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ORIGINAL PAPER

# Do regular timetables help to reduce delays in tram networks? It depends!

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**Abstract** In public transit planning, regularity of timetables is seen as an important means to improve capacity efficiency by assuring an even trip distribution, as well as to improve product attractiveness and appreciation. This paper focuses on examining whether a regular timetable can also help to reduce network delay, especially resulting from inevitable small disturbances. Following the formulation of a mathematical optimization approach, we propose a number of conditions a network has to fulfill for timetable regularity to have a delay reducing impact. A set of three network properties is identified, which consists of (a) the sharing of resources between tram lines, (b) a low variability of driving times, and (c) the non-redundancy of the network's central resources. To test the impact of these properties, a series of optimization and simulation experiments is conducted on models of the tram network of the cities of Cologne, Germany, and Montpellier, France. Small disturbances are introduced to the simulated operations to check whether the presence of all three properties is necessary for a network to benefit from a regular timetable. The results show that while with all properties present a

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regular timetable can indeed help to reduce delays resulting from small disturbances, the non-compliance with any one of the conditions nullifies the impact of regularity on the result.

**Keywords** Regularity · Optimization · Simulation · Tram network · Schedule design

## 1 Introduction

Timetable optimization models can consider several optimization objective, e.g. robustness against disturbances (see Cacchiani et al. 2012), synchronicity of departures to accommodate transfer connections (see Ceder et al. 2001; Eanki 2004; Ibarra-Rojas and Rios-Solis 2012), or the minimization of passenger waiting time (see Saharidis et al. 2014; Wu et al. 2015). Another common objective is regularity as a measure of the resilience of a timetable against small inevitable disturbances (see Genç 2003; Bampas et al. 2006; Ullrich et al. 2012).

This paper examines the conditions a tram network has to meet for a regular timetable to reduce delays resulting from small disturbances. To reach this goal, we first present a method to generate regular timetables and then formulate several conditions to the network structure, which are validated by examining models of two real-world tram networks. The described software tool is applied to generate regular timetables for these network models, and the influence of regularity on punctuality is examined by utilizing a microscopic simulation engine (described in Lückerath et al. 2012).

This paper continues with sharing some background on timetable generation (Sect. 2). Following on that, the above mentioned conditions are presented (Sect. 3). To further examine these ideas we conduct a series of simulation experiments on models of the networks of the cities of Cologne, Germany, and Montpellier, France (Sect. 4). The paper ends with a short summary of the lessons learned and some thoughts on further research (Sect. 5).

## 2 Background

### 2.1 Timetable generation

Several well researched approaches to the generation and evaluation of transit timetables exist. Caimi et al. (2010) introduce a method to generate conflict-free, periodic train timetables based on a flexible version of the Periodic Event Scheduling Problem. Instead of fixed departure times their approach allows the definition of flexible departure time intervals to increase the chance to find exact train routings. Cacchiani et al. (2012) describe a Lagrangian heuristic to generate railway timetables which are robust against disturbances by allocating buffer times to train departures. Their approach allows the collection of heuristic solutions with different trade-offs between robustness and efficiency, so that the user can choose a timetable that best fits her needs. Another optimization approach was introduced by Ceder et al. (2001) and later extended by Eanki (2004). It enables the generation of aperiodic timetables with maximum synchronization at dedicated transfer nodes while simultaneously adhering to given minimum and maximum headways for vehicles of the same line. Based on a graph representation of the transit network Ceder et al. develop a mixed-integer linear program (MILP) to maximize the number of simultaneous arrivals at the nodes of the network. To solve the MILP the authors develop a constructive algorithm, which first identifies the most promising transfer node at a given moment and then tries to schedule as many simultaneous arrivals at this stop as possible. If no more (synchronous) arrivals can be scheduled, the next most promising node is identified, and the process is repeated. Ceder et al. show the correctness and applicability of their approach by applying it to a set of artificial transit networks, as well as to a model based on an Israeli bus network. A more recent approach for the generation of synchronous timetables is described by Saharidis et al. (2014). They develop an approach to generate bus timetables, which minimize cost associated with passenger waiting time at transitional nodes and also take phases with high passenger demand into account. They formulate a MILP with several different extensions and show the applicability of their approach on the bus network of the Greek island of Crete. Wu et al. (2015) propose a stochastic integer programming model to generate bus timetables that minimize passenger waiting times under consideration of stochastic travel times. To mitigate the randomness of travel times they, like Cacchiani et al. (2012), allocate buffer times to bus departures. They develop a genetic algorithm to solve their model and compare the obtained solutions to solutions generated with deterministic travel times.

An important objective often found in timetable generation is regularity, which is a service characteristic especially important for high frequency transit systems and can be defined as the degree to which departures are equally distributed in the available basic interval. Regularity of timetables is seen as an important means to improve capacity efficiency by assuring an even trip distribution, as well as to improve product attractiveness and appreciation (see Van Ort and van Nes 2009). Achieving regular service for as many stops as possible requires solving a specialized form of the periodic event scheduling problem which is NP-hard (Vince 1989).

Genç (2003) develops an integer programming formulation to generate regular, periodic tram timetables, heightening the resilience of tram systems against small disturbances. He develops a branch-and-bound solver and verifies its efficiency by applying it to the tram network of Cologne and comparing the obtained results to solutions computed using CPLEX. Bampas et al. (2006) solve a similar problem for special network structures like chain or spider networks. They examine the computational complexity resulting from the different network structures and show the NP-completeness for tree networks. Ullrich et al. (2012) also address the problem of generating regular, periodic tram timetables but also incorporate transit planning requirements (e.g. guaranteed transfer connections, core lines serving only the city centers, or coordination with intercity rail traffic) into their optimization model to assure applicability during daily operation. Ibarra-Rojas and Rios-Solis (2012) develop an integer programming formulation to generate bus timetables, which maximize the number of synchronous departures to optimize passenger transfers, while also targeting regular departure times and the avoidance of bus bunching. To solve the problem they develop a multi-start iterated local search algorithm and apply it to different network instances based on the bus network of the City of Monterrey, Mexico. They compare the generated timetables to solutions obtained with CPLEX and find that their algorithm generates good solutions very quickly (15–60 s), while CPLEX does not solve to optimality in under 2 h.

As shown by Genç (2003), Ullrich et al. (2012, 2015), regularity can also be utilized as a measure of the resilience of a timetable against small inevitable disturbances: with an assumed basic interval of 10 min two lines sharing resources can be arranged in such a way that each vehicle has a 5 min clearance to its predecessor. Thus, any vehicle can accumulate a delay of over 4 min without propagating it to the succeeding tram. If the departures are distributed extremely unequal—with an offset of 9 min followed by an offset of 1 min—one vehicle can accumulate a delay of 8 min without affecting the following tram, but the other tram will transfer even a small delay to its successor. Assuming typically small delays, the former distribution is thus more beneficial to punctuality than the latter. Under which network structure conditions this effect is most potent will be examined in the remainder of this paper.

### 2.2 Generating regular timetables

The following optimization approach combines heuristic and exact methods to generate timetables of maximum regularity. These timetables adhere to a common basic interval. By choosing this interval accordingly, both peak periods with high frequencies of traffic and non-busy or night periods can be examined. The described optimization model was already presented in Ullrich et al. (2012).

The foundation of the model is a network $N(S, C, t, L, T)$ with a set of stops $S = \{s_1, \ldots, s_n\}$, a set of connections $C = \{c_1, \ldots, c_v\}$ with travel times $t : C \to \mathbb{N}_0$, a set of lines $L = \{l_1, \ldots, l_m\}$ with line variants $V(l_i) = \{l_{i1}, \ldots, l_{ik}\}$, and a common basic interval $T$. A line variant $l_{ij} = (s_{ij1}, s_{ij2}, \ldots, s_{ijk(ij)})$ is a simple, directed path in the directed graph $G = (S, C)$. Let $\lambda_{ij}$ be the departure time at the first stop of line variant $l_{ij}$ of line $l_i$, then a periodic timetable is a vector $\lambda$ defining departure times for all line variants of the examined network. Because we only examine periodic timetables the departure times at the first stop can be limited as follows:

$$0 \leq \lambda_{ij} < T \qquad \forall l_i \in L : \forall l_{ij} \in V(l_i) \tag{1}$$

To compute the regularity of a timetable $\lambda$, the planned headway $\delta_{l_{ij},pred(l_{ij})}(s, \lambda)$ in minutes between a departure of line variant $l_{ij}$ and its immediate predecessor $pred(l_{ij})$ is examined for each stop $s$. To penalize small headways at highly frequented stops, the inverse values of the headways are added up. Thus, the objective function grows reciprocally proportional to the regularity of the timetable.

To reduce the complexity of the computations, consecutive stops served by the same set of line variants are combined (see Genç 2003) to a maximum stop type $s'$, which is weighted by the number $\varphi_{s'}$ of included stops (see Fig. 1). This reduced set of stops is described as $S'$.

Equation (2) shows the resulting objective function $\phi$ of a timetable $\lambda$.

$$\phi(\lambda) = \sum_{s' \in S'} \sum_{l_{ij} \in V(s')} \frac{1}{\delta_{l_{ij},pred\left(l_{ij}\right)}(s', \lambda)} \times \varphi_{s'} \tag{2}$$

Here $V(s)$ defines the set of line variants that serve stop $s$.

To qualify as a valid solution a timetable has to adhere to another constraint: The headway between the consecutive departures of two line variants has to be at least 1 min (see Eq. (3)). This makes sure that a stop cannot be occupied by two vehicles at the same time and the timetable thus is collision-free.

$$\delta_{l_{ij},pred(l_{ij})}(s') > 0 \qquad \forall s' \in S' : \forall l_{ij}, pred\left(l_{ij}\right) \in V(s') \tag{3}$$

The described model is implemented using a branch-and-bound solver (see Dakin 1965) which is preceded by a genetic algorithm (see Dréo et al. 2006) supplying initial upper bounds. This avoids a cold start of the branch-and-bound algorithm, and thus helps to rapidly exclude large areas of the solution tree.

The genetic algorithm used in this specific approach encodes a timetable as an array of integer values, where each entry represents the first start time of a line variant. The application generates a start population of valid timetables, i.e. timetables with no collisions on network nodes (see (3)), using random start time values chosen from the range of the basic interval $\{0, \ldots, T-1\}$. To reduce the computational complexity we apply a simple deterministic tournament selection and a two-point-crossover operator (as described in Dréo et al. 2006). During tournament selection individuals are chosen from the population and compared with one another in pairs. The individual with the higher fitness is entered into the mating pool, while the other individual is removed from the population and later replaced by the best one of the individuals newly created. Those new individuals are created from pairs of individuals from the mating pool using a two-point-crossover operator. After the evaluation of several mutation methods, including random, minimal, and maximum enhancement mutation, we choose a minimal mutation method that only allows altering single start time entries of an individual by adding or subtracting 1 min. A mutation rate of $r = 0.01$ yields best results. We utilize a standard steady state replacement method, also described in Dréo et al. (2006). To balance solution quality and execution time, the algorithm terminates after

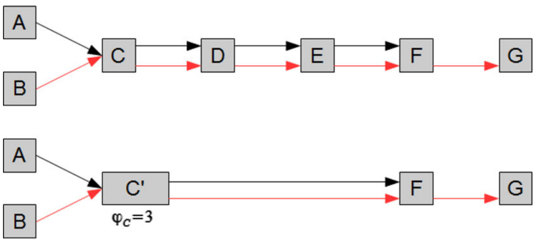


**Fig. 1** Stops C, D and E are combined to stop type C′, which is weighted by $\varphi_{C'} = 3$

calculating 500 generations of 450 individuals each. Finally, a hill climbing algorithm is applied to the best individual to further improve its fitness. The fitness value of this best individual is then provided to the branch-and-bound solver as initial upper bound. Thereby, instead of having to traverse major parts of the solution tree to find a valid first solution candidate with a good objective function value, the solver is enabled to exclude significant areas of the tree from the start.

To implement the branch-and-bound solver, the objective function described in Eq. (2) is modified (see Eq. (4)). The set of stop types $S'$ is divided into $\widehat{S}$ and $\tilde{S'}$. Here, $\widehat{S}$ includes all stop types which are exclusively served by line variants whose start times are already set by the solver, while stop types in $\tilde{S'}$ are also (or exclusively) served by lines whose start times are not yet set.

$$\phi'(\lambda) = \sum_{s' \in \widehat{S'}} \sum_{l_{ij} \in V(s')} \frac{1}{\delta_{l_{ij},pred(l_{ij})}(s', \lambda)} \times \varphi_{s'} + \sum_{s' \in \tilde{S'}} \sum_{l_{ij} \in V(s')} \frac{1}{\tilde{\delta}_{l_{ij},pred(l_{ij})}(s', \lambda)} \times \varphi_{s'} \quad (4)$$

Here, $\tilde{\delta}_{l_{ij},pred(l_{ij})}(s', \lambda)$ represent local lower bounds for safety distances adhering to already set start times. These values are determined by iteratively splitting the largest remaining gap in stop's $s'$ local sequence of departing trips, and setting departure times for not yet determined variants accordingly. This calculation method typically underestimates the individual safety distance values, as the calculation disregards any dependencies on departures at other stops. The resulting values are then applied to the modified objective function described in Eq. (4) in order to find lower bounds for the solution candidates in the currently examined branch of the search tree, thereby facilitating an efficient exclusion of branches. For further implementation details, see Ullrich et al. (2012).

## 3 Effectiveness of regular timetables

A regular timetable decouples consecutive vehicles, so that small, inevitable delays are less often propagated to succeeding trams. This reduces the number of delayed departures, because delays are confined to the local vehicle and yield less often global consequences. Because smaller delays can accumulate over the operational day, this also reduces the number of delays perceived as significant (here: more than 60 s). Thus, a regular timetable can reduce both the number of delays and the average lengths of those delays.

As a secondary effect the equidistant headway between departures result in a larger time span for recovery measures, which might get necessary as a consequence of larger disturbances (see Lückerath et al. 2013). Though the average length of available time spans stays the same (as the departure frequency is constant) a regularity induced increase of the response time from 1 to 2 min has a higher practical value than an increase from 8 to 9 min, as the marginal utility of additional response time is diminishing.

In order for a regular timetable to reduce the number and amount of delays, a tram network has to comply with one precondition and three main conditions:

*Precondition:* The line and network structures have to allow sufficient latitude for the optimizer software to generate regular timetables. Difficulties may arise if several lines share a sequence of stops, then split, and converge again after serving sections with different traversal times. Because the optimizer can only generate valid timetables which guarantee a headway of at least 1 min at each stop, the latitude for the scheduling of the concerned lines may be reduced significantly in this case. If no regular scheduling is possible, we consider those lines locked (for an example see Sect. 4.2), and no delay reduction can manifest here.

*Condition* (*a*): *Shared resources.* Regular timetables decouple consecutive vehicles at shared resources. Regularity can therefore only be effective if resources like tracks and stops are shared by several lines, and thus a competition for those resources exists. Without such a competition no dependencies exist which could be solved by a regular timetable; the regularity would not affect the overall punctuality. Obviously scarce resources profit most from the utilization's decoupling. These are usually clusters of switches in the vicinity of central hubs (see Sects. 4.1 and 4.2), which are traversed by many vehicles with a low maximum velocity.

*Condition* (*b*): *Low variability of driving time.* In timetable generation, regularity is a static criterion applied during the tactical planning phase (see Desaulniers and Hackman 2007). It can therefore only be effective if vehicles' traversal times are known in advance and their variances are small enough for the static decoupling not to be undone by the dynamic behavior of the vehicles during the operational phase (see Turnquist and Bowman 1980).

*Condition* (*c*): *No redundancy of network resources.* A timetable's regularity can only have an effect on punctuality if small delays can propagate. Redundant network resources enable the succeeding vehicle to overtake or avoid a delayed tram (e.g. at connected parallel tracks) so that it does not inherit its predecessor's delay. The availability of those dynamic decisions, which cannot be considered in static planning, limits the influence of timetables on punctuality.

In a tram network which adheres to the precondition and the conditions (a) to (c) a regular timetable can therefore help to reduce the average delay of departures and thus to raise the quality of service.

## 4 Experiments

By conducting a series of simulation experiments we examine whether a timetable's degree of regularity yields effects on punctuality as assumed. We begin by examining a model of the tram network of Cologne's *Kölner Verkehrsbetriebe AG* (KVB) and compare its properties to a model of the significantly smaller network of Montpellier's *Transports de l'agglomération de Montpellier* (TAM). We also examine the impact of the compliance to each condition on the measured delay separately. All generated timetables span the time period from 7 am to 7 pm, and during the conducted simulation runs no early vehicle departures are allowed, following KVB's policy. The experimental runs are executed by the simulation tool described in Lückerath et al. (2012). Statistics are measured between 8 am and 7 pm, to account for the necessary calibration phase of the simulation.

In this simulation tool, the tram network is modeled as a directed graph with stops, tracks and track switches represented by nodes. Connections between nodes are represented as edges. The distributions for the duration of passenger exchange are specific to stop and tram type with the combined duration of opening and closing the vehicle doors as minimum value. Vehicles encapsulate most of the simulation dynamics, which are based upon the event based simulation approach (as described in Banks et al. 2010). Thus trams change their state at events of certain types, like stopping or accelerating, which happen at discrete points in simulation time. These state changes may trigger a change in the over-all model state and generate follow-up events, which are administrated in a priority queue. Main parameters of the simulation are the maximum driving velocity $v_{max}$, the delay probability $0 \leq p_d \leq 1$ (which maps the chance that a tram's driver does not accelerate at a given moment due to external causes), and the delay factor $d > 1$ (which maps the amount of the delay caused by lagging acceleration). Acceleration and deceleration follow the technical specifications published by the utilized trams' manufacturer (see Vossloh Kiepe 2003). The simulated driving times are calculated by multiplying the times resulting from these specifications with the delay factor if a uniformly distributed random value is less than or equal to $p_d$. Combined with the randomly calculated boarding times at stops, this constitutes the simulation's source for small delays.

### 4.1 Modeling Cologne's KVB tram network

The described methods are first applied to a model of the tram network of Cologne's KVB based on publicly available data of 2012. The network consists of 531 stops and 80 switches, which are connected by 586 tracks (see Fig. 2). Eleven lines with 36 line variants cover the network (see Kölner Verkehrsbetriebe 2012). 178 vehicles are employed to execute ca. 2800 trips per operational day.

Cologne's tram network complies completely with the conditions (a) to (c). Dependencies based on the utilization of shared resources between lines exist in most parts of the network, so condition (a) is fulfilled. The clusters of switches near stops Appellhofplatz (APP), Barbarossaplatz (BAB), and Ebertplatz (EBP) are particularly high frequented in this context. Because vehicles in the city center mainly drive on underground tracks, and are elsewhere given priority to individual traffic, variability of driving times is rather low; thus condition (b) is also fulfilled. The same goes for condition (c): Very few redundancies in Cologne's network exist; these are mainly turnaround loops which are not utilized for overtake maneuvers.

To examine our assumptions further, we apply the described optimization method and generate timetables with Cologne's global basic interval of 10 min. After 500 generations with a population size of 450 the genetic algorithm is stopped, and the branch-and-bound solver is started with the best fitness value as an initial upper bound. The optimization run results in 1281 best timetables with an objective function value of 175.86. Compared to this, the average fitness value of the genetic

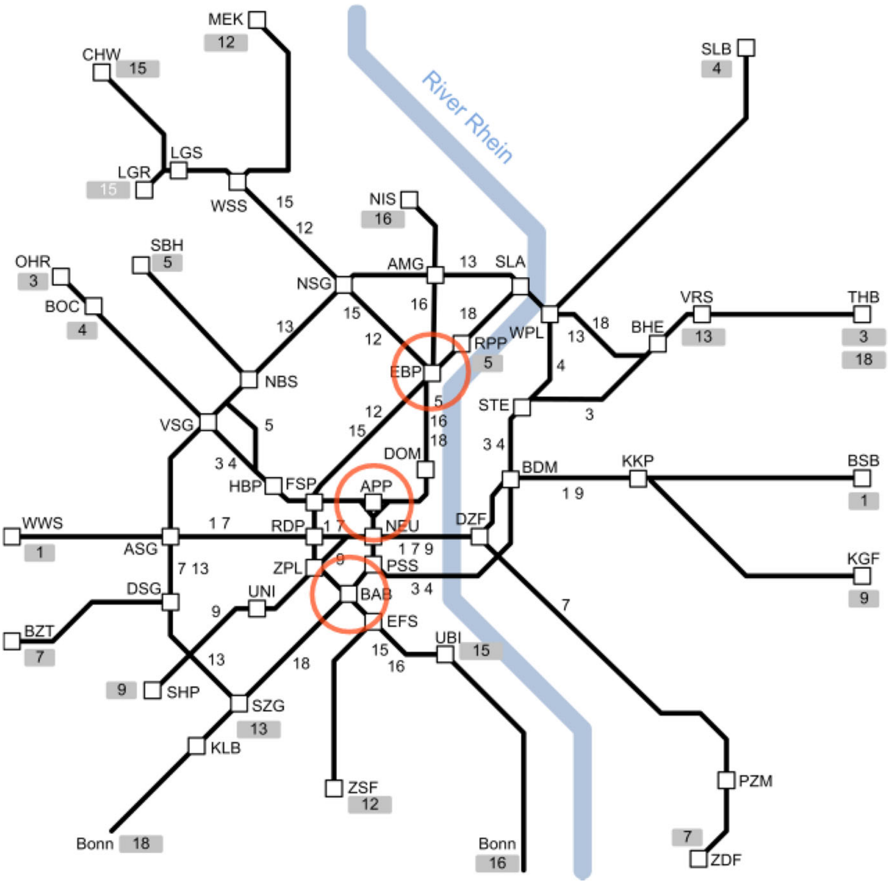


**Fig. 2** Cologne’s KVB tram network

algorithm’s initial generation lies at 192.65 (worst value 200.92). This improvement of 8.7 % shows that the precondition is met by Cologne’s tram network, and—together with its compliance with the conditions (a) to (c)—regularity should thus be an appropriate optimization goal for this network.

To reduce the impact of individual timetable characteristics, we pull ten timetables each out of the pools of initial and best solutions, and execute ten simulation runs for each of these timetables. A comparison of average delay frequencies (see Figs. 3 and 4) shows—as expected—a reduction of the number of larger delays. While the average total number of delayed departures counted during the simulation runs is reduced from 16,848 by 3.5 % down to 16,252, the number of larger delays of at least 60 s is reduced by 28.9 % from an average of 3091 down to 2198 departures.

For a closer examination we choose one timetable each from both pools, and execute 100 simulation runs for each of those two timetables. As seen in Fig. 5 the measured average delay of lines is reduced from 19.8 s under the initial

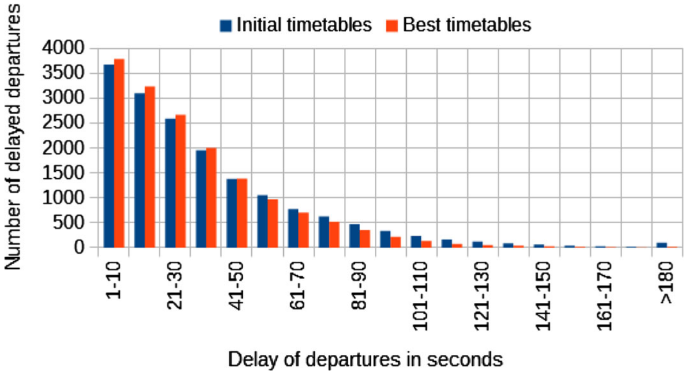


**Fig. 3** Cologne's tram network: distribution of delays

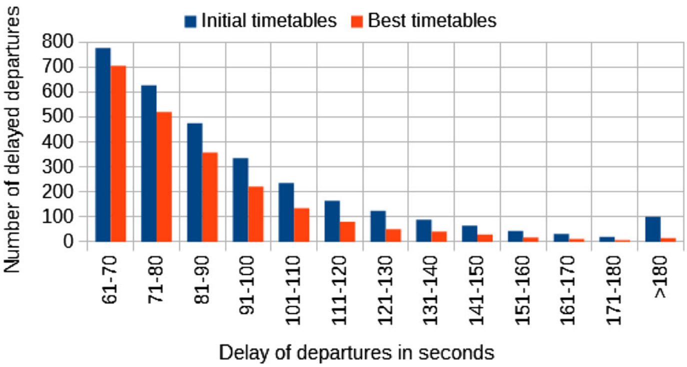


**Fig. 4** Cologne's tram network: distribution of larger delays

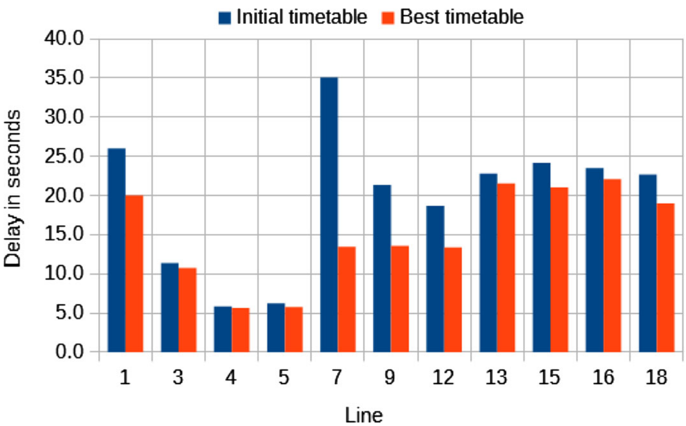


**Fig. 5** Cologne's tram network: line delay

timetable down 24 % to 15.1 s under the best timetable; merely lines 3, 4, and 5 do not gain punctuality. The high delays of line 7 under the initial timetable can be explained by the bad scheduling of line 7's departures at the resources shared with lines 1 and 13. Here, the vehicles executing line 7's trips get behind trams of other lines although they are supposed to precede them. Thereby the vehicles accumulate a large number of significantly delayed departures. Under the chosen best timetable the coordination succeeds much better; local delays are not propagated to the succeeding vehicles.

As seen, the application of a regular timetable raises overall punctuality significantly. Because timetables do change neither line variants nor the pool of available vehicles, the cause for this impact on punctuality has to be found in the structure of the network, and can therefore be attributed to the compliance with the conditions (a) to (c). To further validate these results, the conditions stated in Sect. 3 are examined more closely in Sect. 4.3.

### 4.2 Modeling Montpellier's Tramway network

The described methods are also applied to a model of Montpellier's Tramway network (for an overview see Fig. 6) based on publicly available timetable data of 2013. The system consists of 176 stops and 46 track switches, connected via 232 tracks. 1215 trips per operational day are executed on four lines with 24 line variants; about 282,000 passengers are served on each weekday (see Transports de l'agglomération de Montpellier 2013).

Montpellier's Tramway network does comply with the conditions (b) and (c). Because of the low complexity of the network, condition (a) is only complied with in some areas, i.e. the switch clusters near the stops Corum (COR, see Fig. 6), Gare Saint-Roch (GSR), and Rives du Lez (RDL), which are accessed by at least three lines each.

The Tramway network does not comply with a global basic interval; lines serve the routes in changing patterns over the course of an operational day. In peak hours, vehicles of line 1 and 2 traverse the inner city every 4–5 min; line 3 operates every 6–8 min, the interval between consecutive trams of line 4 alternates between 8 and 9 min. To find an adequate approximation we assume a global basic interval of 8 min, and double the frequency of lines 1 and 2 at inner city stops by inserting shorter lines 1A and 2A.

The initial solution candidates have an average fitness value of 83.58 (worst value 95.00); the optimizer proposes 128 best solutions with an objective function value of 75.22. The objective function value is reduced by 10.0 %, the best timetables are therefore significantly more regular than the initial solution candidates. Nevertheless, the precondition is only partially conformed to: Lines 1, 3, and 4 are locked and cannot be arranged freely in relation to each other. They form a block which can be arranged relatively free in relation to line 2. The network therefore complies with the precondition concerning line 2 and the block consisting of 1, 3, and 4.

Again, ten timetables each are picked from the pools of initial solutions and best solutions; for each of these 20 timetables ten simulation runs are executed. The

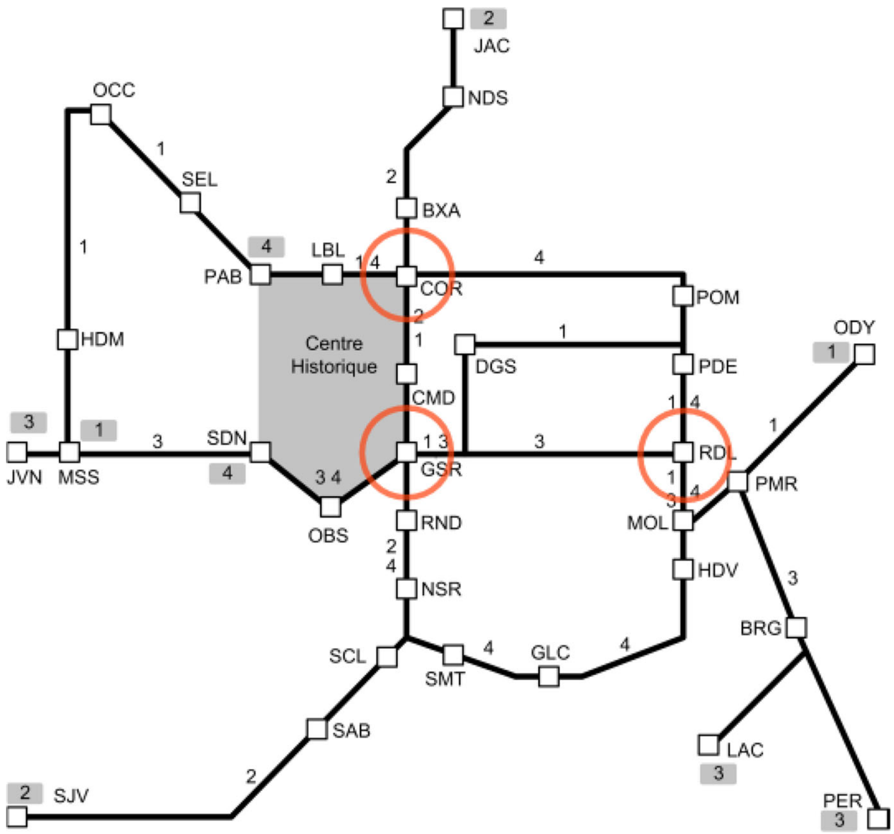


**Fig. 6** Montpellier's TAM tram network

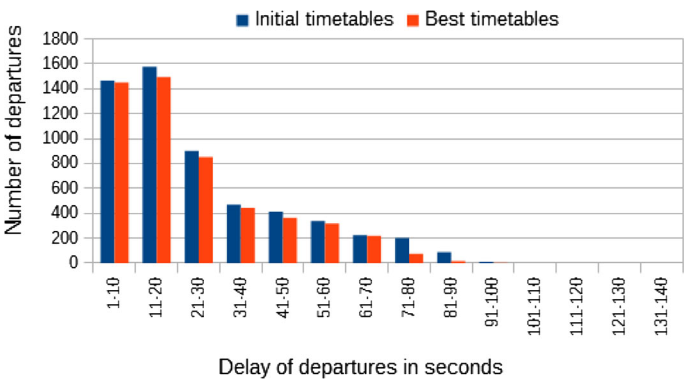


**Fig. 7** Montpellier's tram network: distribution of delays

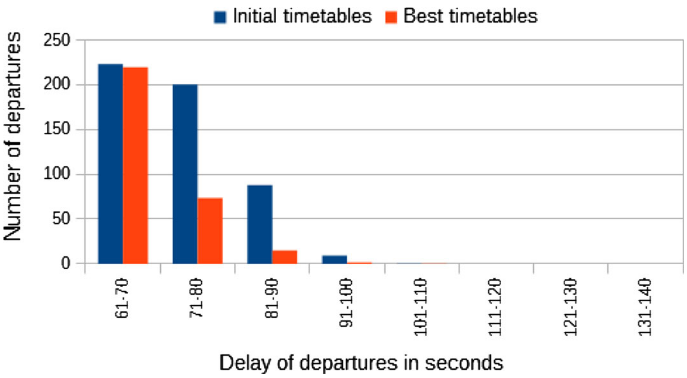


**Fig. 8** Montpellier's tram network: distribution of larger delays

average delay frequency (see Fig. 7) shows a reduction for each class. This effect is especially significant for larger delays of at least 60 s (see Fig. 8). The average number of delayed departures counted during the simulation runs is reduced from 5691 by 8.0 % down to 5234 departures. The average number of larger delays is reduced from 521 under the initial timetables by 40.4 % down to 310 departures.

As seen, the application of a regular timetable does reduce the overall delay in this network. Especially at those three points where condition (a) is primarily met—the switch clusters around Corum, Gare Saint-Roch and Rives du Lez—a regular timetable caters for better coordination of resource sharing, and thus for raised punctuality. Stop Rives du Lez is only served by the locked lines 1, 3, and 4, their punctuality does not change; the other two stops are served both by the locked lines and line 2. To examine further the model's behavior at these points, the development of the delay of one of line 2A's vehicle serving trips for two opposing variants is explored.

For that purpose we pick an initial timetable with an objective function value of 92.69 out of the pool of initial timetables, and a best timetable out of the pool of best timetables. For each of these timetables 100 simulation runs are executed.

The initial timetable yields an average line delay of 8.7 s, which is reduced under the best timetable by 17.2 % to 7.3 s. As expected, this reduction is due almost completely to the raised punctuality of line 2, its delay is reduced by 24.2 % from 21.6 down to 16.3 s (see Fig. 9).

We take a closer look at trips 3 and 4 (see Figs. 10 and 11) of a tram serving opposing line variants of line 2A. While measured delays of most departures vary only slightly depending on the applied timetables, major differences occur in the inner city areas around stops Corum and Gare Saint-Roch.

In the course of trip 3 to Sabines (SAB, see Fig. 10), after leaving stop Corum, vehicles of line 2A enter a cluster of switches which they share with trams of the lines 1, 1A, 2, and 4. Under the initial timetable a vehicle has to wait to be granted access to these resources and can only catch up the resulting delays after the lines diverge after stop Nouveau Saint-Roch (NSR). Under the best timetable with its

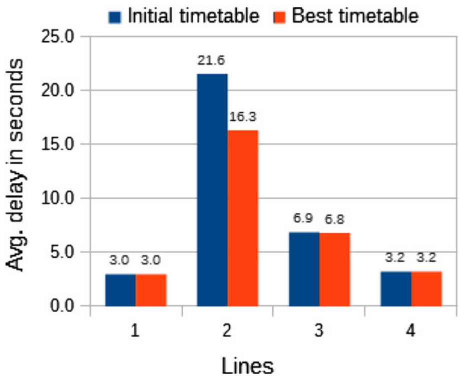


**Fig. 9** Montpellier's tram network: line delay

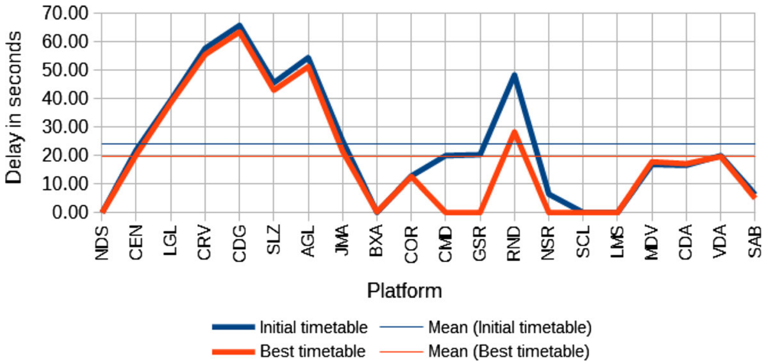


**Fig. 10** Montpellier's tram network: course of trip 3 of vehicle 2005

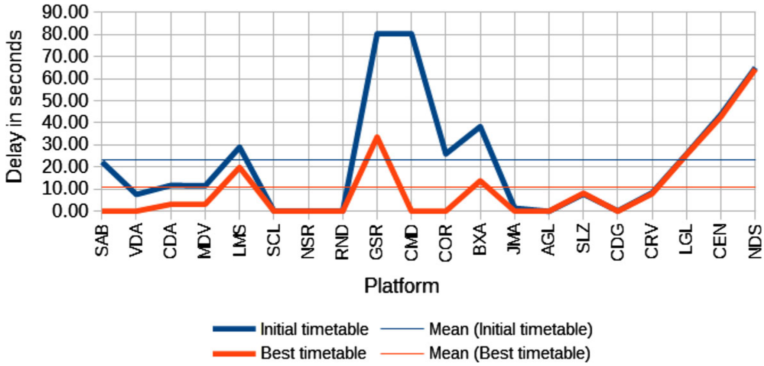


**Fig. 11** Montpellier's tram network: course of trip 4 of vehicle 2005

more equally divided basic interval the resources are available to the vehicle without delay, the vehicle delay stays low.

On its way back to Notre Dame de Sablassou (NDS, see Fig. 11) the vehicle has to navigate four consecutive track switches between the stop Rondelet (RND) and

Gare Saint-Roch, which are also utilized by all other lines. Under the randomly generated initial timetable the vehicle gets behind a tram of line 1, despite being scheduled to precede that vehicle by a minute. The vehicle subsequently has to wait until the preceding tram clears the stop at Gare Saint-Roch, and thereby obtains a delay of about 80 s. It can only begin to catch up on this delay after the routes of lines 1 and 2 diverge between the stops of Comedie (CMD) and Corum.

As assumed, the application of a regular timetable does affect punctuality in the vicinity of the highly frequented switch clusters near Corum and Gare Saint-Roch. The observations again confirm the thoughts described in Sect. 3.

For a more detailed examination of Montpellier's tram network see Ullrich et al. (2015).

### 4.3 Examination of conditions (a) to (c)

The conditions formulated in Sect. 3 are examined in more detail by experimenting on the more complex tram network of Cologne. In three sets of experiments each one of these conditions is purposefully not complied with in order to examine its impact on overall punctuality. Again, 100 simulation runs per timetable are executed.

At first we examine the impact of the utilization of shared resources (condition (a)). For this a set of lines (1, 4, 13, and 15, see Fig. 2) is chosen which covers most parts of Cologne's tram network without sharing resources. Under these conditions the average line delay does not change significantly under initial and best timetables (see Fig. 12). The lines' delay is therefore independent from the applied timetable and thus from its degree of regularity.

To examine condition (b) the variability of the vehicles' driving time is raised by spreading the distribution of acceleration times. Under standard conditions, acceleration times of the simulated vehicles are randomized using a delay probability $p_d = 0.3$, and the delay factor $d = 1.3$. To spread the variability of the vehicles' driving times we now raise the delay probability to 0.5 and the delay factor to 2.0, thus significantly randomizing the driving times. The deceleration times cannot be distributed arbitrarily, because the simulated trams would otherwise have accidents when driving up to obstacles. Under these imperfect conditions, the average delay is barely reduced from 8.2 s under the initial timetable down to 7.9 s under the regular timetable (see Fig. 13), which is a reduction of 3.7 % (compared

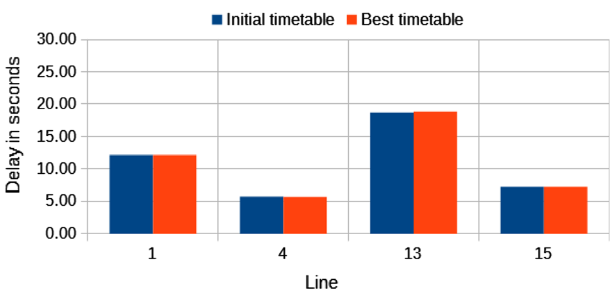


**Fig. 12** No shared resources: line delay

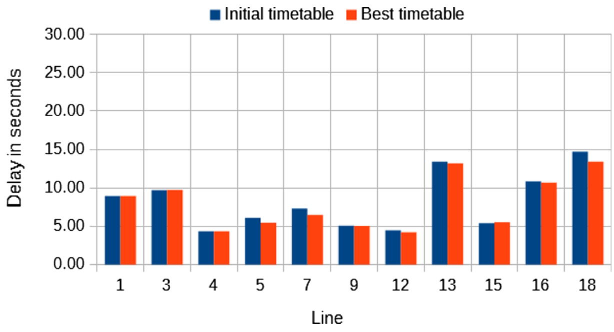


**Fig. 13** High variability of driving times: line delay

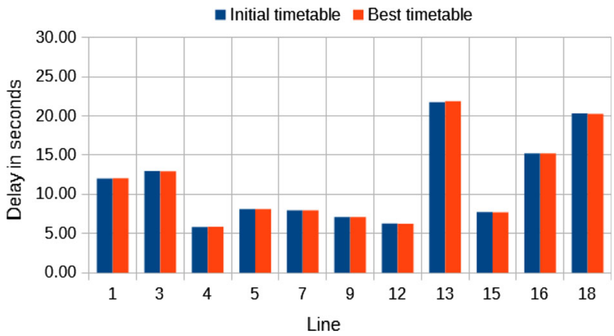


**Fig. 14** Redundant resources: line delay

to 24 % under standard conditions). This implies that the impact of regularity on the punctuality of a timetable is reduced by a high variability of driving times.

To test condition (c) we establish an approximation to resource redundancy by granting infinite capacity to all network resources. Under these conditions, the average delay under both examined timetables does not change significantly (see Fig. 14). Obviously, with competition for resources eliminated in this way, the degree of regularity of a timetable has no longer any impact on the punctuality of the vehicles.

Apparently the non-compliance with any one of the described conditions has a critical effect on the impact of regularity on punctuality in a tram network. The application of regular timetables therefore helps to reduce delays if the tram network's structure complies with the conditions described in Sect. 3.

## 5 Conclusions

We proposed that a tram network has to fulfill a set of conditions for a timetables' regularity to have a reducing impact on delays resulting from small disturbances. These three necessary network properties consist of: (a) lines have to compete for common resources, (b) the vehicles' driving times have to show a low variability, and (c) the network resources must not be redundant. These findings are confirmed by a series of simulation experiments, which examine the influence of regular timetables on punctuality in models of the tram networks of Cologne and Montpellier. While the yielded delay is significantly reduced as long as these networks adhere to the described conditions, the simulation results show that the abolition of any one of these three conditions reduces the effect of regularity decisively.

Based on these results, the consideration of regularity as an objective for timetable optimization can be recommended, as long as the examined tram network fulfills the described criteria. Adding to its usefulness for a number of other reasons, like assuring an even trip distribution or lowering the impacts of peaks in demand, regularity should therefore be included in timetable optimization models and software as a means to reduce delay resulting from small operational disturbances. However, considering regularity as an exclusive goal is not sufficient to generate practically applicable tram timetables, as valid timetables have also to adhere to sets of planning constraints originating from economic, technical, and political requirements. For a mathematical optimization model to contribute genuine utility for practitioners, these constraints also have to be considered.

As a next step, further tests will be conducted on multi-modal transit networks, including light-rail, as well as express and community bus transit elements. Also, the described results will support research on real-time and predictive dynamic re-routing and re-scheduling in multi-modal transit networks.

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## References

Bampas E, Kaouri G, Lampis M, Pagourtzis A (2006) Periodic metro scheduling. In: Proceedings of ATMOS

Banks J, Carson JS, Nelson BL, Nicol DM (2010) Discrete-event system simulation. Pearson

Cacchiani V, Caprara A, Fischetti M (2012) A Lagrangian heuristic for robustness, with an application to train timetabling. Transp Sci 46(1):124–133

Caimi G, Fuchsberger M, Laumanns M, Schüpbach K (2010) Periodic railway timetabling with event flexibility. Networks 57(1):3–18

Ceder A, Golany B, Tal O (2001) Creating bus timetables with maximal synchronization. Transp Res Part A Policy Pract 35:913–928

Dakin RJ (1965) A tree-search algorithm for mixed integer programming problems. Comput J 8:250–255

Desaulniers G, Hackman M (2007) Public transit. In: Barnhart C, Laporte G (eds) Handbooks in operations research and management science, vol 14. Elsevier, Amsterdam, pp 69–127

Dréo J, Pétrowski A, Siarry P, Taillard E (2006) Metaheuristics for hard optimization. Springer, Berlin

Eanki A (2004) A model to create bus timetables to attain maximum synchronization considering waiting times at transfer stops. Master thesis, University of South Florida

Genç Z (2003) Ein neuer Ansatz zur Fahrplanoptimierung im ÖPNV: Maximierung von zeitlichen Sicherheitabständen. Dissertation, Mathematisch-Naturwissenschaftliche Fakultät, Universität zu Köln

Ibarra-Rojas O, Rios-Solis Y (2012) Synchronization of bus timetabling. Transp Res Part B Methodol 46(5):599–614

Kölner Verkehrsbetriebe AG (2012) Deutsche Bahn AG, VRS GmbH (Hrsg.): Bahnen in Köln 2012. Netzplan

Lückerath D, Ullrich O, Speckenmeyer E (2012) Modeling time table based tram traffic. Simul Notes Eur 22(2):61–68

Lückerath D, Ullrich O, Speckenmeyer E (2013) Applicability of rescheduling strategies in tram networks. In: Reichardt R (ed) Proceedings of ASIM-Treffen STS/GMMS 2013, ARGESIM Report 41, ASIM-Mitteilung AM 145, ARGESIM/ASIM Pub., TU Vienna/Austria

Saharidis G, Dimitropoulos C, Skordilis E (2014) Minimizing waiting times at transitional nodes for public bus transportation in Greece. Oper Res Int J 14(3):341–359

Transports de l'agglomération de Montpellier (2013) Un réseau en étoile. http://www.montpellier-agglo.com/tam/page.php?id_rubrique=31 (Accessed 21 Feb 2013)

Turnquist MA, Bowman LA (1980) The effects of network structure on reliability of transit service. Transp Res Part B Methodol 14(1–2):79–86

Ullrich O, Lückerath D, Franz S, Speckenmeyer E (2012) Simulation and optimization of Cologne's tram schedule. Simul Notes Eur 22(2):69–76

Ullrich O, Lückerath D, Speckenmeyer E (2015) A robust schedule for Montpellier's Tramway network. Simul Notes Eur 25(1):1–8

Van Ort N, van Nes R (2009) Regularity analysis for optimizing urban transit network design. Public Transp 1(2):155–168

Vince A (1989) Scheduling periodic events. Discrete Appl Math 25:299–310

Vossloh Kiepe GmbH (2003) Elektrische Ausrüstung des Niederflur-Stadtbahnwagens K4000 der Kölner Verkehrs-Betriebe AG. Druckschrift 00KV7DE

Wu Y, Tang J, Yu Y, Pan Z (2015) A stochastic optimization model for transit network timetable design to mitigate the randomness of traveling time by adding slack time. Transp Res Part C Emerg Technol 52:15–31