Dynamic Pricing of Track Capacity in the Short-Term Allocation Process

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Abstract

Short-term track allocation is conventionally made on a first-come-first-served basis, but when capacity is scarce, more welfare efficient procedures are needed. Market prices for capacity is looking increasingly interesting as more train traffic is conducted on commercial terms. This is especially true for freight train operation, which dominates short-term allocation processes. In this paper we propose a dynamic pricing mechanism for the short-term allocation process. We use simulation to test the mechanism for stability, reliability, safeguard against manipulation and the welfare of the outcome.

Keywords: railways; deregulation; dynamic pricing; capacity allocation; short-term

1. Introduction

Railway operations are increasingly deregulated, with open access competition now common, especially on the freight market. This trend has made capacity allocation more challenging (see e.g. (Tomeš et al. 2014)). A welfare-efficient allocation prioritises traffic based on the value of each service, but in order for the infrastructure manager to calculate that value they require information that commercial operators typically hold secret, such as passenger numbers, fares and cost structure (Broman, Eliasson, and Aronsson 2018). An alternative to calculating the value of train services is to introduce market pricing of track capacity, thus forcing operators to reveal their own valuation of track access rights (Eliasson and Aronsson 2014).

Most of the capacity allocation is done through yearly timetabling processes, but it is also often possible for operators to request idle train paths in a short-term process; the latter is the focus of this paper. A common practice in short-term allocation is first-come-first-served, but when capacity is scarce a more welfare efficient method would be needed. We suggest in this paper to introduce market prices in the short-term allocation process through dynamic pricing. It is essential that the value of scarce capacity is properly assessed both in the standard allocation process and in the short-term allocation, in order to balance the number of train slots allocated through each method in a more welfare efficient way.

We argue that a good allocation mechanism for the short-term process fulfils the following criteria: the infrastructure is not under-used, i.e. capacity does not stand idle while potentially profitable traffic is requesting access; the most welfare-generating traffic is prioritised; access fees are not unreasonably volatile; access fees cannot be manipulated; and the mechanism is reliable in the sense that the line does not become fully booked unreasonably early.

We show through simulation that a dynamic pricing mechanism that we have constructed fulfils the above criteria and makes an allocation that is more welfare efficient than the optimal static price strategy. The simulation is built to resemble a line segment with known capacity and known historic booking-pattern in the short-term allocation process. We let a randomised number of actors request capacity at a randomised maximum price, let the dynamic pricing mechanism compute the access fee, and then make the booking if the fee is sufficiently low. This is done for a number of scenarios, including demand equal (on average) to the historic pattern, low/high demand, and demand that changes late in the allocation process. We also look at capacity restrictions. We then evaluate the mechanism's ability to meet our stated criteria and to produce an efficient outcome.

We present a dynamic pricing mechanism for the short-term track capacity allocation process that is shown to be more welfare efficient than the optimal static price strategy, and at the same time meet our stated criteria of stability, reliability and safeguard against manipulation.

2. The pricing mechanism

We use a definition of 'capacity' that is simple but adequate for the context: The railway network is divided into long line segments that each have fairly uniform capacity and demand. Breaking points between segments are put on important stations and nodes, and at places where capacity changes, for instance from double track to single track. The line segments can often be around 50-100 kilometres long. The day is divided into four time blocks, each six hours long. Each line segment that the train passes is combined with the corresponding time block at the time when the train passes.

To decide a line segment's capacity, a skilled planner looks at real timetables for a line segment and then adds new train-paths one-at-the-time as long as possible. The added train paths are made to fit the train-type that most commonly uses the short-term allocation process (often freight trains). The average maximum number of train paths is defined as the capacity of that line segment.

The pricing mechanism is designed as follows. The amount of available capacity for each combination of line segment and time block is continually updated. A default fee is calculated for each combination of line segment and time block as the optimal static price strategy. The mechanism calculates an access charge that is higher than this default fee when there is less available capacity, and lower when there is more available capacity than the historic average availability for the same number of days ahead of departure. When a train path is requested, the access charge is calculated as the sum of the charges for all the passed line segments at the time blocks that will be passed.

The price p_t is set at each time $t \in [0, T]$ to maximise expected welfare, expressed as

$$V(Q_t) = \max_{p_t} E\left[\frac{\hat{p}_t + p_t}{2} min\big(Q_t, D(p_t; \beta_t)\big) + rV\left(max(Q_t - D(p_t; \beta_t), 0)\right)\right]$$

where $Q_0 = 0; D(p_t; \beta_t) = 0 \; \forall t > T$, $\hat{p}_t$ is defined by $D(\hat{p}_t; \beta_t) = 0 \; \forall t$, Q_t is the available quantity at time t, β_t is a random vector with known distribution, $E(\beta_t) = 0 \; \forall t$ and r is the discount rate. Since the second term of the expression, which is the expected value of the capacity that is saved to the following period, is equal to zero when t=T, the expression can be rewritten as

$$V(Q_t) = \max_{p_t} E\left[\frac{\hat{p}_t + p_t}{2}\left(min\big(Q_{T-2}, (1 + T - t)D(p_t; \beta_t)\big)\right)\right]$$

3. Verification through simulation

For verification, we use as case study a line segment in Sweden that is often congested and frequently booked through the short-term allocation process. We use data on the short-term process from previous years that we get from the Swedish Traffic Administration (Trafikverket), showing the dates that requests have been made. From this we calculate the distribution of "antecedence", i.e. the time from a capacity request being filed to the desired time for departure. This is then used in the simulation.

The model looks as follows. For a number of actors (train operators), access requests are randomised in time around historic averages of "antecedence". Actors' willingness-to-pay (WTP) is randomised around an estimated value. (Robustness tests are made for different values.) Actors have varying flexibility in terms of what exact time they wish to depart, and they search for the cheapest train path near their preferred departure time.

When an actor makes a capacity request, the access charge is calculated according to the dynamic pricing mechanism. The booking is then made if a train path is found within the actor's flexibility range with an access charge not higher than the WTP of the actor. The available capacity is updated accordingly.

The simulation is made for several scenarios, including lower and higher demand than expected, demand that shifts late in the process, and capacity restrictions. A large number of runs are made for each scenario in order to see both the average and the variance of a range of parameter values. We compare the outcome of the dynamic pricing mechanism to that of the optimal static-price strategy and of a first-come-first-served strategy, in terms of welfare, stability, reliability and safeguard against manipulation.

4. Results

The price algorithm steers the booked capacity towards the historic pattern, as intended. An example of this is shown in Figure 1, where an unusually low demand early on causes prices to drop, which in turn supports demand.

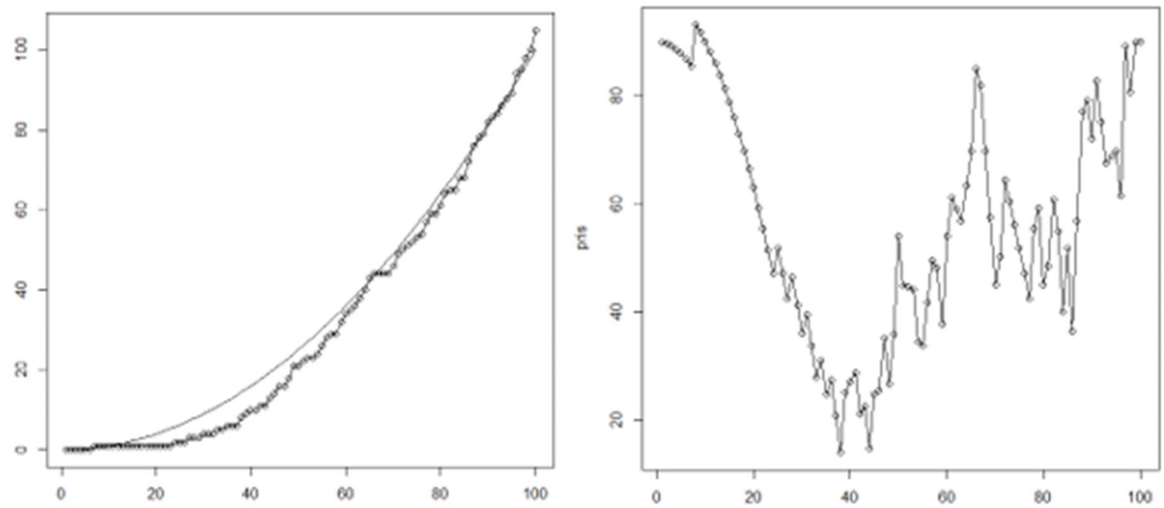

Figure 1. Left: Accumulated booked capacity in example trial (circles) compared to historic pattern (line). Right: Track access charge in same example trial.

When comparing how the different allocation mechanisms respond to the same randomised data, we note that dynamic prices select train path requests with a higher combined WTP, compared to both the optimal static price strategy and to first-come-first-served with no charge, indicating that dynamic prices increase the socio-economic efficiency of the system. Furthermore, dynamic prices successfully delay the point in time when the tracks get fully booked until close to the departure date, which arguably increases the reliability of the allocation method.

The simulated train operators sometimes respond to the dynamic prices by choosing an earlier or later departure time than their first choice, or by adapting the speed when this is possible. These adaptations allow for more trains to fit in the timetable, and make a positive net contribution to the socio-economic efficiency of the system.

5. Conclusion

We propose in this paper a dynamic pricing mechanism for track capacity allocation in the short-term process. The mechanism is designed to generate a more welfare efficient outcome than the optimal static price strategy, as well as first-come-first-served procedures. It is also designed to hold for criteria of stability, reliability and safeguard against manipulation.

The characteristics of the mechanism are tested through simulation. The aim is to show that the mechanism's performance is superior to that of the benchmarks both for demand patterns that follow historic precedent and for other important scenarios, including unexpectedly high or low demand, demand that changes late in the process, and capacity restrictions.

6. References

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