Optimization of timetable supplement from a passenger based socio-economic point of view

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Abstract

This article discusses how to optimize the timetable supplement in timetables. The focus of this article will be on railways, but the principle will in theory apply to all transportation modes within the area of public transportation.

When constructing timetables it is important to plan the right amount of timetable supplement. Too little timetable supplement will result in many delays, while too high timetable supplement will result in a (too) high planned travel time which will affect every departure whether or not the train is delayed. At present timetable supplement is chosen based on experience or estimates. Through an optimization process it is possible to find the optimal timetable supplement. A way to do so is by using the passenger delay model in a socio-economic analysis as done by (Thorhauge & Piester, 2010). In this process the train delays (or a simulation of the train delays) are needed. The overall process is (if the train delays are not already known):

Simulation of train delays → modeling passenger delays → estimation of the socio-economic effects

A case study of an upgrade of Sydbanen between Ringsted and Rødby has been conducted using the passenger delay model and the methods are described in this article. The case study has shown that the optimum timetable supplement is between 6-9 % depending on the scenario. By optimizing the timetable supplement it is possible to achieve a surplus of 250-500 mio. DKK during the evaluation period compared to the proposed timetable by the *Danish Transport Authority* (Trafikstyrelsen, 2008). Note however that none of the investigated scenarios are socio-economic viable even though the timetable and timetable supplement is optimized.

Note that this paper is regarded as a sequel to the article "*The usability of passenger delay models in socio-economic analysis*" (Thorhauge, 2010). This article is based on the results of (Thorhauge & Piester, 2010).

Keywords: Timetable supplement, train delays, passenger delay model, optimization, socio-economic cost-benefit analysis, upgrade of Sydbanen

Introduction

This article discusses how to optimize the timetable supplement in timetables for railways. Timetable supplement is necessary in order to insure that the train will be on time in case of minor delays. This is important because delays have a higher value of time than (planned) driving time according to the socio-economic unit prices published by *Modelcenteret* (Modelcenter, 2009). On the other hand timetable supplement should not be unrealistically large, since timetable supplement will increase the planned travel time, meaning that – in the case of no (or very small) delays - the passenger will spend more time on a journey than necessary. Therefore it is crucial to incorporate the "right amount" of timetable supplements when planning timetables. However the right amount of timetable supplement varies from timetable to timetable. So how to find the right amount of timetable supplement? This paper will discuss a method using the passenger delay model combined with a socio-economic analysis in order to optimize the timetable supplement from a socio-economic point of view. Please note that this paper will not discuss (or use) traditional optimization algorithms to "optimize" the timetable supplement.

The overall hypothesis is that it is possible to increase the timetable supplement (and thereby decrease delays) to a certain point, from which it is not socio-economic viable to increase the timetable supplement any further, due to longer scheduled travel times for every departure. This point can be considered as the most socio-economic viable timetable supplement, and can be described as "equilibrium" between the amount of delays and the scheduled travel time. (Landex, 2008) illustrates the principle as shown below:

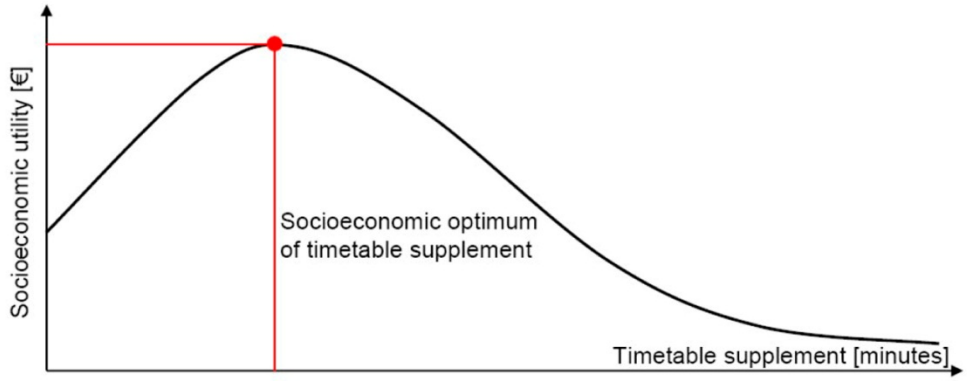

Figure 1: *The hypothesis that it is possible to optimize the timetable supplement so that the socio-economic surplus cannot improve any further. Source:* (Landex, 2008).

The hypothesis is based on the fact that it can be shown that[1]: 1) cost of scheduled travel time goes towards infinity when the timetables supplement goes towards infinity and 2) cost of delays goes towards zero when the timetable supplement goes towards infinity. It seems reasonable that the optimum timetable supplement occur as "equilibrium" between these two opposing trends. The optimum timetable supplement is therefore dependent of the amount of (passenger) delays[2], and the ratio of the value of time for driving time and delays respectively.

[1] Cost of waiting time, changing time, hidden waiting time, etc. is neglected.
[2] Delays in general depends on several factors; the overall available capacity of the railway line, the capacity consumption, the homogeneity of the timetable, the trains driving characteristic, etc.

Methods of analysis

In order to conduct different types socio-economic analysis three methods have been developed. These methods increase in complexity, with method 1 being the most simple and method 3 the most complex. The three methods of analysis (and their limitations) are described below:

- *Method of analysis 1* can be used to find the optimum timetable supplement for a given timetable. This is useful in order to optimize (the timetable supplement in) a given timetable without changing the overall structure of the timetable[3]. Method of analysis 1 however cannot be used to compare two (or more) different timetables. To compare different timetables method of analysis 2 or 3 must be used.
- *Method of analysis 2* includes the everyday cost of using the infrastructure and the trains, and can therefore be used to compare different timetables to find the timetable and timetable supplement with the overall highest socio-economic surplus. This is useful when deciding on the structure of the timetable (i.e. homogeneous vs. heterogeneous timetable, number of trains, etc.) as well as the optimal timetable supplement for that specific timetable. The limitation of method of analysis 2 is that all timetables must use the same infrastructure.
- *Methods of analysis 3* include cost of upgrading the infrastructure and works with an evaluation period making it possible to see the gains (or cost) in the future. This method can therefore be used to compare different timetables where the infrastructure, timetable, and timetable supplement are different in order to find the socio-economic optimal scenario. This is for example useful in order to investigate whether an infrastructure upgrade (and thereby a new timetable) is socio-economic feasible. It is possible to investigate several timetables on the upgraded infrastructure and compare these with the base-scenario and find the optimum timetable supplement of each of the investigated timetables in order to find the overall most socio-economic feasible timetable and timetable supplement.

Figure 1 summarizes the capabilities and limitations of the three methods of analysis and shows which effects should be included in the socio-economic analysis in the three methods above. The overall principle is that when using method 1 all passenger related effects should be included. When using method 2 all passenger and train related effects should be included. Train (or timetable) related effects are the operation cost and the externalities (air pollution, noise, accidents, etc.) since these will vary depending on the specific number of trains (or more precise; kilometer driven) in the timetables according to (Trafikministeriet, 2003), (Transport- og Energiministeriet, 2004) and (Modelcenter, 2009). Finally when using method 3 all socio-economic effects should be included. Since the construction cost is included, the cost-benefit analysis must be conducted over an evaluation period in order to see whether or not a given infrastructure upgrade are socioeconomic feasible.

[3] In reality the operation/running cost (fuel expenditures) may decrease as the timetable supplement increase due to a decrease in the average running speed. However this fact is neglected in this analysis. In this analysis the operation cost (along with the externalities) is therefore based solely on the number of kilometer driven, and is assumed not to be affected by the speed.

Socio-economic characteristicas		Method of analysis 1	Method of analysis 2	Method of analysis 3
Investigates timetable supplement		+	+	+
Investigates different timetables			+	+
Investigates different infrastructures				+
Calculated over an evaluation period				+
Socio-economic effects		**Method of analysis 1**	**Method of analysis 2**	**Method of analysis 3**
Passenger based effects	Driving time	+	+	+
	Waiting time	+	+	+
	First waiting time	+	+	+
	Hidden waiting time	+	+	+
	Change penalty	+	+	+
	Delays	+	+	+
	Negative delays	+	+	+
	Incomplete trips	+	+	+
Timetable based effects	Operation		+	+
	Externalities		+	+
Infrastructure based effects	Maintenance			+
	Construction costs			+

Figure 2: *Overview of socio-economic effects in methods of analysis 1-3.*

In this article the main focus will be on *method of analysis 3*. Note that *method of analysis 1* and *2* can be considered as simplifications of *method of analysis 3*. The overall calculation principles are identical among the three methods of analysis.

Small example

In this section a small example of *method of analysis 1* is conducted in order to illustrate the principles. Assume an example with a timetable containing three trains. The minimum (physical) driving time from A to B is assumed to be 10 minutes, and the three trains are assumed to experience the following three driving times in the realized timetable (due to delays):

- Train 1 uses 10,2 minutes to drive from A to B.
- Train 2 uses 10,3 minutes to drive from A to B.
- Train 3 uses 10,5 minutes to drive from A to B.

Furthermore, for simplification it is assumed that the three trains will have a total of one passenger each (although this is obviously not going to be economically feasible) and that these passengers only experience driving time – and in some cases delays[4]. In a real life case study the train delays[5] will have

[4] Waiting time, changing time, hidden waiting time, etc. are ignored for simplification.

[5] Please note that train delays and passengers delays are two very different elements (although they are the same in this little example due to the fact that each train has exactly one passenger). In reality the effects of train delay will vary depending on the amount of passenger the train is carrying. For example a little train delay in the rush hour may have a large impact on the total passenger delay due to high passenger volumes, while a large train delay is insignificant if the train is not carrying any passengers (if we ignore the fact that large train delays can cause secondary delays for other trains carrying passengers due to railway network effects (Landex et al., 2006)).

to be simulated (unless the methods of analysis are use to evaluate existing railway section/timetables where the train delays are known) and then converted to an input for the passenger delay model. The value of driving time is assumed to be 100 DKK/hour, while the value of time for delays is assumed to be the double (according to (Transport- og Energiministeriet, 2004) and (Modelcenter, 2009)), namely 200 DKK/hour. With these assumed simplifications the table below shows how to calculate the optimal timetable supplement as equilibrium between the socio-economic cost of driving time and the socio-economic cost of delays according to different timetables supplements. The optimum timetable supplement is marked within the red box.

Timetable supplement		**0%**	**1%**	**2%**	**3%**	**4%**	**5%**	**6%**
Scheduled running time [min]		10	10,1	10,2	10,3	10,4	10,5	10,6
Delays according to the scheduled running time [min]	Train 1	0,2	0,1	-	-	-	-	-
	Train 2	0,3	0,2	0,1	-	-	-	-
	Train 3	0,5	0,4	0,3	0,2	0,1	-	-
Total delays [min]		**1**	**0,7**	**0,4**	**0,2**	**0,1**	**0**	**0**
Total cost, driving time [kr.]		50	50,5	51	51,5	52	52,5	53
Total cost, delays [kr.]		3,3	2,3	1,3	0,7	0,3	0,0	0,0
Total socio-economic cost [kr.]		53,3	52,8	52,3	52,2	52,3	52,5	53,0
Socio-economic surplus [kr.]		**0,0**	**0,5**	**1,0**	**1,2**	**1,0**	**0,8**	**0,3**

Table 1: *Simple example of how to calculate the (relative) socio-economic surplus as a function of the timetable supplement.*

In order to calculate the socio-economic surplus the total socio-economic cost of all the investigated timetable supplements must be calculated (as done in the row marked with blue). This is possible since the time spend on transportation is considered a cost (or in other words; as "lost time" for the passenger and/or the society). In order to calculate the total socio-economic cost the cost for driving time and the cost of delays must be calculated. The total cost of driving time is calculated as[6]:

$$Total\ cost, driving\ time = \sum_{passenger\ i=1}^{passenger\ I} SDT\ A \rightarrow B_{passenger\ i} \cdot unit\ price_{driving\ time} \quad \text{(Formula 1)}$$

The total cost of delays is calculated as:

$$Total\ cost, delays = \sum_{passenger\ i=1}^{passenger\ I} (RDT\ A \rightarrow B_{train\ i} - SDT\ A \rightarrow B_{train\ i}) \cdot unit\ price_{delay} \quad \text{(Formula 2)}$$

In order to calculate the socio-economic surplus, the timetable supplement with the highest total socio-economic cost must be identified (in this example a timetable supplement of 0 % will have the largest socio-economic cost). This scenario will be used as the scenario of reference. The (relative) socio-economic surplus is then calculated as the difference between the total socio-economic cost of the timetable supplement which has the highest overall socio-economic cost and the socio-economic cost for a given timetable supplement. The formula is listed below:

$$Socio\ economic\ surplus_j = \max(socio\ economic\ cost_{j\ to\ J}) - \ socio\ economic\ cost_j \quad \text{(Formula 3)}$$

[6] Abbreviations in equation are as follows: *SDT = Scheduled Driving Time*, *RDT = Realized Driving Time*.

Figure 3 illustrates the principles of how to convert the socio-economic cost to a relative socio-economic surplus, as done in formula 3. As explained the scenario with a timetable supplement of 0% will be the scenario of reference from which the relative socio-economic gain from all the other investigated scenarios will be calculated. In other words; this means that a timetable supplement of 3 % is 1,3 mio. DKK more socio-economic feasible than a timetable supplement of 0 % (which is considered as the least socio-economic feasible scenario).

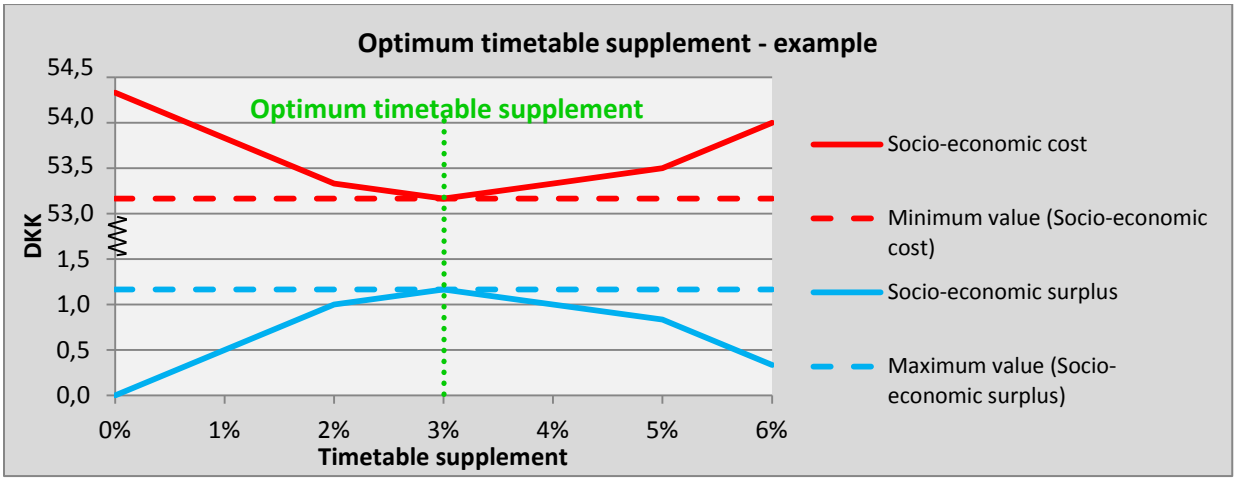

Figure 3: *Graph illustration the conversion from socio-economic cost (red) to socio-economic surplus (blue).*

As discussed above the gain is relative to the scenario of reference. Therefore the socio-economic surplus calculated in this example cannot directly be used in comparison with similar analysis conduction on other scenarios (i.e. other timetables on other railway lines). In order to compare different timetable (and/or different infrastructur upgrades) methods of analysis 2 or 3 should be used.

A casestudy: Sydbanen

The following chapter will use the principle described in *Methods of analysis* applied to a specific case study; an upgrade of Sydbanen between Ringsted and Rødby. An upgrade of Sydbanen is interesting in accordance with the forthcoming Fehmarn-connection, see more (www.fehmarnlink.com, 2010). In this case Sydbanen is assumed to be upgraded to a double railway line and prepared for speeds of 160 km/h (Thorhauge & Piester, 2010). A total of four different variants of the upgraded scenario are investigated as illustrated in Table 2.

	Timetable A: Few trains	Timetable B: Many trains
Storstrøm as a single railway line	**Scenario 1**	**Scenario 2**
Storstrøm as a double railway line	**Scenario 3**	**Scenario 4**

Table 2: *Overview of investigated scenarios for an upgrade of Sydbanen. Storstrøm is a bridge consisting of a single railway line and is a bottleneck in the infrastructure.*

In order to model the passenger delays, the train delays must first be determined. In this project the train delays are simulated using the simulation software RailSys. Afterwards the output from RailSys is

converted to a *realized timetable-input* for the passenger delay model. *Method of analysis 3* will be applied in this case since different infrastructures will be compared. The four scenarios are tested with different timetable supplements ranging between 0-15%[7] and compared to the proposed timetable (supplement) by the *Danish Ministry of Transport* (Trafikstyrelsen, 2008)[8]. The scenarios are tested against a base-scenario (do-nothing-scenario), as illustrated in Figure 4.

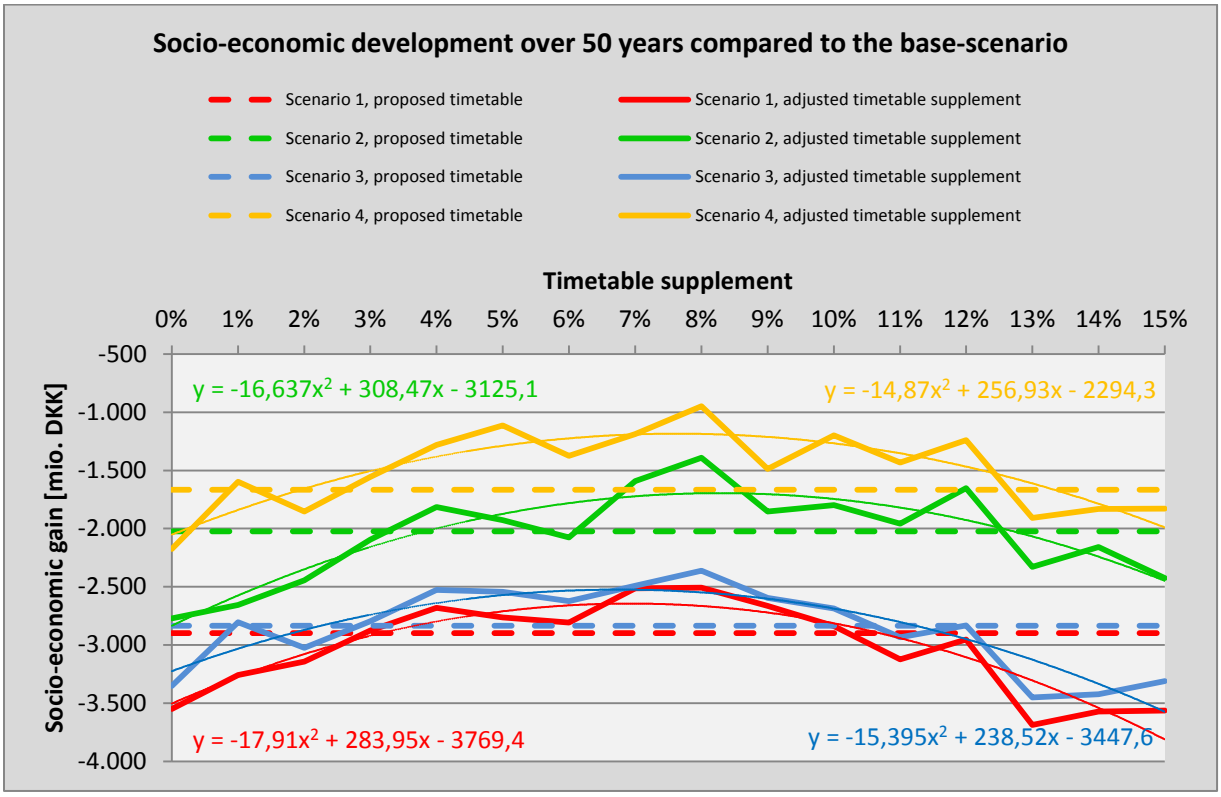

Figure 4: *Socio-economic development over 50 years compared to the base-scenario.*

First of all, it must be noted that none of the investigated scenarios are socio-economic feasible compared to a do-nothing-scenario. This is due to high construction costs of the investigated scenarios[9]. However the figure shows two tendencies; 1) the timetable with many trains is more socio-economic viable than the timetable with "few" trains (although the operation economy might show otherwise)[10] and 2) a double railway line across Storstrøm seems as the better of the two investigated infrastructure from a socio-economic point of view (when looking at the two infrastructures within the two timetables respectively). Note that, the figure show a linear dashed line and a dotted parabola. The linear line

[7] The timetable supplements are evenly distributed as additional running time along the investigated railway section (between Ringsted-Rødby).

[8] The timetable supplement in the proposed timetable by the *Danish Ministry of Transport* vary over the investigated railway section, but have been estimated at 12,6-12,7 % on average.

[9] Around 8-9 billion DKK depending on the specific scenario – based on estimates from (Trafikministeriet, 2008) and (COWI, 1999).

[10] Note that, the structure of the two different timetables are identical – the only difference is that timetable A has some departures which only runs in rush hour (once per hour) oppose to timetable B where these departures runs once every hour all day.

shows the socio-economic value of the timetable proposed by the *Danish Ministry of Transport* (Trafikstyrelsen, 2008) while the dotted line is a regression of the parabola, which will provide information about the "theoretical" optimum[11]. From the equation of the parabola it is possible to calculate the top-point of the parabola, and thereby calculate the optimal timetable supplement. Doing so for the four different parabolas gives the following results:

Scenario	Optimum timetable supplement	Annual gain of optimum timetable supplement compared to the proposed timetable	Total gain after an evaluation period of 50 year compared to the proposed timetable	NPV (Total gain after an evaluation period of 50 year compared to the do-nothing-scenario)
Scenario 1	6,9 %	14 mio. DKK	254 mio. DKK	-2644 mio. DKK
Scenario 2	8,3 %	18 mio. DKK	328 mio. DKK	-1695 mio. DKK
Scenario 3	6,7 %	17 mio. DKK	310 mio. DKK	-2524 mio. DKK
Scenario 4	7,6 %	26 mio. DKK	482 mio. DKK	-1184 mio. DKK

Table 3: *Optimum timetable supplement and the socio-economic surplus.*

The table shows that the optimal timetable supplement is between 6-9 %. Furthermore the table shows that it is possible to optimize the timetable supplement (from a socio-economic point of view) compared to the proposed timetable with an annual gain of 14-26 mio. DKK, which will transform to a surplus of approximately 250-500 mio. DKK (depending on the scenario) during the evaluation period. Last but not least the table shows that NPV<0 and it is therefore not socio-economic viable to upgrade Sydbanen compared to the existing infrastructure (do-nothing-scenario) even though the timetable supplement of the proposed timetables is optimized.

Discussion and conclusion

The methods developed and described in this paper are useful in order to optimize the infrastructure, timetables and timetable supplement of the Danish railways. However there are some weaknesses with the method which are described below:

- **Knowledge of (future) realized travel times is necessary in order to determine the train delays:** If the method is used to evaluate existing railway lines, this is not going to be a problem. On the other hand, if the method is used in order to predict whether a change in the infrastructure, timetable and/or timetable supplement is socio-economic viable, knowledge of the delays of the future railway line is necessary. Obviously this information is not available, so in order to compensate for the lack of knowledge the future delays must be estimated (in this case by the

[11] It is useful to use the theoretical optimum in order to avoid the fluctuations. The fluctuations occur due to simplification in the model process where number of launch in the passenger delay model is set equivalent with the number off minutes – meaning that the model will have a launch per minute. Although this number is fairly high (often a launch per 10 minutes is used), it is not detailed enough to avoid large fluctuations as seen in the graph (small fluctuation could be expected). It is possible to decrease these fluctuations by increasing the number of launch to approximately a launch per second, but keep in mind that this will increase the computational power needed as well as the time consumption.

use of the simulation software RailSys). However estimating future delays is a time consuming and difficult task, which can cause biased results.

- **Lack of a "solve to optimum"-function:** The problem is very well demonstrated with the small example in this article. The main problem is that it is necessary to manually calculate each of the scenarios in order to compare different timetable supplements. In the example timetable supplement of 0 %, 1 %, 2 %, 3 %, 4 %, 5 % and 6 % were calculated and the timetable supplement of 3 % seems to be the optimum timetable supplements among the investigated scenarios. However in theory a timetable supplement of (for example) 3.1% or 2.9% can prove to be the overall optimum timetable supplement. One way to overcome this problem is to calculate the regression to the polynomial of second order, as done in the case of Sydbanen. In the end it all comes down to the number of the investigated scenarios as well as the number of launch for each scenario. Of course many scenarios (with a large amount of launches) will increase the accuracy of the results. The downside is that the workload and time consumption increases very rapidly. Another possibility is to set up an optimization algorithm as an outer loop of the passenger delay model, and have it determine the "step size" of the timetable supplement. However this require heavy programming and a lot of computational power since such an algorithm should have the ability to (automatically) created timetables (which can be simulated in order to determine the train delays) in order to be fully automatically.
- **Lack of model data in the "right" format:** The fact that the passenger delay model originally is developed for the S-train means that model data[12] only are available for the S-train network. It is not impossible to obtain model data for other railway lines, but these have to be imported and converted to a specific format and in worst case made manually. The task of creating new model data can quickly prove to be a time consuming task, especially when taking the debugging-aspect into consideration as well.

All in all, despite the drawbacks listed above, the methods described in this article allows for incorporation of passenger delays when conduction cost-benefit analysis. Thereby, the main strength is that the methods can be used for optimizing the infrastructure, timetables and/or timetable supplement from a socio-economic point of view. For example *Method of analysis 2* can be used to optimize the entire Danish railway network without even upgrading the infrastructure at all. Especially DSB S-tog can use the method described in this article to optimize the suburban railway lines in the greater Copenhagen area since all the model data and timetables already exists. The *method of analysis 3* can be used to predict whether or not a project is viable from a socio-economic point of view when modeling with delays – as illustrated by the example of an upgrade of Sydbanen.

The long term vision is that the model and method is expanded to take other (public) transportation modes[13] into account as well, and thereby optimize the complete public transportation network for the entire greater Copenhagen region (or all of Denmark) as a coherent public transportation network.

[12] Station-nodes, links, timetables, modelparameter, etc.
[13] Busses, metros, regional trains, harbour busses and maybe future light rails.

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