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RAIL TRANSIT NETWORK DESIGN SUPPORTED BY AN OPEN SOURCE SIMULATION LIBRARY: TOWARDS RELIABILITY IMPROVEMENT

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ABSTRACT

Rail transit network design is extremely cumbersome and complex. Reliability should be adequately considered at strategic, tactical and operational levels of the design, which requires skilled professionals as well as technological support. This paper describes an open source Java rail simulation library that supports distributed microscopic multi-formalism simulation considering the impact of different aspects of the rail network design in one self-contained simulation package. It uses configurable components that represent the physical rail infrastructure and diverse control strategies as model building blocks. The fact that it is open source provides a unique possibility to improve the package, and it adds flexibility for further research. The case study presented shows that at the early design stages, analyzing the generated data provides designers with an overview to compare the impact of different design alternatives. Refined simulation studies are needed when more information is available. Further research is proposed to extend the library with components that allow for automatic model validation and calibration.

1. INTRODUCTION

The development of public transportation is a crucial topic in modern society *(1)*. How well a transit network provides users with cost-effective service is the key for competitiveness and attractiveness. In the UK, for example, about 25~35% of the people would use transit service more often if the service was improved *(2)*. Reliability is one important dimension of transit quality of service *(3)*. Many studies *(3, 4, 5, 6)* show that punctuality and travel time have a main influence on reliability. These performance indicators are sensitive to transit network structure and service frequency *(7, 8)*. Therefore improving service reliability should be tackled at different stages of transit network design, i.e. not only at the operational level but also at strategic and tactical levels *(9, 10, 11)*.

For large and complex rail networks, the planning and design are cumbersome and time-consuming; the same holds for the microscopic modeling of the networks. As such, model construction and modification require flexible model composition and configuration to enhance reusability. An open source component-based Java rail simulation library has been developed for this purpose. The library supports distributed microscopic multi-formalism rail simulation. Its main functionality is presented in this paper. A case study shows the application of the library in supporting rail transit network design. By studying design alternatives, designers could obtain a more insightful analysis. Such an approach leads to virtual integration of rail network planning and operations, and it potentially results in a more robust and reliable design. Reliability in transit networks can be classified into three categories *(12)*: (i) schedule reliability (regarding departure times), (ii) travel time reliability, and (iii) connectivity reliability. The first two are the focus of this paper.

The remainder of this paper is organized as follows. Section 2 discusses transit network design concerning reliability issues, and the role of simulation in this regard. In Section 3 the motivation for developing the rail simulation library is explained. Section 4 gives an introduction to the library. Section 5 presents a case study for the Groningen project, in which a light rail line is to be constructed in a city of the Netherlands. Future research is described in section 6 to conclude the paper.

2. RAIL TRANSIT NETWORK DESIGN AND RELIABILITY ISSUES

In transit network design, service reliability should be adequately considered at strategic, tactical and operational levels *(9)*. However, the attention to reliability issues has been mostly focused on the operational level, with a lack of sufficient research at the other two levels *(9, 12)*. At the strategic level, long-term decisions are made, such as the design of transit route and networks; at the tactical level, decisions related to the service offered to users are made, such as frequencies and timetables *(13, 14)*. Network design focuses on increasing redundancy and flexibility, while timetabling aims at increasing spare capacity to prevent delay propagation *(10)*. Reliability is then measured as the match between the planning and the actual operations. Therefore two ways of improving reliability are possible: conducting operations in accordance with the planning, and adjusting the planning to be more realistic and easier to adhere to *(9)*. Some reliability enhancing measures are relatively inexpensive to implement, e.g. preventing earlier departure and setting appropriate slack times (as long as no extra vehicle is required) *(8)*; some others need more costly tradeoffs *(1)*.

Contemporary transit network design requires skilled professionals as well as technological support. Important developments in transport modeling have taken place since the mid 1970s, and these are now better recognized *(15)*. Simulation offers designers opportunities to experiment with the models, to analyze the system performance under given conditions, to discover potential problems and drawbacks, and to test strategies that could improve the reliability. As many design decisions are also made by transit authorities, the cooperation between the transit operators and the authorities is of importance. In this context, advanced animation and visualization capabilities can efficiently provide all involved parties a common platform for communication and understanding. Because simulation increasingly becomes a common decision support tool for rail network designers, and design alternatives (and changes) often ask for reconstruction and modification of the models, there is a growing need for component-based rail simulation models that are reusable and extensible and at the same time accessible in terms of cost. The Java rail simulation library discussed in this paper offers such model components. Using the library in HTM, the public transit company in The Hague, the Netherlands, shows that it is effective in providing reliability provision of transit network design, and assisting the organization in reaching agreements on the design issues.

3. THE NEED FOR A SELF-CONTAINED OPEN SOURCE RAIL SIMULATION LIBRARY

Since decades, we benefit from modern technology for complex decision support *(15)*. However technology alone is not sufficient, there is still a huge gap between the needs of decision makers and the functionalities provided by decision support tools *(16)*. In the field of rail transport network planning and design, a number of simulation tools have been developed, e.g. simulation models of stations and terminals *(17, 18, 19, 20, 21)*, and train network simulators such as SIMONE *(22)*, Simon/TTS *(23)*, TOPSim *(24)*, SimMETRO *(25)*, Open Track *(26)*, VirtuOS *(27)*, RailSys *(28)*, UX-SIMU *(29)*, and Multi-train simulator *(30)*.

An open source rail simulation library has been developed at Delft University of Technology. The motivation of developing a new rail-based simulation tool is multi-faceted. First, some existing tools are designed to assess only a limited number of aspects (e.g. timetabling, signaling control) of the operations or to study a particular part (e.g. a station, a junction) of the rail system *(30)*. It is impractical to carry out various studies with different tools *(30)*. Some models have a high abstraction level *(31)*, which may cause a significant difference between model outcomes and real transport operations on a lower abstraction level *(32)*. Although rail-based operations can be decomposed into different aspects, all of them should be taken into consideration in a self-contained simulation package for analyzing rail-based transportation systems on the micro level *(33)*. The microscopic modeling offers simulation experiments with high precision, which is important for exact running time calculation, timetable construction, and conflict detection and resolution *(34)*. Second, very few rail simulation tools support tramway or light rail operations. To the authors' knowledge, one of the few examples is RailSys *(35)*. In comparison with heavy rail operations, various differences occur when simulating light rail operations *(35)*. Heavy rail vehicles drive in signaled blocks, while light rail vehicles also “drive on sight” *(36)*. Given the large number of cities with tramway and light rail systems, there is a growing need for simulation tools that specifically aim at modeling light rail operations. Third, tools designed for diverse transport agencies are very specific to the individual agencies’ needs, often making the tools less suitable for other agencies or transport operators. This asks for generic simulation tools that can be applied for different situations and allow for analysis from different viewpoints, or tools that can be adapted or extended for such purposes. Fourth, commercial rail simulators generally have good performance, but they raise proprietary issues. Concerning inter-operability, it is difficult to modify these tools, link them with other tools or information systems such as databases or GIS *(37)*. Cost is obviously another concern.

The research team therefore decided to develop an open source rail simulation library which allows for light rail simulation, considering the combined impact of different aspects of the infrastructure design in one self-contained simulation package. The fact that it is developed as an open source project provides a unique possibility to improve the package, and it adds flexibility for further research. The package is available for any party to conduct research.

4. THE RAIL SIMULATION LIBRARY

The rail simulation library is component-based *(37)*. It supports distributed microscopic rail simulations that use configurable components (different infrastructure and signaling control logic) as model building blocks. Statistical plotting, generation of output files, and animation help the users evaluate the simulation results. The previous studies, e.g. *(37, 38)*, show that the tool is suitable to forecast rail operations and that it is helpful for improving the reliability of rail network design. During the past year, due to the emerging requirements for new functionalities, the simulation library has been adjusted and extended. The library provides model components that are able to deal with “driving on sight”, which is an important aspect in tramway and light rail operations *(36)*. Another strength is that the library supports the co-existence of multiple formalisms. Both discrete and continuous behavior can be represented in the model at the same time. For example the state transition of a traffic light is discrete, and the movement of a vehicle is continuous. The multi-formalism feature is supported by DSOL (Distributed Simulation Object Library) *(39)*, an open source general-purpose Java simulation library developed by the same research group. The rail simulation library is built as an extension of DSOL.

The rail simulation library has a service oriented architecture that consists of model components and simulation service components *(37)*. The model components can be divided into a physical layer and a control layer. As such, a physical component can implement different control strategies, e.g. a traffic light can be configured to have a fixed time for state transition, or to change state depending on the traffic situation.

The model components such as tracks, traffic lights, stations (or stops) are positioned by real-world coordinates that can be obtained from CAD or GIS software while designing the infrastructure. If appropriately configured, the modeled infrastructure can precisely match the designed or the real one. The animation is able to plot maps as background. Some screen dumps of the animation can be found in FIGURE 3.

A vehicle (or driver) can have a smooth, standard, or aggressive driving profile that determines how the vehicle moves. The driving profile assignment is based on a configurable ratio, e.g. 20% smooth, 60% standard, and 20% aggressive. The vehicle movement is modeled using differential equations solved by the Runge-Kutta integrator. Given the speed of a vehicle at time t_n, it computes the vehicle's speed and position (distance) at time t_{n+1} based on the vehicle's acceleration changes during the integration time-step. The acceleration rates are chosen based on what objects the vehicle (or driver) “sees”. The objects being considered in the model are: traffic lights, changes of infrastructure (e.g. stops or stations, curves), speed limits, obstacles (e.g. a vehicle in front), and other objects (e.g. an intersection) that a vehicle must cross with reduced speed. Gradients are not yet considered in the model. In principle, at each integration time-step, the vehicle “checks” if there are any objects on the tracks in front of it. According to the objects it “sees”, the vehicle decides whether to accelerate, brake or cruise, then chooses the correct change rate according to the vehicle’s speed from the corresponding driving profile. While driving, these objects may change state, e.g. a traffic light changes color or a vehicle changes position. If so, the object notifies the approaching vehicle using the publish-subscribe interaction scheme (40), an event-based asynchronous communication scheme that prevents disproportionate polling between objects (39). To reduce computation, only the objects within a certain distance (e.g. braking distance plus safety distance in front of the vehicle) are checked.

The speed profile (speed limits) along a route is normally defined by the transit authority according to road conditions. The speed limits are modeled by means of “speed signs”, although they almost do not exist in reality; rather, they are part of the instructions of the tram drivers. But using these virtual “speed signs”, users can easily add, delete, and change their position and their speed limit value. The speed reduction at curves, on the other hand, is hard coded in the model component. A curve’s radius is saved in the “track” object when the object is instantiated, and the speed limit of a curve is derived from the radius automatically (FIGURE 1) using $V_{max} = \sqrt{r \times 153 \times 0.65 / 11.8}\ (10 \le r \le 200)$.

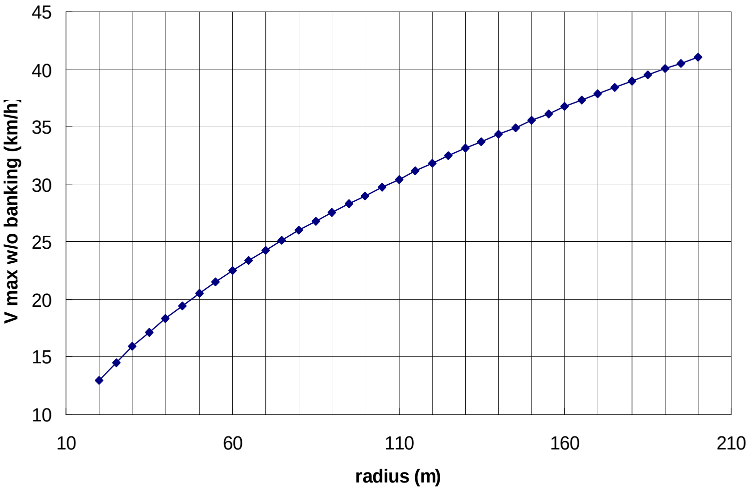


FIGURE 1: Radius vs. maximum speed.

On top of that, a distribution to the speed limits is added to represent the actual speed a tram reaches. Thus every time when a tram reaches an area, its actual “speed limit” (effective speed) is set by the distribution to represent the randomness caused by the street conditions and different driving habits of the drivers. The deviation of the distribution at each area is advised by the designers at HTM. For example, when the city center has a speed limit of 15 km/h, the effective speed is set to be 10~17km/h. But for free tracks where the speed limit is 50 km/h, the effective speed is set to be 45~55km/h (±10%).

Signaling systems are modeled with different control strategies. There are components for absolute blocks and permissive blocks, in which sensors and signaling are modeled according to the corresponding regulations. There are also components that represent street traffic signaling. A transit vehicle may or may not have priority over other street traffic. When two transit vehicles have conflicts at intersections, negotiations of access right will take place based on their priority levels. To deal with different cases, distinct classes of traffic lights are necessary.

The probability distributions for dwell times at stops and waiting times at intersections can be configured individually for each location with respect to the time whether it is during peak or off-peak hours. Layover times of each vehicle at terminals are calculated based on the trajectory time of a specific line taking turning time and certain other factors into consideration.

Different characteristics of the model components are adjusted by parameter configurations. These parameters typically use values derived from existing comparable services and subject-experts' advises. The generated data files recording the movements, travel times, waiting times, and (t-v, t-x, x-v) graphs are created for each vehicle, line, station or junction per direction. These files become new sources of information for further analysis.

5. A CASE STUDY: THE GRONINGEN PROJECT

5.1. Case Description

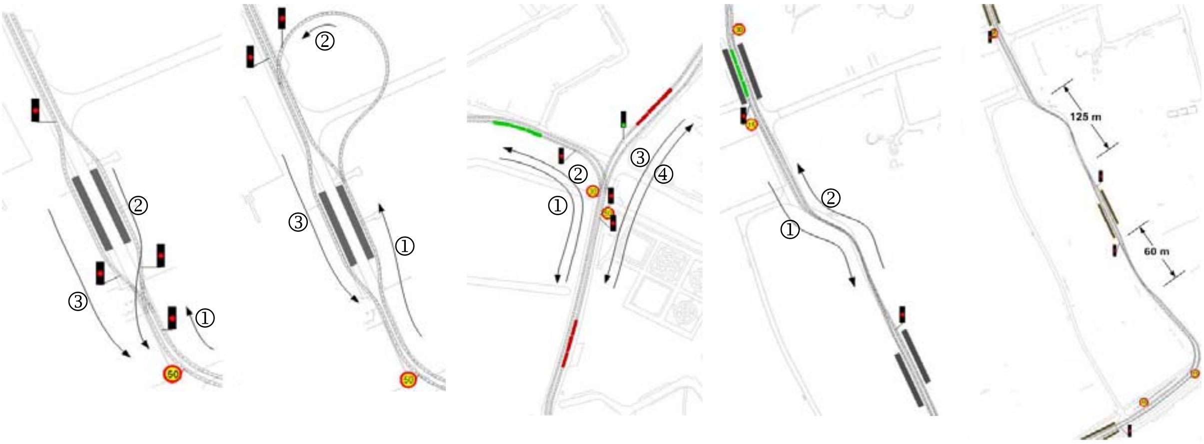
Groningen is the largest city in the north of the Netherlands. The city transit authority plans to construct two *RegioTram* lines to facilitate the growing transit service demand *(41)*. Line 1 will start operation by 2014 between Central Station (CS) and Zernike (ZER). Line 2 is planned to start service in 2016. Currently, the project focuses on finalizing the design of line 1. Line 1 has a length of about 6 km (FIGURE 2). The city center, between Maagdenbrug (MB) and CS, has a pedestrian zone and a cycle network where exclusive lanes for trams are not possible. And at two large crossings in the center, trams do not have priority over other street traffic. Line 1 shall pass a narrow street (arrow①) where interlaced tracks (gauntlet tracks) will be built. This is also the pathway for line 2, which joins line 1 at MB (arrow②). Between MB and CS, two lines share the same route. Both lines have 7.5-minute headways. The interlaced part is the main focus of the study, as it creates a bottleneck on the route. Taking these factors into consideration, some design alternatives were devised. During the course of this project, several of them were improved and selected as strong candidates. These are the ones that were simulated.

FIGURE 2 Groningen RegioTram Line 1 route.

ZER will serve as the main terminal, where vehicles will have longer layover used as slack and breaks for drivers. Drivers need a pause of at least 10% of the driving time. The basic design of ZER is shown in FIGURE 3 (a). Vehicles from direction ① can halt at both halting places, and then depart through direction ② or ③ after layover. The "turning" of a bi-directional vehicle will need 2~3 minutes. An alternative is shown in (b), alighting is on the right side, and vehicles layover (and turn) at the circular tracks (position②). The halting place on the left is for boarding.

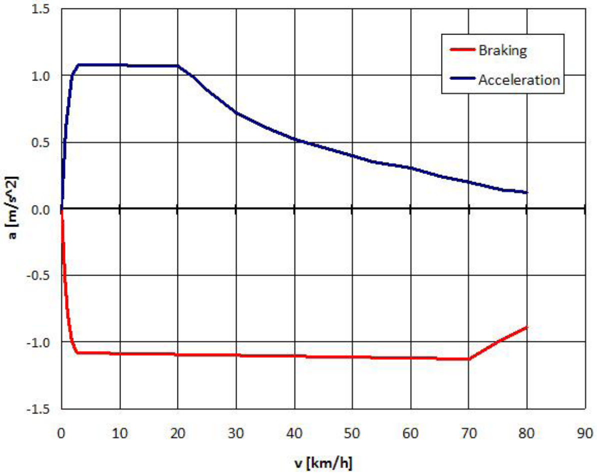
Line 1 and line 2 merge at the MB (FIGURE 3, c): line 1 takes directions①②; line 2 takes directions③④. Here trams won't have priority over the other street traffic. Waiting times at directions②③④ are around 40 seconds at peak and 20 seconds at off-peak. Vehicles at direction① need to wait only if there is another vehicle at direction③. Traffic lights shall be harmonized in this regard.

FIGURE 3 (d, e) shows the interlaced track. It is expected to have a length of 80, 125, or 240 meters. Trams will share this street with pedestrians. If trams from opposite directions encounter each other, waiting is only permitted at stops, as passengers can then still board or alight.

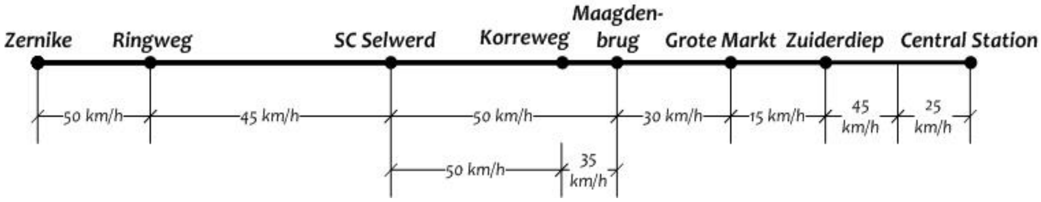


(a) ZER (b) ZER (alternative) (c) Maagdenbrug (d) Interlaced 80/125m (e) Interlaced 240m

FIGURE 3 Simulation animation screen dump segments. The direction signs are added.



(a) Standard acceleration and braking rate of light rail vehicles that operate on the city tramway at 600V DC



(b) Speed limits for line 1

FIGURE 4 (a) Standard driving profile (b) Speed limits for line 1

5.2. Model Configuration and Calibration

The time related variables are generated with probability distributions with respect to the given circumstances. The transit authority did a separate study for the traffic flow at peak and off-peak hours at the two large crossings in the city center. The results are used to calibrate the waiting times at these two crossings. Because no other data for Groningen is available, the authors choose to use the HTM TriTAPT data *(42)* of the tram operation in The Hague, as the two cities are deemed comparable. These data are used to calibrate the dwell time at stops and driving behavior in Groningen. The stops are classified into busy ones and less busy ones that use different halting time distributions.

The standard driving profile uses the acceleration and braking rate of light rail vehicles that operate on the city tramway at 600V DC (provided by HTM), as shown in FIGURE 4 (a). The maximum vehicle speed is assumed to be 50 km/h. Considering different driving behaviors and street conditions, each time a vehicle starts driving its actual speed limit is set to be the allowed speed (in that area) with a deviation. The speed limits for the line 1 route are shown in FIGURE 4 (b). The first row shows the general speed limits. The second row shows a speed limit reduction at Boterdiep (BD) due to mixed street traffic.

Each experiment had independent replications (with different seeds). The simulation run length is 19 hours (from 6 a.m. to 1 a.m.) which corresponds to the actual operation time of a day. The key performance indicators such as travel time, speed, waiting time, and delay of departure were recorded for each run.

5.3. Simulation Experiments and Results

Some optimistic runs were made first to have an estimation of the driving time. Line 2 was not simulated in this case. The basic model has the basic ZER design, 80-meter interlaced track, and the general speed limits. CS functioned as a normal stop without slack. The transit authority was beforehand indecisive over 5 or 6 vehicles for operation (corresponding trajectory times 37.5 and 45 minutes). The results showed an average travel time of 34.5 minutes with a standard deviation (Std-Dev) of 50 seconds, thus 5 vehicles are unable to provide reliable services considering turning times and 10% slack. The resulting travel time was also used to calibrate the departure time and slack at the terminals. The transit authority regarded the slack at CS as a negative influence on total travel time. However the authors argue that an appropriate slack time can compensate some travel time deviation and fewer vehicles would be necessary to accommodate disturbances *(11)*.

Further experiments were configured to have 6 vehicles circulating in the system. The trajectory time was set to be 45 minutes: from ZER to CS 18.5 minutes, and 26.5 minutes for the other direction. Slack at CS can be maximum 2 minutes. (A long layover at CS may block other tram and bus lines.) Each experiment had 148 trajectories.

We first simulated the design alternatives of ZER. The two models have identical configuration except the turning point. The driving times between ZER and CS are presumably similar. The layover times were different, however. The basic design has a layover mean of 10 minutes (“turning” included), 42 seconds Std-Dev; the circular design has a mean of 8.5 minutes, 46 seconds Std-Dev. The latter design is meant to save the 2~3 minutes turning time to be subsequently used as slack. However, the layover position caused the vehicles to move to the boarding position a bit earlier before departure. As the layover times in both cases are already over 6 minutes, the benefit of the circular design does not appear to be distinct. The basic design is simpler (in terms of construction) and easier for passenger boarding. It is the ZER design used in the rest experiments.

Some additional experiments are listed in TABLE 1. They are combinations of speed reduction at BD, 3 lengths of the interlaced track, and operation with 1 or 2 lines between MB and CS. Std-Dev of the travel times are calculated, as travel time reliability is one of the measures of the service reliability *(43, 44)*. Percentage Regularity Deviation Mean (PRDM) is calculated as $PRDM_j = (\sum_i | H_{i,j} - H'_{i,j} | / H_{i,j}) / n_j$, where $PRDM_j$ is the PRDM for stop j, $H_{i,j}$ is the scheduled headway for vehicle i at stop j, $H'_{i,j}$ is the actual headway for vehicle i at stop j, and n_j is the number of vehicles serving stop j *(48)*.

In general, the results confirmed that using 6 vehicles for line 1 operation is feasible: in the worst case (under ordinary conditions), the travel time would sum up to 39.5 minutes (Exp. IX, Max), which still fits into the trajectory time of 45 minutes after adding 10% slack time. By ordinary conditions, we mean that the current model simulates stochastic traffic situations, but without heavy disturbances such as equipment failure in service, nor does it simulate the recovery from disruptions.

Operating only with line 1 poses little problems. Speed limit reduction at BD and 125m interlaced track slightly increase the driving time, but don’t have negative impact on regularity. The reason could be that the reduced speed limit causes less variation in drivers’ effective speed. The 240m interlaced track (Exp. VIII), however, introduces 30% more driving time deviation compared to others (Exp. I-IV). About 23% of the vehicles have to wait at Oosterstraat (OS) to access Zuiderdiep (ZD); the waiting times range from several seconds to 1.5 minutes. From ZD to OS, 33% of the vehicles need to wait, and the waiting time is up to 0.75 minute. Thus the irregularity at the later stops increases. OS-ZD rises from 6.0% to 10.2%; OS-ZD rises from 5.3% to 8.7%.

Two lines operating together in the center (between MB and CS) would cause more conflict, as one can expect. For the 80m and 125m interlaced tracks (Exp. V-VII), about 6~7% of the vehicles at each direction have to wait for the access. The waiting times range from 10 seconds to more than 1 minute. Generally, the waiting time at OS to GroteMarkt (GM) direction is longer than that at GM-OS. This is likely caused by the longer waiting distance at OS-GM. The 240m interlaced track (Exp. IX) forms a bottleneck for the two lines. The waiting time in front of the interlaced track is up to 1.5 minutes, and the amount of waiting vehicles is one third at each direction. The driving time deviation doubled compares to that of Exp. I-VII at direction ZER-CS, 40% for the other direction. The regularity worsens accordingly, the most irregular among all the experiments.

The short slack time at CS could mitigate some irregular arrivals. The irregularity accumulated from ZER to CS is brought down at ZD by the slack of 0.5~2.5 minutes. But the effect is limited when the discrepancy exceeds the possible slack. In the case of the 240m interlace track, for example, the slack is not able to lighten the PRDM by more than 5%. Despite this, the results show a better overall regularity at stops between CS and ZER than the original one that did not implement slack time at CS. The layover at ZER provides 5.4~11.5 minutes for slack (over 85% vehicles could have more than 8.2 minutes) which appears to be effective in terms of restoring regularity.

The extension of the interlaced tack to 125 meters doesn't have much influence on the travel time, nor does the speed limit reduction at BD. But the 240m version does yield more differences, both when operating with 1 and with 2 lines. As the interlaced track is at the forepart of direction CS-ZER, it could be considered to reduce waiting time variance at ZD-OS (as a first step), which would benefit the rest stops of direction CS-ZER. Watching the animation of the experiments, one would notice that vehicle bunching occurs often when both lines are in operation. Coordination at MB is necessary to achieve minimal waiting times *(48)* as both lines share route. Measures to minimize waiting time variance and driving time variance *(45)* include exclusive lanes *(46)*, priority of trams at crossings *(47)* where possible, holding point *(11)* e.g. at ZD, coordination *(48)* at shared tracks. For this project, further simulation studies will be needed to access the impact of these measures on the design.

6. CONCLUSIONS AND FUTURE RESEARCH

In rail transit network planning and design, the use of the open source Java simulation library shows a lot of potential. The library supports distributed microscopic multi-formalism simulation that provides flexible component composition as model building blocks. The model has been validated throughout the development and by case studies *(37, 38)*. Not only does the library support rail transport design from an engineering perspective, its advanced animation and visualization capabilities also makes it an efficient means of communication and enforces common understanding between transit authorities, service providers, as well as other parties involved. The case study in this paper shows an example of generating data for analysis at an early network design stage. While little data for this particular case is available, the tram operation data from a comparable city is used to configure and calibrate the model parameters. The generated data provide new sources of information. By analyzing the output, the designers can gain an overview to compare the impact of different scenarios. More simulation studies are needed to further evaluate the measures that can be used to improve reliability, and refined parameter configuration and calibration will be necessary when more data are collected as the project moves forward.

Future research will explore the possibilities to extend the library with components that allow for more customer-oriented reliability analysis, i.e. to analyze the inter-connection dependencies and delay propagations caused by such dependencies in a complex network. The authors plan to model the full light rail transit network of The Hague, the Netherlands, in which automation of model validation and calibration will be performed based on the comparison of model output and the real operation data. By doing so new operation data can be incorporated dynamically into the model to simulate more reliable strategy modifications.

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TABLE 1 Line 1 Simulation Results

Experiment	**I**		**II**		**III**		**IV**		**V**		**VI**		**VII**		**VIII**		**IX**	
BD	50km/h		35km/h		50km/h		35km/h		50km/h		50km/h		35km/h		50km/h		50km/h	
Interlaced Track	80m		80m		125m		125m		80m		125m		125m		240m		240m	
Lines	1		1		1		1		1 and 2		1 and 2		1 and 2		1		1 and 2	
Travel Time	Z-C	C-Z	Z-C	C-Z	Z-C	C-Z	Z-C	C-Z	Z-C	C-Z	Z-C	C-Z	Z-C	C-Z	Z-C	C-Z	Z-C	C-Z
Mean	17.2	16.3	17.3	16.5	17.2	16.4	17.3	16.5	17.3	16.5	17.4	16.4	17.3	16.5	17.4	16.4	17.8	16.6
Std-Dev	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.6	0.5	0.5	0.5	0.7	0.6	1.0	0.7
Max	19.2	18.1	18.9	18.4	18.7	18.2	19.2	18.4	19.1	17.73	19.3	18.2	19.1	18.3	19.7	18.1	20.8	18.7
85 percentile	17.7	16.8	17.8	17.1	17.7	16.9	17.7	17.0	17.8	16.9	18.0	17.0	17.9	17.1	18.2	17.0	18.8	17.2
15 percentile	16.7	15.9	16.8	16.0	16.7	16.0	16.9	16.0	16.8	15.9	16.8	15.9	16.8	16.0	16.7	15.8	16.8	16.0
Min	16.0	15.3	16.1	15.4	15.9	15.1	16.2	15.2	16.3	15.2	16.2	15.1	16.2	15.5	16.2	15.4	16.2	15.1
Layover	ZER	CS	ZER	CS	ZER	CS	ZER	CS	ZER	CS	ZER	CS	ZER	CS	ZER	CS	ZER	CS
Mean	10.1	1.4	9.8	1.3	10.1	1.4	9.9	1.3	10.0	1.4	10.0	1.4	9.8	1.3	9.7	1.2	9.3	1.2
Std-Dev	0.7	0.4	0.7	0.4	0.6	0.4	0.6	0.4	0.7	0.5	0.8	0.4	0.7	0.4	0.8	0.5	1.0	0.4
Max	11.5	2.3	11.1	2.1	11.7	2.5	11.5	2.3	11.3	2.4	11.2	2.3	11.0	2.4	11.5	2.3	11.1	2.4
85 percentile	10.7	1.8	10.5	1.8	10.6	1.9	10.5	1.7	10.6	1.9	10.7	1.9	10.5	1.7	10.5	1.8	10.2	1.7
15 percentile	9.5	1.0	9.3	0.9	9.4	0.9	9.2	0.9	9.4	0.9	9.2	1.0	9.1	0.9	8.9	0.8	8.2	0.8
Min	7.3	0.6	7.7	0.5	8.2	0.5	8.0	0.6	6.8	0.6	7.5	0.5	7.6	0.6	7.2	0.5	5.4	0.5
PRDM																		
ZER*	-	6.7%	-	6.8%	-	6.1%	-	6.0%	-	7.7%	-	7.0%	-	6.5%	-	9.5%	-	12.5%
Campus*	2.6%	6.4%	2.7%	6.6%	2.6%	5.6%	2.9%	5.7%	2.7%	7.6%	2.6%	7.0%	2.7%	6.1%	2.5%	9.1%	2.6%	12.1%
Ringweg	3.2%	6.2%	3.5%	6.6%	3.2%	5.5%	3.1%	5.5%	3.4%	7.5%	3.3%	6.7%	3.3%	6.0%	2.7%	9.1%	3.3%	11.8%
SC Pad.	3.3%	6.1%	3.6%	6.8%	3.3%	5.5%	3.1%	5.2%	3.7%	7.2%	3.5%	6.6%	3.4%	6.1%	3.1%	9.0%	3.6%	11.7%
SC Sel.	3.5%	5.9%	3.7%	6.8%	3.4%	5.4%	3.4%	5.1%	4.2%	7.2%	4.0%	6.6%	3.7%	6.0%	3.4%	9.2%	4.0%	11.6%
NS*	3.8%	5.6%	4.0%	6.4%	3.6%	5.2%	3.6%	4.8%	4.3%	7.0%	4.3%	6.2%	4.0%	5.5%	3.5%	9.3%	4.5%	11.6%
Korreweg	4.2%	5.3%	4.3%	5.9%	4.5%	4.9%	3.9%	4.6%	5.0%	6.7%	5.0%	5.8%	4.4%	5.2%	4.5%	8.9%	5.3%	11.2%
BD	4.5%	5.1%	4.5%	5.5%	4.4%	4.7%	3.9%	4.3%	5.2%	6.4%	5.1%	5.9%	4.6%	5.2%	5.0%	9.0%	5.3%	11.2%
GM*	4.9%	4.7%	4.7%	4.9%	4.8%	4.2%	4.4%	4.1%	6.2%	6.1%	5.7%	5.2%	4.8%	4.9%	5.3%	8.8%	6.4%	11.0%
Oosterst.	5.4%	4.4%	5.3%	4.6%	5.5%	3.8%	4.5%	3.6%	7.2%	5.4%	6.7%	4.6%	5.3%	4.5%	6.0%	8.7%	10.0%	11.5%
Zuiderdiep*	5.8%	3.5%	5.4%	3.7%	5.5%	3.4%	4.7%	3.1%	7.5%	4.7%	6.9%	4.0%	5.7%	3.9%	10.2%	5.3%	14.4%	10.9%
CS*	6.2%	-	6.2%	-	5.9%	-	5.2%	-	8.2%	-	7.0%	-	6.4%	-	10.8%	-	14.7%	-
Vehicles waited at interlaced track																		
	0%	0%	0%	0%	0%	0%	0%	0%	6%	6.8%	6.8%	6.8%	8.8%	6.7%	23.0%	33.1%	33.8%	37.2%

BD: Speed limit at Boterdiep.

Travel time and layover time are in minutes.

**Busy stops.*

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