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

Al Ibrahim, A.

Chapter 4

Results of the Fork$_R$ model

In the previous chapter we have constructed the SMD model for the Fork$_R$ junction. The goal of this chapter is to examine the performance of the SMD strategy (the strategy of the SMD model) and compare it to a number of heuristics. Also, the structure of the SMD strategy itself will be studied in order to comprehend the decisions that the SMD comes up with. To this end we will focus on the most basic case, namely a Fork$_2$ junction where trains from two directions come together. Moreover, we will consider only two types of trains: a fast and light passenger train (P) and a slow and heavy freight train (F).

We begin by defining the basic scenario (Section 4.1) and study its optimal strategy in Section 4.3. Then we compare the performance of the strategy with that of some simple heuristics. This is done through a simulation study. In Section 4.4 we discuss our choice for using the simulation technique to this end and in Section 4.5 we introduce the heuristics that are used for comparison. The remaining part of the chapter is devoted to the robustness analysis of the SMD model. In this part we test the performance of the SMD strategy within settings which are different from the basic scenario and analyse their effect on the performance of the SMD model. Finally the conclusions are presented.

4.1 Basic scenario

Let us define the basic scenario. In this scenario the junction consists of two arrival tracks. To limit the number of states, each arrival track will have a capacity of two trains. The length of the destination track will be 12 kilometres long.

There will be two types of trains: the fast passenger train (P) and the slow freight train (F). The characteristics of these trains are given in Table 4.1:

Characteristics	**P**	**F**
Speed (km/hr)	120	80
Approach time (sec)	180	270
Acceleration time loss (sec)	25	75
Arrival rate (per hour)	8	4

Table 4.1: Characteristics of the trains in the basic scenario

There are on average 8 passenger train arrivals per hour (4 on track 1 and 4 on track 2) and 4 freight train arrivals per hour (2 on track 1 and 2 on track 2) which makes it a fairly busy junction. Note that in reality, the number of train types is higher (one can think of Intercity trains, Inter-regional trains, local trains, freight trains, etc.). In this Chapter, we are interested in examining the structure of the resolution rules produced by the SMD model, and would want to keep things simple. At a first glance, 4 freight trains per hour seems to be an overestimation of the reality. One or two freight trains per hour would have been a more realistic case. However, the model with 10 passenger trains and 2 freight trains per hour would lead to an underestimation of the number of conflicts found in reality. Fast passenger trains are not only slowed down by the freight trains but are also hindered by slower passenger trains. This way, the model with 4 freight trains per hour, in our view, seems a better representation of the reality and thus more suitable for the definition of the basic scenario. Anyway, in Section 4.7.4 we will be examining the influence of the different ratio's of the passenger and freight trains on the performance of the SMD model.

The passenger trains move at a speed of 120 km/hr which approximately corresponds to the speed of the Intercity trains running in The Netherlands[1]. The speed of the freight trains is more difficult to estimate. In reality this speed depends on a lot of factors

[1]In The Netherlands the maximum speed is 130 or 140 km/hour but due to accelerations, decelerations and local speed limitations the average speed of the Intercity trains measured over the length of some track section is usually lower.

including the type of locomotive, the length of the train, the mass of the train and that of its load etc. In the basic scenario the freight trains will be running with 80 km/hour.

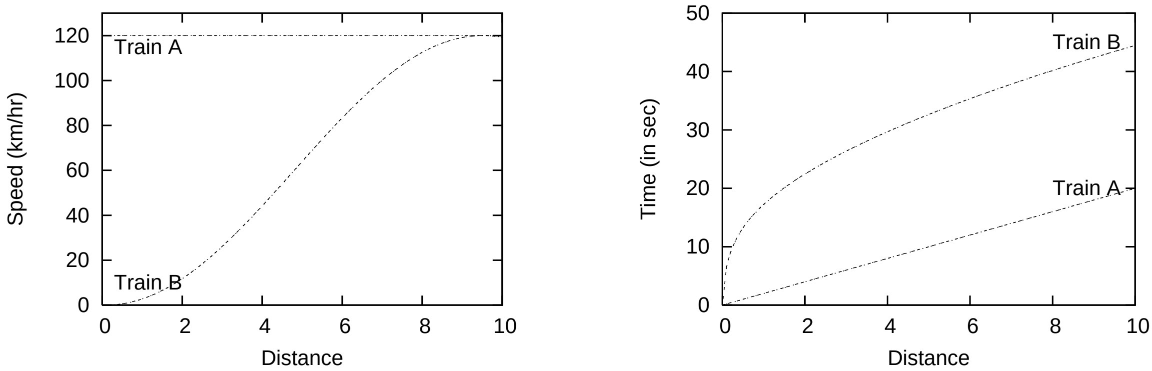
The approach time is defined as the time a train needs to cross the junction and clear it for the other trains, from the moment it has entered the arrival track and when it is not slowed down by other trains. The passenger trains have an approach time of 3 minutes, which given the speed of the train, corresponds to a distance of 6 kilometres, i.e. the passenger trains enter the scope of the model and thus enter the arrival track when at a distance of 6 kilometres from the junction[2]. If not slowed down, the train crosses this distance and clears the junction in 3 minutes. A freight train needs 270 seconds to cross the same distance.

Since the destination track is 12 km long, a passenger train will spend an additional 360 seconds within the system before exiting it while a freight train needs 540 seconds to cross the destination track.

If the junction is blocked, a train will have to stop. To keep things simple there will be nothing in between: A train is either running (speed indicator = 1) or stopped (speed indicator = 0). In case of a passenger train, the loss in time when stopped is 25 seconds. That is, from the moment the train starts with acceleration, the train loses 25 seconds when compared to the case where the train has not been stopped. The concept of the *acceleration time loss* is explained in Figure 4.1. Of course, the total delay of the train will be higher since the train needs to wait for a certain time until the junction is available before starting with acceleration. Since the mass of a freight train is substantially higher than that of a passenger train, a freight train is assumed to have a higher acceleration time loss. Here, the value of 75 seconds is used.

From the above definition of the Acceleration time loss, one might think that in the model an assumption is made that the trains always accomplish their acceleration process before reaching the end of the arrival track and thus the trains on the destination track will not be affected by the low speed of the train. At a first glance this might sound like a simplification which does not reflect the reality in the way it should have been but actually this aspect is fully covered by the concept of the acceleration time loss. The trains that will enter the destination track after the accelerating train will be delayed by the amount of time corresponding with the acceleration time loss, it then does not matter whether the trains have suffered from this delay at an arrival track or at the destination track. This is thus a much more compact way to model the effect of the acceleration of a train on the trains behind it than somehow incorporating the speed of the trains and

[2]Actually the distance is slightly smaller. To be precise, the train enters the model when at the distance of 6 kilometres minus the length of the train.



(a) The speed-distance diagram (b) The time-distance diagram

Figure 4.1: Illustrating the concept of Acceleration time loss. Consider two trains with equal characteristics. Train A moves at its maximal speed, train B accelerates from speed 0. After 10 units of distance, the trains have the same speed but train B has lost 25 seconds due to acceleration. In this example, train B experiences an Acceleration time loss of 25 seconds.

their acceleration rate within the state description of the destination track.

The minimal time between trains, *the headway time* will be three minutes, i.e. the trains will enter the arrival tracks and the departure track as well as leave the model with at least three minutes of time in between. In The Netherlands this value is usually between 3 and 4 minutes and depends on the pair of trains. Again, for simplification reasons, we will use a constant value of 3 minutes.

As has been previously explained in Section 2.2.6, the length of the blocks on the destination track corresponds to the distance that the slowest train can pass within the headway time. Since the headway time is 3 minutes and the slowest train runs with 80 km/hour, the block length is set to 4 km long. The destination track is thus divided into three blocks of 4 km long. Note that, as discussed in Section 3.8, when the total length of the blocks exceeds the total length of the destination track then the trains will leave the destination track somewhere halfway through the last block.

4.2 Relevant states at the destination track

Before continuing to the next section to study the structure of the SMD strategy, let us examine the possible states at the destination track. As said earlier, the destination track consists of three blocks and every block can either be empty, occupied by a passenger train or occupied by a freight train. There are thus in total 27 possible states at the destination track. However, in accordance to section 'State space reduction' (see Section

3.6) the majority of these states can be simplified to a number of 'relevant' states. The idea behind state simplification was the fact that when some trains are too far to hinder trains behind them, then it is safe to remove them from the state description. This practice will result in a compact set of only relevant states. In our case we can reduce the 27 original states to get a set of only 5 relevant states. Table 4.2 shows these states. The states are ordered by the amount of hinder caused to the next arriving train. The first state does not cause any hinder while the last state causes the maximal hinder.

State of X_0	**State description**
`- - -`	destination track is empty
`- P F`	freight train is followed by a passenger train
`P P F`	freight train is followed by two passenger trains
`P F -`	freight train is followed by a passenger train
`F - -`	freight train is at the first block

Table 4.2: Relevant states at the destination track of the basic scenario

4.3 SMD strategy for the basic scenario

Solving the model for the basic scenario gives us the SMD strategy for every possible state. Looking closely at this strategy, we find that it is always beneficial to give one of the trains the right of way if at least one arrival track is occupied. In other words, the decision $a = 0$, i.e. no train will cross the junction, will only be taken if both arrival queues are empty. Having said this, we can look at the so-called SMD decision matrix given in Table 4.3. The matrix describes the SMD decisions in a very compact way by aggregating over the possible states on the destination track. The value in the matrix can be either an integer value, which indicates that the decision to be made is independent of the state at the destination track, or a combination of two integer numbers between brackets. The latter case indicates that the SMD decision depends on the state at the destination track. The first number gives then the number of times that decision is in favour of arrival track 1; the second number indicates the number of times that the optimal decision prescribes that a train from arrival track 2 may proceed. As has been explained in the previous section, there are 5 relevant states at the destination track. So the sum of these two digits will be 5.

At the first glance one may think that $y_1 = 1$ and $y_2 = 1$ should never occur since having this situation would lead to train crashes but this is actually not true. This state basically states that (some of the) trains have just entered the scope of the junction while the others are still moving. The decision needs to be taken which arrival track to block and which to keep moving. On the other hand the situation $y_1 = 0$ and $y_2 = 0$ does not occur since there is no decision within the matrix that prescribes to stop the traffic from both (all) arrival tracks.

			x_1						
x_2	y_1	y_2	**-**	**P**	**P P**	**F P**	**F**	**P F**	**F F**
-	**0**	**0**	0	1	1	1	1	1	1
-	**1**	**0**	0	1	1	1	1	1	1
-	**0**	**1**	0	1	1	1	1	1	1
-	**1**	**1**	0	1	1	1	1	1	1
P	**0**	**0**	2	1	1	(1,4)	2	2	2
P	**1**	**0**	2	1	1	1	1	1	1
P	**0**	**1**	2	2	2	2	2	2	2
P	**1**	**1**	2	1	1	(2,3)	1	1	1
P P	**0**	**0**	2	2	1	2	2	2	2
P P	**1**	**0**	2	1	1	(1,4)	(3,2)	1	(3,2)
P P	**0**	**1**	2	2	2	2	2	2	2
P P	**1**	**1**	2	2	1	2	(1,4)	(3,2)	(1,4)
F P	**0**	**0**	2	(4,1)	1	1	2	2	2
F P	**1**	**0**	2	1	1	1	1	1	1
F P	**0**	**1**	2	2	(4,1)	2	2	2	2
F P	**1**	**1**	2	(3,2)	1	1	(3,2)	1	1
F	**0**	**0**	2	1	1	1	1	1	1
F	**1**	**0**	2	1	1	1	1	1	1
F	**0**	**1**	2	2	(2,3)	2	2	2	2
F	**1**	**1**	2	2	(4,1)	(2,3)	1	1	1
P F	**0**	**0**	2	1	1	1	2	1	2
P F	**1**	**0**	2	1	1	1	1	1	1
P F	**0**	**1**	2	2	2	2	2	2	2
P F	**1**	**1**	2	2	(2,3)	2	2	1	2
F F	**0**	**0**	2	1	1	1	2	1	1
F F	**1**	**0**	2	1	1	1	1	1	1
F F	**0**	**1**	2	2	(2,3)	2	2	2	2
F F	**1**	**1**	2	2	(4,1)	2	2	1	1

Table 4.3: SMD decision matrix of the basic scenario. For each combination of (x_1, x_2, y_1, y_2) a decision is given. 1 indicates that a train from arrival track 1 receives permission to cross the junction. 2 indicating that a train from arrival track 2 may proceed. Values between brackets indicate that the decision depends on the situation on the destination track (x_0). e.g. $(1, 4)$ indicates that for 1 of the 5 possible values of x_0, the decision is to give a train from arrival track 1 the right of way, in other cases, a train from arrival track 2 may proceed.

Since the problem is symmetric (the two arriving tracks have the same capacity and same load, i.e. $\lambda_1 = \lambda_2$), the matrix is symmetric as well, i.e. mirrored states have mirrored decisions. For example, the best decision for x_1 =(P P), i.e. two passenger trains approach from arrival track 1, x_2 =(P) and $y = (1, 1)$ is 1 while the best decision for the mirrored state x_1 =(P), x_2 =(P P) and $y = (1, 1)$ is 2. In both cases the best decision prescribes that the two passenger trains get priority above the single passenger train.

Next, in the situation where trains on only one track are moving while the trains on the other track are standing still (situations $y = (1, 0)$ or $y = (0, 1)$, the moving trains will almost always get the priority above the trains from the other track. An exception to this rule is the situation where two passenger trains are standing still on an arrival track while the destination track is empty or the trains on it are too far to hinder. Then, in a number of cases it will be decided to stop the traffic from the other arrival track and give the two passenger trains the right of way.

The SMD rules become more complicated when on both tracks the trains are moving. Then the best decision depends on the type of trains on the arrival tracks and on the situation on the destination track. In these cases, a freight train is more likely to be prioritised above a passenger train to minimize the acceleration time loss. However, when there are no freight trains on the destination track or these are too far to hinder, a passenger train may get priority above the freight train and enter the destination track first.

4.4 Simulation technique

In order to compare the performance of the SMD strategy to that of other strategies a simulation tool has been built. An advantage of using simulation is that it provides the possibility of modelling strategies like the FCFS strategy which can not be modelled with other techniques like Markov Chains or Queueing theory. Moreover, the simulation does not suffer from queue length limitations and can easily provide us with a lot of useful statistics.

The simulation tool has been built with the programming language Delphi. The choice for building an own simulation tool rather than using commercially available simulation tools, has been motivated by the freedom and customisation possibilities that one gets from building own tools. Moreover, the available commercial tools do not have off-the-shelf built-in solutions for all the requirements and needs that we needed for this research. Extending the possibilities of these tools requires extensive knowledge of the tool, programming language that the tool uses and the knowledge of the available components, that the software offers. Acquiring this knowledge takes some time and in our view does not weigh to the freedom one gets from building own tools.

The simulation model, which has been built, resembles that of the SMD in a lot of aspects. The states, the transitions, the arrival process, the costs have the same mechanism except for the fact that the time is now incrementing and at each stage one alternative is chosen, i.e. while within the SMD model different future states are considered, given the transition process, within the simulation environment only one future state is considered, based on a realisation of an uniformly distributed random variable.

In order to obtain statistically significant results, we will use the Batch Means technique [71] to cut a long simulation run into 500 sub-runs of 1100 trains each. To make the results of the sub-runs independent, the results of the first 100 trains of each sub-run are omitted.

Moreover, every strategy is simulated separately. By means of the common random numbers technique [71] the input for every strategy is exactly the same, i.e. the same trains arrive at exactly the same moments. This way, all the differences in the strategy performances are attributed to the strategies themselves and not to the stochastic influences of the simulation process.

4.5 The heuristics

The performance of the SMD strategy will be compared to the performance of a number of other strategies. The following strategies are considered:

FCFS First come First served strategy is a very natural strategy and the one which is often used in practice. The train that arrives at the junction first, may cross it first.

P-F This strategy prioritizes passenger trains (P) above freight trains (F). That is, whenever a passenger train and a freight train are found at the two arrival tracks, then the passenger train will always get the right of way. If two trains of the same type are found, then the strategy will choose the one that is running above the one that is stopped. Finally, If both are running then the trains are treated according to FCFS.

By prioritising the passenger trains above the freight trains, the strategy will send the passenger trains to the destination track before sending the freight trains. This will minimize the amount of delay the passenger trains will have on the destination track as a result of 'getting stuck' behind a freight train.

F-P This strategy prioritizes freight trains (F) above passenger trains (P) in the same way as it has been explained for the P-F strategy. This strategy makes sense, since by giving priority to the freight train, the strategy tries to avoid delaying the trains with the highest acceleration time loss and thus aims at clearing the junction as quickly as possible.

Follow Also known as Exhaustive Control. This strategy processes trains from one arrival track until all trains from that track are processed. Only then the attention is moved to other tracks. A new track is chosen according to the FCFS principle. This strategy optimizes the throughput at the junction by minimizing the number of times the decision switches tracks.

In later chapters also some other strategies will be considered. These strategies are not applicable here.

We realize that it would be very interesting to compare the performance of the SMD strategy to that of the models from literature. Due to time limitations this comparison was not possible. The reason is that it would take an enormous amount of time to build software that solves these models and then incorporates it to the simulation software.

4.6 Results of the basic scenario

The criterion that we will use throughout this chapter is the amount of delay the trains get under a certain strategy. The delay is defined as the difference between the time that the train spends in the system and the time it needs to cross both arrival track and destination track if not stopped at the arrival track and not delayed at the destination track. Thus, this delay is measured at the end of the destination track. Sometimes also the punctuality of the trains will be given. A train is regarded as being punctual when its delay at the end of the destination track is less than 3 minutes.

By simulating the junction and comparing the performance of the SMD strategy to that of simple heuristics we get the results listed in the Tables 4.4 and 4.5.

In Table 4.4 the delays per train type are given. The values in the column *mean* are the delays averaged over the train types, i.e. each value represents the average delay a train, regardless of its type, will have at the end of the destination track. Table 4.5 lists the punctuality of train types as well as the mean punctuality.

Let us consider the strategies one by one; The FCFS strategy performs very poorly, the average delay of a train is the highest of all strategies. Only 54% of the trains were

Discipline	P	F	Mean
SMD	235	138	203
FCFS	293	220	269
P-F	211	312	245
F-P	297	93	229
Follow	234	150	206

Table 4.4: Mean delays in seconds of the basic scenario

Discipline	P	F	Mean
SMD	71.3	80.6	74.4
FCFS	52.6	56.4	53.9
P-F	68.0	47.8	61.3
F-P	51.6	79.8	61.0
Follow	72.7	76.1	73.8

Table 4.5: Punctuality percentage of train types of the basic scenario where the train is punctual if its delay is less than 3 minutes

punctual at the end of the destination track. In comparison, the SMD strategy reduces the average delay by almost 25%. Both passenger trains and freight trains are well off when the SMD strategy is used and the overall punctuality increases to nearly 75%.

Furthermore, we see that always giving priority to the fast passenger trains turns out to be unwise since the decrease in delay for the passenger trains is not steep enough to compensate the sharp increase in the delays of the freight trains. The decrease of the delays of the passenger trains is not substantial because stopping the freight train in favour of the passenger train turns out to be very disadvantageous for the passenger trains behind the freight trains. As a result, the punctuality of the passenger trains is even slightly lower compared to when SMD is used while the punctuality of the freight trains is dramatically low.

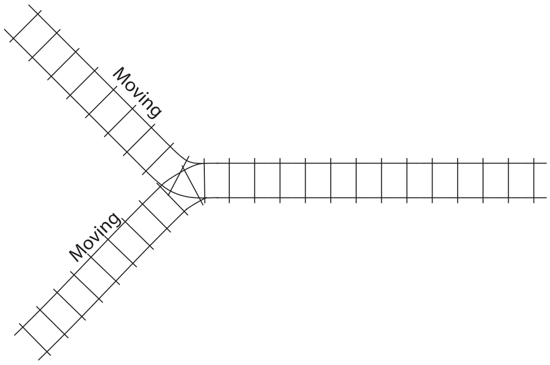
Next there is the F-P strategy. This strategy has a quite nice performance since the freight trains keep running. The delays of the passenger trains are the highest of all strategies but the overall average delay is relatively low. The delays of the freight trains are not zero since there is a probability that two freight trains are on both arrival tracks at the same time. Then no matter the decision, one of the trains will get delayed. Also, the freight train might be delayed due to its predecessor which is standing still to let trains from other directions go first. Interesting to see is that the overall punctuality of the F-P strategy is slightly lower than that of the P-F strategy (61.0 vs 61.3) while the average delays are lower too (229 vs. 245). This is because there are fewer trains that are punctual when strategy F-P is used while the trains that are not punctual have on average higher delays than when strategy P-F is used.

The Follow strategy does very well and has comparable results with the SMD strategy. The explanation for this is the fact that the two very often take the same decision. The essence of the Follow strategy is to process all the trains from one direction before changing to another direction. Doing so will keep the trains moving as much as possible which reduces the junction load. In most cases the SMD strategy does exactly that. A close examination of the decisions learns us that the SMD-strategy differs from the Follow strategy only when one of the following cases occur:

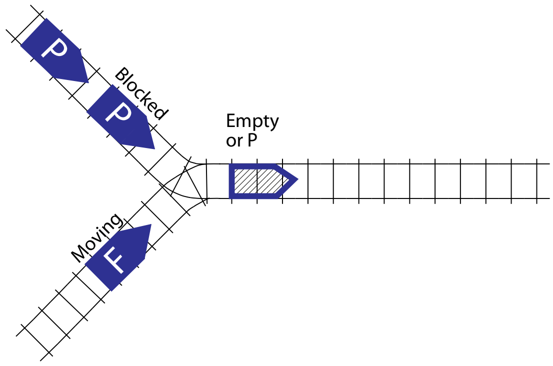
- When both arrival tracks are empty, there is a possibility that new arrivals occur on both tracks within the same time jump interval (Figure 4.2(a)). Simulation statistics show that in 9.5% of all time jumps, the state changes from two empty arrival tracks to both arrival tracks being non empty. When this happens, the Follow strategy will choose the track according to the FCFS principle while SMD will use its own strategy.

- Another difference between the Follow strategy and SMD occurs when there are 2 passenger trains on one track and either, 1 freight, 2 freight or a passenger train followed by a freight train on the other track (Figures 4.2(b), 4.2(c) and 4.2(d)). In these situations, when the two passenger trains face a red signal, it will be decided to give the two passenger trains the right of way when there is no freight train on the first block of the destination track. Within the simulation, this occurs in only 0.5% of the cases.

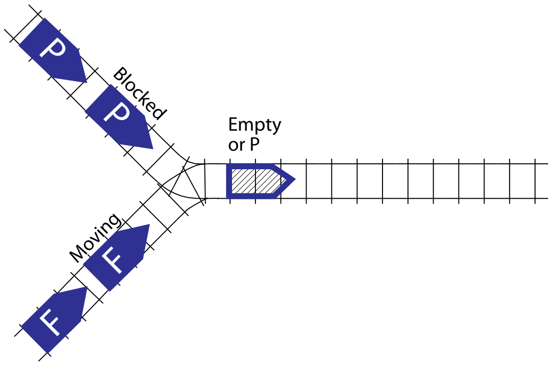
In other words, in at least 90% of the situations the Follow strategy is 'optimal' and identical to the SMD strategy which explains why the differences between the two being small.



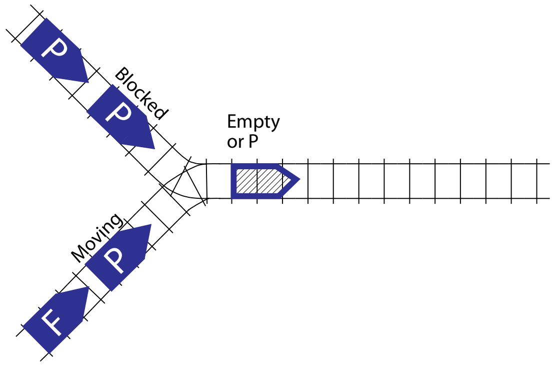
(a) The first train to enter the model, will be given permission to cross the junction when Follow strategy is used, while the SMD strategy uses its own rules depending on state.



(b) SMD strategy gives the right of way to the blocked passenger trains while Follow strategy processes the moving freight train.



(c) SMD strategy gives the right of way to the blocked passenger trains while Follow strategy processes the moving freight trains.



(d) SMD strategy gives the right of way to the blocked passenger trains while Follow strategy processes the moving trains.

Figure 4.2: States where the Follow strategy differs from the SMD strategy

4.7 Variations of the basic scenario

In the previous section we have examined the performance of the SMD strategy for the basic scenario. We concluded that the strategy performs quite well. In this section we will investigate whether this performance changes when tested within different model settings. The cases that we will study are the influence of the acceleration loss of the freight train (Section 4.7.1), the impact of the utilisation rate of the junction (Section 4.7.2) and the effect of the shorter headway time (Section 4.7.3). Also the effect a different mix of passenger and freight trains can have on the strategy is studied (Section 4.7.4). Another interesting question is whether the SMD strategy can cope with train priorities (Section

4.7.5). A number of other factors are then shortly mentioned in Section 4.7.6. For each of the above instances, the SMD strategy is obtained and compared to the heuristics.

4.7.1 Freight train acceleration

In the basic scenario the acceleration time loss of the freight trains was three times higher than that of the passenger trains. Since in practice a variety of factors (cargo weight, type of locomotive, number of wagons etc.) can influence the acceleration time loss, we would like to investigate whether other ratio value will affect the performance of the SMD model. In this section we will examine the case where the ratio is 2:1 and 4:1 respectively (2:1 indicates that the acceleration time loss of a freight train is twice as high than that of a passenger train). The results are presented in Table 4.6 and Figure 4.3.

Acc.time loss of F train in sec	**FCFS**	**SMD**	**P-FR**	**FR-P**	**Follow**
50	246	195	219	226	200
75	269	203	245	229	206
100	297	206	274	232	212

Table 4.6: Influence of the acceleration time loss of the freight train on the mean delay

Figure 4.3 shows that the performance of the SMD strategy does not vary much. The reason for this is that the SMD strategy stops freight trains only occasionally. Thus, the change in the value of the acceleration time loss of the freight train does not influence the results much. The same holds for the performance of the Follow strategy and that of the F-P strategy which are also more or less ‘stable’. In both cases the freight trains are rarely stopped. It is interesting to follow the performance of the P-F strategy. This strategy performs better than the F-P strategy when the freight trains are light. This is because stopping the freight trains becomes relatively ‘cheap’. The performance drops substantially though when the freight trains become heavier. Also the FCFS strategy stops the freight trains relatively often and thus suffers too from the higher value of the acceleration time loss.

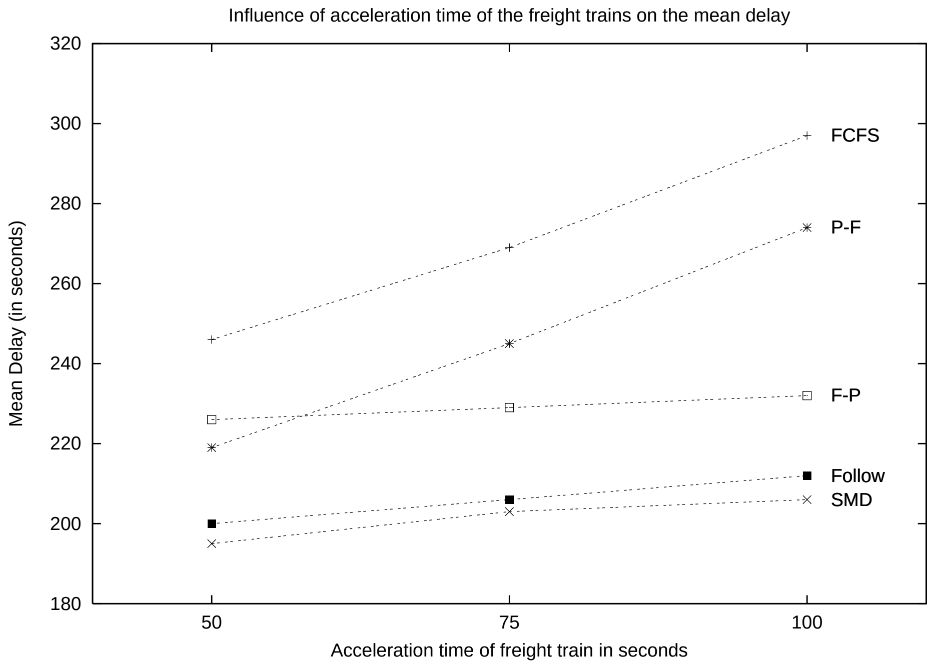


Figure 4.3: Influence of the acceleration time loss of the freight train on the mean delay

4.7.2 System load

Next we will look at the system load which is expressed in terms of the number of trains arriving at the junction per hour. Figure 4.4 depicts the mean delays at different system loads. Due to scaling, the differences are not clear when the load is low. This is why Figure 4.5 is more suitable to base conclusions on. The latter figure depicts the relative deviation of the mean delay of the strategies to that of the SMD strategy (e.g. a value of 120% indicates that a strategy gives mean delays that are 20% higher than that of the SMD strategy).

When there are very few trains arriving per hour then there are almost no conflicts. But even when only 0.1 trains arrive per hour, conflicts can still occur. Figure 4.5 shows that in such event, the mean delays for F-P strategy are almost 20% higher than for the SMD strategy. The best strategy turns out to be to prioritize passenger trains above freight trains which is done by both SMD and the P-F strategy. Since both FCFS and the Follow strategies give the first arrival the right of way, their performance will be between that of the P-F and the F-P strategy. However, due to the very low number of arriving trains, the absolute difference between these two strategies is negligible.

When the system load increases then the differences between the strategies increase (Figure 4.4), the best strategy then becomes the one which keeps the trains moving as much as possible. Thus the performance of the SMD and the Follow strategies converge

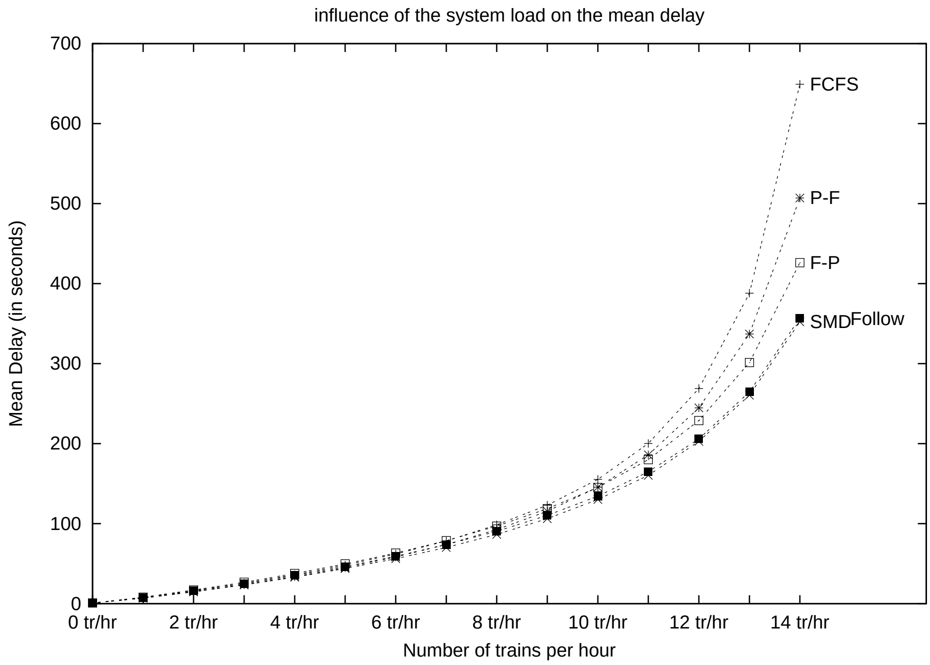


Figure 4.4: Influence of the system load on the mean delay

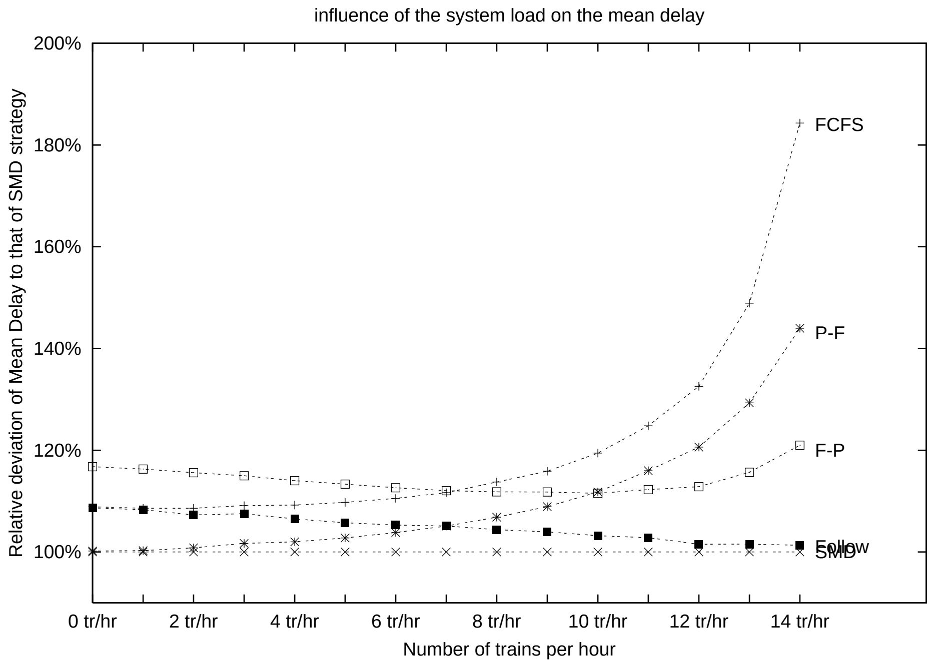


Figure 4.5: Relative performance of different strategies at increasing system load

towards each other (Figure 4.4) while the other strategies, which tend to stop trains more often, result in increasing delays.

4.7.3 Shorter headway

In the previous sections, the headway, the safety margin between trains was three minutes. These three minutes reflect the current situation pretty well. It is thinkable, though, that due to technological advances, this margin can be lowered in the future. In this section we will study the performance of the SMD strategy when the headway is reduced to two minutes.

Shorter headway implies shorter block lengths, since the trains may now run closer to each other. In accordance with the calculations made in Section 4.1, the block length on the destination track is shortened from 4 km to $2\frac{2}{3}$ km. The total number of blocks then has to be increased to 5. The trains however will leave the destination track after crossing exactly 4.5 blocks (12 km).

Since the trains run closer to each other, the approach time (the time the trains need to approach the junction) is also shortened. This way the junction is blocked for a shorter time period. The new characteristics of the trains are shown in the following table:

Characteristics	**P**	**F**
Speed (km/hr)	120	80
Approach time (sec.)	120	180
Acceleration time loss (sec.)	25	75
Arrival rate (per hour)	8	4

Table 4.7: Characteristics of the trains when headway is shortened

The absolute and relative results are shown in Figures 4.6 and 4.7 respectively.

When comparing these results to Figures 4.4 and 4.5 of the last section, one can see that apart from the scaling the figures are almost identical. Indeed, the strategies behave in the same way and the difference in performance is comparable too. The scaling is different since the capacity of the junction is increased. More trains can cross the junction within the same time. Either way, the SMD model can cope with the smaller headway and shows a good performance.

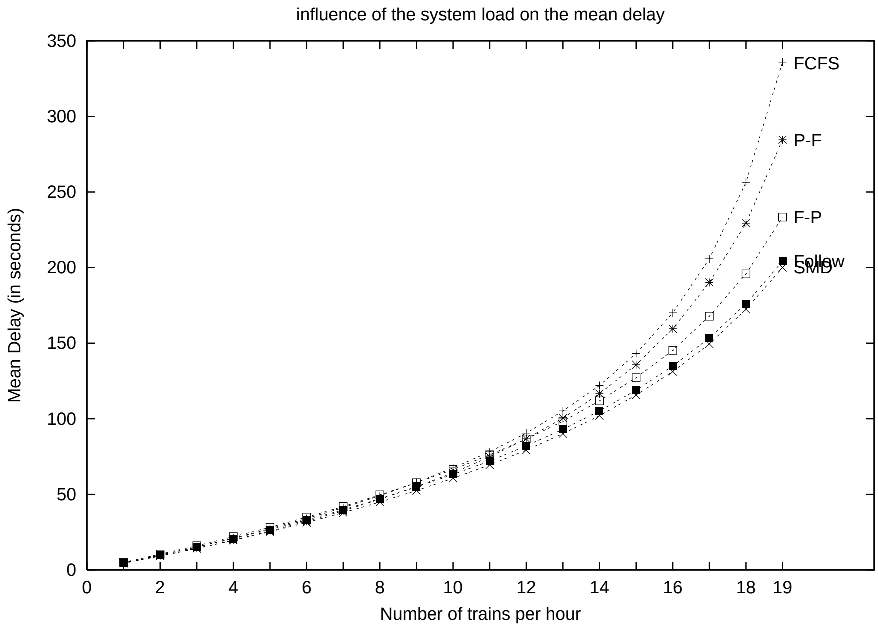


Figure 4.6: Influence of the system load on the mean delay when headway is 2 minutes

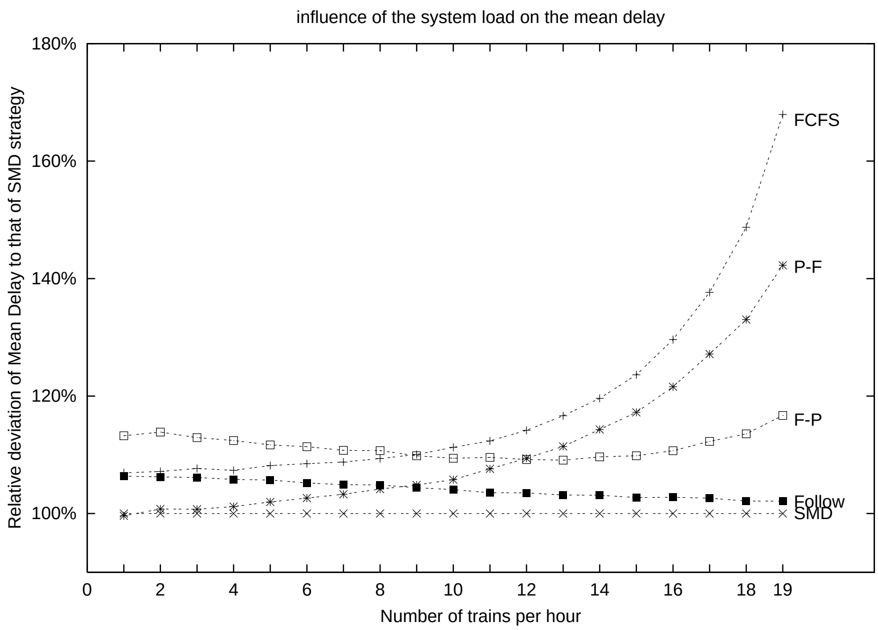


Figure 4.7: Relative performance of different strategies at increasing system load when headway is 2 minutes

4.7.4 The passenger-freight train ratio

Another interesting aspect to look at, is the ratio of passenger trains to freight trains. In the previous sections this ratio was 8:4, with on average 8 passenger trains and 4 freight trains arriving per hour. In this section we will vary this ratio in order to see how the performance of the SMD strategy changes.

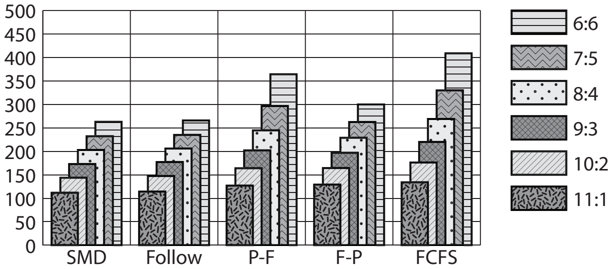


Figure 4.8: Performance of different strategies at different P:F ratio

If there are almost no freight trains, then almost all trains arriving at the junction are of the same kind. Then, the best strategy is to keep as much as possible trains moving. The SMD strategy then resembles the Follow strategy. Nevertheless, since passenger trains are fast accelerators, strategies like FCFS are also performing relatively well. This situation changes when more freight trains are introduced. The worst strategies are then the P-F and the FCFS strategies. The latter strategy stops too many trains decreasing the junction capacity while the P-F strategy is short-sighted: It gives the passenger trains the right of way but blocks the freight trains together with all the trains behind them resulting in overall bad performance. The SMD strategy, however, performs well in all cases.

4.7.5 Train type priorities

Up to this moment the priority of passenger trains was equal to the priority of freight trains. The SMD model offers possibility to prioritize one train type over the other. This can be achieved by introducing weights in the objective function, i.e. multiplying the time a train of type s spends in the system by some factor U_s. This way, some train types will be more expensive to delay than others. In order to implement this, the cost function is changed. As has been said earlier, the cost function is the sum of the arrival track costs, the destination track costs and the train rejection costs. Let U be the vector of the train type priorities. Then the approaching costs can be rewritten as

$$c^a(x, y, a) = \tau(x, y, a) \cdot \sum_{r=1}^{R} \sum_{i=1}^{N_r} U_{x_{ri}} \tag{4.7.1}$$

The destination track costs $c^d(x, y, a)$ can simply be multiplied by U_s when s is the train type that may cross the junction to enter the destination track (x_{a1}) or 0 if no train makes the transition.

Also the train rejection costs need to be altered. In Section 3.5 we have mentioned that the total stay time of the rejected train of type s is equal to $W + b_s + d_s$ where W is the time the rejected train will spend on the arrival tracks before being selected to cross the junction, b_s is the time the train needs to approach the junction and d_s is the time the train needs to cross the destination track. These costs are now multiplied by U_s resulting in $U_s \cdot (W + b_s + d_s)$.

We will denote by SMD-P the SMD strategy that gives two times more priority to passenger trains (i.e. $U_P = 2$, $U_F = 1$). The SMD-F strategy is the SMD strategy that gives two times more priority to freight trains (i.e. $U_P = 1$, $U_F = 2$).

Table 4.8 shows the results of the SMD-P strategy in comparison to other strategies. The last row within the table (row 'mean') denotes the weighted delays of the trains and are calculated in the following way:

$$mean = \frac{delay_P \cdot U_P \cdot N_P + delay_F \cdot U_F \cdot N_F}{U_P \cdot N_P + U_F \cdot N_F} \tag{4.7.2}$$

where N_P is the number of passenger trains and N_F the number of freight trains.

Delay	SMD-P	FCFS	P-F	F-P	Follow
P	195	293	211	297	234
F	233	220	312	93	150
Mean	203	278	231	256	217

Table 4.8: Performance of SMD-P strategy compared to other strategies

From the table one can see that the SMD-P strategy does very well when looking at the delays of the passenger trains. These trains have the lowest delay with the SMD-P strategy. Even under the P-F strategy, the delays of the passenger trains are not that low. Both strategies prioritise passenger trains above freight trains, but while the P-F strategy will always give passenger train the right of way, the SMD-P strategy will do that only when it is 'optimal' to do so. As a result, the freight trains will be stopped less frequently which results in a better utilisation of the junction and thus less delays at the arrival tracks. Since the freight trains are stopped less, the passenger trains that run behind them are also delayed less.

Even though the passenger trains are prioritised with the SMD-P strategy, the delays of the freight trains are not that high. As a result, when looking at the delays of all trains (the mean delays) the SMD-P strategy does very well. The Follow strategy does not do well when looking at the delays of the passenger trains. The strategy does not protect priority trains. The mean delay of this strategy is still quite good although the difference with the SMD-P strategy is enlarged. The same can be seen in Table 4.9 where the results are shown for the situation where freight trains have twice as much priority as the passenger trains.

Delay	**SMD-F**	**FCFS**	**P-F**	**F-P**	**Follow**
P	279	293	211	297	234
F	79	220	312	93	150
Mean	179	257	262	195	192

Table 4.9: Performance of SMD-F strategy compared to other strategies

4.7.6 Other robustness tests

Besides the robustness tests presented above, a number of other tests were conducted to find out whether the SMD model is sensitive to certain factors which can lead to a drop in its performance. Among these tests is the test involving the length of the destination track. The longer the destination track the more influence a freight train will have on the trains running behind it on the destination track. This is precisely what is observed. As a consequence, the SMD strategy will give the passenger trains more often the right of way. In all the cases the performance of the SMD strategy was superior to other strategies. Moreover, the difference in performance between the Follow strategy and that of the SMD strategy grows when the length of the destination track increases. The reason for this is that the order of the trains, that enter the destination track, plays a bigger role when the destination track is longer. The SMD strategy takes this into consideration while the Follow strategy does not.

Also the influence of the speed differences between the train types has been studied. The larger the difference, the more important the order of the trains on the destination track becomes and the more appealing the SMD strategy will be.

Finally, the influence of the track load has been analysed. If one track is busier than other tracks, i.e. more trains arrive on a certain track in comparison to other tracks, then the SMD model will prefer trains from the busier track above other trains. Stopping a train from a busier track will more likely affect the trains that will arrive later than is the case with trains from other directions.

4.8 Conclusions

In this chapter we have applied the SMD strategy to the Fork_2 junction. We have compared the performance of the SMD strategy with that of the simple heuristics. In the basic scenario, we have chosen some characteristics of the tracks and trains and looked at the performance of the strategies. The SMD strategy turned out to perform very well, outperforming all other strategies. By changing one of the characteristics of the basic scenario at a time, we have tested the robustness of the performance of the SMD strategy. In all cases, the SMD strategy proved to be superior to others.

The FCFS strategy has performed very poorly throughout all tests which has been conducted in this chapter. While the P-F and the F-P strategies do perform better than the FCFS, these strategies are no match for the SMD.

The performance of the Follow strategy is in most cases only a fraction lower than that of the SMD strategy. The reason for this is that in most cases the decisions made by both strategies are identical. Only in a small portion of situations, the SMD strategy makes a different decision. This small portion of decisions, however, leads to the overall superiority of the SMD strategy. It is however not difficult to think of the situations where the performance of the Follow strategy will be poor. One may imagine that for example increasing the number of arrival tracks and spreading out the trains through these tracks will lead to the Follow strategy with performance close to that of the FCFS strategy. The reason for this is that the probability of two trains arriving behind each other on the same arrival track will be low and thus more switches between the tracks will be made on the basis of FCFS principle.

As a final remark we would like to point out that the estimation of the externality costs has an influence on the quality of the SMD strategy. The performance of the SMD strategy can be even further enhanced by looking critically at these costs, however, as this is not the subject of this research project we will leave these costs as is. We conclude that the SMD strategy seems to perform very well within the Fork_2 environment.