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Comparison of microscopic and macroscopic approaches to simulating the effects of infrastructure disruptions on railway networks

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Abstract

The current state-of-the-art in timetable analysis in the presence of disruptions is to use railway microsimulation, which typically yields detailed results on infrastructure or timetable performance. However, micro-simulation is time-consuming and requires a detailed infrastructure model. This paper outlines a macroscopic approach which aims at reducing execution time by restricting the level of detail to high-level relations between significant events. In particular, the effect of disruptions is modelled by sampling delay times from probability distributions obtained from historical data. In this paper, we test whether this approach, given common disruption scenarios, still allows accurate results on delays to be obtained. Two disruption scenarios were simulated in RailSys and with the new method, using limited parameter tuning. In the results, visually similar delay distributions were observed. Although there is some room for improvements in accuracy, the new approach appears promising, and we found no evidence against its suitability in the presence of disruptions.

Keywords: railway; simulation; timetable; capacity; disruptions

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1. Introduction

1.1. Background and motivation

Microscopic simulation (microsimulation) is currently the state-of-the-art in analysis of timetables and projected new infrastructure. Using microsimulation, it is possible to accurately estimate delays, travel times, and capacity utilization. However, microsimulation requires a detailed model of the infrastructure to be analysed and is time-consuming, thereby making microsimulation infeasible for analysis of complete networks. At the same time, purely local simulation of a limited network may miss complex network effects. Furthermore, as simulation tools are technically advanced, simulations need to be performed by experts for the results to be meaningful. In this paper, we propose a micro-macro simulation approach designed to overcome this shortcoming. In the approach, detailed statistics from either previous microsimulation runs or historical delay and travel time data are used as input to a macroscopic simulation model, where rail traffic is modelled as a directed graph of arrivals and departures in the rail network. The main advantages of the macroscopic approach are twofold: first, it has a fast runtime, which allows simulating an entire day of operation on a large railway network (e.g. the entire German network) within a few minutes. Second, it requires less infrastructure information than a microscopic simulation, which makes maintenance of the model and testing of different scenarios easier. These advantages are bought at the cost of lower accuracy of modelling results.

The paper deals with a case study of the Southern main line in Sweden. The focus of the study is tactical planning and operational processes, where the overall objective is to investigate new methods based on simulation that can also help in the later stages of the planning phase. The research question considered is whether a macroscopic modelling approach that is feasible for simulating the operation in large networks can also capture the essential characteristics of the effects of infrastructure disruptions, as evident in a detailed microsimulation. In other words, is the reduced accuracy of the macroscopic model critical, or can it provide meaningful results in a disruption scenario?

1.2. Related work

Simulation is a commonly used method for modelling railway traffic and to evaluate infrastructure alternatives and timetables. It is for example possible to test several infrastructure alternatives and measure the impact on the traffic and also to test timetable alternatives for feasibility and delay propagation. An overview of early approaches to simulation models for train movement, power supply systems and traction drives was written by Goodman et al. (1998). Other work in railway simulation include papers by Ho et al. (2002), who describe a general-purpose railway simulator for signalling, power systems and traction equipment, and Azadeh et al. (2008) who proposes a decision analysis model based on the Analytical Hierarchical Process (AHP), data envelopment analysis and a macroscopic queueing simulation model for the scheduling of cargo and passenger trains.

Microsimulation models include low-level details on railway operations and typically models a large number of rail segments, switches, signals and train-to-object interactions, which gives a close and realistic representation of reality. The two most commonly used microsimulation software programs in Europe are Railsys (Radtke and Hauptmann, 2004; Siefer and Radtke, 2005) and OpenTrack (Nash and Huerlimann, 2004), which are used both in research and in industry (for examples of RailSys applications, see e.g. Lindfeldt and Sipilä, 2014; Sipilä, 2010, 2011, 2014 2015, and Warg and Bohlin, 2016). However, microsimulation models tend to become very large and the simulations runs therefore become time consuming, which might require a delimitation of the simulated network or traffic system. Macros both optimization and imulation models in contrast do not model as many infrastructure objects in the railway network, and the simulations therefore become faster. For example, Büker and Seybold (2012) examine how to deal with simulation in large networks using a macro-simulation model.

In the literature, simulation is often combined with optimization in such a way that an optimization model is used for generating a timetable which is later evaluated via simulation (Fischetti et al., 2009; Dewilde et al., 2013; Takeuchi et al., 2007). Salido et al. (2012) propose analytical and simulation methods to measure robustness in a single railway line. Hassannayebi et al. (2014) developed a two-stage GA-based simulation optimization approach in order to minimize the expected passenger waiting times. A further developed methodology with robust multi-objective stochastic programming models for train timetabling is presented by the same author (Hassannayebi et al., 2016). Pouryousef et al. (2016) use a multi-objective linear programming model together with a rail simulation tool to improve capacity utilization or level of service. The model uses both conflict resolution and timetable compression techniques.

Together with an infrastructure model, suitable railway timetables are necessary to ensure that simulation results are valid with respect to the analysis task. There is a large body of research in timetabling, and timetabling approaches can also be used for capacity and sensitivity analysis, in particular when robustness and uncertainty in data is considered. The approaches can, according to Fischetti and Monaci (2009), be divided into stochastic programming methods and robust programming methods. Cacchiani and Toth (2012) underlines the efforts made to develop methods and models for producing robust timetables. Fischetti and Monaci (2009) have proposed a method called Light robustness to solve LP-problems with uncertainty in data. The approach and others are applied to timetabling in Fischetti et al. (2009). Forsgren et al. (2013a) and Forsgren et al. (2013b) introduced the planning approach of successive allocation of train paths. They developed a method for optimization of timetables by redistribution of buffer time to minimize train running times by reallocation of train crossings, with regards to robustness. Jovanovic et al. (2016) focused on optimal distribution of buffer times based on priority of events, modelled as a knapsack problem, not to consume too much capacity. Finally, Andersson et al. (2013, 2013) quantify and increase robustness of timetables in critical points.

1.3. Contribution

The contribution of the paper is as follows.

- A new macroscopic approach for timetable simulation, based on high-level interactions between trains and the infrastructure and therefore suitable for network level evaluation, is introduced.
- In an experimental study, the feasibility of the new approach is analysed by comparing the delay distributions generated with the new macroscopic approach to those obtained in a standard micro-simulation approach using the tool RailSys.

1.4. Paper outline

The rest of the paper is structured as follows. In Section 2, the new approach as well as the reference microsimulation model RailSys is described. Section 3 describes a controlled simulation study performed on the Southern main line in Sweden, where the two models are compared. Section 4 concludes the paper with a discussion of the results and the usability of the method.

2. Approach

2.1. Macroscopic simulation using a train interference graph

The macroscopic simulation is a graph-based simulation utilizing Monte Carlo methods to model train operation, interference between trains and disruptions. Timetable information of a planned train route serves as the basic input for the simulation. From the timetable, nodes of a graph are constructed, containing the information when a train is planned to arrive at and depart from a point on the railway network. The nodes are connected via directed edges corresponding to the train travelling between the two nodes. No further infrastructure information is needed to construct the basic graph.

The interference between trains, e.g. one train having to wait because a delayed train is in front on the same track, is taken into account via so-called “interference functions” (see Figure 1). The interference functions parameterize how much delay is added to an influenced train by the influencing train. The functional form of the interference function can be freely chosen and usually depends on the minimum headway between the trains or the point at which the trains change position. This is realized by adding additional directed edges between two trains which are at the same infrastructure node within a certain time window. For this work, the time window has been chosen to be -25 minutes and +60 minutes. Hence, the interference edges are going both for- and backwards in time. Interference functions going backwards in time lead to circles in the graph which need to be avoided in order to be able to sort the resulting graph. The number of introduced circles is largely reduced when splitting the nodes into two separate nodes A and B. These are again connected via directed internal edges going from A to B. The interference edge is constructed in a way to always go from the A node of the interfering train to the B node of the affected train. Therefore, these can be seen as a train entering an interference zone at node A and leaving it influenced at node B. A few more complex circles remain due to a combination of edges being positive and negative in time. These are solved by removing the edges going negative in time which are related to the circle.

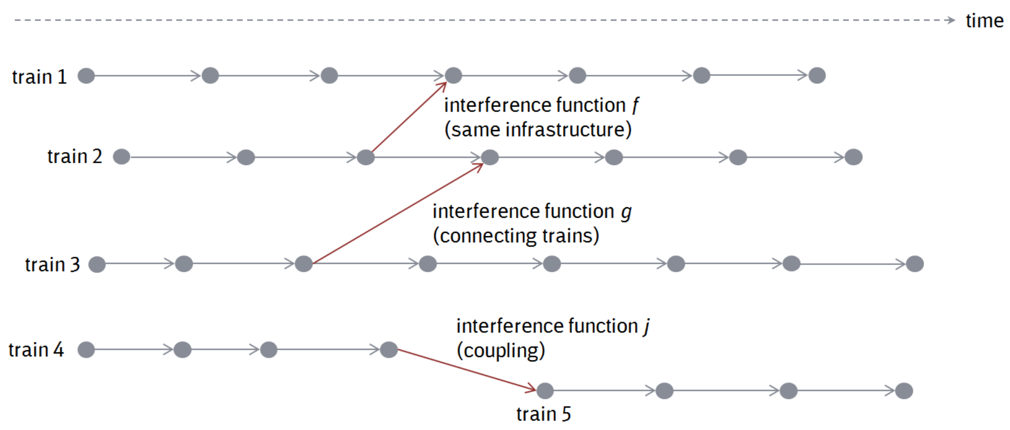

Figure 1: Schematic of the train interference graph.

One crucial ingredient for the interference functions is the minimum headway time between trains. These are calculated using basic infrastructure information and parameters for generic model trains with the formulas described in Wendler and Nießen (2005). For infrastructure, parameters such as maximum speed, installed safety systems, distance between two nodes, the length of the block and the distance to the next passing loop is needed. For the model trains, basic parameters such as maximum speed, deceleration rate and train length are needed. Interference due to trains waiting for a connecting train or trains using the same rolling stock is currently not implemented. The final, cycle-free, graph is in the end sorted for later processing.

Disruptions are modelled via a Monte Carlo method. Probabilities that certain disruptions occur are extracted from historical train data which in the present study is represented by the simulation results from the microscopic tool RailSys. In general, two types of disruptions can be thought of: disruptions which directly affect a single train and disruptions affecting a part of the infrastructure, and by that affecting all trains running on that section. For the latter, the duration of the infrastructure disruption is sampled from a log-normal distribution which can be fitted to empirical data. The delay that a train receives when being affected by a disruption is sampled from a Weibull distribution which can again be fitted to empirical data.

Additionally, for each driving time between two nodes, a random delay is sampled from a normal distribution. This random delay accounts for minor influences which lead to short deviations from the planned drive time but which are not specifically recorded. However, for the comparison presented in this paper, no such random influences are simulated to make the simulation methods more similar. Instead a random initial delay for each starting train or for each train entering the simulated corridor is sampled.

The actual simulation can be subdivided into three steps. First all the needed information, like the sorted graph, the calculated minimum headway time, and the parameters for the disruption modeling are read in. In a second step, a day of the simulation is prepared by sampling infrastructure disruptions for each infrastructure edge and general disruptions for each edge of the train ride. Finally, the simulation goes through the sorted graph and processes each node. If a train is using an infrastructure segment which is at that time disrupted, then an additional delay is sampled from a Weibull distribution using the parameters corresponding to the disruption types. At each node for all interfering trains the resulting delay is calculated and the maximum delay is added.

This approach, in the current prototype implementation, allows simulating one day of operation of the entire German railway network in approximately one minute of computation time.

2.2. Microscopic simulation using RailSys

For the microsimulation infrastructure and train types are modelled on a detailed level in RailSys. Among others, the exact position of signals, switches, speed reductions and gradients as well as the characteristics and performance of the trains (maximum speed, length, weight, acceleration and deceleration etc.) is defined. Based on that, train runs are created and located on the infrastructure and allocated to the belonging train routes and signals. Running times and occupation of block sections are estimated based on the available infrastructure and vehicle data. This enables also the detection of conflicts between trains. To the technical minimum running time that can be reached by the train type on the assigned infrastructure, different kinds of allowances can be added. In the same way, time supplements can be added to scheduled stops. All kinds of allowances can to a user-defined share be used for recovery from disruptions.

To evaluate the performance of a timetable, a certain amount of days is simulated with randomly applied primary

delays (entry delays for trains entering the network dwell time delays at stations with scheduled stop and run time delays on the line). These primary delays are based on historical delays and aim to model the timetable´s performance according to real operation. To evaluate certain disruptions, these are modelled explicitly (e.g. track closure or speed reduction for a line section or a train) and the outcome of a simulation with these disruptions is compared to the initial scenario.
Conflicts are detected in the program and in the simulation solved by the program´s dispatching function. For example, a fast train catching up with a slower train receives delays, or results in a rerouting. Decisions are based on the priority of the trains in conflict, which is based on the train type and its current on-time performance. RailSys offers a wide range of settings for adjusting the simulation.

2.3. Schematic of research methodology

For the present research, the results of the microscopic simulation are used to calibrate and validate the macroscopic model. The flow of information is depicted in Figure Figure 2.

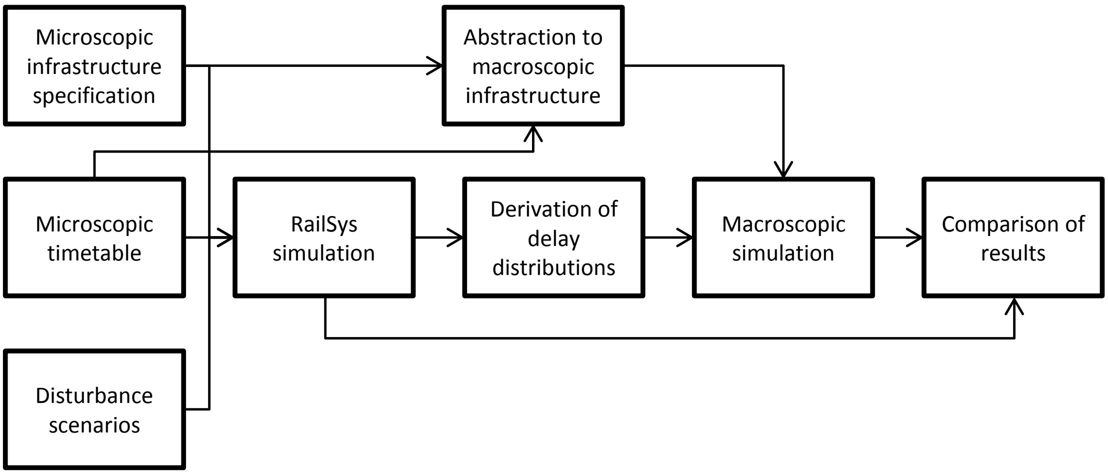

Figure 2: Flow of information between microscopic and macroscopic model.

3. Evaluation

3.1. Description of test case

For the present study, we were interested in understanding the effect of simulating disruptions with the macroscopic model. An advantage in terms of simplicity, but potential disadvantage with regard to model accuracy, is that the macroscopic approach does not consider the details of any specific disruptions. In order to assess the consequences of this modelling choice, we construct a controlled experimental scenario, where we do not use actual empirical train operation data as the input to the model, but the output of a microscopic simulation in RailSys. We assume that RailSys accurately models the effect of infrastructure disruptions (in our case speed reductions on a certain line segment) on train traffic. In reality (as well as in RailSys), a speed reduction on a line segment usually implies that the speed of all trains travelling on this line will be reduced to the new speed limit. On a given day, the speed limit will usually not vary between trains. However, the macroscopic simulation does not explicitly model such details. Instead, delays of individual trains are sampled from a distribution that is fitted to the delays observed across all days on which a certain type of disruption was present on the line segment. Therefore, this distribution will contain delays generated by very different speed limits (or even more diverse disruption types). This approach will make the distribution of delay times across different trains on a single simulated day more heterogeneous than they would be in real operation. The research question is whether this increased heterogeneity leads to a systematic bias in simulating disruptions with the macroscopic model.

3.1.1. Examined network and timetable

For this study, the 357 km double track line between Mjölby and Malmö, a part of the Swedish Southern main line, is chosen. Traffic on that line is dense and heterogeneous with services entering and exiting the line on

several parts and different properties regarding stopping patterns and vehicle characteristics. Fast long-distance passenger trains on their way from Stockholm to Copenhagen share the line with different kind of commuter trains, regional trains and freight trains.
Infrastructure, train models and a basic timetable are provided by the Swedish Transport Administration (Trafikverket). The timetable was adjusted to contain all scheduled trains for a typical day in September 2016. Adjacent lines are partly included by simulating the entry and exit of services from/to those lines. In order to have a controlled simulation environment with as few unaccounted random effects as possible, we reduced the timetable to minimum technical running times including 3% standard allowance. Random disturbances based on empirical delays for 2016 are added for the simulation in RailSys for every train that enters or starts on the line. However, random run and dwell time delays which are usually part of Trafikverket's simulations on this corridor were excluded. As a consequence, we also had to remove time buffers at stops, because without dwell time delays these buffers would have allowed to reduce other delays, and eliminated almost all random fluctuation from the arrival time. That means that further allowances which usually are included have been removed, and that delayed trains will proceed with delay until they leave the system. Under these settings, the chosen timetable was not conflict-free, and trains accumulated additional delays due to train interference on the line. Further, we did not allow trains to use tracks other than scheduled which differs from real operation.

3.1.2. Types of disruptions

The type of disruption itself is not critical for the research question, because only the distribution of delay times is used as an input in the macroscopic model. Thus, the essential feature of the test case is that there are different disruptions (occurring on different simulated days) on the same line segment, and that these different disruptions lead to (a) different distributions of additional delay on the disrupted line segment, and (b) different delay distributions on the final stop of the line.
For the test case, we picked a speed reduction as the type of disruption, because this is the easiest to model in RailSys. To obtain different delay distributions, we used two different maximal speeds, 40 km/h and 80 km/h on a 9.8 km long segment of the north-going track between Eslöv and Stehag (regular speed limit 160 km/h, on 0.4 km 100 km/h) on the southern part of the chosen line. The speed reductions correspond with the two speed limits that can be shown by signals. 80 km/h is for instance the speed limit if some parts of the signal system are malfunctioning. Figure 3 shows the infrastructure and timetable for the chosen section in RailSys.

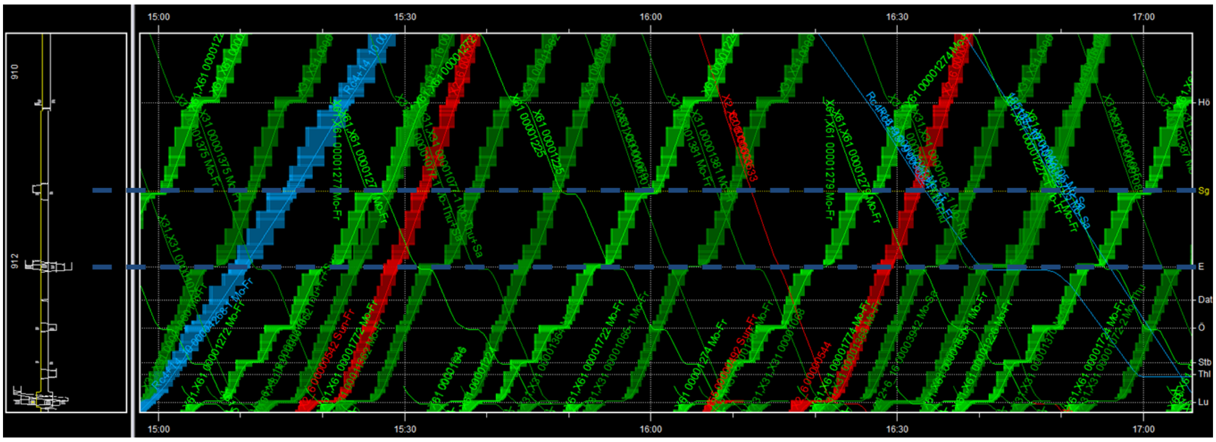

Figure 3: Left: Track layout for the chosen line section. Disruption was applied between Eslöv (E) and Stehag (Sg), se dotted lines. Right: Extract from the graphical timetable for the same section. For trains operating the affected track, block occupation is displayed.

3.2. Results for microscopic modeling

We quantify the immediate effect of the disruption on runtimes between Eslöv and Stehag by looking at the additional delay that trains accumulate between Dammstop and Höör, the first station before Eslöv and after Stehag, respectively. This is necessary because due to breaking and acceleration, the disruption already has an effect on runtimes in the line segments immediately surrounding the speed limit Figure 4 shows that without speed limit, there is almost no delay on this line segment. Introducing the 80 km/h speed limit shifts the distribution of delay times to the right. As expected, fast long-distance trains are more severely affected (on average about 5 min delay) than regional trains (ca. 4 min), commuter trains (2.5 min) or freight trains, where the distribution is broader. The more severe speed limit of 40 km/h has a stronger effect on delays, causing more than 10 minutes delay for almost all trains.

The resulting arrival delays are evaluated at Hässleholm, 30 km north of Dammstop. In the case without disruption, there are already considerable delays due to conflicts in the timetable resulting from the input delays, the missing time buffers (see Figure 5) and the fact that trains scheduled on the same track cannot use alternative tracks even if that is possible in reality, especially at larger stations. In this respect, the microscopic simulation is not perfectly realistic.

For the research question, the realism of this delay distribution is not essential. It is more important that the effect of the disruption is realistic. This can be observed in the bottom two rows of Figure 5, where the delay distributions are shifted to the right as a consequence of the disruption, and the shift is more pronounced for the lower speed limit. The facts that the delay distributions at Hässleholm differ between the basic scenario without disruption and the two disrupted scenarios, and also from one disruption to the other, show that the chosen parameters are suitable for investigating the disruption simulation in the macroscopic model.

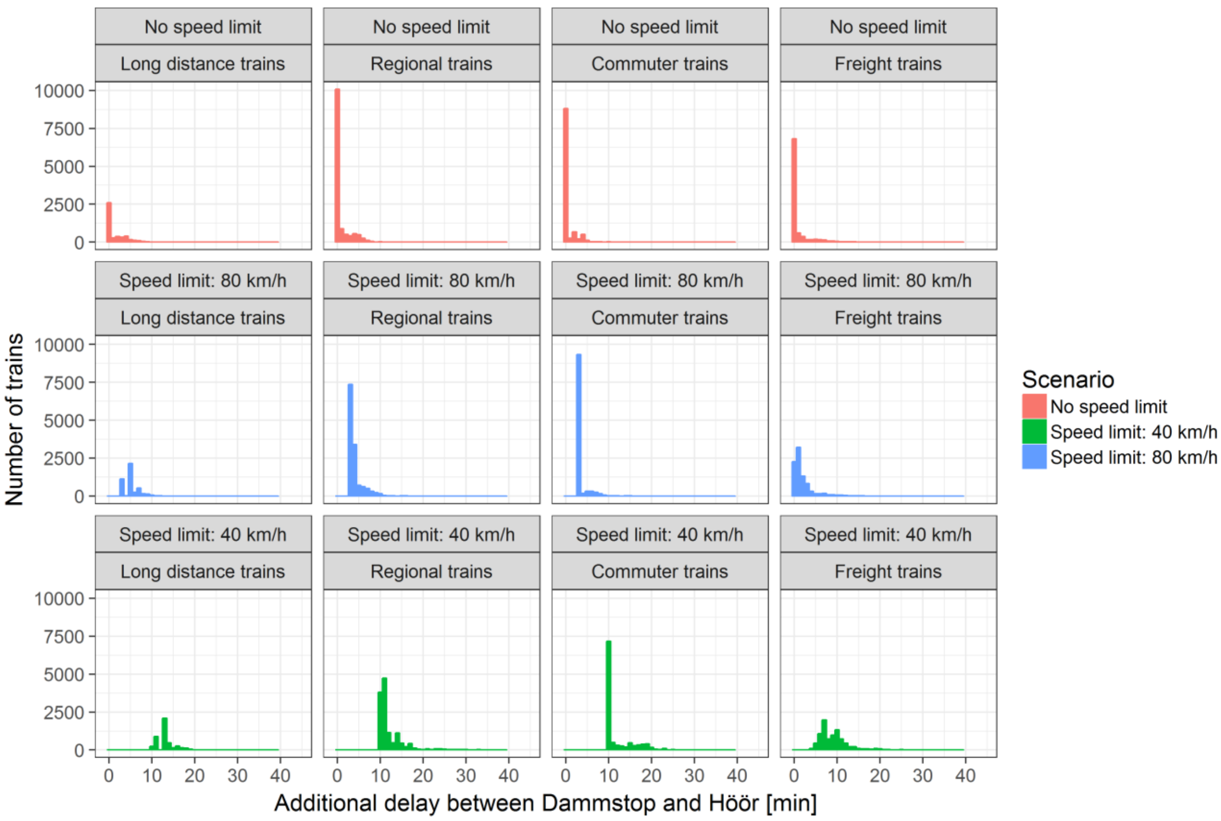

Figure 4: Additional delay between Dammstop and Höör, shown for the three different disruption scenarios and different train categories

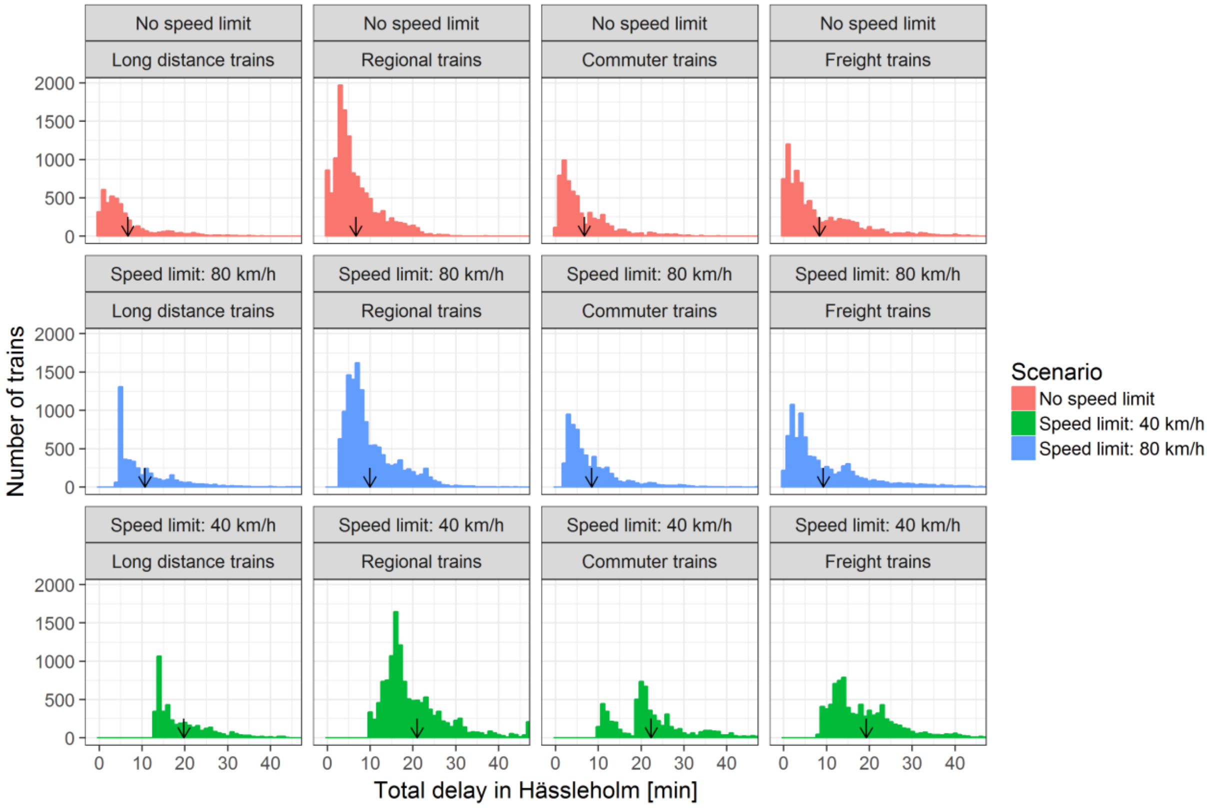

Figure 5: Total delay in Hässleholm, shown for the three different disruption scenarios and different train categories.

3.3. Results for macroscopic modeling and comparison of the results of the two models

The macroscopic simulation is also evaluated by inspecting the delay distributions at Hässleholm. In the basic scenario without disruptions, the general shape of this delay distribution observed in the microscopic simulation is well approximated by the macroscopic model for all train categories (see Figure 6, top row). However, there are also systematic deviations. Most prominently, the macroscopic simulation overestimates the number of trains that arrive with little or no delay, and underestimates the frequency of occurrence of long delays, for all train types except commuter trains. One possible reason for these differences is that some conflicts that occur in RailSys are not captured by the macroscopic simulation. More exact calibration of the minimum headway times might also reduce the discrepancies. The overall agreement between the distributions appears to be sufficient to investigate whether this agreement can be maintained in the presence of disruptions.

The effect of the disruption on the delay distributions predicted by the macroscopic model is depicted in the bottom row of Figure 6. For all train categories, except the commuter trains, two peaks are visible in RailSys, resulting from the two different speed limits. In the macroscopic simulation, the peaks are less pronounced, and more delays in the intermediate range occur. An important question is whether the distributions from the macroscopic simulation contain fewer small delays compared to the RailSys results. This might occur because in the macroscopic simulation, a train that receives a short delay from the disruption might be slowed down by a train driving in front of it and receiving a large delay. In RailSys, this would not happen because the delay is similar for all trains driving on the same simulated day. There are indeed differences visible in the shape of the distributions between the macroscopic simulation and RailSys. However, the mean delays are not higher in the macroscopic simulation. There are slightly fewer short delays in the macroscopic simulation, but the effect is not pronounced.

In the case of the commuter trains, a distribution with three peaks is visible in RailSys. The third peak is caused by train succession conflicts at Hässleholm, where trains arriving late receive an additional delay. This conflict is not adequately modelled in the macroscopic simulation due to a missing interference edge in the model graph.

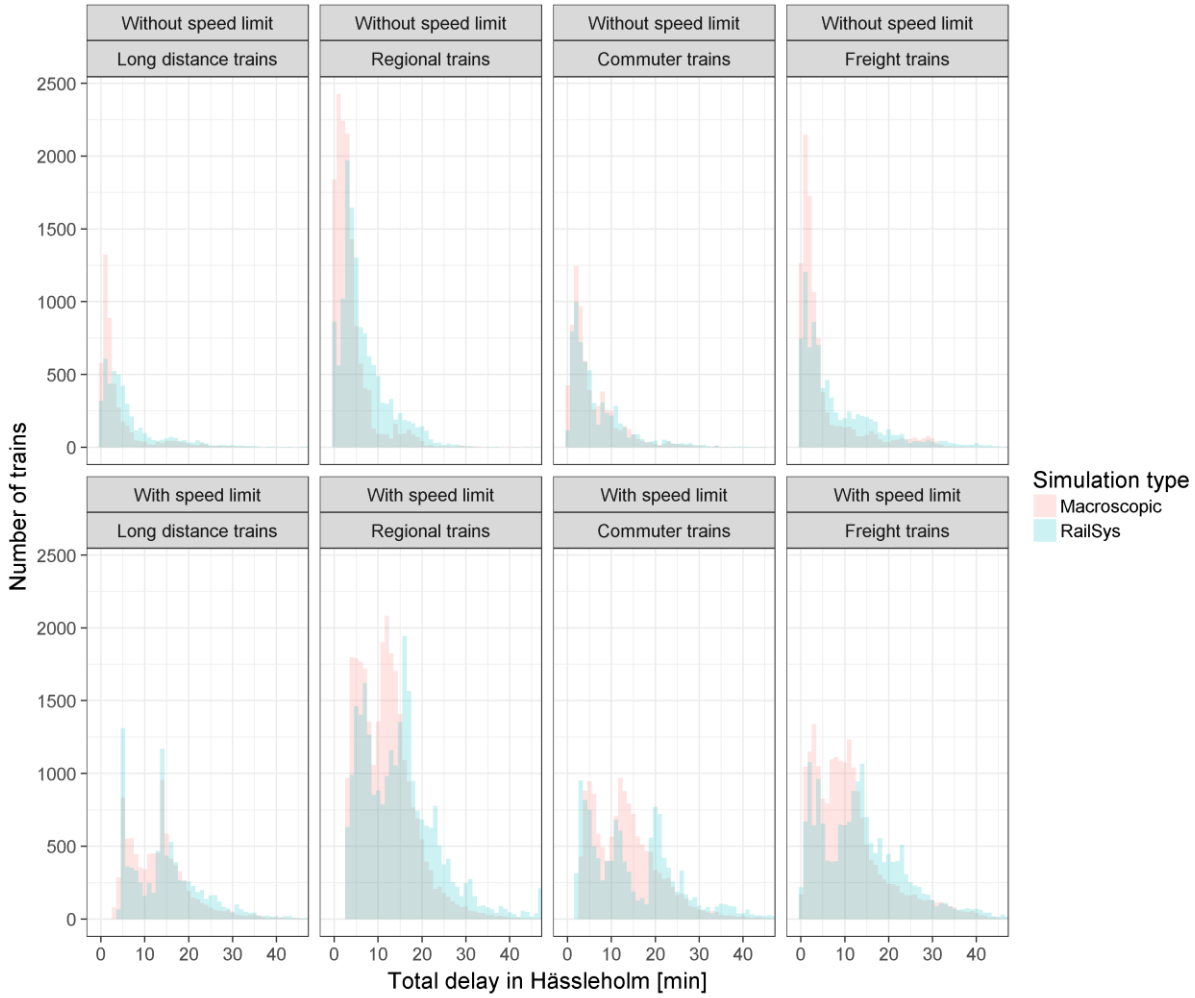

Figure 6: Comparison between macroscopic and microscopic (RailSys) approach, without and with a disruption in the form of a temporary speed limit (top and bottom, respectively).

Although the simulations were executed on different computers it was obvious that the macroscopic simulation is much faster than the microscopic. While the simulation time for 300 days on the examined network is in the order of hours in RailSys, the new macroscopic approach only takes seconds (up to one minute for the whole German network).

4. Discussion and Conclusion

We have presented a new approach to simulate railway traffic on a macroscopic level. This approach allows running simulations without detailed microscopic infrastructure information, decreasing the maintenance requirements of the simulation, and increasing simulation speed. Here, we tested if the chosen method for simulating the effect of infrastructure disruptions leads to systematic deviations between the average effect of such disruptions in a microscopic simulation and the effect predicted by the macroscopic model. Our results indicate that the modelling approach is promising. However, some differences between the microscopic and macroscopic modelling results are visible. These indicate that further refinements of the macroscopic model, especially concerning the train interference at junction points, are required to fully capture the delay distributions that are obtained in a microscopic simulation. Considering that very little calibration effort went into the macroscopic simulation, the agreement between macroscopic and microscopic simulation for many trains is encouraging. To further validate the approach, a comparison to empirical train operation data is planned in the near future.

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6. References

Andersson, E. V., Peterson, A., and Törnquist Krasemann, J. (2013). Quantifying railway timetable robustness in critical points. Journal of Rail Transport Planning & Management, 3(3), 95–110. http://doi.org/10.1016/j.jrtpm.2013.12.002

Andersson, E. V., Peterson, A., and Törnquist Krasemann, J. (2015). Reduced railway traffic delays using a MILP approach to increase Robustness in Critical Points. Journal of Rail Transport Planning & Management, 5(3), 110–127. http://doi.org/10.1016/j.jrtpm.2015.09.004

Azadeh, A., Ghaderi, S. F., and Izadbakhsh, H. (2008). Integration of DEA and AHP with computer simulation for railway system improvement and optimization. Applied Mathematics and Computation, 195(2), 775-785.

Büker, T., and Seybold, B. (2012). Stochastic modelling of delay propagation in large networks. Journal of Rail Transport Planning & Management, 2, 34-50

Cacchiani, V., and Toth, P. (2012). Nominal and robust train timetabling problems. European Journal of Operational Research, 219(3), 727–737. http://doi.org/10.1016/j.ejor.2011.11.003

Dewilde, T., Sels, P., Cattrysse, D., and Vansteenwegen, P. (2013). Robust railway station planning: an interaction between routing timetabling and platforming. In: Proceedings of 5th International Seminar on Railway Operations Modelling and Analysis - RailCopenhagen 2013, Technical University of Denmark in Copenhagen and IAROR, Copenhagen, Denmark

Fischetti, M., and Monaci, M. (2009). Light robustness. In Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics) (Vol. 5868 LNCS, pp. 61–84). http://doi.org/10.1007/978-3-642-05465-5_3

Fischetti, M., Salvagnin, D., and Zanette, A. (2009). Fast Approaches to Improve the Robustness of a Railway Timetable. Transportation Science, 43(3), 321–335. http://doi.org/10.1287/trsc.1090.0264

Forsgren, M., Aronsson, M., and Gestrelius, S. (2013a): Towards shorter lead times in railway timetabling in Sweden, in Proceedings from 16th International IEEE Conference on Intelligent Transportation Systems - (ITSC), 6-9 Oct. 2013

Forsgren, M., Aronsson, M., and Gestrelius, S. (2013b): Maintaining tracks and traffic flow at the same time, Journal of Rail Transport Planning & Management, Volume 3, Issue 3, August 2013, Pages 111–123.

Goodman, C. J., Siu, L. K., and Ho, T. K. (1998, April). A review of simulation models for railway systems. In Developments in Mass Transit Systems, 1998. International Conference on (Conf. Publ. No. 453) (pp. 80-85). IET.

Hassannayebi, E., Sajedinejad, A., and Mardani, S. (2014). Urban rail transit planning using a two-stage simulation-based optimization approach. Simulation Modelling Practice and Theory, 49, 151–166. http://doi.org/10.1016/j.simpat.2014.09.004

Hassannayebi, E., Zegordi, S. H., Amin-Naseri, M. R., and Yaghini, M. (2016). Train timetabling at rapid rail transit lines: a robust multi-objective stochastic programming approach. Operational Research, 1–43. http://doi.org/10.1007/s12351-016-0232-2

Ho, T. K., Mao, B. H., Yuan, Z. Z., Liu, H. D., and Fung, Y. F. (2002). Computer simulation and modeling in railway applications. Computer Physics Communications, 143(1), 1-10.

Jovanović, P., Kecman, P., Bojović, N., and Mandić, D. (2017). Optimal allocation of buffer times to increase train schedule robustness. European Journal of Operational Research, 256(1), 44–54. http://doi.org/10.1016/j.ejor.2016.05.013

Lindfeldt A., Sipilä, H., 2014. Simulation of freight train operations with departures ahead of schedule. In Proceedings of the 14th International Conference on Railway Engineering Design and Optimization (CompRail 2014), Rome, Italy.

Nash, A., and Huerlimann, D. (2004). Railroad simulation using OpenTrack. WIT Transactions on The Built Environment, 74.

Pouryousef, H., Lautala, P., and Watkins, D. (2016). Development of hybrid optimization of train schedules model for N-track rail corridors. Transportation Research Part C: Emerging Technologies, 67, 169–192. http://doi.org/10.1016/j.trc.2016.02.008

Radtke, A., and Hauptmann, D. (2004). Automated planning of timetables in large railway networks using a microscopic data basis and railway simulation techniques. WIT Transactions on The Built Environment, 74.

Salido, M.A., Barber, F., Ingolotti, L. (2012). Robustness for a single railway line: Analytical and simulation methods. Expert Systems with Applications, 39 (18), 13305-13327

Siefer, T., and Radtke, A. (2005). Railway simulation: key for better operation and optimal use of infrastructure. In Proceedings of the 1st international seminar on railway operations modelling and analysis.

Sipilä, H., 2010. Simulation of modified timetables for high speed trains Stockholm–Göteborg. In Proceedings of the First International Conference on Road and Rail Infrastructure, Opatija, Croatia.

Sipilä, H., 2011. Calibration of simulation model on the Southern Main Line in Sweden. In Proceedings of Railway Engineering, 11th International Conference, London, UK.

Sipilä, H., 2014. Evaluation of single track timetables using simulation. Published in: Proceedings of the IEEE/ASME 2014 Joint Rail Conference, Colorado Spings, USA.

Sipilä, H., 2015. A simulation based framework for evaluating effects of infrastructure improvements on scheduled and operational delays. In Proc. 6th International Conference on Railway Operations Modelling and Analysis (RailTokyo), Tokyo, Japan.

Takeuchi, Y., Tomii, N., and Hirai, C. (2007). Evaluation method of robustness for trains schedules. Quarterly Report of Railway Technical Research Institute, 48, 197-20

Warg, J., and Bohlin, M. (2016). The use of railway simulation as an input to economic assessment of timetables. Journal of Rail Transport Planning and Management, 6(3), 255–270.

Wendler, E., and Nießen, N. (2005) „Infrastrukturmodellierung für die strategische Netzplanung“ – In: Proc. : 20. Verkehrswissenschaftliche Tage, Dresden, Session 4b.