

System analysis of train operations and track occupancy at railway stations

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A system analysis approach is presented for investigation of train operations in railway stations based on network, timetable and train detection data. The estimated blocking times, buffer times and track occupancies are compared with real operations data recorded automatically by track circuits. Statistical analysis of train operations between two Dutch major railway stations in The Hague clearly reveals that the trains operate at lower than design speed and the capacity of the critical routes to/from the platform tracks via level crossings is occupied up to 80 %. Furthermore, the dwell times at platform tracks are systematically extended due to hinder by other trains and behaviour of railway personnel. The scheduled headway between arrival and departure of some pairs of trains at critical route nodes proves to be insufficient, because the scheduled dwell times at stations and running times at junctions are generally exceeded and often leads to route conflicts if the headway times are short. The quality of timetable design and train operations in stations would be improved significantly if the feasibility of the scheduled arrival and departure times at major transfer stations was proven by a detailed estimation of the blocking and buffer times based on observed running times and delays during operations. The buffer time at junctions and level crossings should reflect the distribution of real train speeds and blocking times.

Keywords: Timetable, operations, station, track occupancy, blocking time, buffer time

1. Introduction

Train delays are one of the most important performance indicators of railway operations, which result from many related factors, such as the layout of the infrastructure, the occupancy of the infrastructure, the variation of running times, arrivals and departures, and the traffic control. First, the infrastructure must provide enough capacity and smooth routes. The timetable is the basic plan for train operation. On the one hand, the timetable should ensure the efficient and balanced use of the infrastructure. On the other hand, it should be flexible enough to cope with stochastic disturbances during operations.

Suitable recovery times in a timetable are very important to reduce train delays, whereas buffer times can decrease delay propagation. Stochastic disturbance of operations cannot be eliminated and will always occur, but its statistical distribution can be grasped by analyzing historic and actual train operation data. To some extent, this will help to forecast and prevent train delays. Traffic control is the final means to supervise and improve the train punctuality. The effectiveness of traffic control in case of perturbations, however, depends on the quality of the actual schedule, the time and precision of conflict detection and the available means for disposition. The interdependencies among the related factors are strengthened with the increase of traffic density and train speed, not only, which requires a further enhancement of the precision of time calibration a more comprehensive and accurate analysis of train operations.

Train detection data and train delays at stations can be analyzed with a high precision of about a second by means of the recently developed tools TNV-Prepare and TNV-Filter (Goverde, et al., 2000a and 2000b). Earlier publications (Goverde, et al., 2001a and 2001b, Yuan et al. 2002) deal with the distribution of train delays in some stations of the Dutch Railways. Tromp (2001) analyzes in detail one of the crossings of East of Eindhoven station and reveals a significant increase of the blocking times of the hindered trains resulting in much higher occupancy of the critical track sections and a reduction of capacity.

Other publications analyze the stability and robustness of railway timetables using analytical models, mathematical programming or micro-simulation. Wendler (1999) presents a stochastic model for the estimation of scheduled waiting time at station tracks for train-triples and gives a closed solution for the problem of non-utilizable time gaps at branching-off points. Huisman & Boucherie (2001) provide a queuing model reflecting the approximate dependence between free running times and scheduled headway times. The forecasted running time distribution for each train service is obtained by solving a system of linear differential equations based on Markov chains.

Zwaneveld et al. (1996) and Kroon et al. (1997) propose a Linear Programming model for the determination of optimal routes and train sequences through stations depending on scheduled train running times and fixed minimal headways. They present a branch-and-cut solution for the Weighted Node Packing Problem and applied it to a number of Dutch railway stations. Powell & Wong (2000) determine the maximum cycle performance for particular terminal station layout with up to six platforms by means of Integer Programming solved with a branch-and-bound algorithm. Billionet (2003) uses a standard commercially available integer programming software like MLP or AMPL for solving the train-platforming problem. When applying an objective function, e.g. to maximize the use of a certain track, the computing time, however, became too important. Kroon & Peters (2003) develop an optimization model for constructing cyclic timetables with variable trip times using periodic time window constraints in order to improve the robustness of a network timetable. For large timetabling

problems, a cycle fixation heuristic is required to solve the algorithm in a reasonable amount of time.

Malavasi & Ricci (2001) analyze the stochastic elements in railway system using a neural model. They develop and test a self-learning simulation model capable to reproduce the impact of track occupations by delayed trains on the performance of other trains in a regional railway network of the Italian Railway. Zhu develops a simulation model based on stochastic Petri nets in order to assess the impact of incidents on the quality of operations. With a simple sensitivity analysis, the most critical elements of the network could be identified. Kaminsky (2001) introduces a so called 'buffer train' to the blocking times of each train path compensating up to 80 % of the cumulative primary delays according to an assumed negative-exponential distribution. After establishing a conflict-free timetable for a large network in a part of the German Railway, the corresponding distribution of buffer times by time and space is evaluated by means of the simulation tool Railsys.

Rodriguez et al. (2002) develop a constraint programming model for the routing of trains in saturated corridors with explicit representation of the capacity constraints by block signals and of the temporal constraints by occupation and release of the track circuits. They apply a greedy algorithm, while the set of feasible routes is restricted to one route. Carey & Carville (2000, 2003), after having investigated the possibility for solving the train scheduling at complex stations by integer programming methods, finally present a heuristic approach for resolving conflicts between train paths and routes, while satisfying track infrastructure and headway constraints. They test the reliability and robustness of timetable options by means of simulating exogenous random delays in order to compare the costs and penalties for preferred train times and platforms including knock-on delays.

Steckel (1991) first developed a stochastic model for the estimation of train running times and proposed to replace the currently applied deterministic running time margins by the superior value of simulated running time distributions at a given level of significance (95 %). From the analysis of simulation results he concluded a good fit of the experimental data with the Weibull distribution.

Hermann (1996) analyzed the development of delays of long distance passenger trains in the traffic control area of Frankfurt/Main based on train detection data recorded over a period of 10 months and developed a model to forecast the growth of delays in the network. He found a good fit of the Chi-square distribution and of the Weibull distribution with the observed primary delays and most of the consecutive delays, while the Gamma, Negative exponential and Erlang distributions were rejected for either the primary or consecutive delays. As the average delays of the trains leaving the network were slightly less than at their entry he stated that the main reasons for perturbations of operations are located in the nodes, whereas the timetable is stabilized by the running time margins applied for the links.

Recently, Wendler & Naehrig (2004) confirmed the earlier finding of Schwanhäusser (1974) concerning the fit of the negative exponential distribution with the delays of the delayed trains recorded by Deutsche Bahn in the area of Nürnberg. Systematic primary delays of several minutes and a big variation of delays of freight trains, however, were observed which led to a shift of the distribution function.

From the comprehensive literature review it becomes clear that there exist only very few number of publications, which take into consideration the variation of train speed, blocking and buffer times in station areas with conflicting routes as observed in real operations. So far, the research is mainly limited to experiments by means of simulation or mathematical

analysis applying assumed distributions of primary delays and deterministic running and minimum headway times of trains.

The following paper presents the objectives and approach applied for a detailed analysis of the variations of train operations at railway stations. It describes the way of estimating the scheduled and real use of track capacity by means of blocking time graphs in order to determine the critical track sections and the resulting time margins. Then, a detailed analysis of arrival and departure delays and speed is performed on the basis of automatically recorded train detection data in order to estimate the corresponding distributions in the case of a major Dutch station. The paper concludes with the most important findings concerning the stochasticity of train operation variables and recommendations how to improve the quality of timetable design accordingly.

2. Research objectives and approach

The cyclic process of train scheduling and operation is shown in Fig. 1. At first, basic mainly periodic schedules for a long time period are prepared. Due to daily and hourly traffic fluctuations, some modifications of basic schedules may be necessary in daily use. During operations, in general, a part of the trains are more or less delayed. If necessary and possible, the operations of delayed and/or hindered trains are re-scheduled in order to recover at least partly from delays. However, random variations still affect train operations and use of track infrastructure. Actually recorded train delays may lead to an adjustment of the current schedule by re-timing, re-ordering or re-routing of train paths.

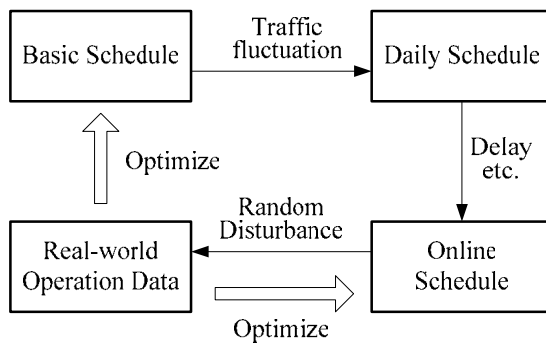


Figure 1. The cyclic process of train scheduling and operation

This paper aims at describing the relationship between scheduled and the real operation through analyzing train detection data and determining its impact on punctuality, speed and track occupancy. The analysis results with regard to train delays, running times, buffer times, critical routes and trains are to be fed back in order to improve the timetable and the performance of operations. This may support a decision to upgrade the track infrastructure at bottlenecks in case an increase of capacity and a reduction of operating cost are desired (see Figure 2).

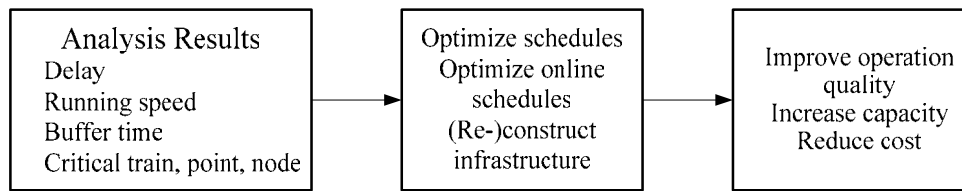


Figure 2. Research objectives

The principal approach adopted is system analysis. The research is decomposed into three parts, including infrastructure (network) analysis, schedule (timetable) analysis and train operation (train delay and speed) analysis. In network analysis, the conflicting routes and nodes in the network are identified. In timetable analysis, state-of-the-art methods are applied to estimate the blocking times and track occupancy in order to determine the scheduled time margins and to identify the critical headway times between pairs of train. Standard statistical methods are used for train operations analysis in order to describe the distributions of train delays, speed and buffer times and to estimate precisely the necessary buffer times between trains that avoid knock-on delays to enable a higher quality reliability and punctuality of operations.

The basic research issues treated are as follows:

1. Which are the critical route nodes and the maximal track occupancy within a complex railway station for a given timetable?
2. How much variation exists between scheduled and realized running, blocking, headway, arrival and departure times respectively at a busy railway station?
3. How the necessary buffer time between pairs of trains can be determined in order to avoid consecutive delays and to increase punctuality?

In this paper the infrastructure, timetable and realized operations analysis at the Dutch railway stations The Hague CS and HS are chosen as case study. However, the research method can be applied analogously to any other railway station.

3. Network analysis

The considered railway network consists of two main stations: The Hague Holland Spoor (HS) and The Hague Central Station (CS) connected to each other, while The Hague HS is a through station on the line Amsterdam/Leiden – Rotterdam and The Hague CS is a terminal station of the lines to/from Amsterdam/Leiden, Gouda/Utrecht and Rotterdam respectively (Fig. 3).

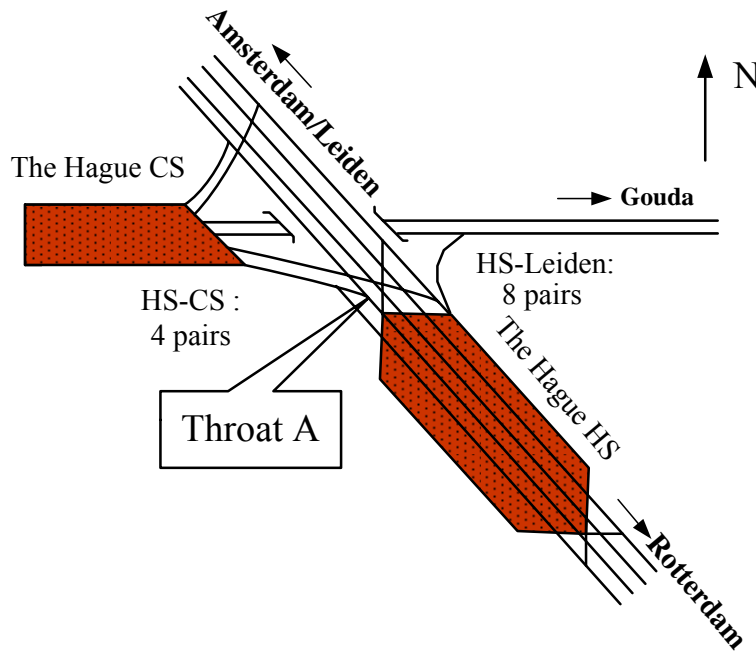


Figure 3. Scheme of railway network of The Hague

This study is limited to the occupation of tracks and the route nodes (points) between the two stations with four and three platform tracks respectively, three level crossings and several crossovers. Node A is obviously the busiest part of the network, as the tracks to/from Gouda are grade-separated from the other line and serve other platform tracks at The Hague CS. Details concerning track layout, switches and signals can be found in Appendix A.

4. Timetable analysis

The timetable analysis comprises time-distance train graphs between the stations and platform track occupation diagrams, estimation of blocking times for the different track sections, calculation of minimal headway times, buffer times and track occupation times. As reference timetable here was chosen the year 1999, because train detection data was available for the month of September of that year. Between The Hague HS and Amsterdam/Leiden 8 pairs of passenger trains per hour were scheduled, while 4 pairs of passenger trains per hour operated between The Hague HS and The Hague CS. Detailed timetable information and main train data are listed in appendices B and C. The timetable includes very close intervals between local trains departing to and arriving from The Hague CS on the one hand, and interregional/ international trains from Amsterdam /Leiden to Rotterdam on the other hand (Fig. 4).

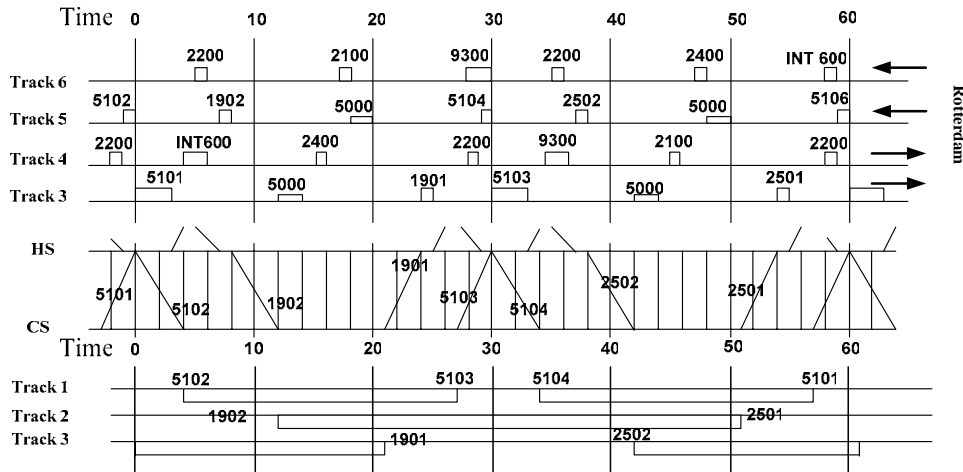


Figure 4. Train graph and platform track occupancy of The Hague HS and CS (NS timetable 1999)

The blocking time is defined as the minimal time of a train needed for traveling at design speed over the minimal space headway between two consecutive trains. It consists of the switch time for the signals and the new route to be set-up, the reaction time of the driver (10 s), the approaching time (running time of the train over the sight distance until the distant signal plus the distance until the main block signal), the running time within the signal block, the release time of the block, and the switch time for release of the route. It is estimated according to the German and UIC railway standard (Pachl 2002, Wendler 2001, UIC 2004). In case the distance between the distant signal and the main block signal is much bigger than the braking distance, the approaching time is estimated according to the running time of the train over the braking distance corresponding to the scheduled speed. As the trains accelerate and decelerate within the station area, the passing speed at the signals and train movement recorders and the mean speed corresponding to the scheduled running times is adopted. This results in characteristic blocking time graphs with stepwise release after conflict points (Fig. 5). More details concerning the length of blocking times of other trains, too, are listed in appendix D.

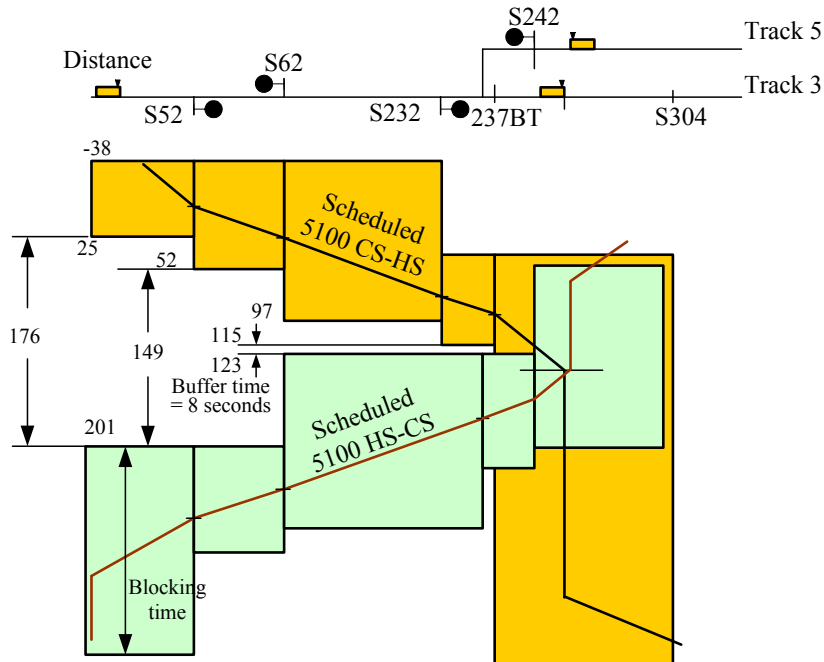


Figure 5. Blocking times and buffer time between 5100 CS-HS and 5100 HS-CS

After calculation of the blocking times of each train, it is easy to compute the minimal headway between two successive trains according to the prevailing safety constraints. The minimal headway at the critical block section corresponds to the time lag between the start of blocking times of the leading train and of the following train, if the blocking time graphs of the pair of trains are virtually squeezed such that they just touch each other. When referring to the time lag between a pair of trains leaving from a preceding station, while the second train runs faster than the first one, the difference in running time until the following station must be added. The minimal headway between a pair of the same type of trains running with the same speed is, thus, identical to the blocking time at the critical block.

The buffer time is the difference between the scheduled headway and the minimal headway at the critical block section. In case of the local trains 5100 leaving the station The Hague CS for HS and arriving from HS at the point where both routes diverge the remaining buffer time is only 8 sec! Detailed minimal headway and buffer times for all train pairs at the station The Hague HS can be found in appendix E.

The occupancy of any track section or route node in stations can be computed by the ratio of the total of the minimal headway times between all the pairs of trains at this track section divided by the total time period (60 min peak hour or 1440 min a day). The computation results with regard to the occupancy of the individual points at the station The Hague HS are listed in table 1. The connected route occupation is defined as the time period from the set-up of the route that includes the mentioned track section and switch respectively until the release of the track section or platform track. As the running times over the whole route until the release of the considered section is much longer than the pure occupation time of the section itself, the connected route occupation values are much bigger and reveal clearly the most critical routes.

Table 1. Occupation time of switches at The Hague HS [sec.]

		249BT	247BT	231BT	241BT	225BT	229BT	237BT	227T	235BT
Direct	Time [sec]	499	310	166	651	460	603	603	312	407
occupation	Occupancy [%]	13.9	8.6	4.6	18.1	12.7	16.7	16.8	8.7	11.3
Connected	Time [sec]	1452	1452	1596	2447	1773	2441	2948	2948	1678
route	Occupancy [%]	40.3	40.3	44.3	68.6	49.3	67.9	81.9	81.9	46.6
occupation	Connected track	5	5	5	4+5	4+Ha	4+5	3+5	3+5	3+ Hb

Note: Ha is hindrance from 5100, 1900, 2500 HS-CS;
Hb is hindrance from 5100 HS-CS.

The occupation of the switch itself seems to be not very high. However, if the blocking time starting from the set-up of the route until the release of the crossing and the platform track at HS are included, the occupancy of the routes passing at the level crossings is extremely high, e.g. from 69 % up to 82 % respectively. The scheduled occupation rates of the platform tracks in this station range between 41 % and 47 % (Table. 2).

Table 2. Occupation time of platform tracks of The Hague HS

	Occupation time		
	Track 3	Track 4	Track 5
Total [second]	1674	1475	1516
Occupancy [%]	46.5	41.0	42.1

The timetable analysis, thus, confirms that the block sections including the level crossings of node A are the most critical ones and limit the throughput of the station tracks at The Hague HS.

5. Operations analysis

Punctuality of train services, in general, is expressed as the percentage of trains passing, arriving or departing at given locations of the railway network no later than a certain time in minutes. Delays smaller than 5 minutes are usually not considered as delays by most of the European railway undertakings because of limited precision of the applied modes of measurement, tolerances of the timetable and insufficient means of control of operations in practice. As the precise time of train arrivals and departures at the platform cannot be measured by the standard track mounted equipment, the recorded times are modified by certain offset values for the remaining running time between the measurement points and the train stand at the platform. However, the offsets used in practice are rounded values and do not reflect differences in train characteristics, variable braking distances and actual train speeds. Furthermore, the punctuality rates underestimate systematically the mean delay due to discarding smaller delays than the threshold values and give no information on the variance of data.

The tools TNV-Prepare and TNV-Filter were applied for the analysis of train detection data at the stations The Hague HS and CS in order to obtain precise train arrival and departure times at the platforms, as well as train delay distributions. Statistical analysis of real running

times, speed, blocking times and delays of the lines operating between both stations during the whole month of September 1999 was performed by means of the tool S-Plus. The main results are presented as follows.

5.1 Running time and speed

The mean running times of the train series from The Hague HS to CS (1650 m distance) are a little more than 3 min and about 1 min less than scheduled, whereas the mean running times in the opposite direction exceed the scheduled one, which is 1 min less (Tab. 3). The average speeds of the train HS-CS series are a little faster than that in the other direction, but they are still about 10 % lower than design speed (40 km/h) even when the time loss due to acceleration and deceleration is eliminated. All the data sets of the running times between both stations fit the Normal distribution at a level of significance of 0.05 according to one-sample KS tests. The hypothesis of Normal distribution is, thus, not rejected. This is surprising, as the running times between stations cannot be less than the minimum technically feasible. This phenomenon may be explained by the rather short distance between the two stations and the scheduled big running time and dwell time margins.

Table 3. Running time and speed of the train series between The Hague HS and CS

Train	Running time [sec]				Mean speed [km/h]			Distribution
	Schedule	HS-CS	Open Track	Switch area	Schedule	Actual	Open track	
HS to CS								
5100	240	183	86	28	25.4	33.4	35.0	Normal
2500	240	193	94	27	23.4	29.1	33.3	Normal
1900	240	193	92	23	24.3	30.2	34.0	Normal
CS to HS								
5100	180	187	96	17	32.8	31.6	30.9	Normal
2500	180	211	91	17	33.4	28.5	32.9	Normal
1900	180	205	95	17	31.3	27.5	31.8	Normal

The observed mean speeds, however, are significantly lower than the design speed of the route (40 km/h) passing at the points, but in the direction from The Hague HS to CS they are higher than scheduled, because the latter ones seem to be extended voluntarily.

5.2 Blocking times

Almost all the blocking times in each section based on observed speeds are increased by some sec compared to the values based on scheduled speed (see Appendix Tab. D-4 and 5), because the trains are operated within the complex junction at less speed than permitted. In fact, the blocking times are not deterministic but stochastic due to the variation of speed and train lengths (Appendix F). A detailed statistical analysis of the blocking times of the local trains passing at the most critical level crossing 237BT gives a mean of the actual blocking time of 77 sec and a standard deviation of only 3 sec (Fig. 6).

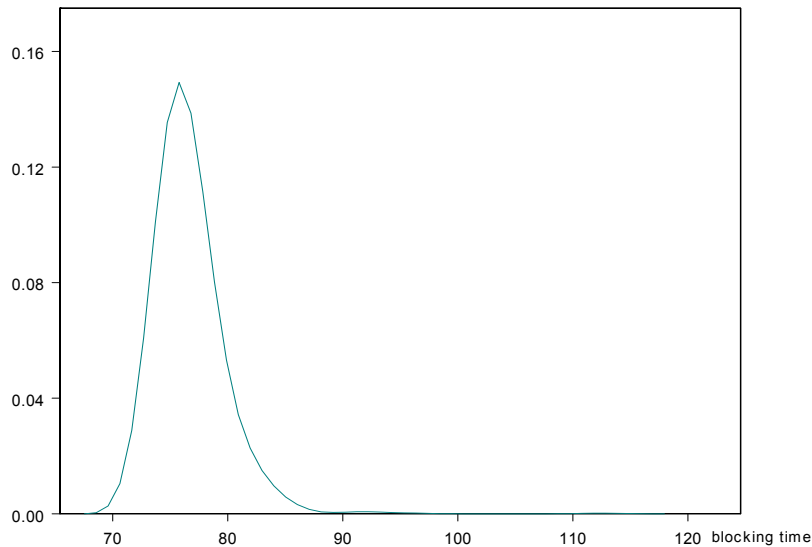


Figure 6. The distribution of blocking time at 237BT based on the train detection data of 5100 CS-HS

The speed and blocking times of the interregional and international trains, which approach at higher speed to the station The Hague HS, are expected to vary much more because these trains may be hindered by late clearance of the route due to delayed local trains directed to The Hague CS.

5.3 Train delays

The local trains 5100, in general, arrive punctually at The Hague HS, even a little bit early with a mean of -17 sec. However, almost 83% depart more than 30 sec behind schedule with an average departure delay of 92 (!) sec (Appendix Tab. F-1). About half of the local trains, which are ready to depart to The Hague CS, are hindered by late clearance of the route (Appendix Tab. F-2). The reasons are the scheduled time interval between the inbound trains 2200 from Leiden and departure from HS to CS is only 2 min. and zero (!) time difference with regard to the arrival of local trains from CS to HS. On arrival at The Hague CS the average delay is reduced to only 37 sec due to the scheduled running time providing an extra margin for the trains which depart late from The Hague HS. The IC-trains departing from The Hague HS to CS are on the average almost 2 min late and have large standard deviations. However, these trains are hindered at the level crossings much less than the local trains, because the time headway is much bigger.

Although The Hague CS is the starting station of the trains 5100 CS-HS and the scheduled layover time is sufficiently large (28 min), these trains have a mean departure delay of 57 (!) sec. and increases by about 9 sec until arrival at The Hague HS (Appendix Tab. F-6 and F-7). The histogram of departure delays of 5100 CS-HS at the station The Hague CS is shown in Fig. 7. The P-values of Wilcoxon rank-sum test between the departure delay and the arrival delay is 0.9385, which means the departure delay of 5100 at CS almost totally propagates to The Hague HS. However, because of a longer dwell time (3 minutes) at The Hague HS, the

average departure delay of these local trains at The Hague HS is reduced to 35 sec by shortening the scheduled dwell time.

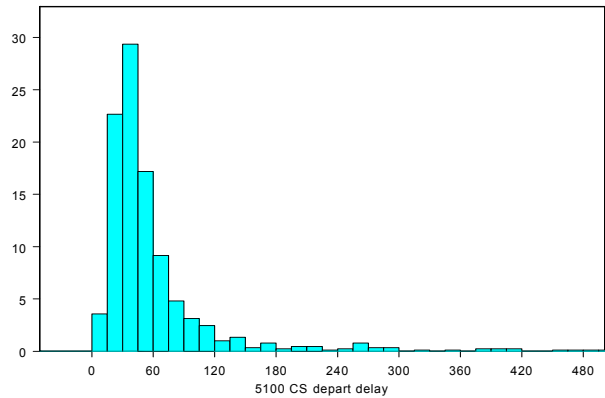


Figure 7. Histogram of departure delays of train 5100 at The Hague CS

The other train series starting its service at The Hague CS in the direction of HS have about the same mean departure delay. As there is, in general, no route conflict at throat A of the station The Hague HS it seems that the delays are mainly caused by behavior of the train personnel.

5.4 Buffer times

The buffer times between five critical pairs of trains at The Hague HS are recalculated based on the observed speed and blocking times (Appendix Tab. E-2 and E-3). The actual buffer times between 4 pairs of trains are reduced marginally by 6-10 sec compared to the earlier estimate. Although the blocking times of both of train 5100 CS-HS and train 5100 HS-CS increased based on observed speeds, the buffer time between this pair of trains is still increased slightly. Including the arrival and departure delays respectively of both trains (57 sec vs. 92 sec), the actual mean buffer time at the point 237BT is much longer than estimated originally in the timetable and reaches 44 sec (Fig. 8).

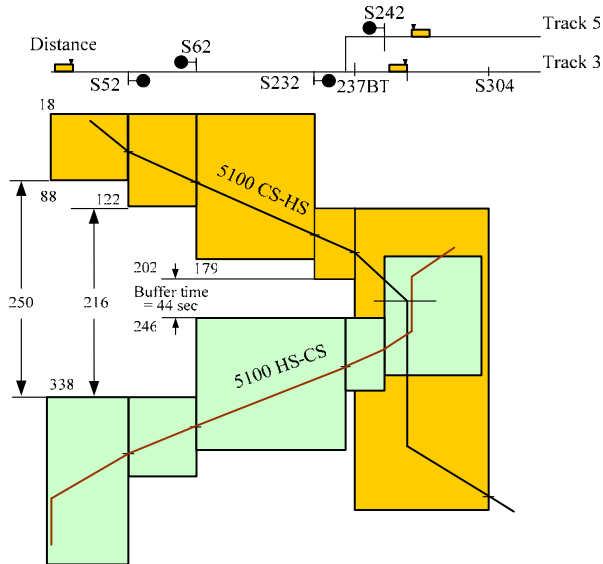


Figure 8. Buffer time between 5100 CS-HS and 5100 HS-CS based on observed mean train delay and speed

The distribution of buffer times estimated on the basis of recorded train speeds and release times at the critical point 237BT (Fig. 9) confirms that, in practice, this pair of trains needs a time interval between departure and arrival at The Hague HS of about 1 min.

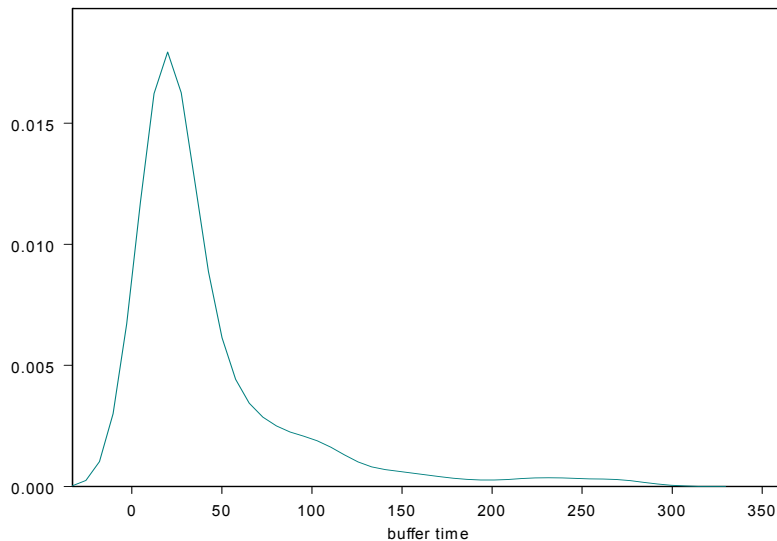


Figure 9. Distribution of buffer times at level crossing 237BT between local trains 5100 CS-HS and 5100 HS-CS based on train detection data

6. Conclusion

A detailed systems analysis of the network, timetable and operations within complex railway stations as The Hague HS and CS is feasible by combining ex-ante design techniques as blocking time graphs with ex-post empirical analysis tools like TNV-Prepare. It reveals clearly, the generation of capacity constraints in stations by routes, which are approaching and departing via level crossings to/from the platform tracks. Although the track occupancy of individual route nodes (points) may not be higher than about 40 %, the total occupancy of the blocks including the platform tracks can be twice as high (80 %) due to interlocking constraints. The estimation of blocking times and buffer times between the scheduled train paths enables a very high precision of timetable design at a scale of 5 to 10 sec, by which insufficient timetable margins are detected between train paths at critical track sections, where routes are crossing and merging. This allows a 5 to 10 times more precise scheduling of the arrival, departure and passing times nearby conflict points than the current standard design by train paths at a time scale of minutes.

The statistical analysis of empirical track occupation and release data within stations provides not only a sound basis for estimating realistic distributions of arrival delays, dwell times and departure delays, but also for estimating the probability and amount of knock-on delays at heavily occupied track sections. Further, a distinction between signaling constraints and human factors can be made with regard to their impact on punctuality and performance of train services. In the case of the stations The Hague HS and CS a systematic generation of train delays during dwelling and layover respectively at the platforms has been proved and confirms earlier findings.

The analysis of train delays clearly shows that more than 50% of the departing local trains from HS to CS are hindered by late release of level crossings. In case the buffer time between the slots is increased, the number of directly hindered trains reduces significantly. Even at the terminal station The Hague CS, the trains have a mean departure delay of about 1 min. Besides a few possible route conflicts, human behavior (lack of discipline) is probably the main reason for the departure delays at the terminal station. Thus, a higher level of awareness of the involved railway personnel regarding the importance of punctual train departures, as well as the design of sufficient buffer times between conflicting train paths would enable to reduce primary and consecutive train delays significantly.

The hypothesis of Normal distribution of running times between both stations is not rejected in most of the cases due to the fact that the short distance allows only a low speed and the rather big running time and dwell time margins scheduled. The observed mean speed of most of the trains operating between The Hague HS and CS is slightly lower than the scheduled speed except for the delayed trains from HS and is less than the design speed of the route even when considering the acceleration and deceleration time loss. The buffer times between the critical pairs of train slots at The Hague HS could therefore be further increased if the trains depart more punctual and travel according to design speed. With regard to the distribution of train delays of the lines operated between both stations, neither the departure delays nor the arrival delays at both stations fit a known distribution by one-sample KS test. The big variations in train operations observed might be explained by inconsistencies in the timetable design, big running time and dwell time margins, which leave much freedom for the drivers, conductors and dispatchers to act and generate regularly conflicts between train paths.

The characteristics of other stations and timetable bottlenecks may be different to those of The Hague HS and CS, but the following generic conclusions remain valid:

- In any heavily occupied network, there exist critical track sections (points) which affect the operations quality of a much wider area.
- The actual mean train speed in track junctions, in general, is considerable less than design speed and leads to relatively high track occupancy.
- The running times and speeds of train lines between closely interconnected stations can be described reasonable by Normal distributions. The distributions of train delays in complex stations are varying too much for fitting to a known statistical distribution due to multiple knock-on effects.
- The blocking, minimal headway and buffer times of individual train lines operated between closely situated stations are stochastic parameters with a rather small variance.
- Departure delays are due to actual route conflicts, signaling constraints, passenger and railway personnel behavior and generate consecutive delays if the scheduled buffer times are insufficient. In general, the scheduled dwell times are exceeded considerably.
- The buffer time at level crossings should correspond to the distribution of train delays and real distribution of time lags between the release by the leading trains and occupation of the following trains and must not be less than 1 min.

Train operations and traffic control could be improved further by the introduction of a comprehensive management information system concerning the distribution and reasons of primary and consecutive train delays. Such a data base could be incorporated into an advanced decision support tool for dispatchers and provide realistic models of the propagation of actual trains delays in stations and networks. Such analysis and tools would contribute to an optimization of online scheduling, such as to forecast route conflicts more precisely and to estimate better the expected blocking times and remaining buffer times.

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Appendix

Appendix A. Track layout of the stations

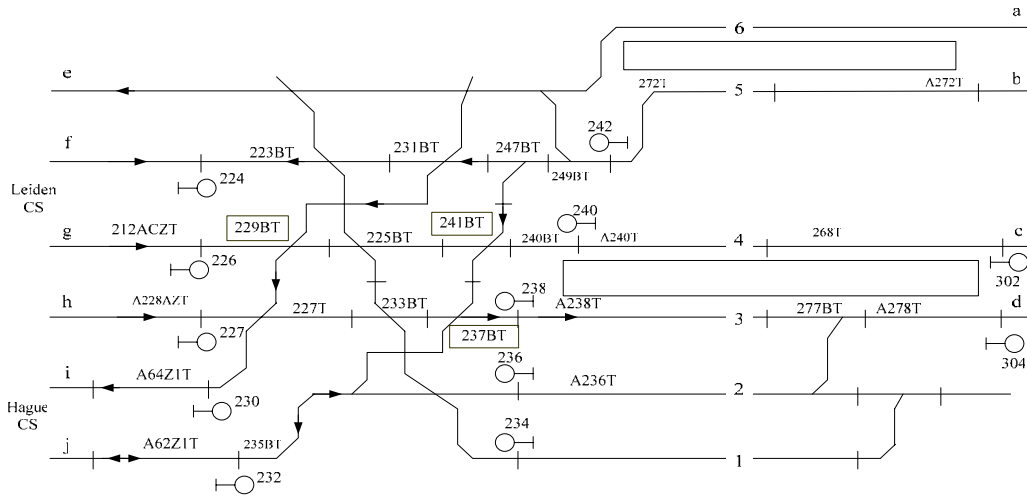


Figure A-1. Tracks and signals of The Hague HS

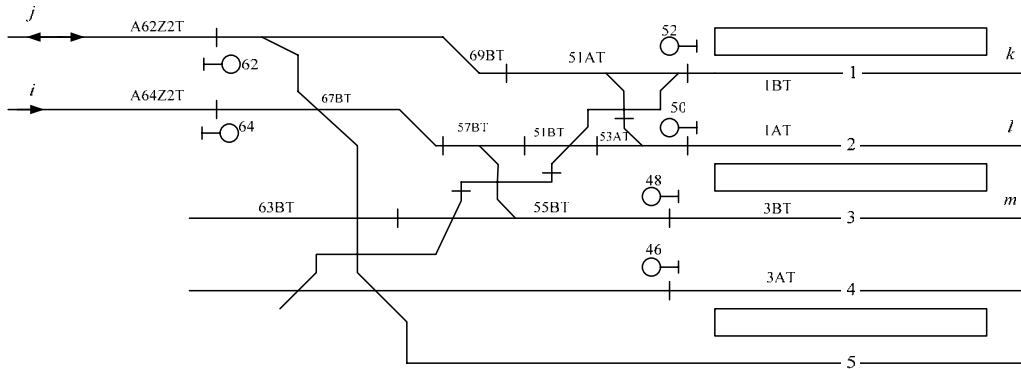


Figure A-2. Tracks and signals of The Hague CS

Appendix B. Timetable and train routes

Table B-1. Timetable and train routes in The Hague HS

Train series	Direction	Freq./hour	From LD/CS to HS			From RD to HS		
			Arr. time	Dep. time	Route	Arr. time	Dep. time	Route
AR 5000	LD↔RD	2	12 42	14 44	h→d f→d*	18 48	20 50	B→e
IR 2200	LD↔RD	2	28 58	29 59	g→c f→c*	05 35	06 36	A→e
IC 2100	LD↔RD	1	45	46	g→c f→c*	17	18	A→e
IC 2400	LD↔RD	1	15	16	g→c f→c*	47	48	A→e
INT 600	LD↔RD	1	04	06	g→c f→c*	58	59	A→e
HST 9300	LD↔RD	1	34	36	g→c f→c*	28	30	A→e
IC 1900	CS↔RD	1	24	25	j→d	07	08	B→i
IC 2500	CS↔RD	1	54	55	j→d	37	38	B→i
AR 5100	CS↔RD	2	00 30	03 33	j→d	29 59	30 00	B→j

Note: AR-Local train; IR-Interregional; IC-Intercity train; INT-International train; HST-High speed train. LD Leiden direction; RD-Rotterdam direction; CS-The Hague CS; HS-The Hague HS. * - infrequent route.

Table B-2. Timetable and train routes in The Hague CS

Train series	Direction	Freq./hour	Arrival at CS		Departure from CS	
			Arrival time	Route	Departure time	Route
IC 1900	CS↔RD	1	12	i→l	21	m→j
IC 2500	CS↔RD	1	42	i→m	51	l→j
AR 5100	CS↔RD	2	04 34	j→k	27 57	k→j

Appendix C. Train Data

Table C-1. Data of the trains from The Hague CS to The Hague HS

Train number	Train length [m]	Max. running speed [km/h]	CS		HS		Dwell time [s]	Accel. rate [m/s ²]	Max. depart speed [km/h]
			Accel. Rate [m/s ²]	Train tail to track end [m]	Braking rate [m/s ²]	Train front to S304 [m]			
5100 CS-HS	246	40	0.5	5	0.5	185	180	0.44	70
1900 CS-HS	255	40	0.43	5	0.5	130	60	0.4	70
2500 CS-HS	255	40	0.43	5	0.5	130	60	0.4	70

Table C-2. Data of the trains from The Hague HS to The Hague CS

Train number	Train length [m]	Max. running speed [km/h]	HS			CS			Train front to track end [m]
			Braking rate [m/s ²]	Max. Arrival speed [km/h]	Dwell time [s]	Train front to S242 [m]	Accel. Rate [m/s ²]	Braking rate [m/s ²]	
5100 HS-CS	246	40	0.5	70	60	120	0.5	0.5	5
1900 HS-CS	255	40	0.5	70	60	50	0.43	0.5	5
2500 HS-CS	255	40	0.5	70	60	50	0.43	0.5	5

Table C-3. Data of the trains from Leiden to Rotterdam

Train number	Train length [m]	Braking rate [m/s ²]	Max. arrival speed [km/h]	Dwell time [s]	Train front to S302 [m]	Accel. rate [m/s ²]	Max. depart speed [km/h]
600 LD-HS	176	0.5	70	120	220	0.56	70
2200 LD-HS	246	0.5	70	60	220	0.55	70
2100 LD-HS	214	0.5	70	60	220	0.4	70
2400 LD-HS	217	0.5	70	60	220	0.4	70
9300 LD-HS	270	0.5	70	120	230	0.5	70
5000 LD-HS	202	0.6	70	120	185 (to S304)	0.5	70
Train data from Rotterdam to Leiden (through track 5)							
5000 RD-HS	202	0.6	70	120	120 (to S242)	0.5	70

Appendix D. Blocking times

Table D-1. Blocking time of train 5100 HS-CS [s]

	Signal 242	247BT	241BT	237BT	235BT	Signal 62	69BT	51AT	1BT
t_b	-37	-37	-37	-37	-37	41	41	41	41
t_{point}	0	10	13	17	28	75	93	102	148
t_e	25	35	38	42	53	98	118	128	
t_{block}	62	72	75	79	90	57	77	87	

Note: t_b is the begin time of blocking time; t_{point} is the time when passing the switch section; t_e is the end time of blocking time; t_{block} is the blocking time of the blocking section. The blocking times are corresponding to the blocking sections right behind the signals.

Table D-2. Blocking time of train 5100 CS-HS [s]

	Signal 52	69BT	Signal 232	237BT	A278T	Signal 304
t_b	-38	-38	-38	40	40	318
t_{point}	0	27	75	90	138	362
t_e	25	52	97	115	380	380
t_{block}	63	90	135	75	340	62

Table D-3. Blocking time of train 5100 HS-CS after 5100 CS-HS cleared 237BT

	Signal 242	247BT	241BT	237BT	235BT	Signal 62	69BT	51AT	1BT
t_b	115	115	115	115	115	193	193	193	193
t_{point}	152	162	165	168	180	227	244	254	299
t_e	177	187	190	193	205	249	269	279	

Table D-4. Blocking time of train 5100 HS-CS based on observed speed[s]

	Signal 242	247BT	241BT	237BT	235BT	Signal 62	69BT	51AT	1BT
t_{block}	66	77	80	84	98	57	79	90	
t_{inc}	4	5	5	5	8	0	2	3	

Note: t_{inc} is the increased blocking time based on observed speeds

Table D-5. Blocking time of train 5100 CS-HS based on observed speed[s]

	Signal 52	69BT	Signal 232	237BT	A278T	Signal 304
t_{block}	70	104	161	80	346	62
t_{inc}	7	14	26	5	6	0

Appendix E: Headway and buffer times**Table E-1. Scheduled headway and buffer times at The Hague HS**

First train	Second train	Scheduled headway		Minimal headway	Buffer time
		[min]	[sec]	[sec]	[sec]
2500 CS-HS	5100 CS-HS	7	420	231	189
2200 LD-HS	5100 HS-CS	2	120	-5	125
5100 CS-HS	5100 HS-CS	0	0	-8	8
5100 HS-CS	600 LD-HS	4	240	170	70
5100 HS-CS	1900 HS-CS	8	480	228	252
600 LD-HS	1900 HS-CS	4	240	-21	261
1900 HS-CS	5000 LD-HS	4	240	179	61
1900 CS-HS	5100 CS-HS	6	360	231	129
5100 HS-CS	9300 LD-HS	4	240	170	70
9300 LD-HS	2500 HS-CS	4	240	-15	255
2500 HS-CS	5000 LD-HS	4	240	179	61
5100 HS-CS	2500 HS-CS	10	600	228	372

Table E-2. Buffer time estimation based on observed speed

First train	Second train	Scheduled headway	Minimal headway	Buffer time	Reduced Buffer time
		[sec]	[sec]	[sec]	[sec]
5100 CS-HS	5100 HS-CS	0	-9	9	-1
5100 HS-CS	600 LD-HS	240	176	64	6
1900 HS-CS	5000 LD-HS	240	188	52	9
5100 HS-CS	9300 LD-HS	240	176	64	6
2500 HS-CS	5000 LD-HS	240	189	51	10

Table E-3. Statistics of buffer time between 5100 CS-HS and 5100 HS-CS at point 237BT [second]

Item	Sample Size	Outlier	Mean	Std. Dev.	Median	Min.	Max.
Buffer time	845	28	43	49	24	0	289
[sec]	≤ 9	≤ 20	≤ 40	≤60	≤80	≤100	
Number	63	347	576	653	701	735	
[%]	7.7.	42.4	70.4	79.8	85.7	89.9	

Appendix F Delays and running times of trains The Hague HS-CS

Table F-1. Statistics of delay, dwell and running times of 5100 HS-CS [sec]

Item	Sample Size	Mean	Std. Dev.	Median	Min.	Max.
Arrival Delay at HS	816	-17	123	-58	-152	901
Dwell Time at HS	816	170	74	170	28	737
Departure Delay at HS	816	92	106	61	-4	896
Arrival Delay at CS	816	37	114	5	-70	874
Running Time HS-CS	816	183	27	178	152	583
Running Time Except Platform	816	114	25	110	92	524
Running Time Open Track	816	86	30	81	67	580

Table F-2. Delayed trains 5100 HS-CS caused by late clearance at The Hague HS

Critical delay = 0 second		Arrival delay > 0		Arrival delay ≤ 0		Total	
		Count	%	Count	%	Count	%
	All	207	25.4	606	74.3	813	99.7
Departure delay > 0	Affected by 241BT	25	3.1	86	10.5	111	13.6
	late 237BT	42	5.1	376	46.1	418	51.2
	clearance 2 Points	60	7.4	393	48.2	453	55.6
Departure delay ≤ 0		1	0.1	2	0.2	3	0.3
Total		208	25.5	608	74.5	816	100

Note: percent = each kind of count/sample size

Table F-3. Delays caused by late clearance

Point	Time interval [s]	Hindered train	Increased delay to hindered train [s]					Average delay of all trains [s]
			Mean	Std Dev.	Median	Min.	Max.	
241BT	120	111	97	58	88	3	267	14
237BT	0	418	37	42	22	1	283	19
2 POINTs	120/0	453	48	53	27	1	283	27

Table F-4. Delays of train series HS-CS

Train	Departure delay at HS			Arrival Delay at CS		
	Mean	Std. Dev.	Distribution	Mean	Std. Dev.	Distribution
5100	92	106	No	37	114	No
2500	111	219	No	65	225	No
1900	109	220	No	63	223	No

Table F-5. Trains hindered by late clearance of crossings at The Hague HS

Train	Time interval [min]	Buffer time [sec]	Sample size	Crossing	Arrival Delay>0		Arrival Delay<=0		Total	
					Count	%	Count	%	Count	%
5100	0	8	816	237BT	42	5.1	376	46.1	418	51.2
5100	2	125	816	241BT	25	3.1	86	10.5	111	13.6
2500	4	255	375	231BT,	6	1.6	6	1.6	12	3.2
1900	4	261	404	229BT, 227BT	4	1.0	2	0.5	6	1.5

Table F-6. Delay of the train series from The Hague CS to The Hague HS

Train	Departure delay at CS			Arrival Delay at HS		
	Mean	Std. Dev.	Distribution	Mean	Std. Dev.	Distribution
5100	57	60	Gamma (remove 6% outliers)	66	69	No
2500	60	68	Gamma (remove 6% outliers)	93	75	No
1900	65	69	Gamma (remove 4% outliers)	90	70	No

Table F-7. Statistics of delay, dwell and running time of 5100 CS-HS [sec]

Item	Sample Size	Mean	Std. Dev.	Median	Min.	Max.
Departure Delay at CS	896	57	60	41	4	504
Arrival Delay at HS	896	66	69	47	-12	640
Dwell Time at HS	896	149	53	149	20	473
Departure Delay at HS	896	35	60	14	-31	511
Running Time CS-HS	896	187	30	182	138	486
Running Time Except Platform*	896	113	26	108	85	70
Running Time Open Track**	896	96	25	91	335	316

*excluding time along the platform at HS

**time between passing at departure signal and entering at platform track