Self-Organizing Strategies for Dispatching Buses and Drivers

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Self-organizing strategies are a promising concept to increase the resilience of urban bus systems. In such a scheme, the concept of a schedule or timetable is abandoned. Instead, departure times are determined dynamically using a simple mechanism. In the absence of perturbations, an adequate self-organizing strategy will cause the system to converge to some preferable state. As a result, the impact of disruptions dies out spontaneously, without intervention by a control authority.

Self-organizing strategies have already been applied in urban bus systems with the goal to reduce headway variation and prevent bus bunching. In the approach of Bartholdi and Eisenstein (2012), a bus is delayed at a bus stop by a time proportional to the headway to the trailing bus. The authors show that for the case with a single circular line, as long as there are no perturbations, any starting position will converge to some fixed point where the headways between all buses is equal. Note that this directly implies that whenever there is a perturbation, the headways will automatically self-equalize after some time. Even when one of the buses breaks down, a new system headway will naturally emerge. This approach was recently extended by Zhang and Lo (2018), who consider both the backward headway and the forward headway when computing how long a bus should be delayed. The authors show that this leads to a faster convergence, again with a single line.

In this paper, we extend the literature on self-organizing dispatching strategies in two ways. First, we consider more complex bus networks, consisting of multiple lines. In such a system, when a bus reaches a terminal station one not only needs to decide *when* to depart again, but also which line to perform. We theoretically analyze the performance of a simple strategy and are able to prove similar results as Bartholdi and Eisenstein (2012) and Zhang and Lo (2018) find for the single line case. In particular, we find that when one of the buses breaks down, the remaining buses spontaneously redistribute over the network, such that every line has the same headway.

Second, we investigate whether we can devise self-organizing strategies for dispatching both buses *and drivers*. This strongly increases the complexity, since we require that drivers need to

take a break after driving for a number of periods. To effectively synchronize and match buses and drivers, we develop four different strategies, increasing in intricacy. The first one applies a basic greedy algorithm, whereas the last one allows some form of communication exchange between stations and incorporates this information in a locally solved optimization problem. We examine the performance of these strategies in computational experiments.

Problem Statement We assume input in the form of a network $\mathcal{G} = (\mathcal{S}, \mathcal{L})$, where S is the set of terminal stations and $\mathcal{L}$ the set of lines. Every line l is characterized by a unidirectional travel time t_l and has the same target headway h. To operate a service, a driver and a bus should be available. Drivers and buses are not allocated to lines, so it is possible to switch lines after having reached a terminal. Drivers are required to have a break after a certain number of periods. Breaks are only possible at break stations. We assume that there are dispatchers at all stations who are in control of scheduling the resources at their station. All dispatchers operate independently and there is no central control center that instructs the dispatchers. The objective is to have, for every line l, one service per h time units, in both directions.

Scheduling Buses We first consider the case where the drivers are non-restrictive, such that we can ignore them. That is, whenever a service arrives at a station, the driver can directly be used for any new departing service (or equivalently, there will always be another driver to take over the bus). Note that Bartholdi and Eisenstein (2012) and Zhang and Lo (2018) make similar assumptions to allow theoretical analyses. We propose a simple dispatching mechanism of which the performance can be analyzed analytically. In this algorithm, a dispatcher only keeps track of the previous departure times of all lines originating at the dispatcher's stations. Whenever there is an arrival, the dispatchers assigns the incoming bus to the line for which the previous departure time is the longest time ago. The departure time is then based on the previous departure time, aiming for an interdeparture time of exactly h.

We prove that if all dispatchers schedule the buses according to this strategy, the *utilization*, which is the proportion of time buses are driving services, monotonically increases over time (except for an initial dip). Furthermore, we prove that regardless of initial positions of the buses, in the long run, all lines have the same average headway time. Finally, we prove that either (i) the utilization converges to 1 or (ii) at some point all lines have exactly the same number of departures per period. The former case occurs when there are not sufficiently many buses available to meet the headway requirements, even if centralized scheduling would be permitted. The latter case occurs when there are sufficiently many buses. These results are illustrated in Figure 1.

Scheduling Buses and Drivers When we also consider drivers and impose a break constraint for the drivers, dispatching mechanisms necessarily become more involved and a theoretical analysis is no longer possible. Instead, we propose four strategies, varying in intricacy and allowed forms of

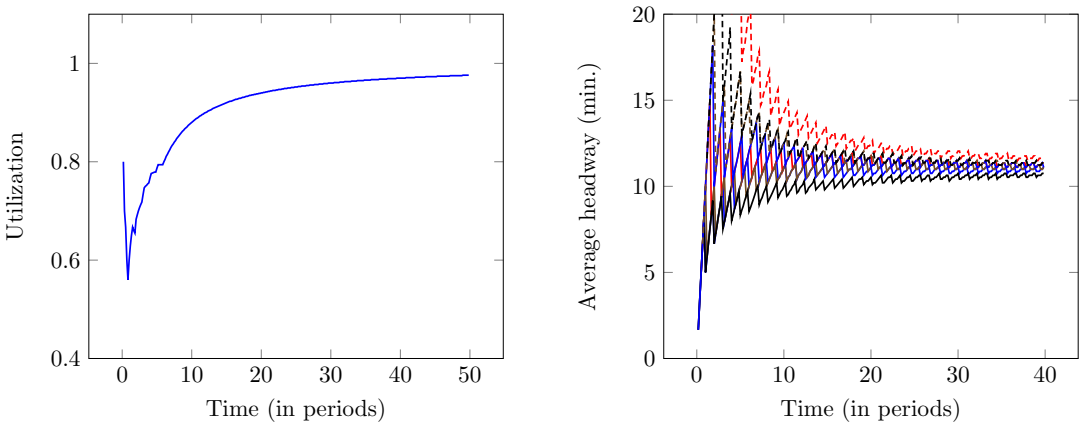


Figure 1 **Convergence of the utilization (left) and the average headways of the different lines (right).**

communication. The strategies are all based on attributing certain rewards to dispatching decisions, depending on the scheduled departure time. When dispatchers schedule a service, they 'earn' the corresponding reward. The rewards are specified such that high earned rewards for dispatchers correspond to good global performance of the system. We propose four mechanisms that optimize the earned rewards by a dispatcher:

1. *Naive*: schedules services one by one in a greedily manner.

2. *Optimize*: considers all available resources at the station at once and solves a mixed-integer program (MIP) to optimize the total reward.

3. *Heads-up*: whenever dispatchers schedule a service, they notify the dispatcher at the destination station. The information about future arrivals is incorporated in the MIP, such that a better solution can be found.

4. *Back-and-Forth*: all dispatchers constantly maintain a function that characterizes how much they would benefit from receiving a driver with a certain break time. This function is communicated with neighboring dispatchers, who take the function into account when solving the MIP, in order to find a more informed allocation of buses and drivers to lines.

We test the four mechanisms in a simulation study. The instance used is depicted in Figure 2. All lines have a target headway of 30 minutes. The unidirectional travel times of lines are specified in minutes. The maximum time without a break is 4 hours and s_3 is the only break station. The challenging aspect about this instance is to create sufficient supply of drivers at s_4 who have sufficient slack in their break constraint to perform line 5. In this instance, we have 9 buses and 11 drivers, which are actually equal to the minimum number required to meet the target headways.

The results of the four strategies are summarized in Table 1. Here, we report the average headways of the different lines over a simulated time of 15 hours, averaged over 5 different starting configurations of the buses and drivers. The naive approach already attains a reasonable performance, with all headways below the target headway except for line 5. The optimization mechanism

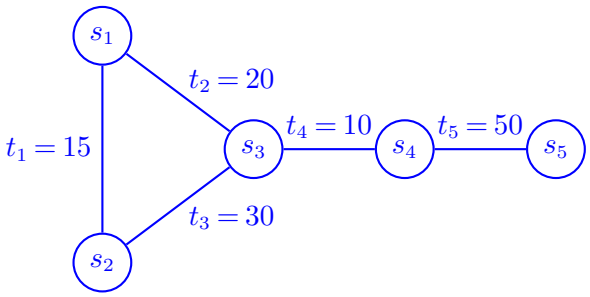


Figure 2 **Instance used for the computational experiments.**

Table 1 **Average realized headways obtained with the four mechanisms.**

	Realized headway (min.)				
Mechanism	Line 1	Line 2	Line 3	Line 4	Line 5
Greedy	26	26	25	25	34
Optimize	28	27	27	25	32
Heads-up	25	24	25	23	37
Back-and-Forth	29	28	27	18	31

is able to serve this line better, with an realized headway of 32 minutes instead of 34. On the other hand, the heads-up mechanism that allows limited communication results in a very imbalanced picture, with very short headways of lines 1, 2, 3 and 4 but a long headway of 37 minutes for line 5. The back-and-forth mechanism, where more information is communicated, is able to pick up on the specific demand at s_4 and brings down the headway of line 5 to 31 minutes. Hence, our results illustrate that communication may improve the performance, but this is not guaranteed.

Conclusions Our research highlights the potential of self-organizing strategies for operating complex urban bus networks. In our full paper, we extend these strategies also to railway networks. Specifically, heavily utilized railway systems from time to time suffer from *out-of-control* situations, where extreme disruptions such as power outages or blizzards have largely disrupted operations (Dekker et al. 2018). In such situations, self-organizing strategies could serve as a back-up plan, as they do not depend on central coordination and can easily be applied by local dispatchers.

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