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Advanced monitoring and management information of railway operations

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ABSTRACT

Improving the performance of railway infrastructure and train services is the core business of railway infrastructure managers and railway undertakings. Train delays decrease capacity, punctuality, reliability and safety, and should be prevented as much as possible. Furthermore, increasing infrastructure capacity utilization causes increased risk of route conflicts and secondary delays, which on its turn prevents increasing infrastructure capacity utilization. Dense railway operations therefore require feedback of operations data to improve planning and control. Typically, train delays at stations are monitored and registered online using train detection, train describers, and timetable databases, but the accuracy is insufficient for process improvements and, in particular, delays due to route conflicts are hard to recognize from delays at stations. To assess the problem of route conflicts, accurate data on the level of track sections and signal passages are required, which can be found in train describer records. This paper presents the data mining tool TNV-Conflict based on train describer records and the add-on analysis tool TNV-Statistics that automatically determines chains of route conflicts with associated secondary delays, and rankings of signals according to number of conflicts, time loss or delay jump. This information is used to automatically identify and analyze structural and serious route conflicts due to timetable flaws or capacity bottlenecks. The aim of TNV-Statistics is to relieve the analyst from routine, time-consuming, and error-prone data processing tasks, so that the available time can be devoted to analyze and manage revealed operations problems. A case-study of real data on a busy railway corridor in The Netherlands demonstrates the tool.

1. Introduction

Providing reliable and punctual train services is a mutual goal of railway undertakings (RUs) and railway infrastructure managers (IMs). For the RUs, train service reliability and punctuality is directly translated into customer satisfaction. The core business of the IMs is the delivery of train paths – time-distance trajectories over the available infrastructure – to the various RUs. Hence, key performance indicators of IMs are the timely and reliably availability and usage of train paths. In the tactical capacity allocation process, the IM must coordinate train paths of different passenger and freight railway undertakings and provide conflict-free timetables and route setting plans. Still, trains may deviate from their scheduled train paths during operations and generate route or timetable conflicts. This leads to unscheduled stops and/or control actions by signalers or traffic controllers. Moreover, unscheduled stops result in larger infrastructure capacity utilization and delays, which may again lead to conflicts with later trains. Also timetable flaws or too tight buffer times may result in conflicts and unscheduled stops. Monitoring train delays and registration of their causes is therefore also an important task of traffic control with the aim of continuous process improvement using feedback to the timetable planners and the capacity allocation department. This monitoring information is an essential element in the quality cycle to continuously improve services and increase train service reliability. In the end, the deviation and variation of the realized arrival and departure times with respect to the published timetable are the punctuality and reliability indicators to the users.

Achieving and improving high reliability and punctuality requires that problems in operations must lead to actions by feedback of realizations data to timetable design, infrastructure design, and control design according to Deming's Plan-Do-Check-Act cycle of quality management. This operations performance analysis based on realization data is applied more and more in Europe, such as in The Netherlands (Goverde, 2005; Nie and Hansen, 2005; Weeda and Hofstra, 2008), Switzerland (Nash and Ullius, 2004; Flier et al., 2009), Germany (Conte, 2007; Conte and Schöbel, 2007), Italy (De Fabris et al., 2008), and Denmark (Richter, 2010).

In general, the railways keep track of train delays online for operational control and performance statistics. However, although the accuracy and detail of the delay registration is sufficient for aggregated statistics like national punctuality, it is insufficient for

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performance analysis and process improvement at the level of individual trains. Typically, delays are measured at stations using train detection, train describer systems and timetable databases, but the accuracy is in minutes due to a mismatch between the measurement and stop location (Goverde, 2005). In particular, train positions are measured by train detection devices near station home and exit signals leaving some remaining running time to or from the platform track that is approximated by deterministic correction terms. Since the speed profile varies from train to train, the error between the correction term and the real running time can be up to several minutes depending on the offset distance and the level of detail of the correction terms. In The Netherlands, for example, correction terms are specified for each signal/platform pair and further depend on train activity (arrival, departure, passage) only. In Switzerland, the correction terms are differentiated by route, train activity, and train type, and moreover, signal locations are optimized leading to a much smaller error of at most 20 s (Ullius, 2004).

Finding the cause of a delay is further complicated due to the fact that delays at stations are measured some time after the delay was actually caused. In particular, delays due to route conflicts are hard to recognize afterwards although they contribute significantly to dispunctuality. For example, route conflicts account for more than half of the dispunctuality on the heavily utilized Dutch railways (Daamen et al., 2006). An important class of route conflicts are *structural* route conflicts corresponding to blocking time overlaps or too tight buffer times between two train paths which in practice results in structural delays (Goverde, 2011). A punctuality analysis based on measured delays at stations would easily result in adding running time supplement to cope with the longer running times. This removes the symptoms (structural delay) but the cause (braking for a route conflict) remains, resulting in unnecessarily running time extensions, energy loss by unnecessarily braking and reaccelerating, and increased risk of a signal passed at danger (SPAD).

Performance analysis of individual train runs and interactions between train movements therefore requires operational data at the level of track sections and an accuracy of seconds. Such accurate train movement and infrastructure data are available in the logfiles of train describers, although these train describer records are typically not accessible for direct analysis. In The Netherlands, data mining of train describer records has been applied successfully over the last decade to determine accurate infrastructure utilization and train path realisations. Goverde and Hansen (2000) showed that train numbers could be coupled to infrastructure messages and thus were able to recover train path realizations on track section occupation level with an accuracy of a second. Since then a range of applications based on train describer records were developed (Goverde, 2005; Stam-Van den Berg and Weeda, 2007; Goverde et al., 2008) that were used for performance analysis of Dutch railway operations. TNV-Conflict (Daamen et al., 2009) is the most up-to-date application that fully automatically finds all realized train paths on track section level. Moreover, TNV-Conflict derives the realized blocking times over the successive signal blocks for all trains based on signaling logic and blocking time theory (Hansen and Pachl, 2008; Pachl, 2002). This information is used to detect route conflicts and identify the conflicting train numbers. Hence, TNV-Conflict is able to automatically derive route conflicts and resulting secondary delays, and thus to distinguish between primary and secondary delays.

This paper presents the add-on tool TNV-Statistics that combines and processes data generated by TNV-Conflict to get advanced operations performance information. In particular, route conflicts that were identified by trains approaching red signals are used to find structural timetable flaws. For any specified period (day, week, month) the tool can present the top signals with most conflicts, the top delayed trains, and the top delayed train lines, to direct the user towards the most serious problems. Further information and visualization of train numbers, train lines, signals, etc. can then be viewed using the interactive graphical user-interface of the tool. TNV-Statistics thus relieves the analyst from routine, time-consuming, and error-prone data collecting, combining, and processing tasks. Instead, the analyst can devote all available time to analyze, interpret, and manage the revealed operations problems.

This paper also introduces two measures to assess the impact of route conflicts: the *delay jump* of two successive scheduled event times, and the *time loss* of a route conflict measuring the impact of braking, running at restricted speed, waiting and reaccelerating with respect to a reference running time. The paper shows that the latter measure is a more effective indicator than the more commonly used delay jump.

Section 2 considers in more detail the issues that are involved in operations performance analysis. Section 3 presents the data mining tool TNV-Conflict and the new tool TNV-Statistics that provides advanced management information based on train describer records. A case study of the Dutch railway corridor Leiden–The Hague–Rotterdam–Dordrecht is presented in Section 4 demonstrating the usefulness of the developed tools for operations performance analysis. Section 5 ends with conclusions.

2. Operations performance analysis

Railways are usually operated according to a timetable consisting of conflict-free scheduled train paths. The actual timetable is usually the result of a detailed planning process up to a year in advance of the actual running, complemented by short-term rescheduling necessitated by disruptions of resources. Nevertheless, the actual train paths always deviate more or less from their schedule due to the stochastic nature of the underlying train running and dwell processes, such as fluctuating driver behavior, weather conditions, and passenger volumes. The scheduled running and dwell times usually contain time supplements to compensate for small delays over the minimum running and dwell times. Moreover, buffer times between train paths prevent that slight schedule deviations instantaneously hinder following trains, but the amount of buffer time depends on the location and is particularly restricted at infrastructure bottlenecks and near transfer stations where connecting train lines are synchronized. If a buffer time is insufficient then a train must brake and possibly wait before a red signal which leads to time loss that usually is not covered by the running time supplement. These route conflicts must therefore be avoided requiring a smooth match between timetable and operations, which is the focus of operations performance analysis.

A route conflict occurs when the movement authority of a train is restricted by a conflicting preceding train. In practice this implies that a running train meets a restricted signal and must prepare to stop before a stop signal protecting an occupied block section. A route conflict then always results in running time loss due to braking and re-accelerating, and if the train has come to a full standstill also in additional waiting until the stop signal is cleared. The actual time loss depends on rolling stock characteristics, local track speed, and the duration of the stop signal. A route conflict may also occur for a dwelling train when an outbound route could not be set in time due to a conflicting train route in which case the departure is postponed. Moreover, unplanned stops may result in a cascade of route conflicts to successive trains, especially in dense traffic areas. These knock-on delays make up a significant share of all train delays. For example, a case study of the Rotterdam–Dordrecht corridor in The Netherlands revealed that 55% of the dispunctuality (delays exceeding 3 min) is caused by route conflicts (Daamen et al., 2006).

Preventing route conflicts is therefore a main quality criterion. In particular, structural route conflicts must be identified and resolved by performance analysis in the planning stage.

Realization data can be used in at least three different ways within quality management:

(1) Providing reliable input to the planning stage.
(2) Finding structural problems in operations that need fine-tuning.
(3) Assigning delays to causes and responsible parties.

First, realization data give accurate input to the timetable construction in the form of reliable scheduled process times, such as dwell times, running times, blocking times, minimum headway times at infrastructure points, and route setting times. Reliable here means that some high percentile of trains is able to complete the processes within the scheduled time. For example, the running time of a certain train line between two stations can be determined as the 90th percentile of a representative set of running time data as is common practice in urban public transport (Van Oort, 2011). For railways, this set should contain free running times of a large number of trains and represent characteristic variations in e.g. used rolling stock, train compositions, and driver behavior. The data set should be free of large running times corresponding to technical malfunctions, temporary speed restrictions, or unscheduled stops before red signals. The latter can be identified and filtered out by a tool like TNV-Conflict directly. The former two require more advanced statistical analysis of the data, e.g. a group of larger running times corresponding to a specific day or period-of-a-day indicates a temporary problem, or larger running times of a certain train over successive segments (in different data sets) indicates a problem with a specific train. Finding such structural deviations from the data requires data mining techniques and proper visualizations.

Second, realization data can be used to find structural problems in the railway operations. Route conflicts occur when trains deviate from their scheduled train paths or when the scheduled train paths are in fact not conflict-free, i.e., the scheduled headway between conflicting routes is too tight. In a robust timetable a train may deviate from its scheduled train path within a certain bandwidth without causing hinder to other trains. At capacity bottlenecks or near synchronization points the bandwidths around the train paths may get very small so that slight path deviations already cause problems. These points therefore need careful tuning with a detailed analysis of blocking time realizations. Structural route conflicts appearing at some signal clearly indicate a problem that needs to be addressed. The purpose of a signal at danger is to prevent trains from entering a piece of infrastructure that is already used by another train. Ideally, trains will be scheduled and dispatched so that a running train will never meet a red signal. This is important for safety reasons since any train approaching a red signal has a risk of a SPAD (signal passed at danger), but it is also important for capacity, punctuality and reliability reasons since unscheduled braking and stopping implies increasing capacity usage, loss of time and variation in running time. Solutions depend on the particular situation, and may entail increasing buffer time or rerouting, or even the need for advanced dynamic traffic control or speed advice depending on actual train delays in the case of serious capacity bottlenecks. In any case, process improvement starts with identifying the problem and investigating the situation. TNV-Statistics is meant to direct attention to the most serious problems and to support the analysis and visualization of identified problems.

The third application area of monitoring and performance analysis is finding cause–effect relations and thus coupling causes to delayed trains and assigning delays to the responsible actors and processes (RUs, traffic control, planning, external parties). Train delays are classified in primary and secondary delays corresponding to a direct or indirect cause, respectively. Direct causes are e.g. signal or switch failures, rolling stock malfunction, erroneous route setting, passenger related delays, or incidents. Indirect causes are route conflicts and waiting in stations to secure passenger transfers, crew transfers or rolling stock connections. Serious disruptions like switch or signal failures result in queuing of trains with a chain of delayed trains that can all be attributed to the direct cause via the primary delayed train. The impact of the direct cause can then be measured by the total delay or number of trains involved in the conflict chain. Finding such conflict chains and computing statistics is supported by TNV-Statistics.

3. TNV-Conflict and TNV-Statistics

3.1. Train describers

The key to automatic collection of railway operations realization data are the train describer systems which keep track of train positions based on train numbers and infrastructure messages received from the signaling and interlocking systems (Exer, 1995). A train number steps from one position to another when the train passes selected signals. The internal logic of a train describer requires signal, track section, and switch information from which it derives the route to the next signal determining the next position. All received infrastructure messages and all generated train number messages are recorded chronologically in train describer logfiles. In The Netherlands, train describers were implemented as the so-called TNV-systems (*treinnummervolgsysteem*) and the corresponding logfiles are known as TNV-logfiles. Since 2009, TNV is gradually being replaced by the new system TROTS (Train Observation and Tracking System). Also TNV-Conflict is being redeveloped based on TROTS logfiles with the same output as used by TNV-Statistics.

3.2. Conflicts and TNV-Conflict

The tool TNV-Conflict matches train numbers to infrastructure messages fully automatically based on the following input, see Fig. 1:

- Train describer records, containing train number and infrastructure messages.
- Infrastructure files, containing the track topology and route specifications (successive sections).
- Timetable files, containing the scheduled train events at stations as reference values for delays.

Based on this input TNV-Conflict generates the following information in separate output files per day or multiple days for a specified period:

- Train events: the realized event times, delays, and delay jumps of all scheduled train events.

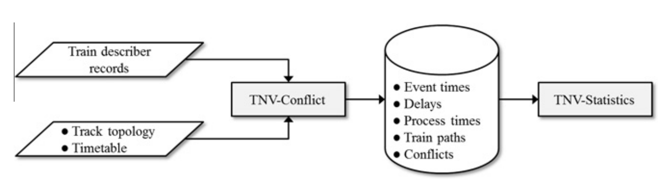

Fig. 1. Relationship between TNV-Statistics and TNV-Conflict.

- Train processes: the realized running and dwell times of all scheduled trains, including a conflict indicator when a route or signal conflict has been identified.
- Train paths: the realized track section occupation times and blocking times of all running trains.
- Conflicts: the identified route and signal conflicts with signal, conflicting train, occurrence time, and delay jump (delay change from last to next event).

For more information on the working and functionalities of TNV-Conflict, see Goverde et al. (2008) and Daamen et al. (2009).

A main feature of TNV-Conflict is the identification of train path conflicts which makes use of blocking time theory (Hansen and Pachl, 2008; Pachl, 2002). Blocking times and route conflicts can be visualized using blocking time diagrams. Blocking time is the time interval during which a block section or interlocked route is allocated exclusively to a specific train movement and thus blocked for other trains. On open tracks with automatic block signaling the blocking time of a block section by a train consists of the following parts, see Fig. 2:

(1) Sight and reaction time before the approach signal (usually taken as 12 s).
(2) Approach time (the running time from the approach signal to the block signal).
(3) Running time in the block.
(4) Clearing time (running time over the train length to clear the block).
(5) Release time to release the block (taken fixed as 2 s).

For three-aspect block signaling systems the blocking times thus exceed the running time over two blocks required for unhindered running. The blocking time of an outbound route block after a scheduled stop in a station does not include an approach time. In an interlocking area with sectional-release route-locking the block is released in steps after clearing the switch sections, and additionally the switching time to setup a route in an interlocking area must be taken into account (about 12 s). For more details, see Pachl (2002).

A train experiences hinder when it must brake or wait before a stop signal. In three-aspect block signaling, each block signal can act as an approach signal to the signal at the end of the block. When a train passes a yellow signal indicating a red signal at the end of the block then it has to start braking, thus increasing the approach time for the next block. If the block is released by the conflicting train before the train has come to a complete standstill it can accelerate again as soon as the automatic train protection system has received the new signal aspect, and move into the block. Otherwise the train comes to an unscheduled stop and has to wait before the signal until it clears. Because of the braking action both the approach time and the running time may be larger than in the unhindered case. In a blocking time diagram a conflict is visualized by an overlap of two blocking times, where of course the hindered train can move into the block only after the conflicting train has released the block. So the overlap applies to the approach time (and sight and reaction time) of the hindered train, which is increased to after the block release time of the conflicting train. Note that a blocking time overlap implies a yellow signal at the entrance of the preceding block. Thus, the hinder of a route conflict indicated by a blocking time overlap is mainly experienced in the preceding block, since the approach time of a block is the running time in the previous block.

When a train approaches an interlocked route block to a platform track where it is scheduled to stop, it is not necessary that the block after the exit signal is already set. Hence, a red signal at the end of an inbound route block after the platform (the exit signal) does not imply a route conflict. Also the departure from a station after a scheduled stop requires special treatment. In this case, a route conflict occurs when a conflicting route has been set at the requested departure time. The latter is determined as the maximum of the scheduled departure time and the realized arrival time plus a minimum dwell time. If the exit signal is not released at the requested time and a conflicting route after this time is identified then this is a potential *departure* (*route*) *conflict*. If no conflicting route is identified this is a potential *signal conflict*. However, the train may also have been held to secure a transfer with a delayed feeder train, because of a late crew, or any other station process. In these cases, a signaler may set a conflicting route for another train first but this conflict is thus not the cause of the delayed departure. These station processes obviously cannot be detected automatically (except in cases where strict waiting time regulations apply) and must therefore be registered by the signaler

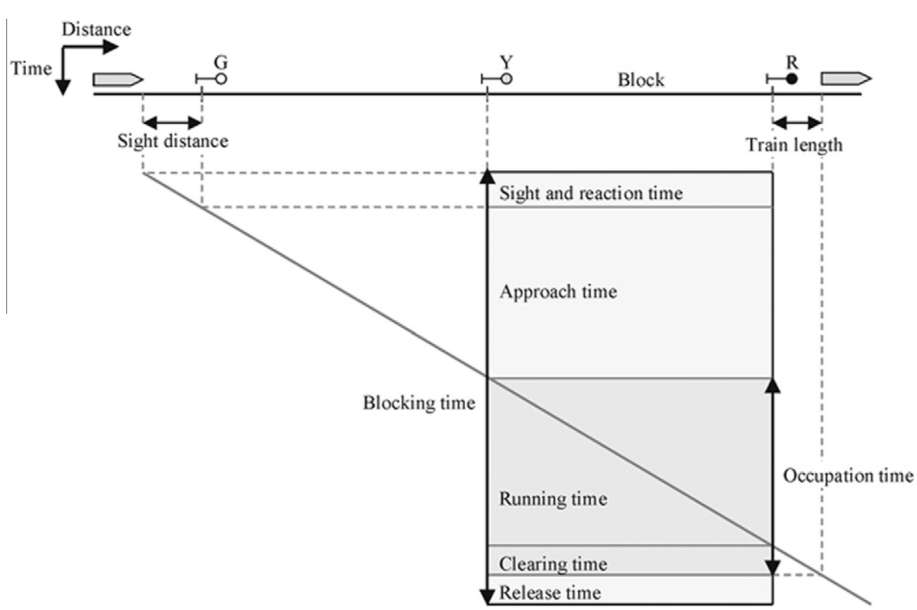

Fig. 2. Blocking time of a running train on open tracks.

or another responsible person at the control center. Using the train number and station as key, the registered delay causes can be linked to the delays identified by TNV-Conflict. This way the departure route conflicts can be corrected if another cause has been registered. Likewise, all secondary delays can be linked to a primary delayed train and its cause as registered in the registration system.

In conclusion, three types of conflicts can be identified from infrastructure data:

(1) *Route conflict:* a running train has to brake due to a restricted signal because of a conflicting preceding train.
(2) *Departure route conflict:* a dwelling train has to postpone its departure because of a conflicting station route set for another train.
(3) *Signal conflict:* a dwelling train has to postpone its departure because of a late outbound route setting without any conflicting train route.

In addition, a dwelling train may have *hidden waiting time* when it postpones its departure while the exit signal shows yellow to avoid bunching after the preceding train, especially if the preceding train is standing still in the next block. In this case, the train may keep waiting at the platform instead of running with restricted speed to the next signal and stopping there.

3.3. TNV-Statistics and measures for the impact of conflicts

TNV-Statistics builds on TNV-Conflict and combines and processes data generated by TNV-Conflict to get advanced operations performance information, see Fig. 1. More specifically, TNV-Statistics generates amongst others:

- Punctuality statistics for any given train number, train line, or station.
- Conflict trees, containing sequences of successive route (and signal) conflicts.
- Realized time-distance or blocking time diagrams, incl. route conflict indicators.

Moreover, TNV-Statistics reports two statistics for the conflicts encountered in TNV-Conflict: delay jump and time loss. A *delay jump* is the change in delay (either positive or negative) between two successive scheduled events. These scheduled event times are arrival and departure times at successive stations as well as passage times at other specified timetable points (stations for through trains, junctions and movable bridges). Delay jumps are therefore defined for dwell times and for running times between timetable points. Delay jumps may be negative when a train has used some running time supplement or positive when a train run has taken longer than scheduled.

On the other hand, time loss related to a route conflict measures the direct impact of the conflict when a train has to slow down. This *time loss* can be partitioned into four parts:

(a) Braking time before a red signal and possibly running at release speed to the signal.
(b) Running at a restricted speed after a yellow signal.
(c) Standstill time before a red signal until it clears.
(d) Reacceleration time until the target speed that the train would have had without the conflict.

If the signal is released before the train reaches zero speed, the standstill time is zero, and the braking time and reacceleration time may be reduced because of earlier reacceleration (depending on the ATP system).

To compute the time losses at different locations during a train run, it must be compared to some *reference running time* of unhindered running. Scheduled running times are usually specified between two stops or passages at specific locations (stations without stop, movable bridge, junction) but not for each block. When blocking time diagrams are used in the scheduling process, like in Germany, the calculated block running times can be used as reference running times. But in general, running times at block level are not available. To determine the local time loss a reference running time must therefore be measured as well. For regular trains a reference running time can be obtained as a percentile of the running time of similar but unhindered trains. In particular, for hourly train services a reference running time can be obtained as a percentile of the running times of all unhindered trains from the same train line with the same route. In this paper we use the 20th percentiles as the reference running times over the blocks. Note that a high percentile corresponds to slower trains which run, for instance, at a lower speed to account for some running time supplement and thus avoid running early.

Time losses due to route conflicts are by definition determined locally at the signal of occurrence. In contrast, delays and therefore also delay jumps are measured at stations or other timetable points. Time loss and the resulting delay at the next scheduled event are therefore not the same, and in particular they are influenced by the running time supplement that can still be used until the next scheduled event.

3.4. Conflict chains and trees

A conflict chain is a linked list of trains that successively hinder one another. The chain can be oriented in either two directions: a *conflict chain* with each successive train hindered by its predecessor, and a *reversed conflict chain* with each successive train hindering its predecessor obtained by reversing the arcs. In a similar way but using a tree structure, a *conflict tree* can depict more complex conflict propagations, which may occur at merging railway lines or complex station layouts. For instance, Fig. 3 shows the conflict tree of some train 1. The tree implies that train 1 hinders train 2 and 3, and subsequently train 2 hinders train 4 and 5. A reversed conflict tree is obtained by reversing the arcs. Note that a conflict chain is a special case of a conflict tree.

It is possible that some train 1 hinders some train 2, while later train 2 hinders train 1 again, thus giving a ‘conflict cycle’. This phenomenon may occur when a train overtakes another train, see Fig. 4. Here, the solid lines are the scheduled time-distance paths of trains 1 and 2 and the dashed ones are the realized time-distance paths. The slow train 1 arrives at station B with some delay. As a result, the fast train 2 is hindered before station B by train 1 and arrives with some delay. Then train 2 overtakes train 1 at station B followed some time later by train 1. Unfortunately, train 2 is delayed on the open track to station C for some reason. This then leads to a second conflict where now train 1 is hindered by train 2 before station C because of a minimum headway constraint. This conflict cycle is reasonable for the conflict tree of train 1. However,

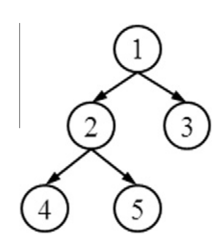

Fig. 3. Conflict tree of some train 1.

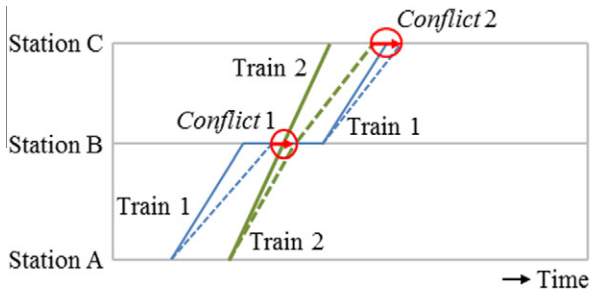

Fig. 4. Overtaking with a conflict cycle.

when considering the conflict tree of train 2 an unreasonable result would occur, that is, train 2 hinders train 1 at some time and train 1 hindered train 2 at an earlier time. Obviously, successive conflicts occur chronologically only. Therefore, a new conflict is added to a conflict tree only if its occurrence time is later than its predecessors in the tree.

Note that conflicts can be partitioned into two groups: *direct* and *indirect* conflicts. For example, in Fig. 3 the conflict between trains 1 and 2 is a direct conflict while the conflict between trains 1 and 5 (via 2) is an indirect one. Both conflicts lead to secondary delays. Conflicts in a conflict tree may occur at different geographical locations. For instance, if a train 1 is delayed by some train 2 and this delay cannot be settled fast enough then this delayed train may hinder another train at some later point. However, if the delay of a train has been recovered at some time and a new conflict occurs then a new conflict tree is generated. In fact, each train number may thus generate a conflict *forest* with separate trees at different locations in the network.

A node in a conflict tree does not only show the train number but also the occurrence time, the signal, the conflict type, the time loss, and the delay jump. The conflict type is either a route conflict to a running train, a departure conflict for a ready-to-depart train when the outbound route is still used by another train after the scheduled departure time, or an exit signal conflict when a train is prevented from departing due to an exit signal that remained red although no conflicting route was used. Recall that the latter two conflicts may have another station-related cause. For instance, a train may wait for a delayed feeder train to secure a transfer and in the mean time the signaler could set a conflicting route for another train first. Monitoring information from a signaler is required to correct the cause of a departure route conflict when a station relation was the actual cause. In TNV-Statistics trees are visualized using a folder view so that even for large trees all information can be shown in each node.

4. Case-study

This section demonstrates advanced monitoring information from TNV-Statistics with a case study of the railway corridor Leiden–The Hague–Rotterdam–Dordrecht in the heavily populated western part of The Netherlands. This railway line is densely operated by heterogeneous train traffic including local, interregional, intercity, and freight trains. The railway corridor has a length of 59 km, is mainly double-track with some four-track parts, and contains 19 stations, including five intercity stations as mentioned in the definition of the corridor with two IC stations in The Hague (CS and HS). Trains operate according to a periodic hour timetable with slight differences between the peak and off-peak hours. Train describer records of the two areas Rotterdam and The Hague that cover this corridor were made available by the Dutch IM ProRail for the entire month of February 2009. On an average working day around 1700 trains were (partially) running on this corridor.

4.1. Conflict chain

The main added value of TNV-Statistics is its ability to automatically generate conflict trees from the output data generated by TNV-Conflict. As an example, Table 1 shows a conflict chain of train 2233 near Dordrecht derived by TNV-Statistics. At the root is train 2233 which triggered a chain of eight route conflicts after Dordrecht towards Dordrecht Zuid. The information shown for each hindered train in the conflict chain is the train number, the last station with a known scheduled event time before the conflict location (all last events are departures), the used platform (or though) track in Dordrecht, the delay at the last scheduled event, the occurrence time of the conflict, the (red) signal, the time loss (including slow driving), and the delay jump with respect to the last and next scheduled events. The time losses are calculated with respect to the 20th percentile reference running times of all trains from the same train line over the same route. All delay jumps are measured from the last known departures (as in the second column) to the arrival/passage of Dordrecht Zuid, the next timetable point just after Dordrecht. The timetable for freight trains is not known at all stations. For two freight trains the last known scheduled event time is the departure from station Zwijndrecht just before Dordrecht, while for one freight train there is no known timetable. The root event is shown with its train number, the delay of the last event of this train before the first conflict (the primary delay) and the associated realized (departure) event time.

All conflicts are route conflicts to running trains and occur at three signals: signal 1182 at the end of through track 6 in Dordrecht, signal 1132 just after Dordrecht (Ddr) where the merged station tracks 5–7 merge into the line towards Dordrecht Zuid (Ddzd), and signal 1130 just after Dordrecht where the merged platform tracks 2–4 enter the line towards Dordrecht Zuid, see Fig. 5. In addition, there are some follow-up conflicts at signal 628 between signal 1130/1132 and station Dordrecht Zuid. Moreover, there are four departure route conflicts resulting in departure delays from Dordrecht, which are indicated in bold. Fig. 6 shows the blocking time diagram of all nine trains involved in the conflict chain. It shows the realized time-distance trajectories of each train and the blocking times visualized by the rectangles. The top of the figure shows the routes (and signals) of each train. Before Dordrecht there are four tracks, so trains could run in parallel from the previous station Zwijndrecht which is shown by two different colors for each of the two tracks to Dordrecht. From signal 1130 and 1132 the trains merge into one track, see also Fig. 5. The blocking times after these signals should not overlap otherwise there are conflicts. As can been seen, however, there are overlapping blocks indicated by a dark gray color. All seemingly overlapping blocking times before the exit signals (1180, 1182, 1174 and 1170) are no conflicts since here the blocking times correspond to different parallel tracks. The overlaps in the blocks before signals 1130/1132 correspond to the two parallel routes to signal 1130 and 1132, respectively, except for the route conflict of the 42961 train before signal 1182.

To explain and appreciate the information given in the conflict chain and the blocking time diagram of Fig. 6, each successive train is briefly considered next. The involved train types are intercities (IC), interregional trains (S, *sneltrein*), a local train (ST, *stoptrein*), and freight trains (G, goods).

(1) Train S2233 departs more than three minutes (222 s) late from platform track 4 in Dordrecht after an extensive dwell time of 5.5 min (326 s), although it had arrived early (104 s) and there was no departure or signal conflict in Dordrecht. The cause of this primary delay is unknown.

Table 1
Conflict chain of train 2233 on February 1, 2009.

Train	Last departure	Track	Last delay (s)	Occurrence time (hh:mm:ss)	Signal	Time loss (s)	Delay jump (s)
S 2233	Dordrecht	4	**+222**	09:46:42	–	–	–
G 341753	Zwijndrecht	6	+344	09:46:52	1132 + 628	105 + 128	375[a]
IC 2133	Dordrecht	5	**+297**	09:51:57	1132 + 628	84 + 75	228
G 42961	Zwijndrecht	6	+126	09:51:48	1182	338	403[a]
ST 5133	Dordrecht	4	+72	09:57:32	1130 + 628	200 + 54	238
IC 1933	Dordrecht	4	**+116**	10:02:56	1130 + 628	36 + 137	245
G 49715	–	6	**–**	10:05:13	1132	291	–
IC 9224	Dordrecht	5	**+194**	10:12:14	1130+628	43 + 51	230
G 54352	Dordrecht	2	–28	10:13:32	1130 + 628	130+63	208

[a] Delay jump with respect to departure from Zwijndrecht.

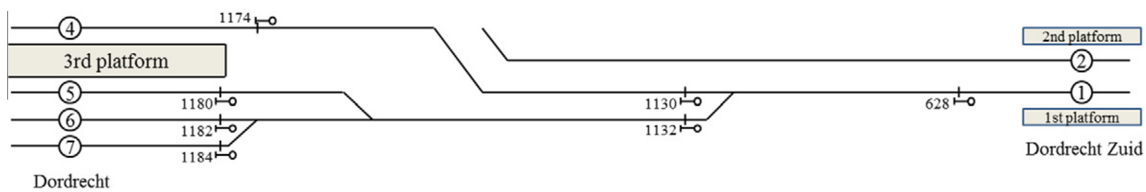

Fig. 5. Relevant track layout of station Dordrecht (left) and the line towards Dordrecht Zuid (right).

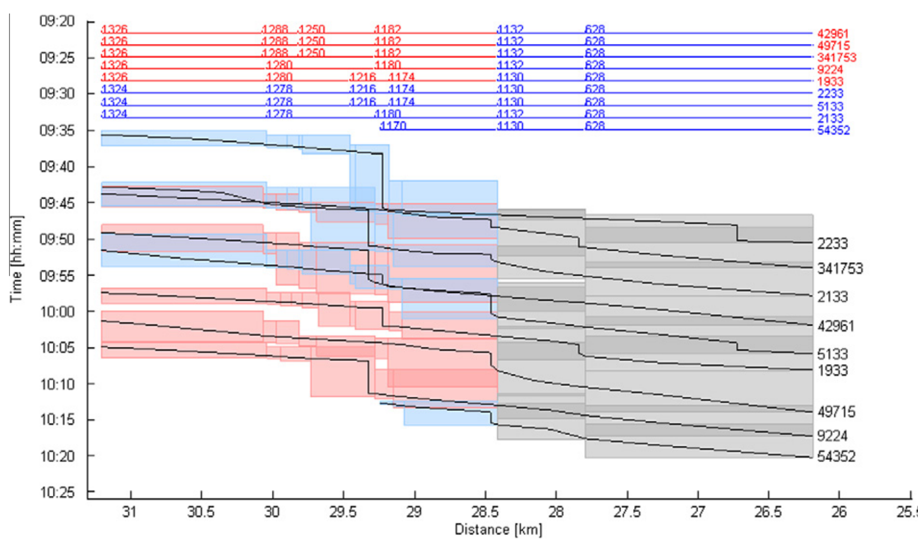

Fig. 6. Blocking time diagram of the conflict chain of train 2233.

(2) Freight train G341753 passes Dordrecht over through track 6 while at the same time train S2233 departs from the parallel track 4. It then suffers two route conflicts with the S2233: first before signal 1132 just after Dordrecht where the route of the G341753 merges into the locked route for the S2233 train, and second before the next signal 628 just before Dordrecht Zuid where the S2233 has a scheduled stop. Before signal 1132 freight train G341753 loses 105 s (braking and standstill time) and before signal 628 another 128 s (slow speed after a yellow signal, braking and standstill time). These time losses contribute together for 233 to a delay jump of 375 s between Zwijndrecht and Dordrecht Zuid. Note that for this goods train no scheduled passage time at Dordrecht is known, but only the scheduled passage time at the previous station Zwijndrecht so that the delay jump is computed over a larger distance.

(3) The IC2133 departs from platform track 5 in Dordrecht with a yellow signal after the freight train G341753, has a time loss of 84 s (slow speed and standstill time) before signal 1132, then passes signal 1132 at yellow with restricted speed until it can reaccelerate again to full speed resulting in another 75 s time loss (slow speed and reacceleration time) up to the next signal 628. It passes Dordrecht Zuid with a total delay jump of 228 s with respect to the departure from Dordrecht. Moreover, the IC2133 departed from Dordrecht with a departure delay of 5 min although its arrival delay was only 1 min, hence in Dordrecht the train had a dwell time extension of 4 min without any additional route or signal conflicts. Possibly, the train waited on the platform track before a yellow signal until the freight train was far away, but still this hidden waiting time was not enough to avoid route conflicts at the next signal.

(4) The freight train G42961 has an unscheduled stop before signal 1182 on through track 6 in Dordrecht where it waits until the IC2133 has cleared the next block. It then follows the IC2133 towards Dordrecht Zuid with a time loss of 338 s including 63 s reacceleration time. The total delay jump from Zwijndrecht to Dordrecht Zuid is 403 s. Note that

also this freight train has no scheduled passage time in Dordrecht and so the delay jump is measured with respect to the previous station Zwijndrecht.

(5) The stop train ST5133 departs with a small delay of 72 s from platform track 4 in Dordrecht and then has to stop before signal 1130 for 200 s (braking and standstill time) until the delayed freight train G42961 has cleared the next block. It then passes signal 1130 at yellow until it can reaccelerate again to full speed resulting in another 54 s time loss (slow speed and reacceleration time) up to the next signal 628. The delay jump to the next stop is 238 s corresponding to an arrival delay of 310 s.

(6) The intercity IC1933 departs from platform track 4 in Dordrecht with a yellow signal and runs with restricted speed to signal 1130 and the next automatic block signal 628 until it accelerates after the ST5133 departed from Dordrecht Zuid. The time loss until signal 1130 is 36 s (slow driving) and until signal 628 there is another 137 s time loss (slow driving). The total delay jump until passing Dordrecht Zuid is 245 s. The IC1933 also departed 2 min late from Dordrecht although it arrived half a minute early without any additional infrastructure conflict. It possibly waited on the platform track until the ST5133 was far away although it still had to run at restricted speed passed two yellow signals.

(7) The freight train G49715 passes Dordrecht on through track 6 and must wait before signal 1132 just after Dordrecht until the IC1933 cleared the block after which it follows the IC1933 towards Dordrecht Zuid. The time loss at signal 1132 is 291 s, including 185 s braking and standstill time before the signal and 106 s extra reacceleration time until signal 628. No timetable is known for this freight train so a delay jump cannot be computed.

(8) The intercity IC9224 departs from platform track 5 in Dordrecht at a yellow signal and runs with restricted speed to signal 1132 (43 s time loss), which it also passes at yellow leading to another time loss of 51 s before it accelerates again to full speed after the G49715 cleared the block ahead. It passes Dordrecht Zuid with a delay jump of 230 s. However, although the IC9224 arrived slightly early in Dordrecht, it departed 3 min (194 s) late without any infrastructure conflict, so it might have waited on the platform track in Dordrecht until the G49715 was far enough. But again not enough to avoid yellow signals.

(9) Finally, the scout train G54352 departs slightly early from platform track 2, waits 130 s before signal 1130 (braking and standstill time) and then passes the signal at yellow with restricted speed leading to another 63 s time loss (slow speed and acceleration) until it passes signal 628. It passes Dordrecht Zuid with a delay jump of 208 s.

The impact of the 222 s (3:42 min) primary delay of the S2233 is eight delayed trains with a computed time loss of 1735 s (29 min) and a total delay jump of 1927 s (32 min), with the side remark that the delay jump of one goods train could not be computed because of an unknown timetable. Note that the standstill time before a red signal is only part of the delay jump. Time loss is also due to braking and reaccelerating and running at a restricted speed (max 40 km/h) after yellow distant signals. Most trains had to wait before the signals 1130 and 1132 where the tracks from six station tracks in Dordrecht merge into a single track, and one train had to wait before an earlier signal at a through track in Dordrecht. Moreover, three of the four passenger trains departed a few minutes late from Dordrecht which also may be attributed to the congestion in the bottleneck to Dordrecht Zuid, as train drivers may have waited to depart on a green signal instead of a yellow signal meaning that they have to stop again just out of the station. These departure delays may thus be hidden time loss before the signals 1130 and 1132 by anticipation at the platform exit signals (which act as the associated distant signals). The only passenger train that departed quite punctual from Dordrecht is the ST5133, but this train had to make space for the IC1933 that arrived on the same platform track 4 just after the departure of the ST5133; the effect was that it had to wait long before the next signal. If the departure delay jumps (relative to the arrival delays) of the three passenger trains in Dordrecht are also attributed to the primary delay of the S2233 then the total delay jump becomes 2474 s (41 min). Finally, for the case study we did not have data from the train describer area after Dordrecht Zuid, but it could be that the S2233 or the eight secondary delayed trains generate more route conflicts after Dordrecht Zuid. This can be checked using the train describer records of the TNV area after Dordrecht Zuid.

For some trains in the case there was also additional time loss before automatic block signal 628 before Dordrecht Zuid, which was however not logged and therefore not recognized as route conflicts by TNV-Conflict. Nevertheless, this time loss is also attributed to the primary delayed train S2233 since all trains in the conflict chain merge into the single track towards Dordrecht Zuid. In the above analysis we did consider the conflict at signal 628 separately, by deriving the blocking time before and after signal 628 using the track section entry and release times that were logged. This can be done for any signal that is not logged, but for which the location is known and lies at a logged section boundary.

In the monitoring system of ProRail all trains with both a delay and a delay jump of 3 min or more must be explained by the signaler. Four of the trains of the conflict chain in Table 1 were also registered in this system (2133, 2233, 9224, 42961) but with incorrect or incomplete causes (e.g. with 1933 and 341753 or completely different trains as root causes) showing that this monitoring system does not yet perform reliably. This example illustrates that TNV-Conflict (with TNV-Statistics) is a valuable tool to improve the monitoring system. Indeed an evaluation of the monitoring system with TNV-Conflict for the February 2009 data revealed that only 46% of the registered causes were correct, with the main errors coming from unidentified or incorrectly identified route conflicts (Goverde, 2010). This result is in line with evaluations by TU Delft of two earlier delay registration systems by ProRail (Daamen et al., 2006; Weeda, 2006), although the monitoring system was designed to improve these earlier systems on this very issue.

4.2. Structural route conflicts

A main topic in railway quality management is the identification and analysis of signals that are often approached at danger, see Section 2. TNV-Statistics can rank all signals according to the amount of conflicts encountered which could be a starting point for analysis. Signals can also be ranked according to delay jump or time loss before a signal, which is very effective for analyzing and improving capacity consumption and service reliability. The ranking may turn out very different. For instance, there may be regular conflicts at some signal but with only small time losses, whereas another signal may be approached at danger only sometimes but with long time losses. Which of these cases then qualifies as the worst one?

Table 2 shows the top three of signal conflicts with respect to five different criteria: total delay jump (TDJ), total time loss (TTL), mean delay jump (MDJ), mean time loss (MTL), and number of conflicts (Conflicts). The (total and mean) delay jump and time losses are daily averages so that periods of different lengths can be compared. For example, total delay jump is defined as the

Table 2
Signal rankings on the corridor Leiden–Dordrecht over February 2009.

Rank	Signal	Location	TDJ (s)	TTL (s)	MDJ (s)	MTL (s)	Conflicts
Top 3 of total delay jump							
1	1132	Ddr–Ddzd	1762 (1)	1054 (10)	235 (10)	157 (25)	7 (11)
2	1112	Dvnk–Ledn	824 (2)	1524 (6)	111 (21)	222 (12)	6 (12)
3	1184	Ddr–Ddzd	716 (3)	354 (36)	716 (1)	315 (1)	3 (15)
Top 3 of total time loss							
1	466	Rsw–Dt	93 (49)	3760 (1)	6 (410)	262 (5)	15 (3)
2	1136	Ddzd–Ddr	650 (5)	1772 (2)	220 (11)	113 (38)	16 (2)
3	338	Zwd–Ddr	54 (147)	1709 (3)	41 (93)	198 (19)	9 (10)
Top 3 of mean delay jump							
1	1184	Ddr–Ddzd	716 (3)	354 (36)	716 (1)	315 (1)	3 (15)
2	116	Sdm–Rtd	515 (6)	209 (51)	417 (2)	81 (63)	2 (16)
3	1182	Ddr–Ddzd	679 (4)	542 (27)	356 (3)	201 (18)	2 (16)
Top 3 of mean time loss							
1	1184	Ddr–Ddzd	716 (3)	354 (36)	716 (1)	315 (1)	3 (15)
2	344	Rtd–Rtb	10 (140)	328 (31)	10 (128)	277 (2)	1 (17)
3	1114	Dvnk–Ledn	367 (8)	747 (12)	137 (14)	273 (3)	3 (15)
Top 3 of number of conflicts							
1	1278	Laa–Gvc	115 (41)	1245 (8)	113 (20)	86 (58)	17 (1)
2	1136	Ddzd–Ddr	650 (5)	1772 (2)	220 (11)	113 (38)	16 (2)
3	466	Rsw–Dt	93 (49)	3760 (1)	6 (410)	262 (5)	15 (3)

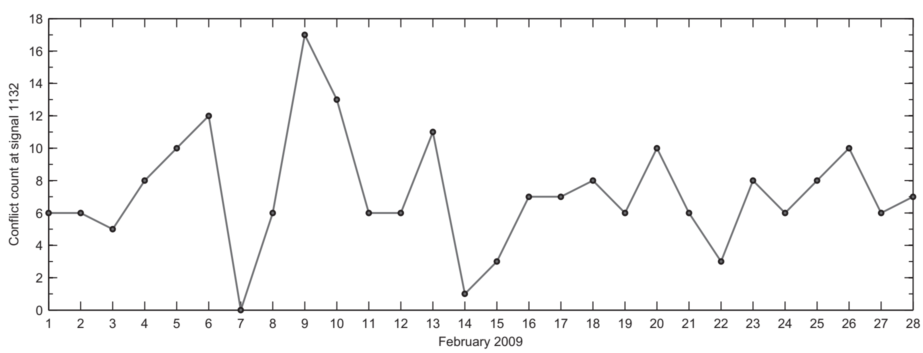

Fig. 7. Conflict counts at signal 1132 between Dordrecht–Dordrecht Zuid (average 7).

sum of delay jumps on each day divided by the number of days, and mean delay jump as the sum of mean delay jump (sum of delay jumps divided by number of conflicts) per day divided by number of days. The time loss is calculated with respect to a reference running time over the route block before the signal, which is computed as the 20th percentile of the running times of all trains from the same train line over the same route. If for some conflict a delay jump or time loss could not be computed due to missing data then these conflicts are discarded in the calculation of these quantities. The means are calculated over all computable delay jumps or time losses, respectively. In Table 2 the ranking with respect to each column is given in brackets behind the values; the total number of signals is 485. For instance, the signal on the corridor Leiden–Dordrecht that scores worst on total delay jump over February 2009 is signal 1132 on the track from Dordrecht to Dordrecht Zuid, which also appeared in the conflict chain of Section 4.1. Signal 1132 has a total delay jump of 1762 s (29:22 min) per day with a daily mean delay jump of 235 s (3:55 min) per route conflict. With on average 7 conflicts daily, see Fig. 7, this signal implies a serious problem for capacity, punctuality and reliability, as well as safety (SPADs). The total time loss before this signal is computed as 1054 s (17:34 min) and the mean time loss as 157 s (2:37 min). This signal is also in the top 10 of total time loss and mean delay jump. It ranks 25th on mean time loss and 11th on number of conflicts. In Section 4.1, we already analyzed four route conflicts at this signal 1132 on February 1, 2009.

When comparing total delay jump and total time loss (4th and 5th column in Table 2), one might expect consistency: small time losses giving small delay jumps and large time losses giving large delay jumps. However, from the table this is hard to see which can be explained as follows:

- Running time supplements compensate for time loss so that delay jumps are smaller. Moreover, running time supplements vary from trip to trip (mainly due to rounding to minutes or synchronization time) so that the relations also vary.

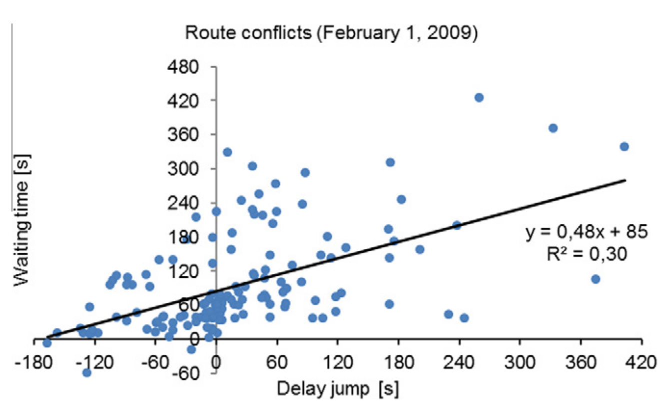

Fig. 8. Relation between time loss and delay jump.

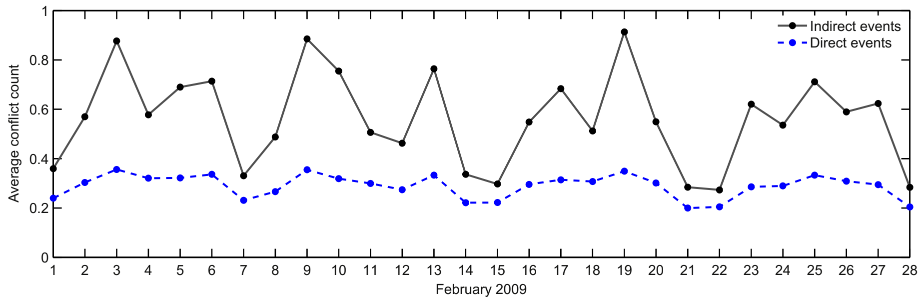

Fig. 9. Daily mean number of conflicts over February 2009.

- A delay jump may be the result of multiple route conflicts with cumulative time losses. This is in particular relevant when the timetable is not entirely known so that the delay jump is calculated over a long distance.

These issues make it difficult to calculate the real time loss/effect of a conflict. Fig. 8 shows a scatter plot of time loss versus delay jump including a linear regression line (with three outliers discarded in the linear regression) for route conflicts at all signals on February 1, 2009. The regression model has 30% explained variation ($R^2 = 0.30$), so there is some consistency between delay jump and time loss.

It can be argued that time loss qualifies as the main criterion measuring the effect of a conflict: If the timetable contains so much slack that large time losses still lead to small or even negative delay jumps then this excessive slack may very well have been added in the past to counter the structural conflict with large time losses. Instead of fighting the symptoms (adding running time supplement to reduce delays) it is preferred to acknowledge the structural time losses and prevent path conflicts by e.g. shifting the previous departure times or changing the scheduled speed profiles of the involved train pairs. Note that unscheduled stops imply increased infrastructure capacity utilization and energy consumption. Two signals in the top three signals ranked by total time loss and by number of conflicts are the same (except for the order) suggesting a strong relation between the two. Note that the ranking of number of conflicts is not unique: although the top three contains three unique conflict counts (17, 16, and 15), many signals have the same (smaller) number of conflicts. The high number of conflicts however corresponds to high total time losses. On the other hand, the top mean delay jump and mean time loss correspond to small numbers of conflicts implying a preference for relatively seldom route conflicts with large time loss/delay jump. The top total delay jump corresponds to intermediate conflict counts. Hence, it pays off to identify conflicts at signals using track section data and compute the resulting time losses to quantify the impact of a route conflict. In Table 2 signal 1184 is in the top three of three different rankings: it has the most mean time loss and delay jump, and also ranks second in total delay jump whilst it has on average three conflicts a day.

In dense traffic areas and at capacity bottlenecks the risk of route conflicts increases while at the same time the resulting increased track occupation time and schedule deviation easily lead to further route conflicts and secondary delays. Fig. 9 shows the mean number of conflicts per day for the Leiden–Dordrecht data over February 2009, separated in direct conflicts and indirect conflicts over conflict chains. The mean number of direct conflicts over the entire month is 0.29, while the mean number of indirect conflicts is 0.56, which is almost twice as much. This implies that each route conflict between two trains propagates on average to one more train. The number of indirect conflicts per signal or the resulting total delay jump and/or time loss of the conflict tree is another possible ranking of signals. Note that in the weekends (February 1, 7–8, 14–15, 21–22, and 28) there are fewer trains than on working days, which explains that there are less (direct) route conflicts and also less indirect conflicts because of larger headways.

5. Conclusions

This paper presented the tool TNV-Statistics, an add-on tool to TNV-Conflict, which combines and processes data generated by TNV-Conflict to get advanced operations information. In particular, route conflicts and conflict trees of successive route conflicts with the associated secondary delays are automatically generated and visualized by TNV-Statistics, disclosing the information generated by TNV-Conflict to analyzers even more user-friendly. The daily total time loss due to route conflicts has been shown to be an effective indicator for ranking signals with structural route conflicts, rather than total delay jump, number of conflicts, or mean delay jump/time loss.

The aim of TNV-Statistics is to relieve the analyst from routine, time-consuming, and error-prone data collecting, combining, and processing tasks, so that the available time can be devoted to analyze, interpret, and manage the revealed operations problems. The tool is still under development and in particular an effective graphical user-interface is currently being developed to guide the analyst best in the task of operations performance analysis.

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