Dynamic delay management at railways: a Semi-Markovian Decision approach

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Chapter 7

Railway networks

Up to this point, the discussion has been restricted to isolated junctions. In the real world the junctions are often part of a bigger network. In this chapter we will investigate how the locally optimized SMD strategies will perform within a network environment.

In Section 7.1 we first introduce networks and explain how the SMD model is used in such an environment. In Section 7.2 we then explain how decomposition rules are applied to divide the network into manageable areas.

Next, we will construct three different networks by combining the Fork_R and the Bidirectional junctions and we will investigate how the SMD strategies perform. Section 7.3 is devoted to the network of three Fork_2 junctions. In Section 7.4 a larger network is analysed which consists of seven Fork_2 junctions. As a last example, in Section 7.5 we will look at the networks containing a bidirectional junction and particularly we will be focusing on a network consisting of two Fork_3 junctions and one bidirectional junction. The chapter is closed with conclusions.

7.1 Networks and SMD

In this chapter we will be talking extensively about networks. Let us first explain what we mean by networks and how the SMD model will be used within these networks.

The network is a combination of a number of Fork_R junctions and bidirectional junctions. The flow of trains is simulated throughout the network. So the trains enter the arrival track of say junction A, cross the junction and enter the destination track of junction A, then at some point in time later enter the arrival track of junction B and so on. Depending on the layout of the network and the routes of the trains, the trains will enter different junctions or disappear from the model since the edge of a network has been reached.

Modelling the network as a whole with the technique of the Semi-Markovian Decision Models is computationally intractable. The state space of the SMD model would be too large, instead, the network is analysed by means of decomposition. Every junction is modelled separately. As a result, the SMD model will come up with local solutions. It is then interesting to investigate how these local solutions perform within the network environment.

7.2 Decomposition and the scope of junctions

To decompose a network into smaller areas, one first needs to think very thoroughly about choosing the 'right' boundaries for these areas. Different boundaries will lead to different performance results of the SMD strategy. Since the SMD model is designed to optimize junctions, the decomposed area should contain exactly one junction where the SMD decision needs to be applied. The length of the arrival and the destination tracks is then the subject of this section.

We will call the decomposed area, the *scope* of the junction since the SMD model will base its decisions on the situation within this scope. When making the SMD decision both the situation on the destination track and on the arrival tracks is evaluated.

Let us begin by addressing the destination track. The destination track has been included as part of the model in order to incorporate the influence of the trains on the track upon the trains that enter the track at some point later in time. For this reason, the length of the destination track should represent the area where the trains can hinder each other. A logical boundary for such an area will be the location where train paths diverge or a location where trains can overtake each other.

Choosing the right boundary for the arrival tracks is a different story. The trains that approach some junction need to claim it beforehand. This is done for security reasons. A train can not stop immediately so if the junction is not available, the train will need to adjust its speed beforehand. This way the train will be able to stop in time if needed. Thus, the length of the arrival tracks needs to be at least the maximal distance which is needed for the trains to stop if it is needed. Now recall that we have modelled the arrival tracks as being queues and the time that the train needs to cross the junction from the moment it appears in the queue is called the Approach time. This time corresponds with the time the trains need to reach the junction from the moment they appear in the queue. So the boundary should be chosen as such as to ensure that the trains entering the scope of the junction still have plenty of time to stop if this is needed.

Taking the above requirements for the length of the arrival and destination tracks into consideration, one can conclude that the decomposed areas may overlap each other. In fact, the areas can either be (partially) intersected or be disjunctive. This is shown in Figures 7.1, 7.2, 7.3 and 7.4. When the two areas intersect, the same train can be within the scope of two junctions simultaneously.

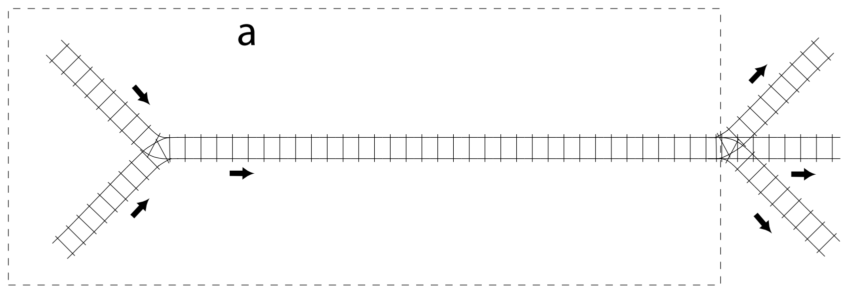

Figure 7.1: The scope of area a

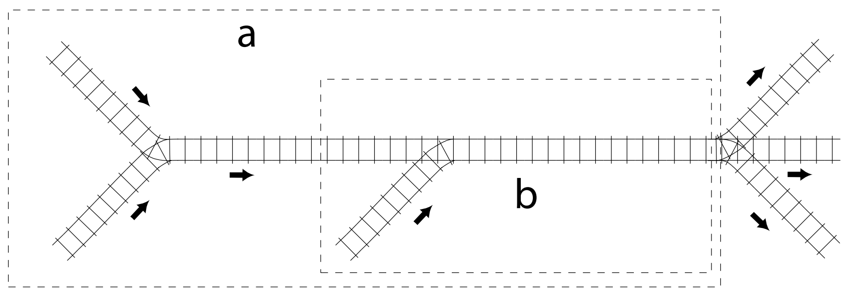

Figure 7.2: Two areas where area b fully falls within the scope of area a

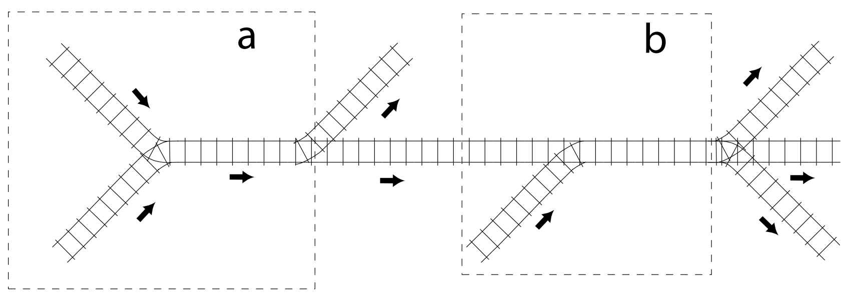

Figure 7.3: Two disjunctive areas

The situation depicted in Figure 7.2 needs special attention. Since the train order which is set at junction a can not change until the end of the destination track, the scope of junction a is very large. In fact, it even entirely covers the scope of the next junction. However, since within a decomposed area the conflicts of only one junction can be resolved at a time, the new trains that enter junction b are dismissed when resolving conflicts at

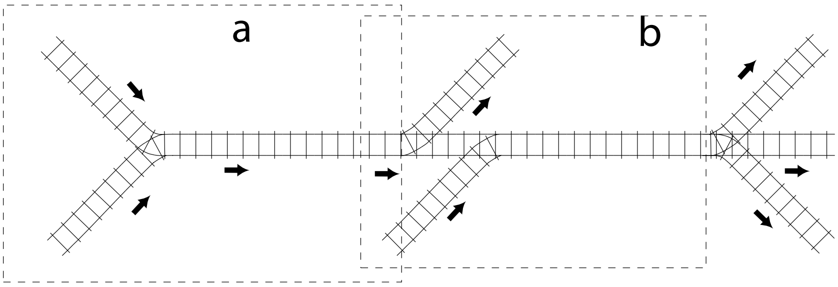

Figure 7.4: Two areas partially intersected

junction a. The conflicts at junction b are then solved separately by the SMD strategy there. Note, that when junctions a and b in Figure 7.2 are very close to each other, one might choose to model the two together by means of one single Fork$_3$ junction.

7.3 A network of three Fork$_2$ junctions

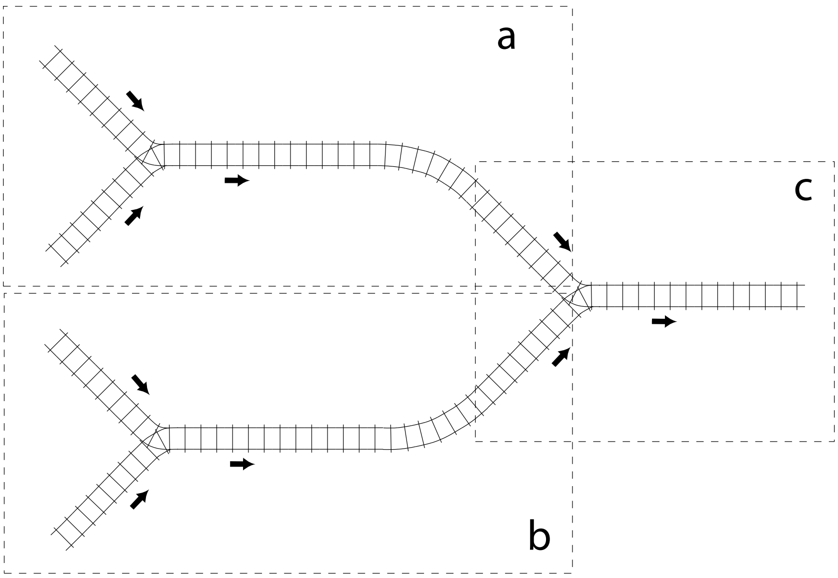

Figure 7.5: Network of 3 Fork$_2$ junctions

In this section we will discuss a network of three Fork$_2$ junctions. Junctions a and b (see figure above) apply SMD strategy to locally regulate the railway traffic. The railway traffic then arrives at junction c where the local SMD rule is applied as well. This rule derives its decisions from the information which is available within the 'scope' of junction c and has no knowledge about the current situation at junctions a or b.

The scope of junction c is the area which is indicated in Figure 7.5. This area consists of two arrival tracks and one destination track. In this example we have chosen to let the areas a, b and c partially intersect each other.

By means of simulation, the performance of the SMD strategy is compared to a number of heuristics. When a certain heuristic is used, it is applied to all three junctions altogether.

All three junctions are identical and consist of two arrival tracks with capacity 2 and a destination track of 12 kilometres long. Table 7.1 summarizes the characteristics of the trains that enter the network at junction a/b.

Characteristics	**P**	**F**
Speed (km/hr)	120	80
Approach time (sec)	180	270
Acceleration time loss (sec)	25	75
Arrival rate (per hour)	4	2

Table 7.1: Characteristics of the trains that arrive at junction a/b

On average six trains per hour will arrive at junction c from junction a and another six trains per hour will arrive from junction b. The trains enter the scope of junction c when still running on the destination track of the previous junction and having exactly the amount of time which corresponds with trains' approach time to reach the end of the destination track. Table 7.2 depicts the results of this network.

Discipline	**Delay at junction a and b**	**Delay at junction c**	**Total delay**
SMD	56	194	250
Follow	59	201	261
P-F	58	230	289
F-P	63	227	290
P-F-Follow	58	230	289
F-P-Follow	63	227	290
FCFS	62	272	334

Table 7.2: Results of the network of three Fork$_2$ junctions

The delays in the table have the following interpretation: it is the amount of time that a train spends in the scope of the junction above the amount that it would have spent if it were the only train in the network and thus could traverse through the junction without any conflicts. The delays that the trains gain at junctions a and b correspond with the delays obtained earlier in the results of Chapter 6. For convenience these results are repeated here in Table 7.3. This table depicts results of the situation where 6 (respectively 12) trains arrive per hour at Fork_2 junction and where the arrival process is modelled with the $\mathcal{HP}$-process. The delays found at junction c are however lower than that of the corresponding column of Table 7.3. This is because the trains arrive at junction c less randomly than it was the case with the $\mathcal{HP}$-process.

Discipline	**6 trains per hr**	**12 trains per hr**
SMD	56	203
Follow	59	206
P-F	58	245
F-P	63	229
P-F-Follow	58	245
F-P-Follow	63	229
FCFS	62	269

Table 7.3: Results of SMD_{ts} model of Chapter 6

The column Total delay within Table 7.2 depicts the mean delay of the trains measured over the whole network. Thus, when the strategy SMD is applied to all three junctions, the delays of an average train at junctions a and b will be 56 seconds. The load at junction c is twice as large and a lot of conflicts do arise. An average train will be delayed by another 194 seconds at junction c resulting in an total delay of 250 seconds per train.

From this table one can see that the SMD strategy maintains its superiority above other strategies within this network environment. Moreover, the difference between the performance of the SMD strategy and other strategies grows at every junction resulting in significant differences when looking at total delays.

7.4 A network of seven Fork$_2$ junctions

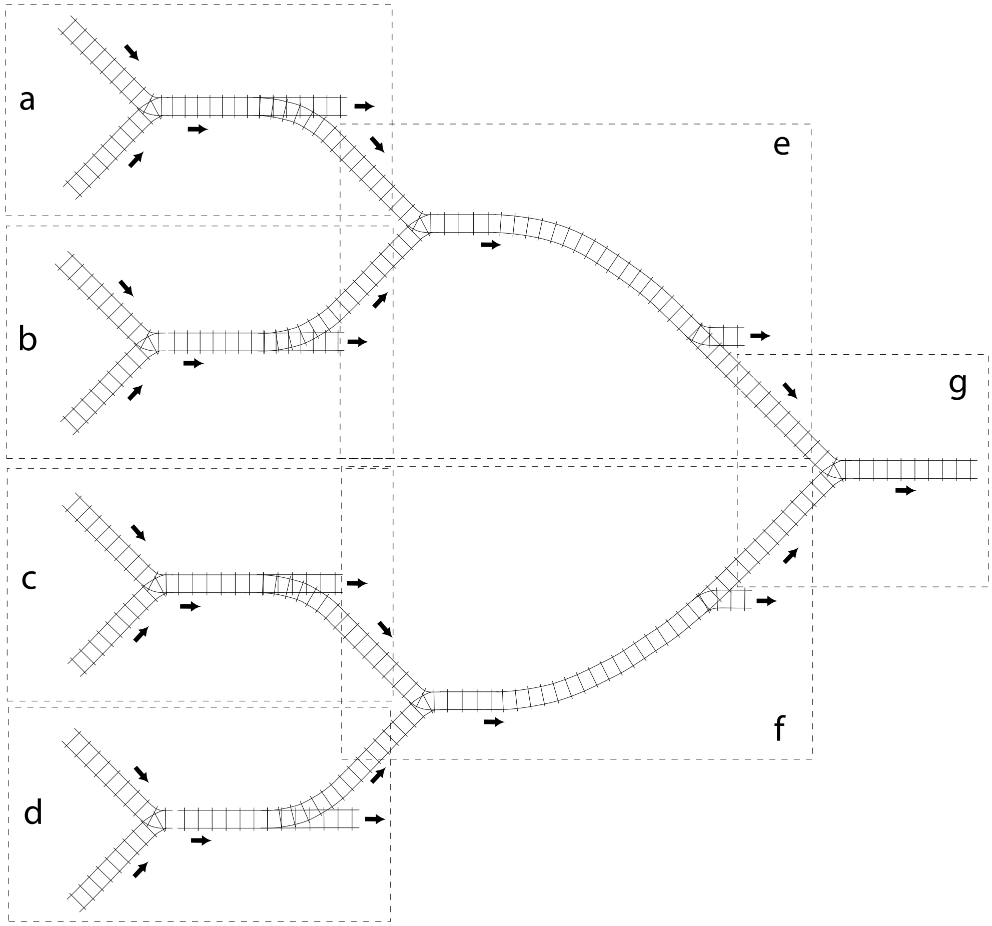

Figure 7.6: Network of 7 Fork$_2$ junctions

The network that is considered in this section consists of seven similar junctions. Every junction consists of two arrival tracks and a destination track with three blocks of four kilometres long. The load will be kept constant for every junction by routing only half of the trains towards the next junction and removing the other half from the network. In the example that we will look at, this load is equal to 12 trains per hour. We will measure the delays at junction g.

By making use of the common random numbers technique, the exact same simulation study will be used by different strategies. At every junction, the same trains will be routed off the network so that the trains reaching junction g are the same regardless of the strategy used. Table 7.4 depicts the total delays of the trains measured at junction g. By the term total delays we mean the sum of the delays that the trains have obtained at every stage of the network through the interaction with other trains.

Discipline	**Total delay**
SMD	586
Follow	599
F-P	642
P-F	688
FCFS	761

Table 7.4: The total delays of trains measured at junction g

From the table one can see that the superiority of the SMD strategy is preserved throughout the network. Moreover, the difference between the performance of the SMD strategy and that of the Follow strategy grows at every junction resulting in a difference of 13 seconds in delay on average per train at the end of junction g. The results of the rest of the strategies is in line with the results of the previous section.

7.5 A network containing a bidirectional junction

Let us consider the more complicated network which is depicted in Figure 7.7. Although the network is not based on a real-life situation, the complexity of the network has similarities with the complexity that can be found in real-life situations. The network contains 8 stations where passenger trains stop (the freight trains do not stop anywhere).

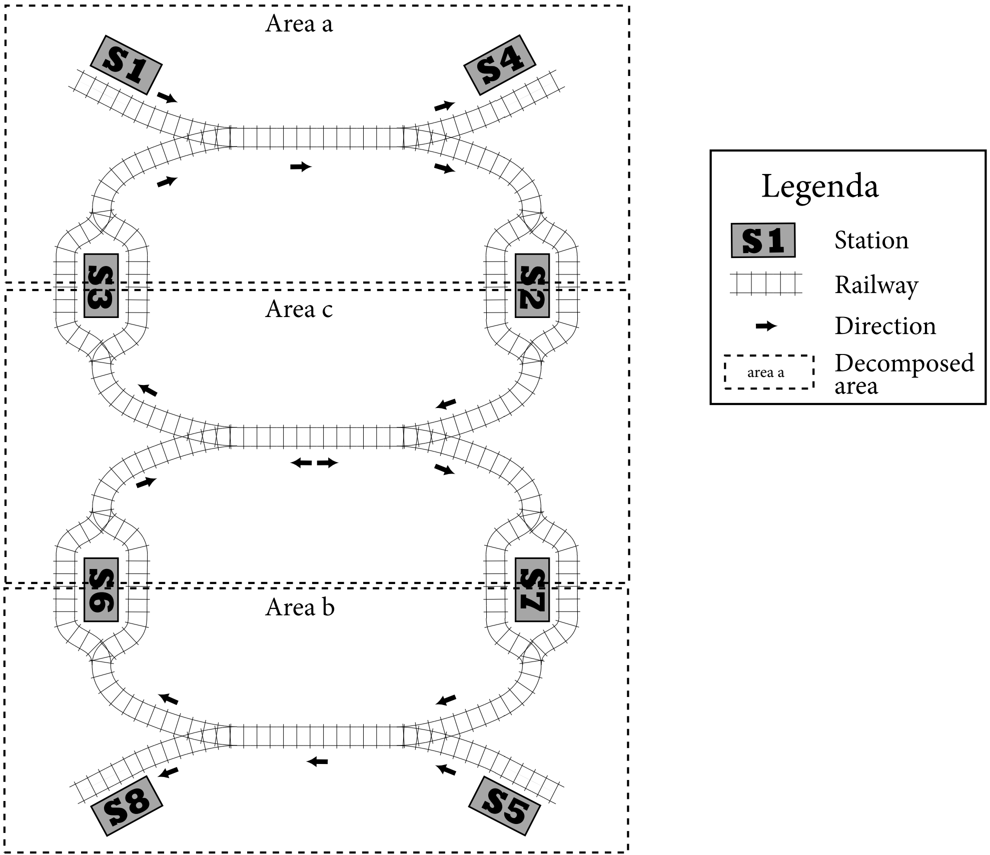

Figure 7.7: Network of 2 Fork_2 junctions and one bidirectional junction

The network contains two train routes, namely a route through stations S1 → S2 → S3 → S4 and another route through stations S5 → S6 → S7 → S8. The routes intersect on the bidirectional track with trains going from S2 to S3 and trains going from S6 to S7. Stations S2, S3, S6 and S7 have double tracks where the trains can overtake each other. One of the two tracks is dedicated to slow freight trains and the other to the halting passenger trains.

Let us refer to the passenger train service within this network by P_{ij} and to the freight train service by F_{ij}. The indexes i and j refer to the origin station and the destination station of the train service. Note that in this network, subsequent services are operated by the same physical train, i.e. the train running from station 1 to 2 continues to station

3 and exits the network at station 4. The same holds for trains between stations 5 and 8.

The network can be decomposed into three areas. Each area contains exactly one junction where conflicts can arise. Table 7.5 depicts the areas and the type of junction it contains. Per junction, the train series are given which run through that junction.

Area	**A**	**B**	**C**
Type of junction	Fork	Fork	Bidirectional
Number arrival tracks	3	3	4
Capacity of each arrival track	2	2	1
Blocks on destination track	4	4	2
Block length (in km)	4	4	4
Train services	P_{12}, P_{34}, F_{12}, F_{34}	P_{23}, P_{67}, F_{23}, F_{67}	P_{56}, P_{78}, F_{56}, F_{78}

Table 7.5: Characteristics of the decomposed areas of the network

On average, the load of every junction is equal: 10 trains arrive per hour of which two third are passenger trains and one third are freight trains.

The SMD strategy has been obtained for every area separately. As an arrival process within the SMD model, the $\mathcal{HP}$-process has been used. Obviously this arrival process does not mimic the arrival process found within the simulation study since within the simulation, the Poisson arrival proces is only found at the entrance of the system, the stations S1 and S5. The arrival process elsewhere is in some way more structured due to conflicts between trains throughout the network and the resulting resolution procedure prescribing minimal headways between these trains.

Table 7.6 depicts the results of the simulation study and shows the delays of train services P_{12},P_{23},P_{34},F_{12},F_{23} and F_{34} throughout the network. The delays of train services P_{56},P_{67},P_{78},F_{56},F_{67} and F_{78} are similar due to the symmetric characteristics of the network.

Table 7.6 should be read as follows: When the SMD strategy is applied, the physical trains running train services between stations S1, S2, S3 and S4 will get delayed in the following way: On average, a delay of 149 seconds will be obtained between stations S1 and S2 as a consequence of a conflict with train services between stations S3 and S4. At the bidirectional junction within area C, an additional delay of 429 seconds is accumulated. Back at area A, a conflict with train services running between stations S1 and S2 will yield an additional delay of 246 seconds. In total, the trains running services between station S1, S2, S3 and S4 will on average be 824 seconds delayed upon reaching

Discipline	**Service S1 → S2**	**Service S2 → S3**	**Service S3 → S4**	**Total delay**
SMD	149	429	246	824
Follow	175	468	269	911
Follow-P-F	175	472	259	907
Follow-F-P	177	474	288	939
P-F-Follow	178	809	217	1205
F-P-Follow	171	789	289	1249

Table 7.6: Delays of train services between stations 1, 2, 3 and 4 throughout the network

station S4.

By examining the table, one can see that except for the last strategy, the delays at area A are much lower for the train services P_{12} and F_{12} than the delays of train services P_{34} and F_{34}. This is because the junction load is not equally distributed among the arrival tracks. The trains running train services P_{12} and F_{12} arrive at junction A from the same arrival track. This arrival track has thus a much higher load than the two other tracks were only one type of trains arrives (train running either service P_{34} or F_{34}). The higher load of this track explains why both SMD and the Follow strategies prioritize trains from this track above the trains from other tracks. The same reason applies to strategies P-F-Follow and F-P-Follow which are more likely to process trains from the track with the higher load.

From the table one can see that the Follow-P-F and Follow strategies are the closest to the SMD strategy yet the difference in delay is substantial, more than 10%. The delay per train is reduced by almost one and a half minute when the SMD strategy is used. Moreover, the strategies FCFS, P-F and F-P are omitted from this simulation study since these strategies can not cope with the load at the bidirectional junction of area C.

7.6 Conclusions

In the previous chapters the discussion has been restricted to isolated junctions while in the real world the junctions usually are part of a bigger network. In this chapter we have discussed how the local SMD strategies can be used within the network environment. By means of decomposition a network can be divided in a number of junction where local rules can be applied. We have discussed how the process of decomposing should be executed and how the borders of the areas should be defined. The separate areas reflect the scope of the junction and different areas may (partially) intersect. By means of simulation the local SMD rules have been compared to a number of heuristics. Three networks have been constructed. On all networks the SMD strategy performed very well even though the underlying arrival process, which is based on a Poisson process, did not match a more structured arrival process found within the simulation. The last of the three networks is a more complicated network having a number of features borrowed from a real-life situation. This network showed that simple heuristic strategies do not perform well, some can not even manage with the high system load. In this network even the Follow strategy had relatively large delays. Compared to this strategy, the mean delays per train were reduced by the SMD strategy with almost one and a half minute.