, that is considered as a valid substitute of the real field. A practical application is realized to the Dutch railway corridor Utrecht-Den Bosch.

Results underline the beneficial impacts on traffic that optimal rescheduling can bring with respect to the case in which no rescheduling is applied and trains keep on following the original timetable. The closed-loop rescheduling approach always outperforms the open-loop. Specifically we observed that the solution quality strongly improves when shortening the *RI* of the closed-loop, although the computation times of the rescheduling tool heavily increase. The choice of the best value for *RI* must therefore allow a satisfactory trade-off between solution quality and computation times. A smaller role has instead the *PH* which improves solution quality if not too short. On the other hand *PH*s longer than a threshold  $\tau$  bring only marginal improvements while increasing computation times. As for quality, the closed-loop shows a similar behaviour for the stability of its plans. Indeed short *RI*s give on average more stable plans in terms of train reordering, although they vary more sharply. Short *PH*s return slighter variations in the plans since in this case less reordering is performed. Plan stability is more or less constant while enlarging the *PH*s over a threshold  $\tau$ .

The main conclusion of this study on closed-loop setups is the recommendation for a short value of *RI* and a length of the *PH* beyond which the quality of the plans do not consistently improve anymore. Preliminary studies are advised to identify for each specific case these values of *RI* and *PH*.

Future research will be addressed to determine these values for different case-studies and how the closed-loop performs in the case of both heavy and slight perturbations. Moreover we will investigate the impacts on traffic performances when plans of the closed-loop are implemented after a certain time needed by the dispatcher to practically communicate them to the field.

### Acknowledgments

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## ON-TIME: Struktura kierowania ruchem kolejowym w czasie rzeczywistym oparta na układzie zamkniętym w rzeczywistym środowisku

### Streszczenie

Istnieje wiele dostępnej literatury na temat modeli i narzędzi do optymalnego kierowania ruchem kolejowym w czasie rzeczywistym, ale wiedza na temat ich wpływu na funkcjonowanie jest wciąż nieprecyzyjna i bardzo ograniczona na skutek słabego ich wdrożenia w praktyce. W niniejszej pracy dokonano analizy zachowań opisanych narzędzi przy zastosowaniu ustawień obiegu zamkniętego w realnym środowisku. Opracowano strukturę łączącą narzędzie do zmiany rozkładu jazdy ROMA z mikroskopowym modelem symulacji EGTRAIN. Możliwe jest zarządzanie ruchem kolejowym w sytuacjach różnych zakłóceń ruchu przy użyciu przesuwnej horyzontu, gdzie optymalne plany są wyliczane na podstawie bieżących informacji o ruchu i ładowane do modelu symulacji. Ustawienia obiegu zamkniętego są badane w różnych kombinacjach parametrów w odniesieniu do jakości i stabilności zmienionych rozkładów. Porównanie jest dokonywane względem typowego podejścia z obiegiem otwartym, które wdraża tylko jeden plan, wyliczony na podstawie przewidywanych opóźnień pociągów. Obydwa podejścia są oceniane w porównaniu do przypadku, w którym pociągi poruszają się zgodnie z oryginalnym rozkładem.

Rezultaty uzyskane w holenderskim korytarzu Utrecht – Den Bosch wykazały, że zamknięty obieg zawsze sprawdza się lepiej niż obieg otwarty.

**Słowa kluczowe:** zmiana rozkładu w czasie rzeczywistym, sterowane predykcyjne zamkniętego układu, analiza stabilności, jakość systemu kierowania ruchem



## **ON-TIME: Структура управления железнодорожным движением в реальном масштабе времени с обратной связью в реальной железнодорожной среде**

### **Резюме**

Существует широкий выбор литературы на тему моделей и инструментов для оптимального управления железнодорожным движением, однако знание об их влиянии на эксплуатацию все таки размыто и ограничено из-за недостаточного их осуществления на практике. В этом докладе анализируем, как они выполняют свою роль в случае употребления обратной связи в реальной железнодорожной среде. Разработана структура соединяющая инструмент для изменений графика движения поездов ROMA с микроскопической моделей EGTRAIN. Управляется движением в случаях разных помехов при помощи подвижного горизонта, где оптимальные планы сгенерированы на основании текущих информации о движении и загружены в имитационную модель. Настройка обратной связи рассматривается для разных сочетаний параметров по отношению к качеству и стабильности изменений в графике движения. Результаты сравнены с типичным подходом отрицательной обратной связи, которая позволяет внедрить только план рассчитанный на основании ожидаемых опозданий поездов. Оба подхода оценены в сравнении с ситуацией, в которой никакие помехи не выступают и поезда двигаются согласно расписанию. Результаты получены в транспортном коридоре Утрехт – Ден Бош показывают, что обратная связь всегда выигрывает у отрицательной обратной связи.

**Ключевые слова:** изменения графика движения в реальном масштабе времени, анализ стабильности, качество координации