Improving the capacity and performance assessment of railway nodes on the French network

TIL5060 – TIL Master thesis

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Improving the capacity and performance assessment of railway nodes on the French network

by

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Preface

When I started my higher education, little did I know that this would lead me to graduate in a foreign university, working on a railway project. Contrary to many people in that field, my interest in railways only appeared late during my years as a student, when I started to take the train more regularly. The good news was, however, that I had so much to discover ahead of me! Working on railway nodes has been a very interesting experience, as they are critical yet often overlooked elements of the railway system, and so much is still to be done to improve their efficiency.

Writing this thesis was one of the most challenging parts of my studies, and I certainly could not have completed it alone. First of all, I would like to thank my graduation committee for their continuous support and guidance throughout the project, and their availability to review my progress when I needed it. They accepted to let me perform this project despite my personal constraining deadlines to finish it, which was a huge relief to me and helped me focus on the topic.

I would like to thank Cyril for offering me the opportunity to conduct this project at SNCF Réseau and learn so much about the fascinating world of railway operations. I had the chance to work with wonderful colleagues at the railway operation studies department, that are deeply passionate about their work and love to share their knowledge (and their humour!) with the others. There really was not a day during these six past months I was not enthusiastic in the morning going to work. I may even start colouring my own railway map one day…

Then, I am grateful to all my friends, in France and in Delft, with whom I spent so many great times over those past years, and on whom I always could count on. I would especially like to thank my girlfriend for always listening to me and supporting me when I needed it.

Finally, I am deeply thankful for the endless support of my family, who always helped me and gave me the strength to carry on in the hardest times. I would like to dedicate this thesis to Nelly, who always believed in me and pushed me to never give up.

I hope you will enjoy reading this thesis as much as I had the pleasure to write it.

Guillaume Ethuin

Paris, August 2023

Executive summary

Context and research question

Railway nodes, that are the junction and switch areas connecting railway track lines and stations, are particularly subject to saturation issues. Assessing their capacity utilisation and performance (through delay propagation evaluation) is of primary interest for railway infrastructure managers. While most analysis methods have focused on railway line track sections, a few methods are also available for railway nodes, and can be classified between timetable-based and timetable-free methods. Yet, it appears the relationship between capacity utilisation and performance has rarely been tested for railway nodes in the literature, and critical capacity utilisation thresholds are still to be determined. The comparison of timetable-based and timetable-free methods also needs to be conducted. The following research question is formulated:

Which methods can be effectively used to improve the capacity and performance assessment of railway nodes in the long-term planning stages?

Filling these research gaps is of primary interest for the French infrastructure manager SNCF Réseau, which seeks to improve its analyses of nodes capacity utilisation and performance in the long-term planning stages.

Methodology

Description of the methods

In this research, a small set of timetable-free and timetable-based methods are studied, applied and compared. The methods are taken and adapted from the literature or developed for the need of this research.

All methods rely on the use of a route compatibility matrix and a matrix of headways between conflicting routes. In this research, and unless stated otherwise, the headways comprise the minimum headways and headway supplements. Then, the timetable-free methods only necessitate the volumes of traffic per routes, assuming the trains arrive in a random order, while the timetable-based methods also require the arrival sequence of the trains at the node. The methods and their characteristics are briefly presented below.

Capacity utilisation assessment methods

- Timetable-free Potthoff method: This method calculates an occupation time of the node with an average number of trains in a virtual critical sequence that it multiplies by an average headway calculated as a weighted average based on the frequencies of the different train combinations. The capacity utilisation is calculated as the ratio of the occupation time over the duration of the studied period.

- Proposed timetable-free SNCF-adapted method: This method is developed in this research from previous works conducted at SNCF Réseau. The method uses a similar process as Potthoff method's, but the calculations of the average number of trains in the virtual critical sequence and the average headway is based on a hypergeometric distribution that assesses the number of conflicts occurring per pair of conflicting routes

- Timetable-based UIC 406 method for railway node capacity utilisation assessment: This method has been published in the second edition of UIC Code 406, in 2013. It consists in compressing a timetable by spacing the trains with the headways contained in the headway matrix, taking into account the routes' incompatibilities.

Delay propagation assessment methods

- Proposed timetable-free Potthoff-adapted method: The original Potthoff method taken from the literature calculates the delays suffered by trains on each route with the routes it conflicts with. The calculation consists in multiplying a probability of conflict by an average waiting time due to the conflict. The adaptation of the method proposed in this research adjusts the average waiting time by taking into account the possibility that the first train (imposing the waiting time) can also have been delay and might consequently run slower than scheduled, thus imposing a greater waiting time. The total delays are computed as the sum of delays suffered by trains from all routes.

- Proposed timetable-free SNCF adapted method: In this method the delays suffered by trains on a route conflicting with another route are calculated by multiplying the average number of conflicts obtained with the hypergeometric distribution with the average waiting time. Here again the possibility of longer waiting time due to a slower-than-scheduled first running train is taken into account.

- Proposed timetable-based UIC adapted method: In this method, trains are initially spaced in the arrival order specified by the timetable, at their respective headways (minimum headway plus headway supplements), leading to the obtention of a "basic timetable". Initial delays are generated by letting the trains' starting times vary slightly around their original starting time in the basic timetable. Delays are then propagated by rectifying all starting times so that minimum headways are respected again. These minimum headways are possibly adapted to take into account the longer headway that a train imposes due to restarting after a precedent conflict. Total delays are calculated as the sum of all individual trains' delay. Several draws of initial delays are performed, and an average total delays value is computed over all draws. The number of initial delays draws are increased until the averaged total delays over all draws does not evolve significantly over a certain number of successive increases in the number of initial delays draws.

Timetable-free adaptation of the UIC methods

The timetable-based UIC methods for capacity utilisation and delay propagation assessment are further adapted into timetable-free versions. The idea is to generate random train arrival sequences and compute an average indicator (capacity utilisation or total delays) over all sequences. An increasing number of randomly generated sequences is tested until the average indicator does not change significantly anymore over a certain number of successive increases in the number of randomly generated sequences.

Evaluation process

The evaluation of the methods is conducted in a two-step process. First, in the verification step, the timetable-free methods' indicators are tested using artificial traffic data; the magnitudes and trends of the different indicators are compared. Then, in the validation step, the timetable-based and timetable-free methods are compared to indicators calculated with real values. The best performing methods are then used to investigate the capacity utilisation – total delays relationship.

Findings

The evaluation of the methods is conducted on the case study of the Lyon Saint-Clair junction at the entrance of Lyon Part-Dieu station's northern switch area, in Lyon, France.

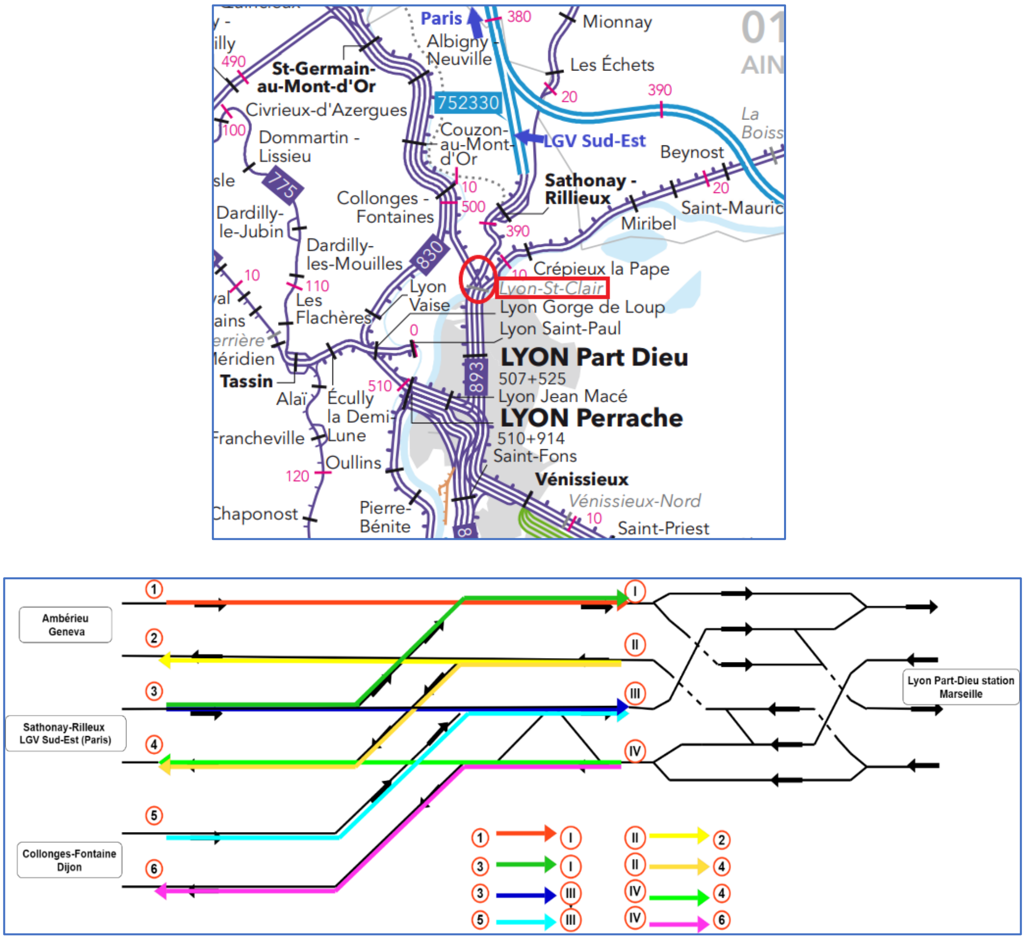


Figure 0.1: Location and track layout of the Lyon Saint Clair junction

Verification step

In the verification step, the timetable-free method are applied using artificial traffic configurations. Traffic values are varied along of the three main branches the Lyon Saint Clair junction. For the capacity utilisation indicators, it is found that Potthoff's and the timetable-free UIC-adapted method's capacity utilisation indicators follow similar trends and that the timetable-free UIC-adapted method's indicator is greater by 16.6% on average. Conversely, it is hard to draws a link between SNCF-adapted's capacity utilisation and the indicators of the two other methods. Regarding the delay propagation methods, it is found that the Potthoff-adapted and SNCF-adapted methods' total delays indicators follow similar trends. On the other hand, it is hard to define a link between the indicators of those methods and the total delays indicator of the timetable-free UIC-adapted method for delay propagation assessment.

Validation step

In the validation step, the timetable-free and timetable-based methods' indicators are compared to real values. Concerning capacity utilisation, it is found that the timetable-free UIC-adapted method and the timetable-based UIC 406 method produce capacity utilisation indicators that are very close to the real values on average (with respective relative differences of -3.7% and -1.2%, taking the real values as reference). The Potthoff method also gives a good result, with a mean relative difference of 16.5% with the real values as reference. The SNCF-adapted method does not provide a satisfying result (mean relative difference of 45.9%). Regarding the delay propagation method, it is found that the UIC methods (both timetable-free and timetable-based) provide indicators that are close in magnitude on average with the real total delays (timetable-free UIC-adapted: 7.9%; timetable-based UIC-adapted: 9.4%), but with a high dispersion (respectively 23% and 21.5%), thus hindering their reliability. Conversely, the Potthoff-adapted and SNCF-adapted methods provide indicators of higher average relative difference with the real total delays in magnitude (resp. 49% and 77.2%) but with low dispersion (15.6% and 7.1%), suggesting the possibility to correct them with a constant factor to obtain closer values in magnitude.

Investigation of the capacity utilisation – total delays relationship

The timetable-free Potthoff and UIC-adapted methods for capacity utilisation are further used to study the capacity utilisation – total delays relationship. For total delays assessment, taking advantage of SNCF-adapted's total delays low dispersion in the difference with the real total delays, a constant factor is calibrated and validated using a random split of the validation dataset. This constant factor then multiplies the total delays of the SNCF-adapted method to correct them. This corrected SNCF-adapted method is used to produce total delays for the assessment of capacity utilisation – total delays relationship.

The selected methods are applied to an enlarged set of traffic configurations made of observed configurations (validation set) and unobserved configurations (verification set). The following results are obtained.

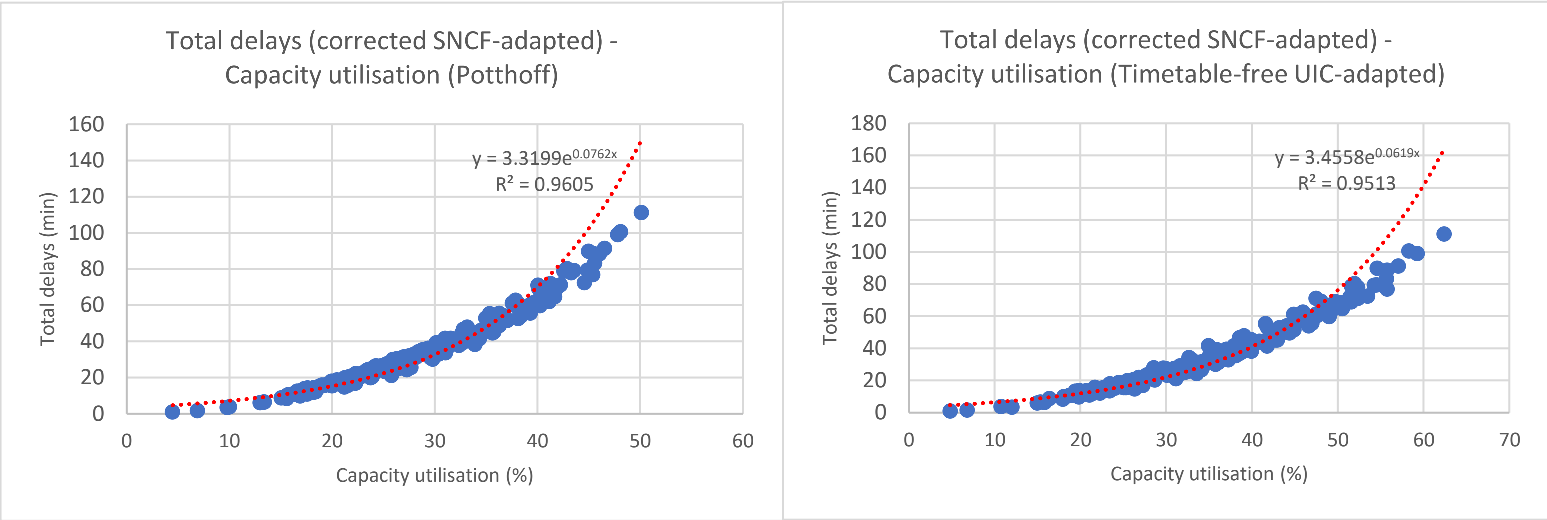


Figure 0.2: Capacity utilisation – total delays relationships

An exponential trend is found for both methods, which is in line with previous findings published in the literature. To better interpret the capacity utilisation values, the total delays per train are computed and the capacity utilisation – total delays per train relationships are shown below.

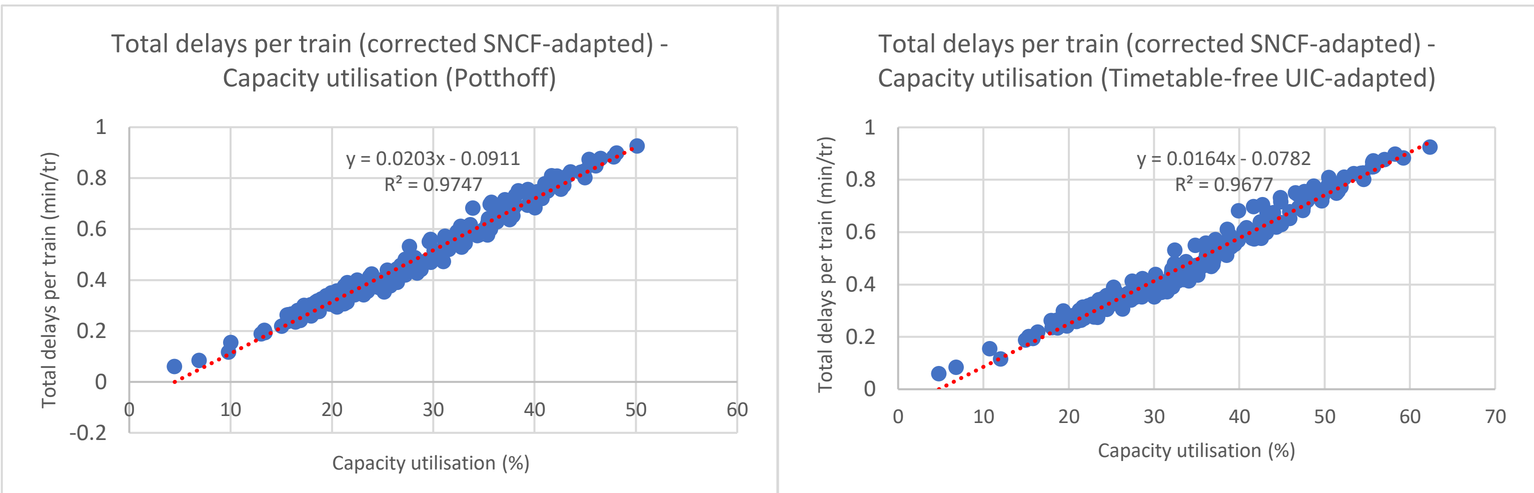


Figure 0.3: Capacity utilisation – total delays per train relationships

Here, strong linear relationships are found. Using the equations from the regression curves, it can be calculated that a critical total delays per train value of 1min/tr lost on average is reached when Potthoff's capacity utilisation reaches 53.7%, or when the timetable-free UIC-adapted's capacity utilisation reaches 65.7%. These thresholds should be considered preliminary results that need to be confirmed over an extended range of different traffic and infrastructure configurations.

Conclusion and recommendations

The results obtained in this research for the case study of the Lyon Saint Clair junction showed that among the timetable-free methods, the timetable-free UIC-adapted and Potthoff methods for capacity utilisation evaluation, and SNCF-adapted method with a correction factor for delay propagation assessment give relevant results in terms of magnitude and trends for the long-term assessment of railway nodes capacity and performance. Then, if there is the need to study particular timetable patterns, the timetable-based UIC 406 method for railway node capacity utilisation assessment can be used. No satisfactory timetable-based delay propagation method was found in this research, thus the infrastructure manager could continue using the current simulation approaches, or use the timetable-free corrected SNCF-adapted method for delay propagation if quick evaluation is needed. Finally, the capacity utilisation – total delays relationships are tested for different capacity utilisation methods, and all show an exponential trend. An early attempt to find critical capacity utilisation is also conducted.

The preliminary findings of this research should further be confirmed with additional studies that could cover larger and denser traffic configurations as well as different track layout configurations. This would allow reinforce the knowledge of the capacity utilisation – total delays for different traffic and infrastructure configurations, which appears mandatory before utilising those indicators in real studies.

1. Introduction

1.1. Context of the research

A railway network can generically be conceptualised as a set of nodes (i.e railway stations or junctions) linked with one another by railway track sections. While stations are the entry and exit points of the railway network for goods and passengers, junctions form the crossing and connections of different rail routes. Nowadays, the transportation demand increases quickly while infrastructure changes happen at a moderate pace. Ultimately, infrastructure saturation problems tend to arise on some parts of the railway network. It is therefore critical for railway planners to be able to assess the available capacity on a railway network in order to maximise capacity provision while maintaining a good quality of service. This issue is particularly crucial for railway nodes as they tend to be the bottlenecks of the railway network.

The scientific literature has mostly been looking at capacity methods for the study of line track sections. Yet, several analytical methods (i.e. relying on formulas and providing general information to planners) have also been developed to study the capacity utilisation of railway nodes, and more specifically the switch area between the line track sections and station platform tracks. In the remainder of this thesis, and unless stated otherwise, the term *railway node* will refer to these switch areas. Such analytical methods can be "timetable-based" (i.e. relying on train arrival times and sequences to perform the analysis) like the UIC 406 method (*UIC, 2013* [18]) or "timetable-free" (i.e. only requiring infrastructure layout data and train traffic volumes and types) such as the methods developed by Potthoff (*Potthoff, 1963-1972* [33]) or the Deutsche Bahn (*DB, 1979* [8]). Some sources (such as *UIC, 2013* [18] and *Armstrong & Preston, 2017* [3]) advocate for the study of the link between capacity utilisation and performance. In the remainder of this thesis, the term *performance* will be evaluated by the delay propagation occurring at a railway node, which is expressed as the sum of the delays suffered by each train due to conflicts at the node (*total delays*). Good performance thus refers to a low delay propagation, while bad performance denotes a high tendency to propagate delays.

1.2. Research problem

Several knowledge gaps emerge from the review of the literature and the analysis of the infrastructure managers' processes for the planning and design of railway nodes.

Regarding the scientific literature, it appears that the relation between capacity utilisation indicators and performance indicators has been rarely tested. While capacity utilisation values are better understood in the case of railway line track section capacity assessment, with reference values such as the ones proposed in *UIC, 2004* [17], such knowledge appears to be lacking in the case of railway nodes assessment.

Then, it is not clear how timetable-based and timetable-free methods compare when assessing the capacity utilisation and performance of railway nodes in the long-term planning horizon. On the one hand, timetable-based approaches rely on scheduled timetable arrival patterns and thus well-defined timetable-based methods shall normally provide an accurate assessment of nodes' capacity utilisation and performance if the real operations do not deviate too much from the planned ones. On the other hand, timetable-free approaches can be used in the medium or long-term horizon planning processes if no detailed timetable is available, but they also rely on random train arrivals assumptions, which can prove to be unrealistic. Yet, the relevance of their output indicators for the assessment of nodes' capacity utilisation and performance in the long-term horizon remains to be thoroughly studied.

In parallel, a set of issues can be identified from the review of the infrastructure managers' design methods and planning processes for railway nodes in France. It appears that the current planning and design process for railway nodes suffers from a lack of coordination between stakeholders, and more specifically at the strategic planning and design phase, where train operations are often considered only after the strategic infrastructure design has been made. In particular, the railway operation studies department of the French infrastructure manager SNCF Réseau, tasked with assessing the feasibility and performance of future railway projects, lacks a methodology to provide first evaluations of the capacity utilisation and quality of train operations at a railway node in the long-term planning and design process.

This is related to the fact that the railway operation studies department is missing reference methods for railway node capacity assessment, and reference values to interpret railway node capacity utilisation indicators. Additionally, the analyses can be hindered by the uncertainty regarding the actual realisation of the projected timetables used in the long-term study process (that is, early timetables that are still being developed).

1.3. Research questions

This master thesis research project aims to reinforce the body of knowledge in the field of railway operations science by answering the previous knowledge gaps and infrastructure managers' issues. Based on the previous gaps, the primary goal of this research is to find analysis methods that can assess the relationship between railway node capacity utilisation and performance. The functional relationship should clearly associate capacity utilisation values with levels of performance, in order to identify capacity utilisation thresholds that are critical for the performance of the system. In that process, the relevance of timetable-free and timetable-based approaches for providing accurate estimates of capacity utilisation and performance in the long-term planning phases shall be studied. The answers to these questions shall help improve the infrastructure managers' long-term planning of railway nodes.

The goals of this research project can be formulated into the following main research question:

Which methods can be effectively used to improve the capacity and performance assessment of railway nodes in the long-term planning stages?

The research process can be structured along the following set of subquestions (“SQ”):

SQ1. Which methods have been developed in the literature and used by practitioners to study railway node capacity and approach railway node performance, and what limitations can be found?

SQ2. Which methods can assess the relationship between capacity utilisation and performance indicators in order to identify capacity utilisation thresholds that are critical in terms of performance?

SQ3. How can these methods be used to improve the long-term planning of railway nodes?

SQ4. Which recommendations can be provided to SNCF Réseau and other infrastructure managers to improve the long-term capacity and performance planning of railway nodes?

1.4. Methodology

In this master thesis research project, a small set of timetable-based and timetable-free railway node capacity and performance analysis methods are studied and compared. The methods are taken and adapted from the literature or developed for the purpose of this research.

The set of methods for capacity utilisation analysis comprises the timetable-based UIC 406 method for railway node capacity assessment (*UIC, 2013* [18]) directly taken from the literature, and three timetable-free methods which are the Potthoff method (*Potthoff, 1963-1972* [33]), a method developed in this research from previous works at SNCF Réseau (later called “SNCF-adapted method”) and another method developed in this research as an adapted timetable-free version of the UIC 406 method for railway nodes (later called “timetable-free UIC-adapted method for capacity utilisation assessment”). Then, the methods for delay propagation assessment are all contributions of this research to railway operations science and are made of a timetable-based method based on the philosophy of UIC 406 (later called “timetable-based UIC-adapted method for delay propagation assessment”) and three timetable-free methods which are an adapted version of the Potthoff method (“Potthoff-adapted method”), a further development of the “SNCF-adapted method” mentioned earlier, and a timetable-free version of the UIC-adapted method for delay propagation assessment.

The methods are first evaluated on a case study node. The evaluation process consists of two steps. In the first step, the timetable-free methods are tested using artificial traffic data inputs, and their outputs compared. In the second step, the timetable-free and timetable-based methods are compared on their ability to reproduce indicators obtained from real traffic data. At this end of this second step, capacity utilisation thresholds are investigated using the methods that best performed. Finally, the outcomes of the evaluation process are used to provide recommendations aimed at improving the design processes of railway nodes.

The remainder of this document is structured as follows. In chapter 2, two reviews are presented: the first one tackles the scientific literature on railway node capacity and performance analysis, and the second one deals with the planning and design methods used by infrastructure managers. In chapter 3, the methods are presented in details and the evaluation process is outlined. Then, in chapter 4, the evaluation process is performed on a case study. Finally, in chapter 5, the lessons learned from the evaluation process are used to provide recommendations on the usage of the methods to support the long-term planning processes of railway nodes.

2. Review of the scientific literature and infrastructure managers’ processes for railway node planning and capacity analysis

This first chapter aims to review the scientific literature dealing with node capacity and performance analysis topics, as well as to investigate the current processes used by railway infrastructure managers for railway node planning and the issues that they face.

2.1. Review of the scientific literature on railway node capacity and performance analysis

2.1.1 Introduction to the literature review: capacity analysis in railways

Nowadays, railway transportation demand increases quickly, while the infrastructure is evolving slowly. Therefore, saturation problems tend to arise on busy parts of the railway network. Hence, it is critical for railway planners to be able to perform efficient capacity analysis, so as to know how many trains can be accommodated by a railway infrastructure while maintaining a good level of service.

The definition of capacity varies in the literature. As noted in *UIC, 2004* [17], “*Capacity as such does not exist*”, as it depends on how the infrastructure is utilised. *UIC, 2004* [17] mentions several factors affecting the capacity of a railway infrastructure, such as the volumes of train traffic, the heterogeneity of the trains and their speed, and the stability of the timetable. It is important to differentiate the concepts of theoretical capacity, practical capacity, and capacity utilisation. As defined in *Hansen & Pachl, 2008* [15], the theoretical capacity of a railway infrastructure corresponds to the maximum number of train paths that can utilise the infrastructure over a certain period of time. Such a concept is of poor practical relevance however, as theoretically no time margin is then available to compensate variations in the operations, thus providing a very low quality of service. Conversely, for a given traffic pattern, a practical capacity can be defined as the maximum number of trains that can use the infrastructure while respecting operational constraints such as a timetable structure. Then, capacity utilisation can be defined as the extent to which the maximum capacity of a railway infrastructure is being used. According to *UIC, 2004* [17], capacity utilisation, or capacity consumption can be computed as the ratio of the occupancy time of the train paths (to which additional times rates, also called “supplements”, can be added) over a given studied time period.

The literature on railway capacity and its assessment is prolific. For instance, *Khadem Sameni & Moradi, 2022* [21] have recently reviewed more than sixty papers having conducted major research on railway capacity in the last two decades. In particular, the UIC Code 406 timetable compression method published in 2004 [17] has been widely spread throughout the railway industry and now provides an international standard for the railway planners worldwide when it comes to evaluating the level of capacity utilisation of a railway infrastructure. It is important to note that these methods and studies mainly investigate the capacity of lines, while not necessarily being applicable to railway nodes (i.e. stations and junctions). For example, *Lindner, 2011* [25] [26] argues that the UIC Code 406 timetable compression method is not applicable to station areas.

Yet, as pointed out in *Armstrong & Preston, 2017* [3] and *Kianinejadoshah & Ricci, 2018* [22], the complex interactions between trains taking place at railway nodes can often generate delays and disrupt the operations on the rest of the railway network. Hence, railway nodes can be considered as major bottlenecks of railway networks, and the analysis of their capacity utilisation is therefore of paramount importance for planners. As mentioned by *Niessen, 2008* [32], many approaches have been developed to study line as well as station track capacity, but fewer methods have been built to analyse "route nodes". *Schwanhäußer, 1978* [37] defined "route nodes" at a microscopic scale as the greatest possible subsets of points and crossings of an investigated railway network such that every pair of interlocking routes that use the route node are mutually incompatible. These subsets are shown to be disjunctive to each other. In *Hansen & Pachl, 2014* [16], a route node is defined at a mesoscopic scale as the switch area at a junction or at a station, linking the platform tracks and the line tracks. In the remainder of this paper, and unless stated otherwise, the analysis of railway nodes will refer to the study of these switch areas, where conflicts between running trains can occur.

Although less numerous than methods focusing on lines, several node capacity analysis methods have been developed and applied in the literature. Furthermore, these methods sometimes also provide first estimates of nodes' performance. This literature review aims to assess the current state of the art regarding node capacity and performance analysis methods, and the connection that can be made between capacity utilisation and the operational performance of a node.

2.1.2 Main types of approaches in railway node capacity analysis

According to different authors, methods for railway node capacity analysis can be classified as follows. Based on *Crenca et al., 2005* [6] and *Bažant et al., 2018* [4], methods can be differentiated between analytical methods that rely on the application of formulas and provide general information for network planning, and simulation methods that are able to provide detailed information through a duplication of the real systems. *Khadem Sameni & Moradi, 2022* [21] also include operational research methods among these categories. *Weik et al., 2020* [39] provides another type of classification, differentiating the methods based on their reliance on a timetable, or not, in which case coarser information such as approximated traffic volumes can be used. While timetable-based methods are applicable in the short-term with more precise inputs regarding the real upcoming operations, timetable-free methods can be applied at medium or long-term horizons to perform strategic planning analyses.

Regarding the first classification type (analytical, operational research and simulation methods), this literature review will only briefly touch upon operational research and simulation methods, and further focus on analytical methods. Indeed, the idea of the research is to study methods that are easily applicable and that provide comparable results, which is usually not the case of simulation and operational research methods, whose implementation can be time-consuming, and which usually provide customised results for specific case studies.

2.1.3 Overview of operational research and simulation methods for node capacity analysis

This paragraph will briefly touch upon operational research and simulation methods. Some of the papers quoted here have been mentioned in *Khadem Sameni & Moradi, 2022* [21].

Simulation methods aim to reproduce the real operations and they are often used to study the effects of disturbances on the planned operations. For instance, *Han et al. 2016* [14] used simulation to model the stochasticity of train delays in stations and operational processes and evaluate the resulting maximum capacity of stations. Then, *Navarro et al. 2018* [31] used "fuzzy numbers" to incorporate the uncertainty about dwell times at stations in the modelling of urban railway networks.

Operational research methods usually aim to compute the theoretical maximum capacity of nodes and to study some particular aspects of nodes' operations. For instance, *Powell & Wong 1999* [34] followed a linear programming approach to determine the maximum throughput of trains of a node over a certain time duration, based on a given track layout. Similarly, *Guo et al. 2016* [13] used an operation research approach to study the theoretical capacity of a high-speed rail station, while also considering constraints related to train sets. *Mussone & Calvo 2013* [29] built an optimisation model to find the maximum capacity of different elements of a railway system. Their approach does not rely on a timetable and can take into account priority relations and delays. *Wu & Zhang 2019* [41] also made use of an operational research model in order to find the capacity of the bottlenecks of a station.

Operational research methods can also be used to optimise train operations in stations or track layout designs. For instance, in their model, *Wu & Zhang 2019* [41] aimed to optimise the decision-making rules regarding arrival and departure lines and bottlenecks usage. When it comes to the infrastructure, *Jovanović et al. 2020* [20] developed a graph colouring-based approach to optimally design track layouts.

2.1.4 Focus on analytical methods for node capacity analysis

Analytical methods study node capacity through the application of formulas and aim to provide general information for network planning. Methods can rely on a timetable or make use of coarser assumptions on train traffic.

2.1.4.1. Timetable-based methods

Among capacity analysis methods that rely on the sequence of trains given by a timetable, timetable compression methods are popular and widely used.

First works on timetable compression methods for capacity analysis were initiated by *Adler, 1967* [1]. However, it is the publication of *UIC, 2004* [17] that greatly led to a widespread sharing and usage of the timetable compression approach for studying capacity utilisation on railway line track sections.

As the first edition of UIC Code 406 [17] was mostly focused on the analysis of railway line track sections, discussion gradually emerged in the literature about whether the method was applicable to the analysis of railway nodes. *Lindner, 2011* [25] [26] argued that the timetable compression method presented in *UIC, 2004* [17] was not applicable to nodes, because of the high number of partitions required as well as route synchronisation issues in railway nodes' switch areas. However, *Armstrong & Preston, 2012* [2] pursued the idea of utilising a timetable compression method by adapting the British CUI timetable compression method so that it could be used for the analysis of nodes. Similarly, other research such as *Landex, 2011* [23] developed adaptations of the original UIC Code 406 timetable compression method to nodes.

Then, in 2013, a second edition of *UIC, 2013* [18] was published, adding to the previous version an adaptation of the timetable compression method for station and junction areas. In this method, when it comes to analysing station areas, switch and platform areas are analysed separately. Starting from a route matrix describing the switch area, the minimum headways times between each route and the arrival sequence of paths taken from the timetable, the method for switch areas uses an iterative process to determine a critical sequence of paths, between the start and the end of the assigned time period. The concatenation of these critical train paths then leads to the calculation of an occupancy time rate, ultimately providing an occupation time ratio indicator. *Bešinović & Goverde, 2018* [12] also developed a method based on timetable compression. Their method is built on a max-plus automata model that assesses the capacity utilisation of a railway node, by computing the occupation time of a railway node for a given timetable with an ordered sequence of blocking time stairways. Additional timetable constraints can also be taken into account, such as overtaking and connections for passenger transfers.

One of the issues pinpointed in the literature concerns the lack of exhaustivity of the timetables when it comes to referencing all trains movements performed. *Landex & Jensen, 2013* [24] note that several unscheduled movements on the tracks can happen, besides those of the scheduled trains appearing in the timetable. Hence, the authors recommend applying a certain "quality factor" as a time supplement to take into account unscheduled movements. In that line of thinking, *Bažant et al., 2018* [4] emphasises the need to take into account the shunting movements happening alongside the scheduled train movements.

While most timetable-based analysis methods use the principle of timetable compression, it must be noted that other approaches have also been developed. For instance, *Müller, 1960* [28] developed a method that combines the timing of the train sequences presented in a timetable with a route compatibility matrix in order to compute occupation-interdiction diagrams and thus come up with capacity and regularity indicators.

2.1.4.2. Timetable-free methods

In parallel with the development of capacity methods based on timetable structures, various methods using coarser input data have been developed for node capacity analysis at medium and long-term time horizons.

Potthoff's method (*Potthoff, 1963-1972*) [33] provides a global quantitative analysis of a node's capacity utilisation. The method uses as input data the node's topology (i.e. a route incompatibility matrix), the occupation and interdiction times between trains, and the traffic volumes on each identified route. It assumes that trains can arrive at any instant of the assigned time period. Among several other outputs, the method calculates the average number of simultaneous movements that can take place on the track layout, and an occupation time ratio, which provides information on the utilisation of capacity. Finally, the method also derives delay indicators (total delay, average delay per train).

The Deutsche Bahn (DB) 's method (*DB, 1979*) [8] shares strong similarities with Potthoff's method and provides the same average number of simultaneous movements and occupation time ratio indicators. However, the method offers an improved way of computing the expected delays, as it uses priority relations between conflicting train services in order to calculate delay indicators. The method also calculates the average number of trains that can be processed by a node per day.

Later, *Corazza & Musso, 1991* [5] developed an analytical method that also computes indicators such as the average number of simultaneous circulations, and an occupation time ratio, and also makes the assumption of random train arrivals during the assigned time period. However, these indicators are calculated differently, as the authors suggest considering the different possible combinations of simultaneous train movements and to use their probabilities in order to perform the calculation of the average number of simultaneous circulations.

Malavasi et al., 2014 [27] describe and compare these three methods by applying them to several case studies. The authors highlight the similarity of the methods, but also their main differences, which enable the analysis of different aspects of node capacity. While Potthoff focuses on overall results, DB's method introduces priority relations between train circulations. Finally, in *Corazza & Musso, 1991*, different combinations of simultaneous circulations are taken into account, allowing to estimate the average number of simultaneous circulations (and then the other indicators) in a different way.

SNCF Réseau also made use of an analytical method to assess railway nodes' operations. More specifically, the method uses track layout, train itineraries, interdiction times and traffic data in order to come up with conflict probabilities on each pair of conflicting itineraries. Here again, the trains are assumed to arrive at random during an assigned time period, and a hypergeometric distribution is used to compute the probabilities of conflict for each pair of conflicting itineraries.

Other similar analytical methods for nodes have been developed in the literature. For instance, *Landex & Jensen, 2013* [24] present a set of methods that can be used to analyse a node based on "track complexity" indicators. The most basic method only analyses the different routes available on the track layout, as well as their incompatibility. This first method can then be upgraded by incorporating train traffic and compute conflicts probabilities between trains. A third step is to include minimum headway times between trains, which enables the computation of capacity utilisation indicators, similar to those of the methods presented previously. Finally, timetable data can be incorporated into the process in order to assess timetable complexity indicators. This set of methods offers interesting possibilities for the railway planners, by allowing them to choose an approach that is suited for the planning step they are interested in.

Timetable-free analytical approaches also entail models based on queuing theory. *Schwanhäußer, 1974* [36] was among the first to introduce queuing theory models in the field of railway science, but most models were then developed for line capacity analysis. Among other developments, *Niessen, 2008* [32] proposed to study the capacity of route nodes via a multiresource queue approach. Here, a route node is modelled as a multichannel system where two or more trains can run simultaneously. Theoretical capacity is computed via a linear programming programme that maximises the arrival throughput. Unscheduled waiting times are computed with a modified loss-waiting system, while scheduled waiting times are calculated with the enhancement of a formula developed by Schwanhäußer.

2.1.5. Estimation of the delays generated by conflicting trains at railway nodes

The capacity analysis of a railway node is regularly conducted together with an analysis of the delays that can be generated by conflicting trains.

As described previously, Potthoff's method (*Potthoff, 1963-1972* [33]) incorporates an estimation of the total delay produced through conflicting interactions of trains at a railway node, in addition to an analysis of capacity utilisation of the node. The Deutsche Bahn's method (*DB, 1979* [8]) improved Potthoff's indicators by adding a priority hierarchy between conflicting routes.

Then*, Wakob, 1985* [38] extended the queuing theory approach for capacity and delay analysis to railway nodes. His work has been synthesised and analysed in *De Kort et al., 1999* [7]. Here, queuing theory is used to predict the waiting time caused by the random arrival and processing of two trains at an isolated part of the node's track layout. The method is useful for capacity assessment but shows limitations for analysing delay propagation. Furthermore, the waiting times computed by the method are usually larger than those computed in simulation models and cannot be compared to daily observations.

Later, *Yuan & Hansen, 2006* [44] provided a detailed modelling of the propagation of knock-on delays of trains at a station in order to optimise the utilisation of its capacity. Their approach uses conditional probability distributions to model the variations of the trains' running times due to conflicts caused by late arrivals in the node's perimeter.

When the purpose does not necessary lie in assessing the node's capacity, other tools can be used, such as queuing theory's Pollaczek & Chintschin formula to calculate the mean waiting time of a route node, as proposed *in Hansen & Pachl, 2014* [16].

More detailed simulation approaches can be used, with tools such as RailSys (*Radtke & Hauptmann, 2004* [35]) and OpenTrack (*Nash & Huerlimann, 2004* [30]) that can also replicate the propagation of delays throughout a network.

2.1.6 Linking capacity utilisation analysis and operational performance

Several sources in the literature support the relevance of a link to be studied between the capacity utilisation of a node and its operational performance. *UIC, 2013* [18] proposes occupancy time rate limits for switch areas analysis, thus supporting the idea of a relation between capacity utilisation and operational performance. However, as highlighted in the leaflet, there is still little empirical data supporting the proposed limits, thus making them only approximations which should be confirmed with thorough investigations. Furthermore, *Malavasi et al., 2014* [27] also pinpoint the need to explicate the recommended values of capacity utilisation provided in DB's method.

After having proposed an adaptation of the British's CUI methodology to the analysis of nodes in *Armstrong & Preston, 2012* [2], the authors pursued their research on node capacity in *Armstrong & Preston, 2017* [3] by comparing the capacity utilisation ratios given by their method to the performance data (train knock-out delays) recorded at several stations in the United Kingdom. Results provided strong evidence of an exponential relationship between capacity utilisation and delays. The fit of this relationship varies slightly depending on the investigated stations but shows an overall consistency. The same consistency applies to critical values of capacity utilisation, above which the delays increase quickly.

Finally, in *Yuan & Hansen, 2006* [44] an exponential relationship was found between the modelled knock-out delays propagated at a railway node and the buffer times between conflicting trains.

2.2. Review of infrastructure managers' design methods and planning processes for railway nodes

2.2.1. Objective of the review

The aim of this review of the railway node planning processes and design methods used within SNCF Réseau and some other railway infrastructure managers in Europe is twofold. First, it is necessary to know the general processes related to railway nodes planning and design before diving into the rest of the research. The goal here is to understand the general organisational and technical framework behind railway nodes planning and design and look for gaps that this research could help answer. Second, it is also fundamental to know the node analysis methods that are currently used within the railway operation studies department of SNCF Réseau, in order to understand the limitations that the practitioners may face when it comes to evaluating railway node operations in the long-term planning phases.

To that extent, a series of semi-structured interviews were conducted with SNCF Réseau employees that work within the railway operation studies department, as well as within other departments of the company. Additionally, two foreign practitioners were interviewed, working respectively for DB Netz in Germany and ProRail in the Netherlands, with the aim of comparing the practices within different European infrastructure managers. The questions asked during the interviews were related to the two main axes previously mentioned, but the discussions could also deviate in order to develop specific aspects or deal with topics that were not addressed in the initial set of questions. In that way, an extended range of topics could be investigated.

2.2.2. General planning and design processes for railway nodes

The objective of this part is to investigate and understand the general organisational and technical processes related to the planning and design of railway nodes.

2.2.2.1. Fundamental design aspects and main planning processes of railway nodes and their operations

II.2.2.1.1. Factors influencing node performance that should be considered when design a railway node

According to the interviewed practitioners, multiple factors influence the performance of the operations at a railway node.

First, the node's infrastructural characteristics considerably influence the performance of the operations. The main infrastructural factors that influence the performance are:

- The design of the track layout itself and the conflicting routes between trains that it can induce

- The maximum allowed speeds, which depend on: the number of switches that are used and the speed that they allow; the radius of the curves in the layout; and the speed limitations imposed because of various operational reasons.

Then, rolling stock performance and driver behaviour can also affect the planned and observed performance on the node. Rolling stock acceleration and deceleration rates are especially important, as good acceleration and braking will allow the trains to quickly clear track sections so they can be used by following trains. Drivers' behaviour also plays a role in explaining the observed operational performance at a node. In addition to the rolling stock performance, drivers trained to reach the allowed speed limits as soon as possible will make the track sections available more quickly.

Finally, the design of the train operations is a key factor in explaining the performance. Among the main operational factors that influence the performance of a node, the following elements can be pointed out:

- The design of the timetable, which should limit the possibilities of potential conflicts between trains;
- For through-stations, the choice of having terminus trains that will occupy platform tracks for extend period of time;
- The importance of shunting movements, especially when they mix with other commercial train paths before or after the peak periods;
- The operations of freight trains, which tend to be critical when occurring during daytime, alongside commercial passenger traffic (as train stations in France do not usually have dedicated bypass tracks for freight trains, contrary to Germany).

These various factors should therefore be carefully considered when designing the node's infrastructure and train operations.

2.2.2.1.2. Planning and design of the infrastructure

Two different philosophies seem to emerge when it comes to designing the modification or extension of a node's infrastructure. A first approach consists in design a track layout to operate a given timetable structure, with train frequencies, arrival and departure patterns of varying precision. Yet, as mentioned by different interviewees, timetable structures in France tend to change overtime, or even be uncertain until a short horizon prior to the actual operations. Therefore, several interviewees pointed out that a second more robust approach to these uncertainties consist in designing the track layout of a node to answer functional objectives, such as for instance volumes of trains that can be accommodated over a certain time period, taking into account future traffic evolutions.

Then, when it comes to implementing the designed infrastructural changes, again two different approaches can be followed: the "blank sheet" approach, or the "incremental changes" approach. As described in a report by the consultancy firm Arcadis for SNCF Réseau

[10], the “blank sheet” approach consists in redesigning all or a major portion of a node’s layout in a single project. The goal is usually to achieve a better separation of the routes, and to simplify the layout by reducing the number of switches. The major benefits of the “blank sheet” approach are that it diminishes the maintenance costs over time, by reducing the number of switches. The reduction of the number of switches also usually leads to more space available for longer switches that can be used at higher speeds. The main drawback is that revamping a whole railway node is usually very expensive and prevents the utilisation of the node for an extended period of time, which can hinder the rest of the network if no suitable substitution routes are available. Then, the “incremental changes” approach consists in modifying the node’s track layout with limited changes implemented once at the time over an extended time period. In comparison with the “blank sheet” approach, this approach provides the benefits of spreading the infrastructural expenditures over time. However, it comes with significant disadvantages: the layout tends to get more complex over time with new additional equipment added while old unused ones are left untouched; trains have to run over more switches, which limits their speed; maintenance costs tend to increase when additional equipment is added.

Yet, due to the massive costs required by the “blank sheet” approach, and also the difficulty to disrupt a node for a long period of time to conduct the works, the incremental approach is still vastly followed in France. Rare examples of “blank sheet” approaches include the redesign of the track layout of Paris-Nord station in 1993 to prepare for the opening of the LGV Nord (the high-speed line from Paris to northern France and the Belgian border). The track layout was designed to match functionalities in terms of volumes of trains to be accommodated, rather than a specific timetable. Several interviewees spontaneously mentioned this track layout to be one of the most efficient in France.

In the Netherlands, the blank sheet approach was used for the redesign of Utrecht Centraal’s track layout between 2013 and 2016, with the objective of simplifying the track layout, separating the flows and improving the speed.

2.2.2.1.3. Planning and design of the train operations

Because of the predominance of the “incremental changes” approach in France, an historic vision of a railway node’s evolution is necessary when planning the train operations at a railway node. The operations must be conceived according to the operational principles that guided the conception of the historic layout. Moreover, as seen before, the predominance of the “incremental changes” approach led to the complexification of numerous track layouts over time. To clarify the use of such complex layouts, actions were taken during the recent years to define corridors dedicated to certain destinations at the major French railway stations. The objective is to make the use of these corridors mandatory in order to simplify the planning process, standardise the operations and limit the risk of conflicts between trains. Contrary to what is done in the Netherlands, in France the platforms at stations are not necessarily dedicated to certain train lines. This can lead to more flexible real-time disruption management but tends to lower the reliability of the planning process.

These infrastructure and train operations planning processes are carried out by various stakeholders and practitioners, whether belonging to government authorities or the SNCF group.

2.2.2.2. Involved stakeholders and practitioners at SNCF Réseau

Similarly to other infrastructure projects, the changes to a railway node's track layout mainly originate from public authorities' demand, and in particular the national government for national-scale projects (such as the refit of a railway station of national importance), or local provinces governments for local-scale projects (such as small infrastructural changes needed to accommodate changes in the railway services provided by a province).

Upon receiving a demand, strategic infrastructure and financial analyses are conducted at first by SNCF Réseau. Then, infrastructural changes are designed in detail by the national or local infrastructure studies departments. Finally, railway operation studies are conducted, to assess the feasibility of the planned train operations on the planned infrastructure. Railway undertakings can also be involved in those processes, to discuss particular aspects of the train operations. The railway operation studies are usually conducted on the basis of given infrastructural scenarios, yet sometimes feedback loops can occur between the railway operation studies department and the infrastructure studies department, in order to evaluate alternative scenarios that might improve particular aspects of the train operations.

However, the coordination of these processes and actions between stakeholders is hindered by several issues.

2.2.2.3. Main organisational issues

Several of the interviewees mentioned a lack of multidisciplinarity in the process of conceiving railway nodes' layouts and operations. This often results in a lack of systemic vision in the projects' design and often under-performing results. In particular, it appears that there is sometimes a lack of understanding of the impacts of some aspects of the infrastructural designs on the train operations. This is further aggravated by the descending approach from the infrastructure design towards the train operations design. This implies that the feasibility of train operations on the given infrastructure is conducted at the end of the process, thus making the process non-optimal from a train operations point of view.

More generally, concerning the planning of the railway system as a whole, there is a lack of coordination between projects, and a lack of integrative vision to optimise them together. This is particularly true for railway nodes, which regularly suffer from a lack of attention in the general train operations planning process. New projects often focus on the feasibility of train operations at the line level, but less often at the node level.

It is interesting to notice that some of these issues did not necessarily exist in the past. For instance, the refitting of Paris-Nord's track layout in the 1990s is considered to be a major success in the company, thanks to the close cooperation between the involved stakeholders, including train operations planners and infrastructure planners. Yet, as one of the interviewees pointed out, at that time the company was still a bundled entity, which helped favour closer cooperation between stakeholders related to the different aspects of the railway system.

The issues related to lack of cooperation seem to originate from the various organisational changes that affected the SNCF at the end of the 1990s, following the European Union's reforms of the railway sector. At that time, the historic state-owned bundled railway company was split between an infrastructure manager organisation ("Réseau Ferré de France" at that time, "SNCF Réseau" since 2015) and a railway undertaking organisation (nowadays "SNCF Voyageurs"). In that process, the realisation of railway operation studies was progressively diluted between the railway undertaking company and the infrastructure manager entity. Over time, skills were lost and increasing use of external consultancy was made. Furthermore, within the infrastructure manager entity, a department specialised in the design of track layouts was progressively dismantled. Their activities were transferred to local entities of the infrastructure manager entity, that did not necessarily have specialised employees to perform them.

Uncertainty regarding the timetables also affects the long-term planning process. Indeed, the timetable structure is often very uncertain for the long-term planning horizon. Part of the reason for this lies in the fact that the timetables used for the long-term studies (at Y-10) by the department of railway operation studies at SNCF Réseau do not necessarily share the same structure as the timetable that will be sold by another department of SNCF Réseau to the railway undertakings (which is done around Y-3).

The following figure summarises the main organisational issues currently faced in the planning and design processes of railway nodes at SNCF Réseau.

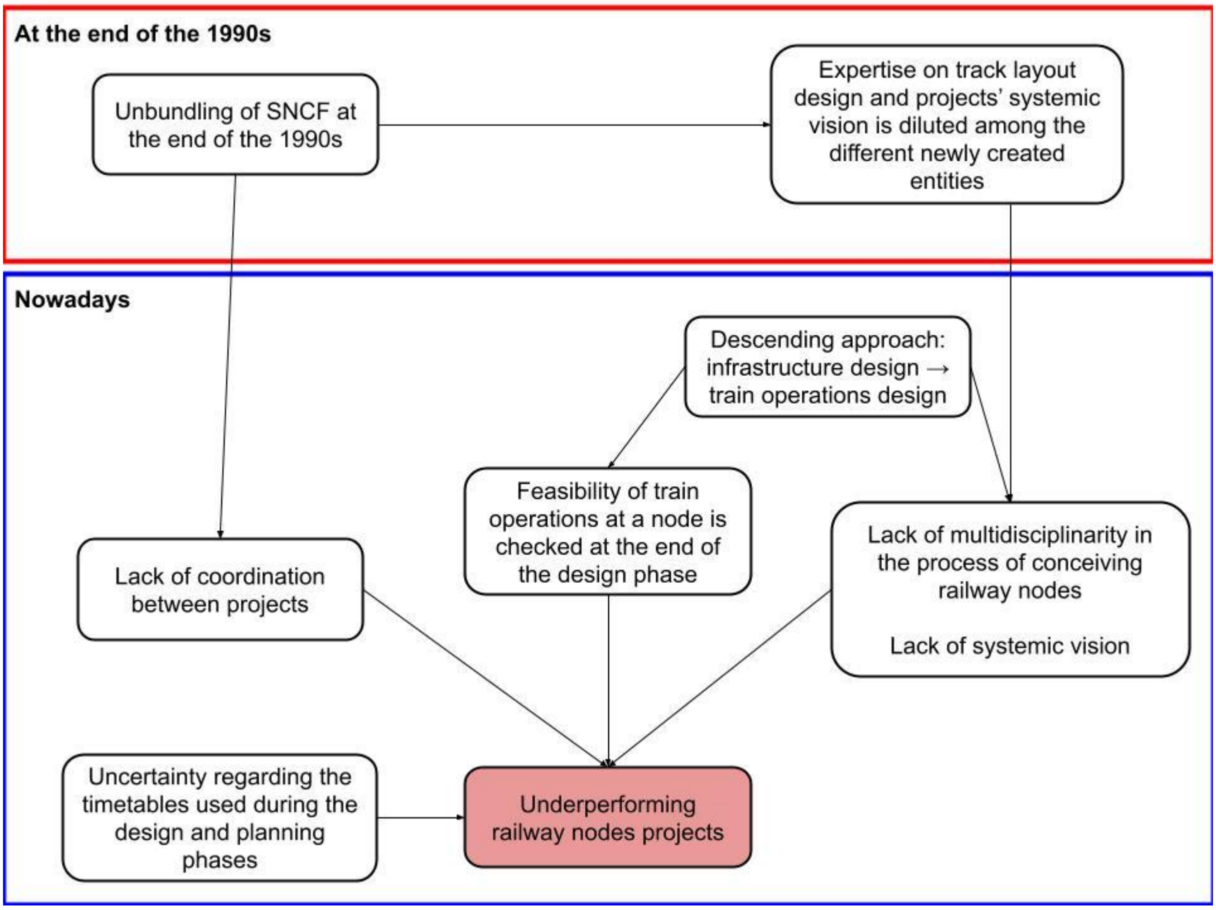


Figure 2.2.2.3.1: Main organisational issues currently face in the planning and design processes of railway nodes at SNCF Réseau

Conversely, in the Netherlands, strong coordination and cooperation between the Ministry of Infrastructure and Water Management, ProRail and the railway undertakings seem well embedded. Timetables are constructed at the medium to long term horizon through the cooperation between ProRail and the railway undertakings, who are then committed to use the structure of the projected timetables. Bottlenecks are then identified at the scale of the whole networks, and infrastructure projects are planned accordingly in order to solve these bottlenecks. This enables better project coordination. For instance, the modification of the track layout at Utrecht Centraal between 2013 and 2016 was made jointly with other projects, such as the Randstadspoor programme aimed at improving the regional connections around Utrecht, in particular by removing end trains at Utrecht Centraal, thus improving its capacity [9].

Additionally, it seems that railway nodes operations are generally better anticipated in the Netherlands and in Germany, as the planning processes are more often conducted at a network-scale, with a combined assessment of line and node operations.

2.2.3. Railway nodes performance assessment methods currently used within the railway operation studies department

This part is aimed at describing the current methods that are used within the railway operation studies department of SNCF Réseau to study railway nodes operations and understanding what are the main issues that the practitioners may face.

2.2.3.1. Assessment methods and metrics currently used when planning the future design and operations of a railway node

For the long-term studies (that is, around 10 years prior to the operations), the analysis of train operations is based on projected timetables and infrastructure scenarios. Projected timetables refer to the early timetables that are built by combining different traffic forecasts in the long-term horizon, and that may still change over time. The analyses usually consist in checking the feasibility of the projected timetable on the node area. To that extent, platform track occupation can be optimised with an operational research tool developed within SNCF Réseau, called "OpenGOV", which aims to optimise the track occupation diagram of railway stations. Then, microscopic simulation tools such as RailSys are used to detect the conflicts that may occur in the switch areas. Additional analyses can be conducted to test the ability of the system to recover from small stochastic delays, or to assess the possibility of positioning additional train paths.

Some attempts to provide estimates of capacity utilisation rates for station areas have been tried, prior to conducting delay recovery analyses. These attempts were conducted using a tool integrated in the simulation software RailSys. Yet, these analyses were conducted per route, and there is a lack of interpretability of these indicators, which seems to have prevented practitioners at SNCF Réseau from using them in their analyses.

2.2.3.2. Problems related to the current approaches and missing aspects

Two main issues are faced by the railway operation studies department regarding the assessment of railway nodes operations in the long-term studies, as depicted in the figure below.

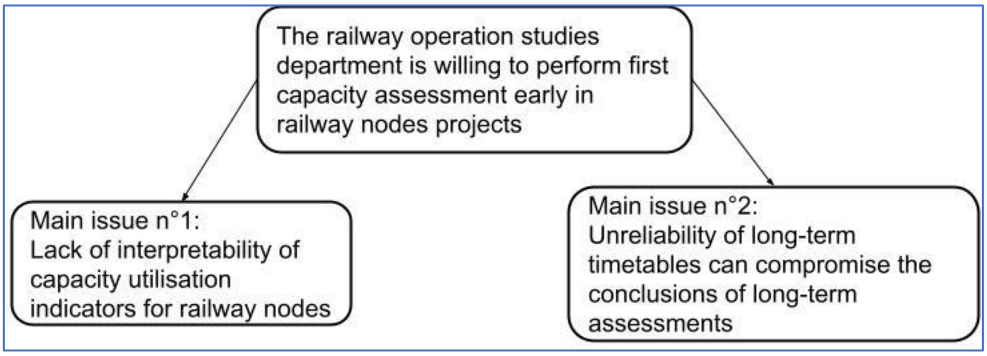


Figure 2.2.3.2.1: Main issues faced by the railway operation studies department in the long-term assessment of railway nodes performance

The first issue is related to a lack of interpretability of capacity utilisation indicators for railway nodes. The railway operation studies department would like to perform first appraisals of the performance of the train operations at a railway node. They feel they are missing a first analytical step in the study process, where more general capacity utilisation indicators could be examined before getting into detailed analyses, with delay recovery assessment for instance. This would allow them to have a first insight into the expected feasibility of the operations at the node, by understanding the extent to which the maximum capacity of a node is being used, for a given traffic and infrastructure scenario. These results could then be communicated to the other stakeholders involved in the planning and design of railway nodes in the early phases of a project. Currently, the practitioners at the railway operation studies department remain uncertain regarding the interpretation of railway nodes capacity utilisation indicators. More specifically, capacity utilisation indicators provided by the RailSys software for given timetables were used in the past for long-term studies, but the lack of references regarding capacity utilisation limits for nodes made it difficult to interpret them. There is a lack of knowledge about acceptable and critical capacity utilisation thresholds for the French railway network.

Then, the second issue is related to the fact that the study process for railway nodes is currently relying on the utilisation of projected timetables. However, as already mentioned in section 2.2.2.3., uncertainty surrounds the realisation of the projected timetable used for the studies, as the real timetable can differ significantly from the projected one. This can jeopardise the conclusions of studies, if real timetables show significant differences with the ones used during the study process. Therefore, the railway operation studies department would be interested in studying assessment methods that do not rely on a detailed trains arrival sequence, but rather on coarser traffic volumes assumptions, to see if such methods could provide relevant results in the long-term planning phases.

2.3. Summary of the main gaps from the scientific literature and the infrastructure manager's practices

2.3.1. Main gaps from the scientific literature

While most capacity analysis studies have been carried out on railway line track sections, the scientific literature also provides several methods to study the capacity and performance of a railway node. Methods can rely on timetable data for their input, or not. They can be based on operational research, simulation, or analytical-based approaches. Additionally, different sources in the literature support the relevance of a link to be studied between capacity utilisation and the performance at a node, described by the amount of delays that originates from train conflicts.

A set of knowledge gaps can be identified from this literature review.

- It appears that the relation between capacity utilisation indicators and performance indicators has been rarely investigated. More specifically, some studies suggest an exponential growth of delays when capacity utilisation increases, but these observations need to be strengthened, and capacity utilisation thresholds still need to be determined. Therefore, a first knowledge gap consists in determining the relation between the capacity utilisation indicators calculated by different capacity analysis methods and the delays generated at a node, and possible capacity utilisation thresholds.

- Although the distinction between timetable-based and timetable-free approaches has been clearly identified by *Weik et al., 2020* [39], no research has compared both types of approaches, to the best of my knowledge. While timetable-based approaches shall normally provide a reliable assessment of nodes' capacity utilisation and performance if the real operations do not deviate too much from the planned timetable, timetable-free approaches can be applied at medium or long-term horizons if no timetable can reasonably be proposed. However, they rely on random train arrivals assumptions, which can prove to be unrealistic. Yet, the relevance of their output indicators for the assessment of nodes' capacity utilisation and performance in the long-term horizon remains to be studied.

2.3.2. Main gaps from the infrastructure managers' practices

A set of issues can be identified from the review of the infrastructure managers' design methods and planning processes for railway nodes.

From an organisational point of view, the current planning and design process for railway nodes seems to suffer from a lack of coordination between involved stakeholders. In particular, the railway operation studies are often conducted after the infrastructure planning has been realised, thus leading to suboptimal results in terms of train operations. In that context, the railway operation studies department seems to be struggling to provide first evaluations of the train operations quality at a railway node early in the planning process.

From a technical point of view, the railway operation studies department is missing guidelines for the interpretation of railway node's capacity utilisation indicators. Furthermore, there is significant uncertainty surrounding the actual realisation of the projected timetables used in the long-term planning processes. Therefore, the railway operation studies department finds it problematic to base its long-term planning analyses on such project timetables, as significant changes are possible until the actual real-time operations, which could jeopardise the reliability of the results obtained in the long-term planning phase.

3. Methodology

3.1. Description of the methods studied in this research

3.1.1. General presentation

In this research project, a few methods for railway node capacity utilisation and performance assessment are studied. The methods are reviewed and adapted from the literature and SNCF Réseau's previous studies or developed for the need of this research.

For *capacity utilisation* analysis, three timetable-free and one timetable-based capacity utilisation assessment methods are studied. The timetable-based method is the UIC 406 method for railway node capacity assessment directly taken from the second edition of UIC Code 406 (*UIC, 2013* [18]). The timetable-free methods are the Potthoff method (*Potthoff, 1963-1972* [33]), a newly developed method based on previous works at SNCF Réseau (later called "SNCF-adapted method"), and an adapted timetable-free version of the UIC 406 method for railway nodes (later referred to as "timetable-free UIC-adapted method"). The last two methods are contributions of this research to railway operations science.

Then, for *delay propagation* assessment, which characterises node performance, again three timetable-free and one timetable-based delay propagation methods are used. The timetable-based method is a newly developed method for calculating delay propagation at a node that is inspired from the UIC 406 compression method ("timetable-based UIC-adapted delay propagation method'). The timetable-free methods comprise an adaptation of the Potthoff method developed for this research ("Potthoff-adapted method"), the newly developed method based on previous works at SNCF Réseau ("SNCF-adapted method") and a timetable-free version of the "timetable-based UIC-adapted delay propagation method" previously mentioned ("timetable-free UIC-adapted delay propagation method"). All of these methods, either adapted or newly developed, are contributions of this research to railway operations science.

The following table summarises the main characteristics of each method, in terms of input data, main assumptions and outputs.

Approach	Method	Inputs	Main principles	Sub-method	Outputs
Timetable-based approach	Timetable-based UIC-adapted method	-Route compatibility matrix -Headways between conflicting routes -Traffic volumes -Train arrivals sequence	Trains arrive and are processed according to the planned arrival sequence	Timetable-based UIC 406 method for railway node capacity utilisation assessment	**Capacity utilisation:** occupation time over studied time period. The occupation time is computed with the timetable's critical sequence.
				Timetable-based UIC-adapted method for delay propagation assessment	**Total delays:** Computed with the sum of the delays suffered by each train when delays are propagated through the train arrivals sequence.
Timetable-free approach	Potthoff method	-Route compatibility matrix -Headways between conflicting routes -Traffic volumes per route	The trains are assumed to arrive randomly over the studied time period, and the indicators are calculated using general formulas.	Potthoff method for capacity utilisation assessment	**Capacity utilisation:** occupation time over studied time period. The occupation time is computed with a virtual critical sequence.
				Potthoff-adapted method for delay propagation assessment	**Total delays:** Computed with the sum of the delays suffered by trains on each route.

	SNCF-adapted method	-Route compatibility matrix -Headways between conflicting routes -Traffic volumes per route	The trains are assumed to arrive randomly over the studied time period, and the indicators are calculated using general formulas. The formulas are based on probabilities of conflicts derived from a hypergeometric distribution.	SNCF-adapted method for capacity utilisation assessment	**Capacity utilisation**: occupation time over studied time period. The occupation time is computed with a virtual critical sequence.
				SNCF-adapted method for delay propagation assessment	**Total delays:** Computed with the sum of the delays suffered by trains on each route.
	Timetable-free UIC-adapted method	-Route compatibility matrix -Headways between conflicting routes -Traffic volumes per route	The indicators are calculated by averaging the results obtained with the algorithm of the timetable-based methods over a set of randomly generated arrival sequences. An increasing number of random arrival sequences is used until convergence in the averaged indicator is achieved.	Timetable-free UIC-adapted method for capacity utilisation assessment	**Capacity utilisation**: Computed by averaging the results obtained with the algorithm of the timetable-based UIC 406 method for railway node capacity utilisation assessment over a set of randomly generated arrival sequences.
				Timetable-free UIC-adapted method for delay propagation assessment	**Total delays:** Computed by averaging the results obtained with the algorithm of the timetable-based UIC-adapted method for delay propagation assessment over a set of randomly generated arrival sequences.

Table 3.1.1.1. Main characteristics of each method

The following paragraphs give a detailed description of each method.

3.1.2. Methods for capacity utilisation assessment

3.1.2.1. Potthoff method for capacity utilisation assessment

Potthoff's railway node analysis method was developed in the 1960s and aims to provide general quantitative information regarding a node's capacity, over an assigned time period. This method requires the matrix of routes' compatibility over a given track layout, the traffic volumes per route, as well as the minimum headways between trains running on incompatible routes. Potthoff assumed that a train can arrive at any moment of the studied time period (random arrivals). The method calculates several indicators, including the average number of simultaneous movements on the node, the capacity utilisation rate, and delay indicators (total delays, average delay per train). This section presents the procedure used for capacity utilisation calculation. The procedure for delay propagation assessment (calculation of total delays) is presented in section 3.1.3.1.

The calculation procedure for capacity utilisation starts by computing an *average number of simultaneous movements* on the node, n_{mean}. From there, a *number of trains belonging to a virtual critical sequence* over the studied time period is calculated as the ratio between the number of trains circulating on the node, N , and n_{mean}. After this, the *average headway between conflicting routes* t_{mean} is calculated.

Finally, the *occupation time over the studied time period* is calculated by considering the trains belonging to the *virtual critical sequence* to be virtually separated by t_{mean}. The capacity utilisation is calculated as the ratio between the *occupation time over the studied time period* and the studied time period T.

The following figure depicts the full procedure.

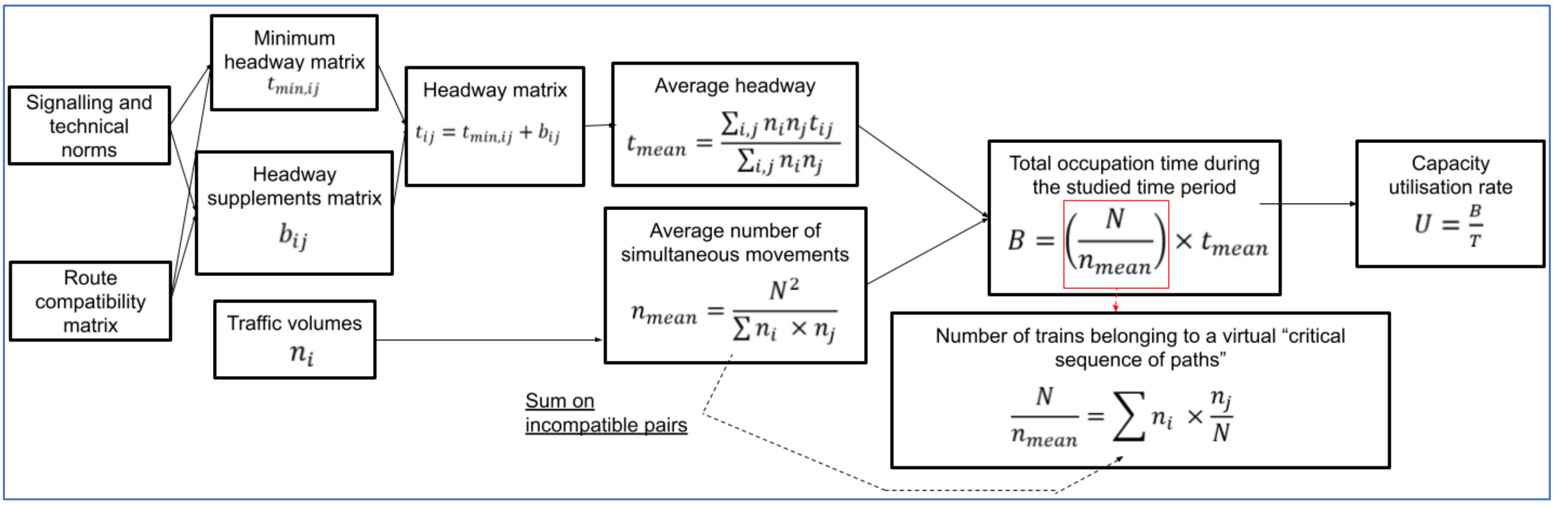


Figure 3.1.2.1.1 : Potthoff method procedure for capacity utilisation assessment

With:

-T: studied time period

- N: number of trains running through the node during the studied time period

- n_i: number of trains on route i

- t_{ij}: headway between two trains running on conflicting routes i and j : sum of the minimal technical headway $t_{min,ij}$ and headway supplements b_{ij}

-n_{mean}: average number of simultaneous movements

-t_{mean}: average headway

- B: total occupation time during the studied time period

- U: capacity utilisation rate

3.1.2.2. Proposed SNCF-adapted method for capacity utilisation assessment

A railway node analysis method punctually used within SNCF Réseau consists in estimating the conflict probabilities of trains running over the conflicting routes of a node. This research proposes two methods derived from this idea: a method that calculates a capacity utilisation indicator, which is presented in this section, and a method that calculates a total delays indicator, later presented in section 3.1.3.2.

This method makes use of the matrix of routes' compatibility over a given track layout, the traffic volumes per route, as well as the headways between incompatible itineraries.Trains are assumed to arrive randomly over the assigned time period. The calculation of the probability of conflicts between two conflicting routes is conducted using a hypergeometric distribution.

The idea for the calculation of probabilities is the following:

Given two distinct[1] incompatible routes i and j, with traffic volumes n_i and n_j , the maximum number of paths [2] that can use the intersection between i and j during the studied time period is called N_{ij}, and is computed using the average minimum headways between i and j:

$N_{ij} = \frac{T}{\bar{t}_{min,ij}}$.

[1] If N_{ij} is not integer, an adapted formula needs to be used. A detailed description of the formula is given in Appendix B.

[2] If the routes i and j are the same, an adapted formula needs to be used. A detailed description is given in Appendix B.

As the minimum headway $t_{min,ij}$, imposed by a first train on i to a second train on j, is usually different from $t_{min,ji}$, a weighted average value is used, calculated with the proportion of the respective traffic volumes: $\bar{t}_{min,ij} = \frac{n_i}{n_i+n_j} t_{min,ij} + \frac{n_i}{n_i+n_j} t_{min,ji}$.

The following analogy is used in order to compute the probability of conflict:

- a bag contains N_{ij} balls, including n_i red balls and $N_{ij} - n_i$ white balls.
- n_j balls are drawn randomly and without replacement.

The probability of drawing k red balls from these n_j balls is calculated using the hypergeometric distribution:

$$P(X_{ij} = k) = \frac{\binom{n_j}{k}\binom{N_{ij}-n_i}{n_i-k}}{\binom{N_{ij}}{n_i}}$$

where X_{ij} is the random variable counting the number of red balls that are drawn. Considering all possible pairs of conflicting routes, it is then possible to calculate the average number of conflicts per pair of conflicting- routes, $E(X_{ij})$ (it must be noted that if i and j do not conflict, then $E(X_{ij}) = 0$).

The next steps are similar to Potthoff's, although the formulas used to calculate the different indicators change (the formulas are given in figure 3.1.2.2.1 below).

The average numbers of conflicts per pairs of conflicting routes are used to compute *average number of simultaneous movements* on the node, n_{med}, and a *number of trains belonging to a virtual critical sequence* over the studied time period. After this, the *average headway between conflicting routes* t_{mean} is calculated.

The *occupation time over the studied time period* is then calculated by spacing the trains of the *virtual critical sequence* by t_{mean}. Finally, the capacity utilisation is calculated as the ratio between the *occupation time over the studied time period* and the studied time period T.

The following figure depicts the full procedure.

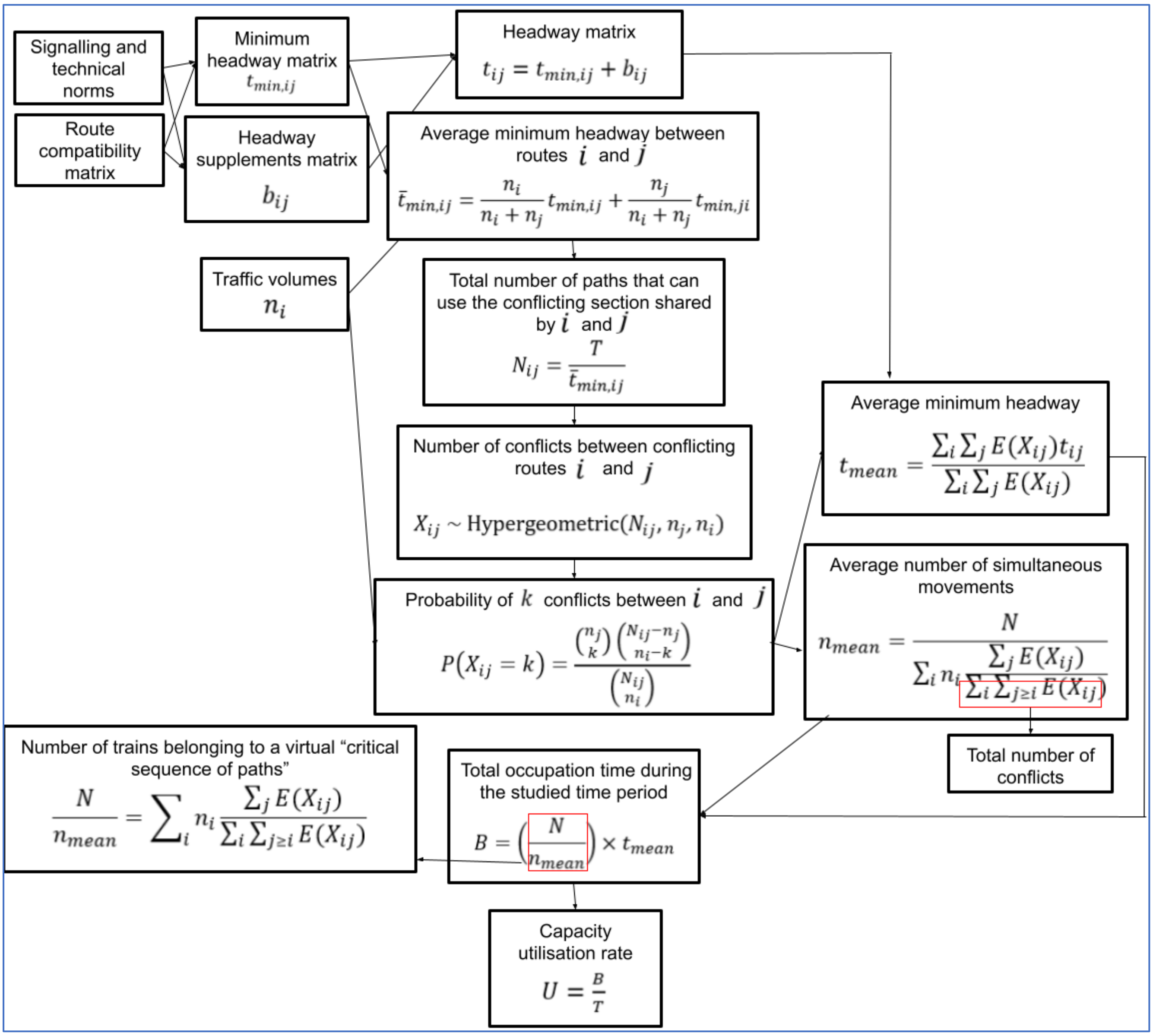


Figure 3.1.2.2.1 : SNCF-adapted method procedure for capacity utilisation assessment

3.1.2.3. Timetable-based UIC406 method for railway node capacity utilisation assessment

The railway node capacity utilisation assessment method described in this section has been published in the second edition of the UIC 406 leaflet, in 2013 (*UIC, 2013* [18]). Following the first edition published in 2004 (*UIC, 2004* [17]) which presented a standardised timetable compression method for railway line track sections, the second edition proposes an adapted version of this compression method for railway nodes. In this publication, nodes' switch areas and track areas are treated separately. This research will further utilise the procedure developed for the switch areas, which is presented in detail in Appendix A of *UIC, 2013* [18] and which will be summarised in this section.

The required data consist of the route matrix of the studied node, the headways between pairs of conflicting routes, and the sequence of arrivals of the trains given by the timetable. The headways comprise the minimum technical headways and headway supplements.

An iterative process is used in order to determine a *critical sequence of paths* between the beginning and the end of the studied time period. Each train paths of the scheduled timetable is allowed to start at a minimum starting time which is calculated based on the preceding trains and the headways that they impose on following trains. When all trains of the timetable sequence have been added*, UIC, 2013* [18] recommends repeating the first train of the sequence at the end. This is relevant for cyclic timetables, in which the first train of a sequence is indeed the first train of the sequence of the next time period. Yet, the timetables used on the French network are mainly acyclic. Therefore, consistent with *Jensen et al., 2017* [19], no train is repeated at the end of the sequence. The *occupation time* is calculated as the maximum of all starting times in the compressed timetable. Finally, the *capacity utilisation rate* is equal to the ratio of the *occupation time* divided by the *studied time period.* A detailed example of the application of the method can be found in Appendix A of *UIC, 2013* [18].

The figure below summarises the general procedure of the method.

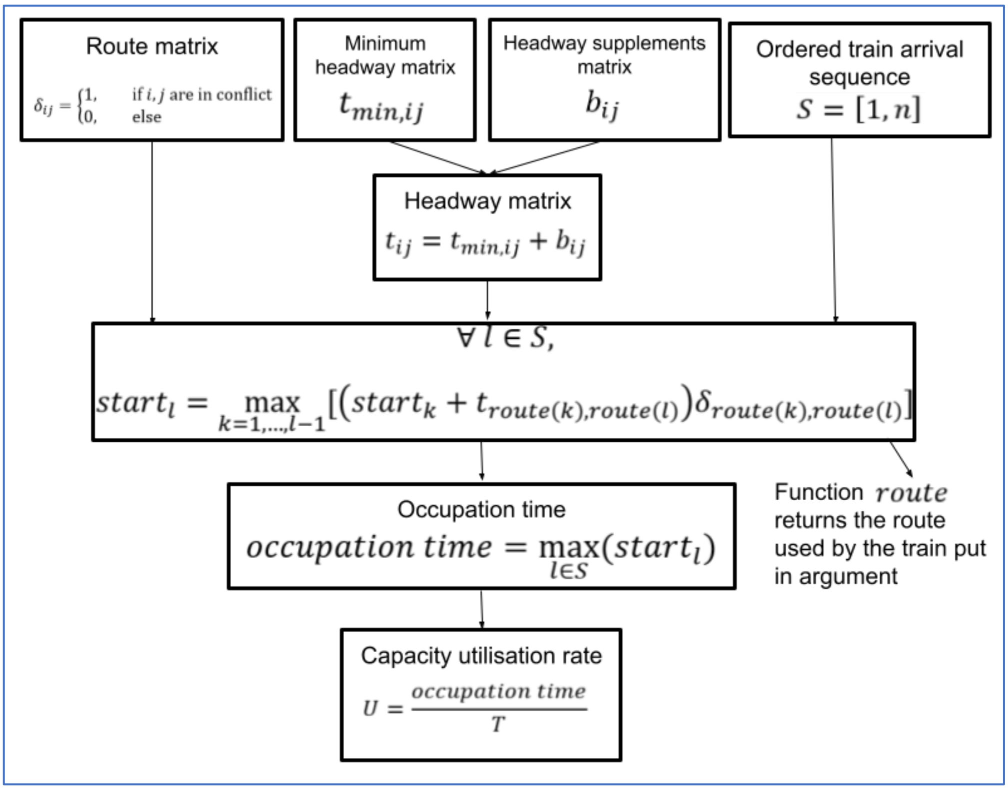


Figure 3.1.2.3.1: UIC 406 procedure for capacity utilisation assessment

3.1.2.4. Proposed timetable-free UIC-adapted method for capacity utilisation assessment

This research project proposes an enhanced version of the UIC 406 capacity utilisation method for railway nodes presented in the previous paragraph, by making it timetable-free. No timetable is required; instead, random train arrival sequences are generated and given as inputs to the algorithm of the UIC 406 capacity utilisation method for railway nodes. Then, an average capacity utilisation indicator U_{mean} is computed over the set of random arrival sequences.

Taking inspiration from the work of *Jensen et al.* 2017 [19], the process is repeated with an increasing number $n_{sequence}$ of random train arrival sequences, until convergence in the averaged capacity utilisation indicator U_{mean} is achieved. Convergence is considered to be achieved when U_{mean} does not vary more than a certain threshold over a certain number of $n_{sequence}$ increase.

By "random train arrival sequences", it is meant that the sequences are created by randomly selecting train orders permutations. Thus, this generation process does not guarantee the representativeness, nor the realism of each drawn sequence taken individually, but the utilisation of a convergence criterium for calculating the mean indicator value aims to compensate for this.

The figure below summarises the general procedure of the method.

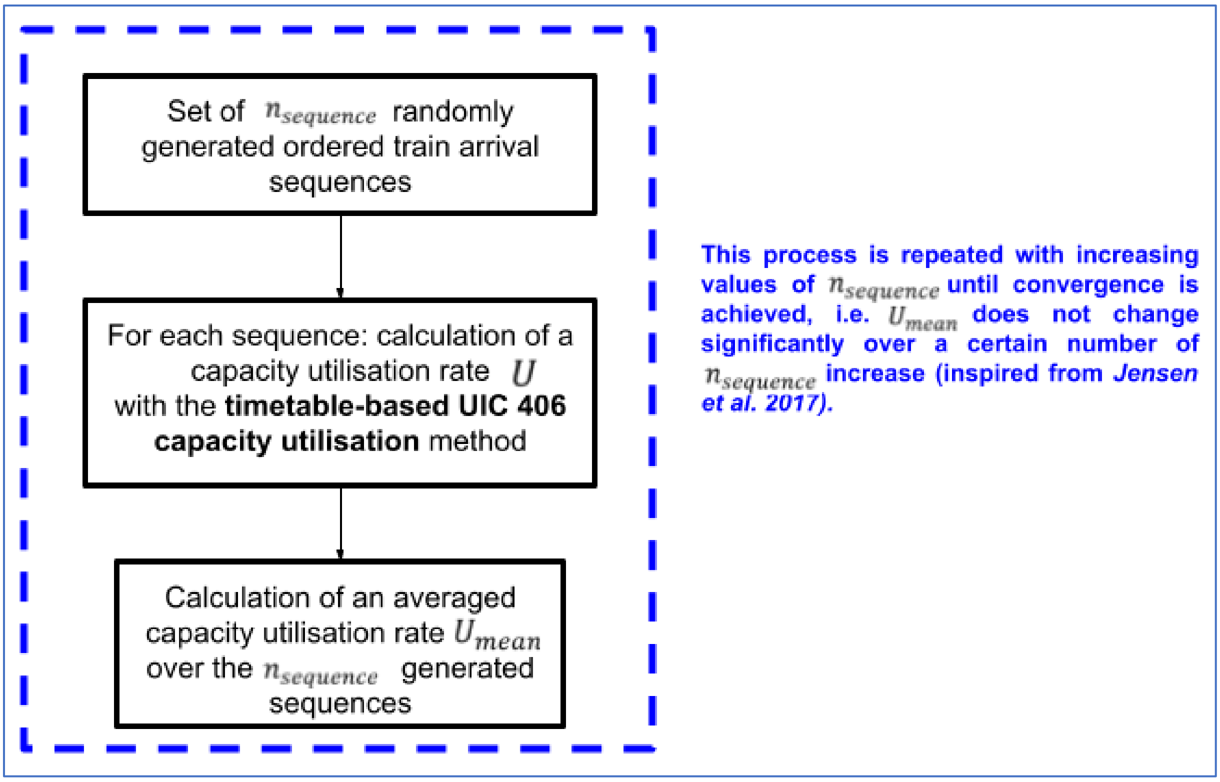


Figure 3.1.2.4.1: Timetable-free UIC-adapted procedure for capacity utilisation assessment

3.1.3. Methods for delay propagation assessment

3.1.3.1. Proposed Potthoff-adapted method for delay propagation assessment

The Potthoff method was introduced in section 3.1.2.1., which described the procedure for capacity utilisation calculation. This section presents Potthoff's method for total delays calculation, and an adaptation of the method proposed in this research to take into account the longer headways imposed by trains having to restart after a stop at a red signal.

As explained in *Malavasi et al., 2014* [27], who studied the Potthoff method, the total delays R_{ij} of all trains on route j conflicting with route i can be calculated as follows:

$$R_{ij} = \frac{n_i t_{min,ij}}{T} \times \frac{t_{min,ij}}{2} \times n_j$$

The idea is the following: given a pair of conflicting routes i and j, each train on i prevents simultaneous trains on j during $t_{min,ij}$. For a train running on j, the probability to be hindered by a train on i over the course of T is: $\frac{n_i t_{min,ij}}{T}$. If a conflict occurs, the train on j can wait for a time ranging from (almost) 0 to $t_{min,ij}$. Given that trains arrival is assumed to be random, a conflict will lead to j waiting on average for $\frac{t_{min,ij}}{2}$. Therefore, on average, a train on j suffers a delay due to trains on i which is equal to $\frac{n_i t_{min,ij}}{T} \times \frac{t_{min,ij}}{2}$. Multiplying this value by the number of trains on j (n_j) gives R_{ij}.

This research attempts to improve Potthoff's approach by adapting it to take into account the longer headways due to trains having to restart after a stop at a red signal. Trains on a route i can also conflict with other trains on different routes. If this occurs, they will impose longer headways $t_{restart,ij}$ to the trains after them. This is due to their lower speed after restarting. In this research, these $t_{restart,ij}$ are computed assuming the trains start at a null speed after stopping due to a red signal. More detail is given in Appendix C. Therefore, the idea in this adapted version of the Potthoff method is to change $t_{min,ij}$ in the R_{ij} formula by a weighted minimum headway $t_{mix,ij}$ that balances $t_{min,ij}$ and $t_{restart,ij}$:

$$t_{mix,ij} = P_i t_{restart,ij} + (1 - P_i) t_{min,ij}$$

Where P_i is the probability for a train on i to suffer at least one conflict:

$$P_i = \sum_{j\ in\ conflict\ with\ i} \frac{n_j t_{min,ji}}{T}$$

Finally, the total delays over all pairs of conflicting routes are calculated as

$$R_{tot} = \sum_{i,j\ in\ conflict} R_{ij}$$

The figure below summarises the general procedure of the method.

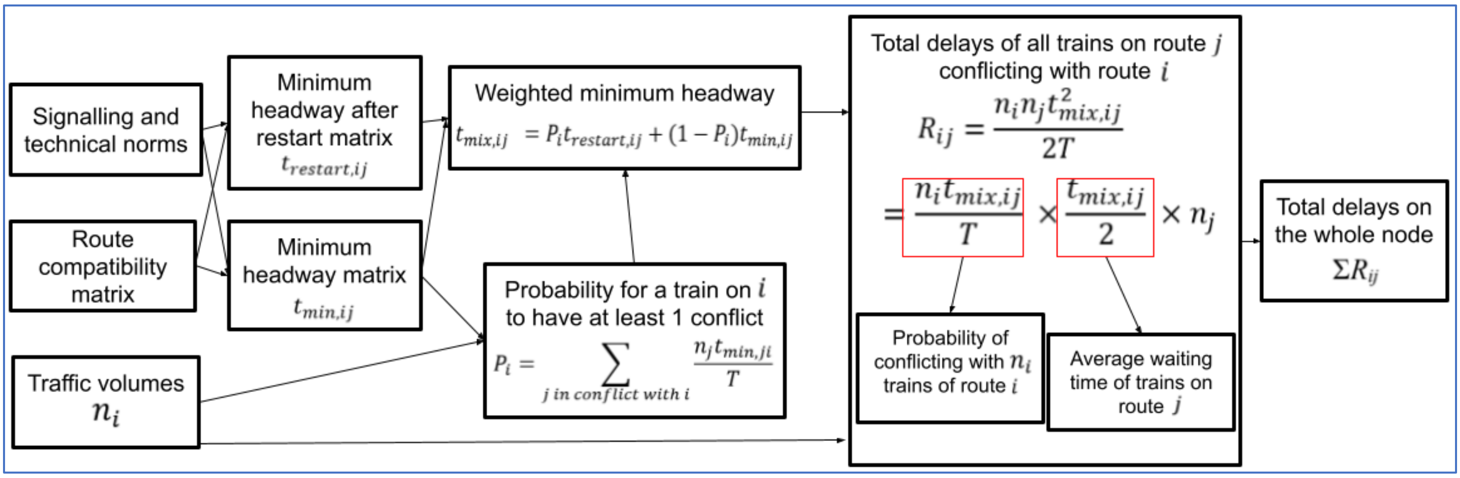


Figure 3.1.3.1.1 : Potthoff-adapted method procedure for delay propagation assessment

3.1.3.2. Proposed SNCF-adapted method for delay propagation assessment

The SNCF-adapted method was introduced in section 3.1.2.1., which described the procedure for capacity utilisation calculation. This section shows how the method can further be expanded to calculate the total delays generated by conflicting trains at the node.

Given a pair of conflicting routes i and j, the use of the hypergeometric distribution (described in 3.1.2.2.) leads to the calculation of an average number of conflicts $E(X_{ij})$ occurring between trains on i and j. This average number of conflicts is then multiplied by the average waiting time resulting from a conflict. Similar to the assumption taken by the Potthoff-adapted method, the average waiting time of a train on j conflicting with a train on i is taken as $\frac{t_{mix,ij}}{2}$. Here again, $t_{mix,ij}$ is a weighted minimum headway that balances $t_{min,ij}$ and $t_{restart,ij}$.

$$t_{mix,ij} = P_i t_{restart,ij} + (1 - P_i) t_{min,ij}$$

Where P_i is the probability for a train on i to suffer at least one conflict:

$$P_i = 1 - \prod_{j\ in\ conflict\ with\ i} P(X_{ij} = 0)$$

Therefore, the total delays suffered by trains on j conflicting with trains on i is:

$$R_{ij} = E(X_{ij}) \frac{t_{mix,ij}}{2}$$

Finally, the total delays over all pairs of conflicting routes is calculated as

$$R_{tot} = \sum_{i,j\ in\ conflict} R_{ij}$$

The figure below summarises the general procedure of the method.

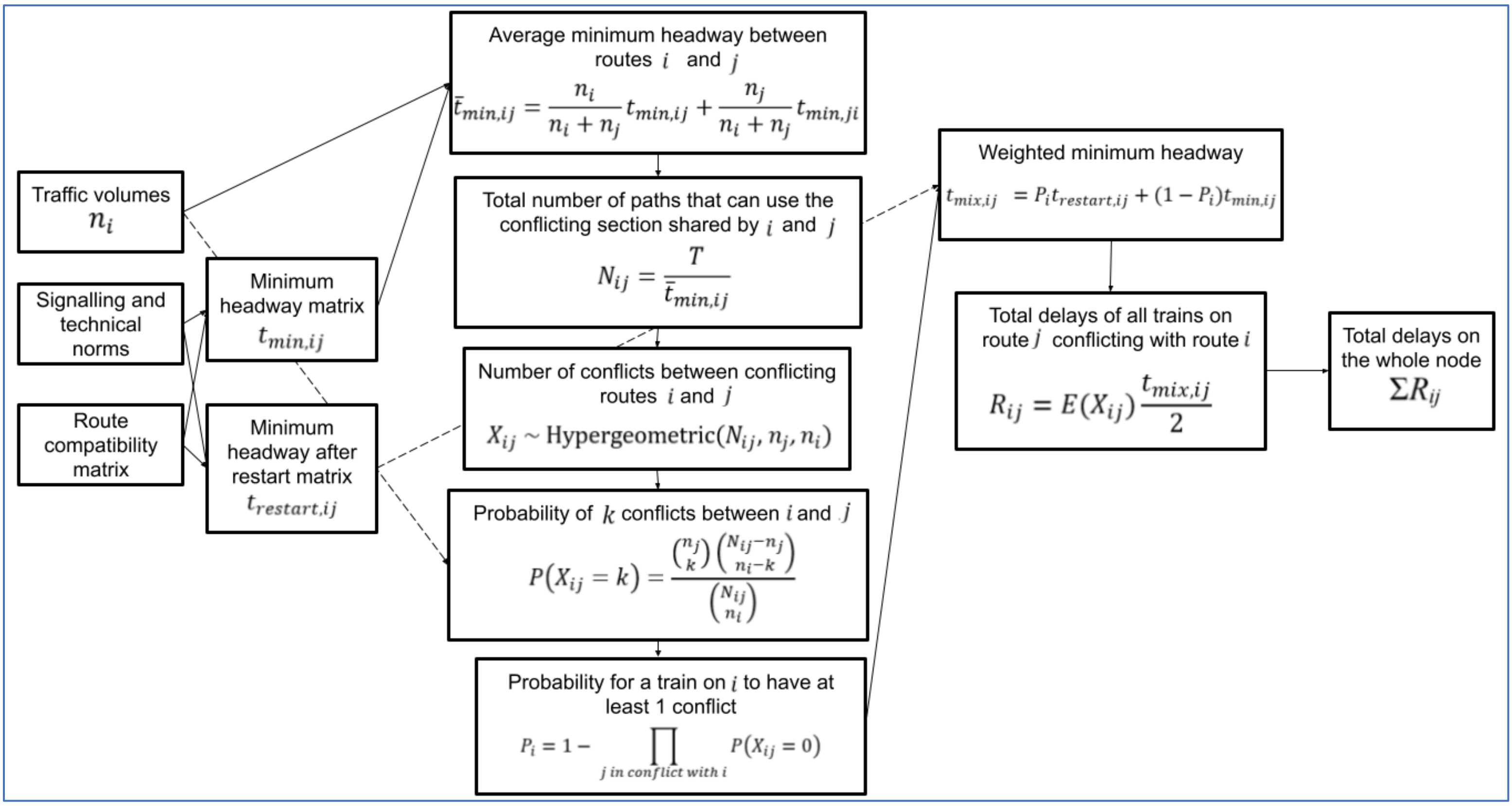


Figure 3.1.3.2.1: SNCF-adapted method procedure for delay propagation assessment

3.1.3.3. Proposed timetable-based UIC-adapted method for delay propagation assessment

This paragraph presents a method built during this research, that aims to compute the total delays generated by conflicts at a node, knowing the arrival sequence of trains given by a timetable.

The difficulty of building such a method lies in defining initial delays in such a way that the method can still be compared with the Potthoff-adapted and SNCF-adapted methods. Indeed, the Potthoff-adapted and SNCF-adapted methods work under the assumption of random train arrivals over the studied time period, thus they do not require to define initial delays. In a timetable-based context, a timetable and thus an arrival sequence are known, and therefore it does not make sense to assume random arrivals for defining initial delays. Yet, to maintain consistency with the Potthoff-adapted and SNCF-adapted methods' assumptions, randomness still needs to be included in the process of defining initial delays.

Thus, it is chosen to follow a mixed approach to formulate a timetable-based delay propagation procedure that will account for the knowledge about the train arrival sequence while still incorporating some random initial delays.

The procedure consists of the following steps:

Step 1: A *basic timetable* is constructed by the spacing the trains in their planned arrival order according to the headways between conflicting routes (thus taking into account the minimum technical headways plus headway supplements).

Step 2: Then, each train can suffer an initial delay drawn randomly from a uniform distribution over a *restricted time interval* surrounding its arrival in the *basic timetable*. This *restricted time interval* has to be defined in such a way that the initial delays that are drawn are not too large in magnitude, while still being able to lead to conflicts between trains and delay propagation. It is proposed to define the *restricted time interval* as follows:

- Lower bound: minus half the headway separating a train from its first conflicting preceding train.

- Upper bound: plus the headway separating a train from its first conflicting following train.

The lower bound is taken as half the headway separating a train from its preceding train, instead of the full headway taken in the case of the following train. This means that trains are allowed to arrive early, but to a lesser extent that late, as early arrivals are assumed to be less likely.

This process leads to the creation of a *delayed timetable*. The following figure illustrates steps 1 and 2.

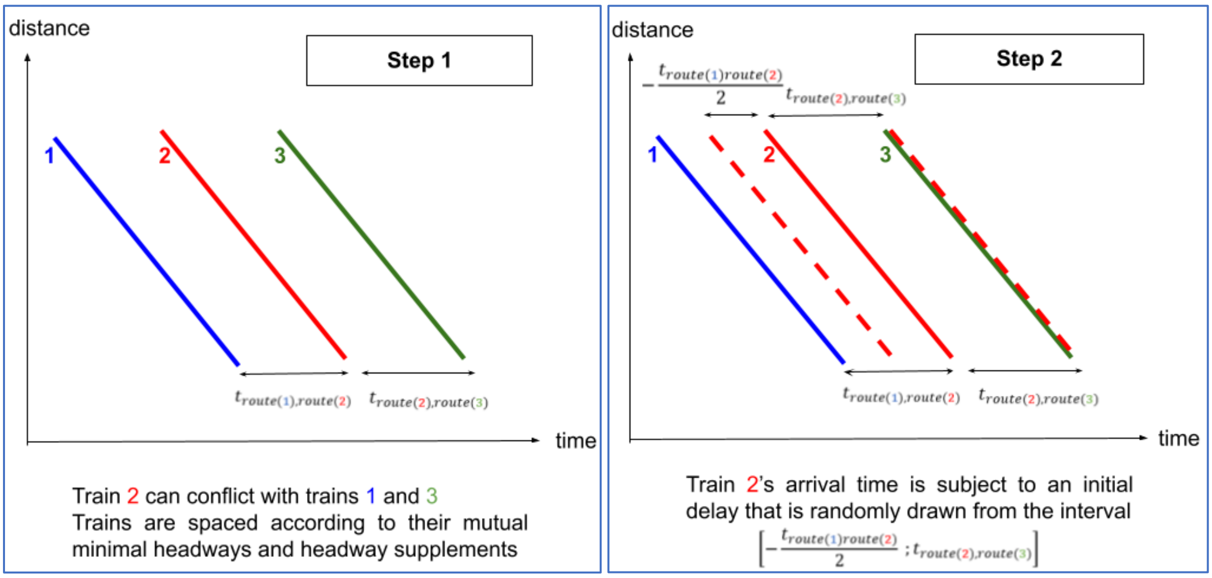


Figure 3.1.3.3.1: Steps 1 and 2 of the procedure

Step 3: The *delayed timetable* is rectified, thus creating a *rectified timetable*. Each train's starting time is checked in the initial arrival order and modified so that minimum headways between conflicting trains are respected. If the starting time of a train on a route i is modified (that is, the train has to stop and is delayed at the node due to a conflict with another train), it will impose a minimum headway $t^*_{min,ij}$ equal to $t^*_{min,ij} = t_{restart,ij}$ to any following train on a conflicting route j. Otherwise, this minimum headway stays at $t^*_{min,ij} = t_{min,ij}$.

Formally written, for a given train numbered l in the arrival sequence, the starting time $T_{rectified,m}$ of any of its successors $m > l$ has to verify the following condition:

$$T_{rectified,m} \geq t^*_{min,\ route(l),route(m)} + T_{rectified,l}$$

If it is not the case, then $T_{rectified,m}$ has to be increased (i.e., train m is delayed) so that the condition holds again. This delay propagation process works on the assumption that no regulation rules are applied, and that the trains are processed according to their scheduled arrival order.

Step 4: Finally, the total delays are computed as the sum over all trains of the difference between a train's starting time in the *delayed* and *rectified timetables*.

Steps 2 to 4 are repeated over a certain number of draws of initial delays. An average total delays value over all draws is then computed. Taking inspiration from *Jensen et al. 2017* [19], the number of draws of initial delays is successively increased until convergence is achieved, that is when the averaged total delays value over all initial delays draws does not significantly change anymore after a certain number of increases in the number of initial delays draws.

The figure below summarises the general procedure of the method.

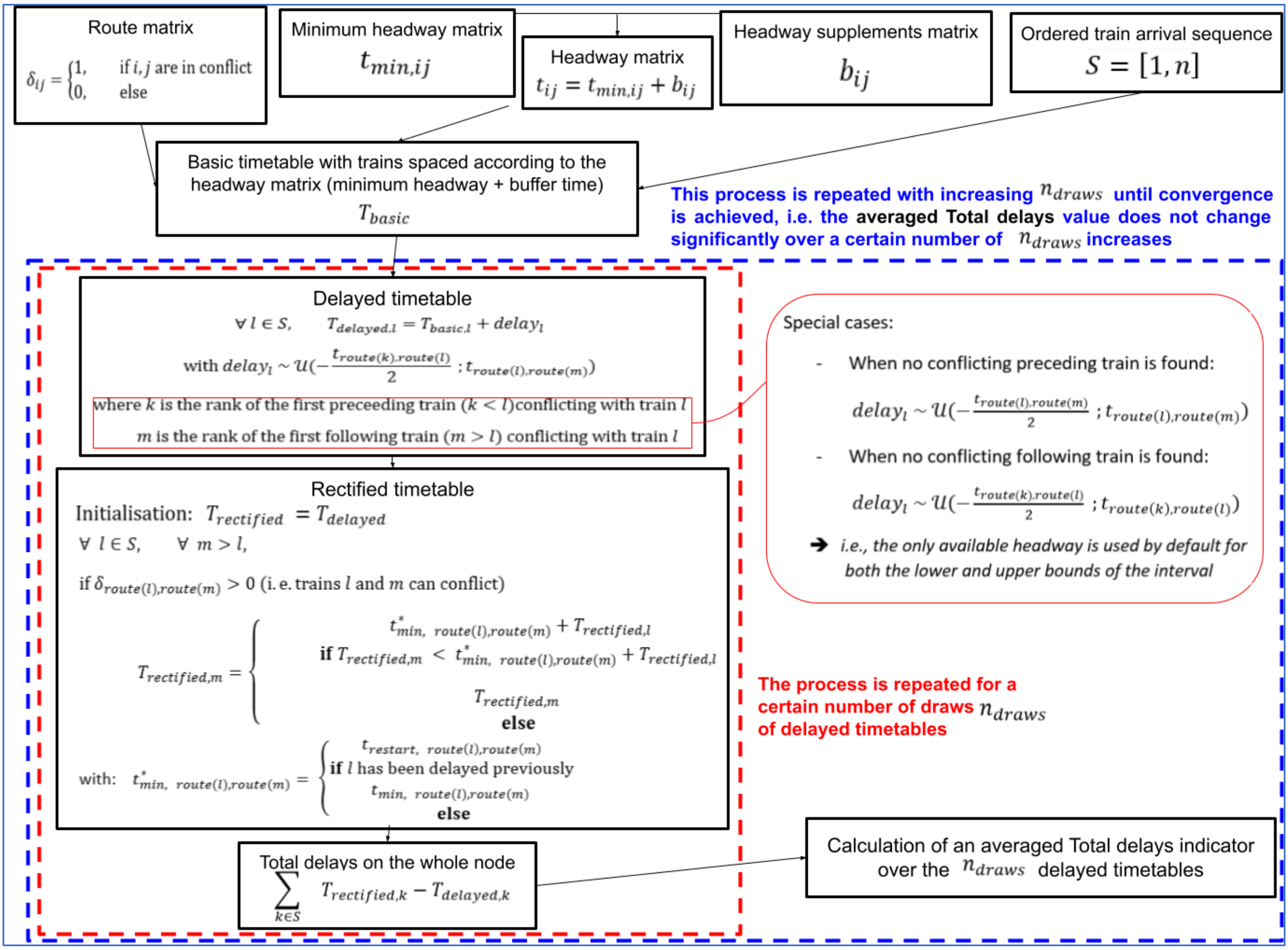


Figure 3.1.3.3.2 : Timetable-based UIC-adapted method for delay propagation assessment

Some reflection can already be provided at this point. One the one hand, defining the *basic timetable* in step 1 by spacing the trains in time by their minimum technical headways plus headway supplements can be criticised. In reality, time spacing can be bigger and thus it could be expected that the chosen formulation might lead to overestimated conflicts when trains suffer initial delays. On the other hand, the *restricted time interval* from which the initial delays are drawn is also defined based on this time spacing. Therefore, the initial delays' magnitude is limited and adapted to the time spacing adopted. All in all, it can be expected that a balance is achieved when modelling conflicts between trains: the initial time spacing is smaller than in reality, but the initial delays' magnitude is also limited.

Nonetheless, the definition of the *restricted time interval* chosen here is a primary attempt to achieve a functioning method. It can already be recommended that further research should be performed to achieve a more relevant definition of this interval, such as through a calibration process that compares the method's total delays output with real delay data.

3.1.3.4. Proposed timetable-free UIC-adapted method for delay propagation assessment

The timetable-based UIC-adapted delay propagation method previously presented is further adapted in a timetable-free version. No timetable is required; instead, random train arrival sequences are generated and given as inputs to the algorithm of the timetable-based UIC-adapted delay propagation method. Then, an average total delays indicator is computed over the set of random arrival sequences.

Taking inspiration from the work of *Jensen et al.* 2017 [19], this process is repeated with an increasing number $n_{sequence}$ of random train arrival sequences, until convergence in the averaged total delays indicator is achieved. Convergence is considered to be achieved when the averaged total delays indicator does not vary more than a certain threshold over a certain number of $n_{sequence}$ increase.

By "random train arrival sequences", it is meant that the sequences are created by randomly selecting train orders permutations. Thus, this generation process does not guarantee the representativeness, nor the realism of each drawn sequence taken individually, but the utilisation of a convergence criterium for calculating the averaged total delays value aims to compensate for this.

The figure below summarises the general procedure of the method.

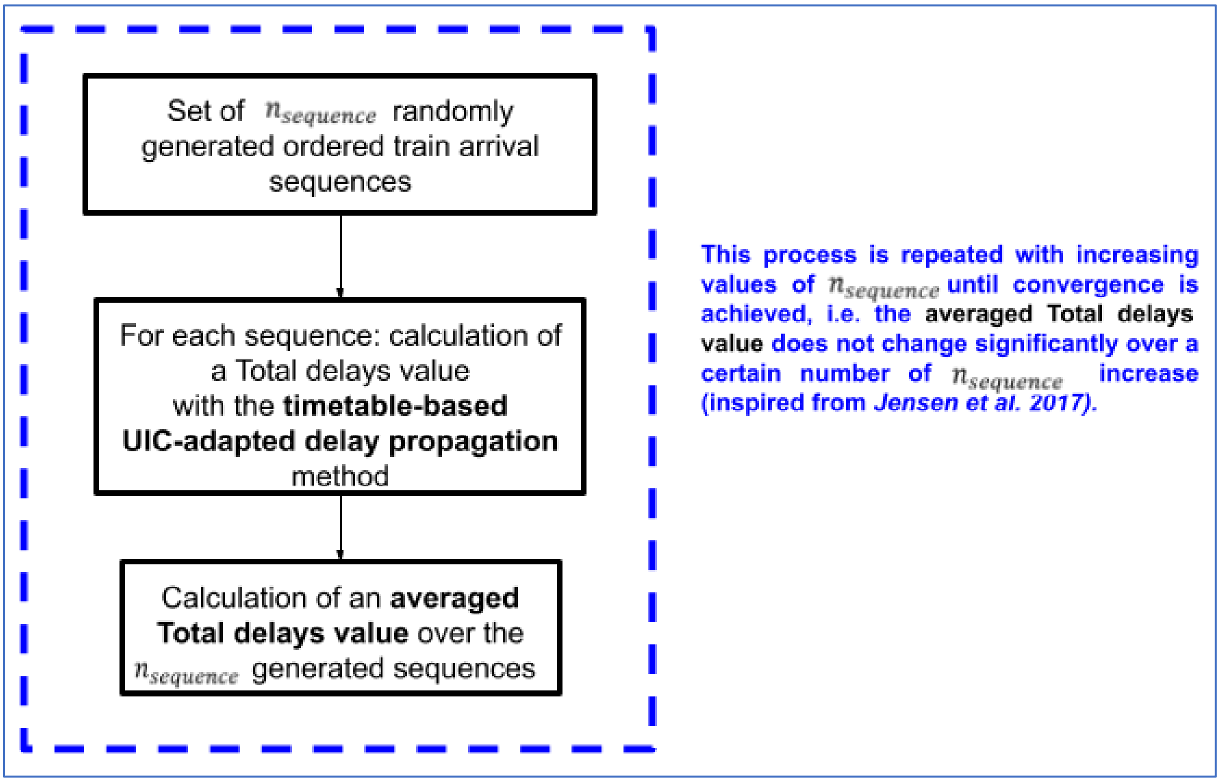


Figure 3.1.3.4.1: Timetable-free UIC-adapted method for delay propagation assessment

3.2. Evaluation process

The evaluation of the selected methods will be conducted in two steps, on a selected case study described in chapter 4.

3.2.1. Step 1: verification

The first step is the verification step. The timetable-free methods are tested and evaluated using artificial traffic data, which is varied along the different branches of the studied railway node. The objective of the verification step is to check whether the different methods provide sensible and comparable results, and to assess the relative differences between the magnitudes and trends of the different indicators.

3.2.2. Step 2: validation

The second step is the validation step. Here the timetable-free and timetable-based methods are compared based on their ability to reproduce capacity utilisation and total delays indicators computed with realised traffic data. The methods' indicators are compared with the values and trends obtained with the real data. The relative difference between the methods' indicators and the real values is assessed to determine which methods can best estimate the real values.

Then, the best performing methods are used to investigate the total delays - capacity utilisation relationship. Critical thresholds of capacity utilisation are investigated according to the corresponding levels of total delays divided by the number of trains (total delays per train). These total delays per train can be computed with the results of one of the methods or with the real total delays, in case no method would show good performance in estimating the real total delays.

3.3. Application of the results for supporting the long-term planning and design processes of a railway node

The evaluation process leads to the identification of the strength and weaknesses of the different methods, and of the best performing ones when it comes to estimating the real capacity utilisation and total delays. In this last step, the implementation of these methods in the long-term planning of railway nodes at SNCF Réseau is investigated and illustrated by looking into the recent study process of a node of the French railway network.

4. Application and results of the evaluation process

4.1. Description of the case study

The chosen case study must allow to assess the delays occurring at a node due to conflicting trains. To that extent, choosing a switch area located in front of a station's platform tracks would not allow to distinguish the delays due to conflicts between trains from the delays occurring because of other external causes at the station (e.g. sudden flow of passengers, late train driver, etc.). Therefore, the studied area shall be a switch area far enough from platform tracks, but still in the vicinity of a station, to provide relevant insights for such areas.

Based on these characteristics, the case study selected for this research is the junction of Lyon Saint-Clair, which is the switch area that marks the northern entrance of the station area of Lyon Part-Dieu station (figure 4.1.1 & figure 4.1.2.).

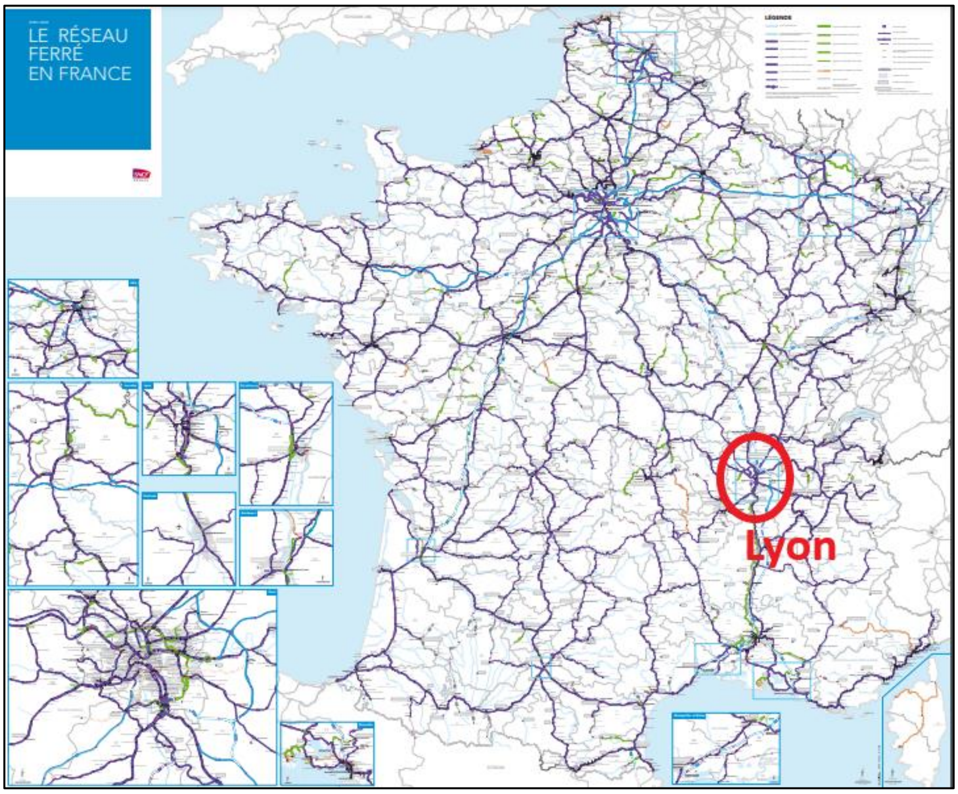


Figure 4.1.1: Location of Lyon on the French railway network

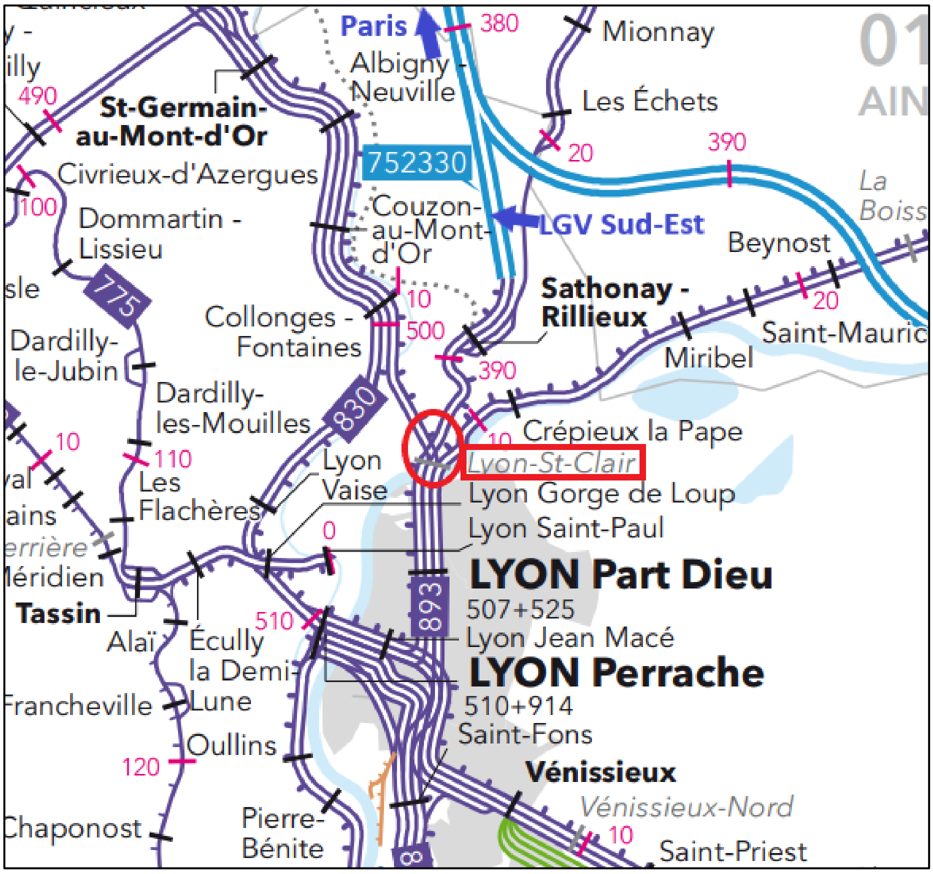


Figure 4.1.2. Location of the Lyon Saint-Clair junction

Lyon Part-Dieu station is the largest passenger railway station in France outside the Paris region, with more than 26 million passengers served in 2021 [11]. It is a major railway hub of the French and European railway networks, and in particular due its connections to and from high-speed lines.

As shown in the figure below, the junction consists of three branches:

- Lyon Part-Dieu <-> Ambérieu/Geneva (Switzerland)
- Lyon Part-Dieu <-> Sathonay-Rilleux/Paris (via the high-speed line, "*LGV Sud-Est*")
- Lyon Part-Dieu <-> Collonges-Fontaines/Dijon (via the historical "*Paris-Lyon-Marseille*" line)

The Lyon Saint-Clair junction is considered a major bottleneck of the regional network around Lyon, due to its position at the crossroad of major lines, while being a level junction. The conflicting routes of the studied area are depicted in figure 4.1.3. The route compatibility matrix is shown in Table 4.1.1.

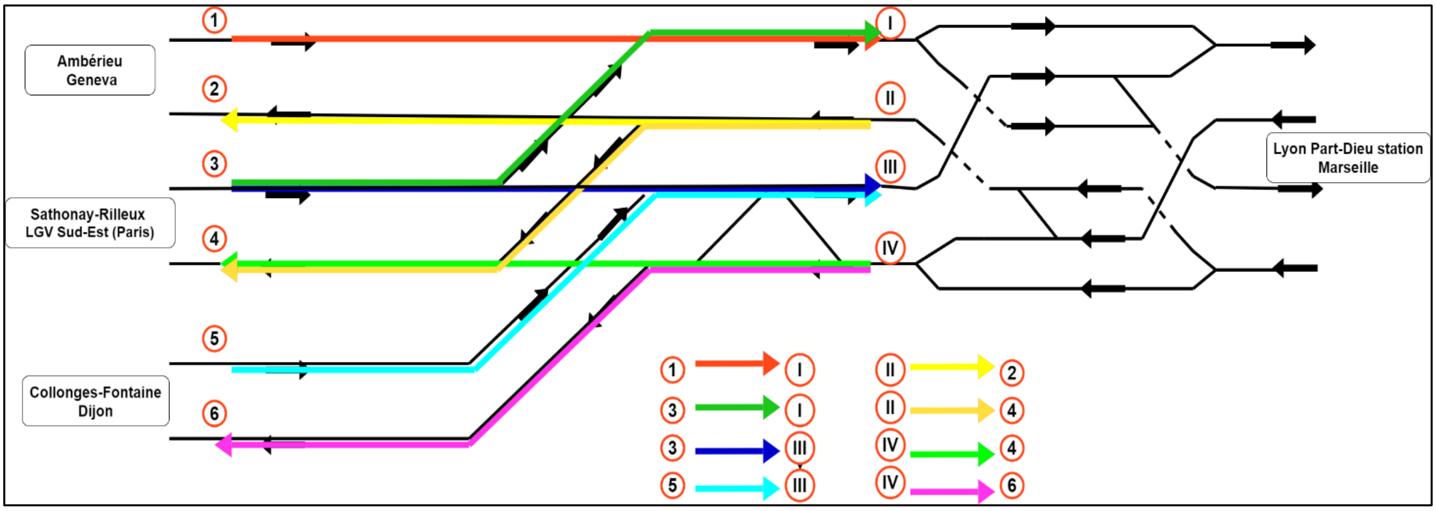


Figure 4.1.3. Studied area and conflicting routes

	1 - I	3 - I	3 - III	5 - III	II - 2	II - 4	IV - 4	IV - 6
1 - I	a	c	.	.	.	.	.	.
3 - I	c	a	d	.	x	.	.	.
3 - III	.	d	a	c	.	x	.	.
5 - III	.	.	c	a	.	.	x	.
II - 2	.	x	.	.	a	d	.	.
II - 4	.	.	x	.	d	a	c	.
IV - 4	.	.	.	x	.	c	a	d
IV - 6	.	.	.	.	.	.	d	a

Table 4.1.1. Route compatibility matrix (a: same route; c: converging routes; d: diverging routes; x: crossing routes)

This railway node almost only consists of one-way tracks, and there is almost always a unique way from an origin to a destination. These characteristics made the route identification straightforward. However, in the case of a more complex node with multiple possibilities for getting from an origin to a destination, route identification might be more complex. In this case, it is recommended to select the routes based on those that are usually used by the trains.

4.2. Data collection

The infrastructural data (tracks, switches, signalling, speed) was collected from SNCF Réseau's technical plans (figure 4.2.1.). For each branch, the entry signals of the studied area (the signals protecting the switches) are circled in red. The minimum headways between conflicting trains are calculated from these positions.

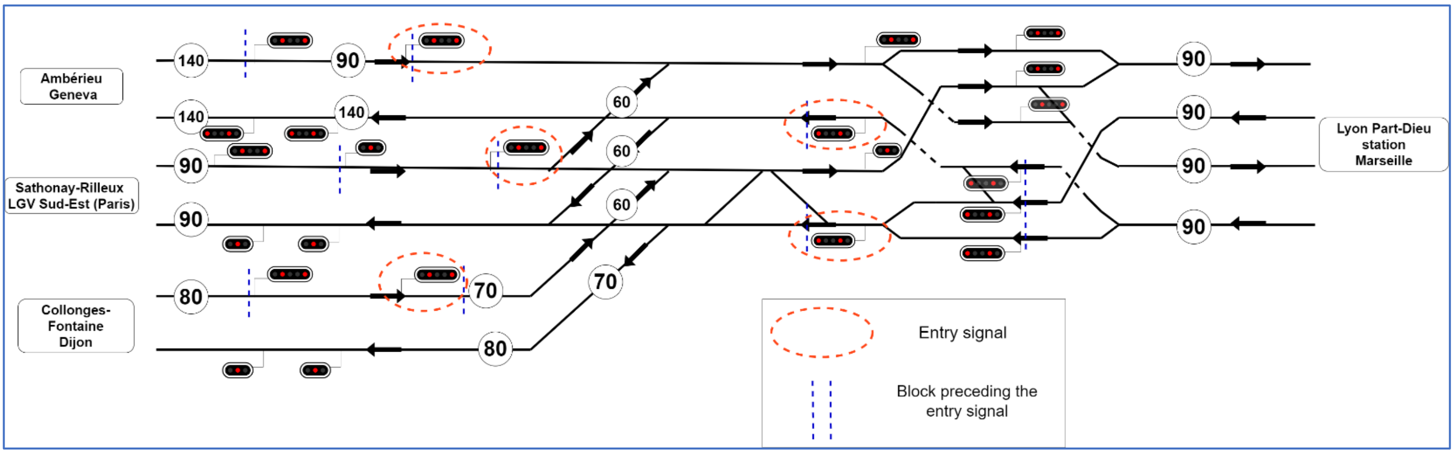


Figure 4.2.1. Technical plan of the studied area (adapted from SNCF Réseau's technical documentation)

The headways are calculated based on SNCF Réseau's technical norms for the BAL (*"Block automatique lumineux"*, 3-aspects block signalling system) signalling system. The detail of these headways calculations is provided in Appendix C.

Realised traffic data was collected from the track occupation data recorded by the local computerised control unit, from 31st May 2021 to 30th June 2021. Three time periods were considered for each day, each lasting three hours: morning peak (6:30-9:30), evening peak (16:30-19:30), off-peak period (10:15-13:15). This gives three observations per day, excepted for the 6th, 13th , 24th and 27th June for which morning peak data was not available. Data for the off-peak period was not available on 24th June either. In total, the dataset of real values contains 88 observations.

Recorded delay data of each train is computed as the variation of the differences to the scheduled passing times at the edges of the block preceding the entry signal (delimited with blue dot lines in *Figure 4.2.1*.). Real total delays are calculated as the sum of each train's delay. Then, taking inspiration from *Yuan & Hansen, 2004* [42], the real capacity utilisation is computed by compressing the realised timetable to the minimal headways between trains, which are calculated from the realised blocking times plus the time during which the routes were set and reserved for an incoming train. This compression process takes into account the compatibility between routes, just as in the UIC 406 method. The occupation time is calculated as the maximum starting time in the compressed timetable. Capacity utilisation and real total delays are computed for each observation point.

4.3. Implementation of the methods and computational parameters

The following paragraphs give the computational parameters used for the convergence of the averaged indicators in the UIC-adapted methods, and the hardware and software specifications of the computer used for the implementation of the methods and the calculations.

4.3.1. Computational parameters for the timetable-based UIC-adapted method for delay propagation assessment

The timetable-based UIC-adapted method for delay propagation assessment was implemented using an increase step for the number of draws of initial delays equal to 5. The calculation process is stopped when the total delays indicator averaged over all initial delays draws has not changed for more than 10% after 3 successive increases in the number of initial delays draws.

4.3.2. Computational parameters for the timetable-free UIC-adapted method for delay propagation assessment

The timetable-free UIC-adapted method for delay propagation assessment was implemented using an increase step for the number of arrival sequence draws equal to 10. The calculation process is stopped when the total delays indicator averaged over all arrival sequence draws has not changed for more than 10% after 3 successive increases in the number of arrival sequence draws.

4.3.3. Computational parameters for the timetable-free UIC-adapted method for capacity utilisation assessment

The timetable-free UIC-adapted method for capacity utilisation assessment was implemented using an increase step for the number of arrival sequence draws equal to 10. The calculation process is stopped when the capacity utilisation indicator averaged over all arrival sequence draws has not changed for more than 5% after 3 successive increases in the number of arrival sequence draws.

4.3.4. Hardware and software specifications

The methods are implemented using Python 3.9.13. The Python scripts are run on a Windows 10 laptop with an Intel Core i5-10210U processor and 8GB of RAM.

4.4. Verification of the models

4.4.1. Implementation of the verification process

The verification process described in section 3.2.1. is applied to the case study.

A range of traffic volumes are tested, as summarised in the following table.

	Lyon-Ambérieu	**Lyon-Sathonay**	**Lyon-Collonges**
Routes	1-I ; II-2	3-I ; 3-III; II-4; IV-4	5-III; IV-6
Traffic variation per route	From 4 to 20 (increase steps: +4)	From 2 to 10 (increase steps: +2)	From 4 to 20 (increase steps: +4)
Traffic variation on the whole branch	From 8 to 40	From 8 to 40	From 8 to 40
Average traffic on the whole branch	24	24	24

Table 4.4.1. Set of traffic combinations used in the verification step

Traffic is assumed to be made of 75% of passenger trains, and 25% of freight trains. Passenger train taffic is assumed to made of TER regional trains for the Lyon-Ambérieu and Lyon-Collonges branch, and of longer TGV high-speed trains for the Lyon-Sathonay, to and from the "*LGV Sud-Est*". This influences the train lengths, and acceleration and deceleration times. More detail about headway calculation is provided in Appendix C. Numerical values of the minimum headways imposed by each train type (TGV, TER, freight trains) are provided in Appendix D.

The application of the verification process yielded the results presented in the following section.

4.4.2. Results and analysis

The following figures show the results of the verification process. The figures show the variation of the different indicators (capacity utilisation and total delays) with respect to the variation of the traffic on the different branches of the node. When the traffic is varied on a certain branch, the traffic on the other branches is kept at their average values, as given in Table 4.4.1.

The following figures show the capacity utilisation indicators of the three timetable-free methods with respect to the level of traffic on a given branch.

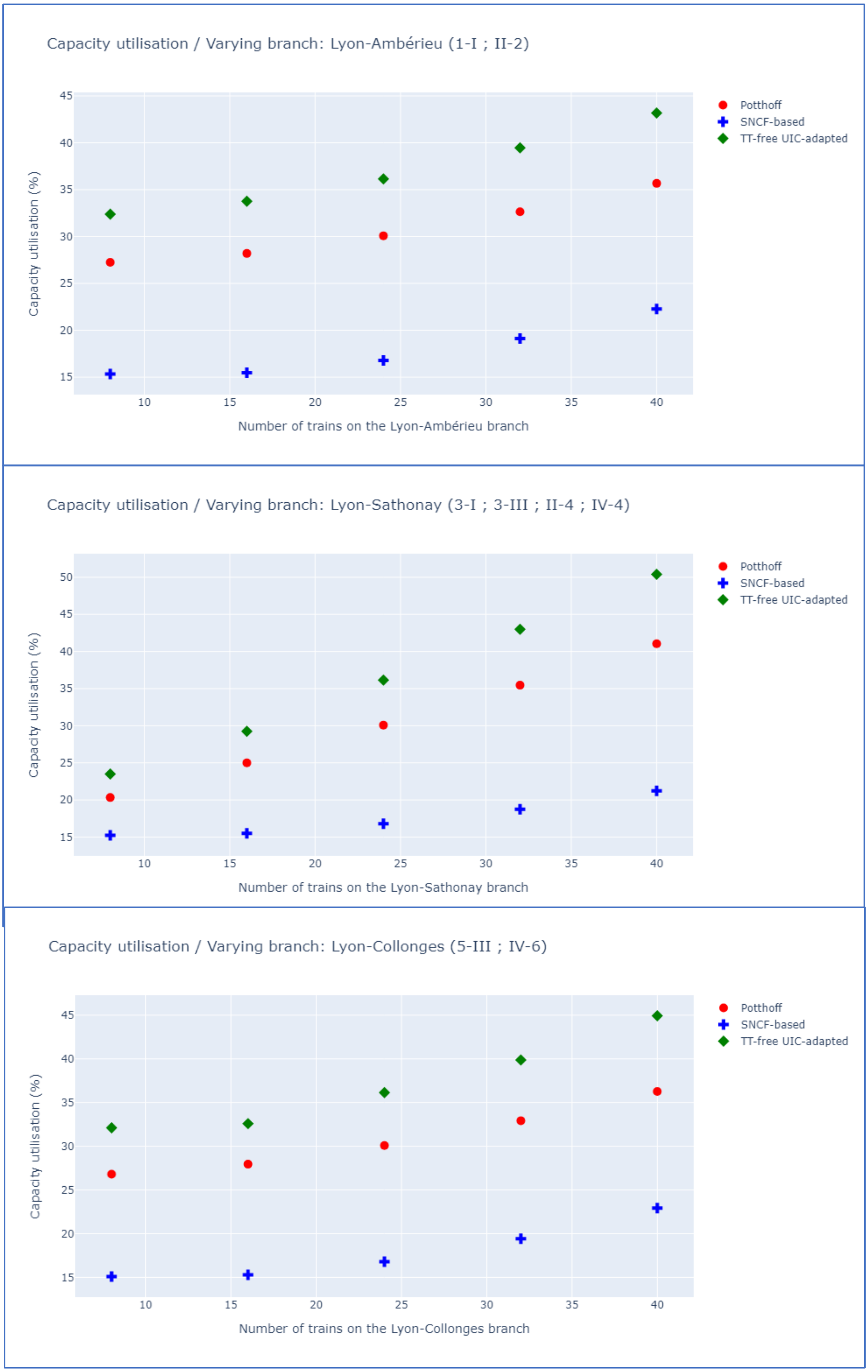


Figure 4.4.2.1 : Capacity utilisation indicators of the three timetable-free methods

It can be seen that the magnitude of the different indicators is ordered as follows. First, the timetable-free UIC-adapted method provides the highest values. Then, Potthoff's capacity utilisation values are close to the those provided by the timetable-free UIC-adapted method, although the difference tends to increase with higher values of traffic. Finally, SNCF-adapted's capacity utilisation indicator provides low values, that still follow an increasing trend nonetheless, which tends to accelerate with higher traffic volumes. Capacity utilisation values' range is the largest for all three methods for traffic varying on the Lyon-Sathonay branch. It was to be expected, as this branch contains the largest number of conflicts with other branches, making it more sensible to traffic increase.

The next figure displays the total delays indicators of the three methods with respect to the level of traffic on a given branch.

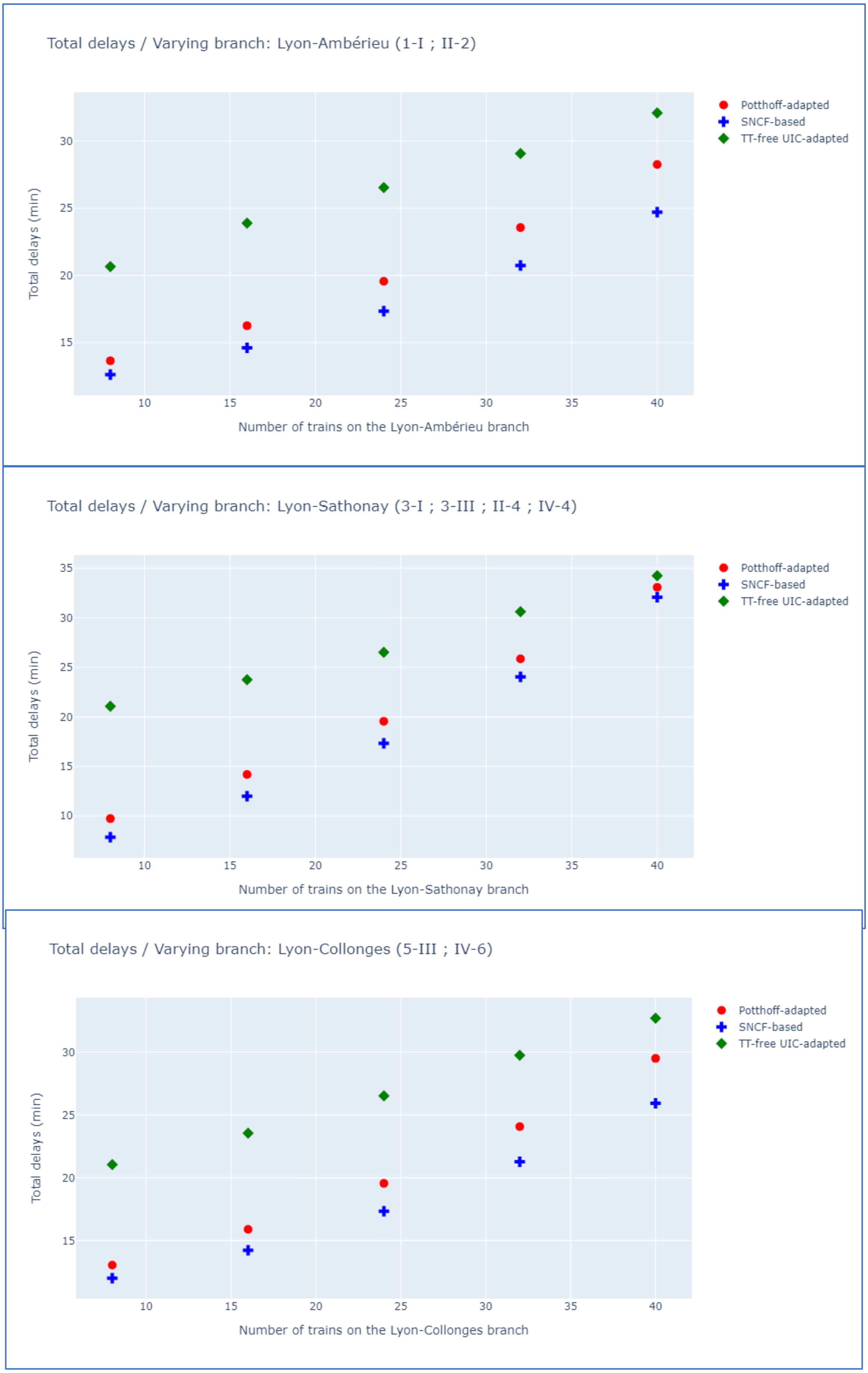


Figure 4.4.2.2 : Total delays indicators of the three timetable-free methods

Here again, the magnitude of the different indicators is ordered as follows: first the timetable-free UIC-adapted method's indicator, then Potthoff-adapted's, then SNCF-adapted's. Potthoff-adapted and SNCF-adapted's values are close and show a similar trend. It is interesting to notice that the increase rate of Potthoff-adapted and SNCF-adapted's indicators is higher than the timetable-free UIC-adapted method's for all three varying branches. Moreover, the timetable-free UIC-adapted method's range of values staysdoes not change much over all varying branches (from around 20min to slightly above 30min). Conversely, Potthoff-adapted and SNCF-adapted's range is larger for traffic varying on the Lyon-Sathonay branch. This was to be expected, as a larger number of conflicts can occur on this branch, thus making it more sensible to traffic increase.

In order to further compare the methods, the relative difference between their indicators' values (capacity utilisation or total delays) is assessed. The timetable-free UIC-adapted methods are taken as reference when comparing with Potthoff-adatped and SNCF-adapted. Potthoff(-adapted) is taken as reference when comparing with SNCF-adapted. The relative differences are expressed in percentages, and calculated as follows:

$$Difference(indicator)_{UIC\_free-Potthoff}(\%) = \frac{indicator_{UIC\_free} - indicator_{Potthoff}}{indicator_{UIC\_free}} \times 100$$

$$Difference(indicator)_{UIC\_free-SNCF}(\%) = \frac{indicator_{UIC\_free} - indicator_{SNCF}}{indicator_{UIC\_free}} \times 100$$

$$Difference(indicator)_{Potthoff-SNCF}(\%) = \frac{indicator_{Potthoff} - indicator_{SNCF}}{indicator_{Potthoff}} \times 100$$

The relative differences are calculated for each data point. The results are shown in the tables below, where mean, median and standard deviation values of each relative difference are presented.

$Difference(Capacity\ utilisation)(\%)$	**Mean**	**Median**	**Standard deviation**
(Timetable-free UIC-adapted)-(Potthoff)	16.6%	17.1%	2.3%
(Timetable-free UIC-adapted)-(SNCF-adapted)	47.5%	51.2%	9%
(Potthoff)-(SNCF-adapted)	37.1%	40.9%	10.6%

Table 4.4.2.1: Relative differences for capacity utilisation indicators

$Difference(Total\ delays)(\%)$	**Mean**	**Median**	**Standard deviation**
(Timetable-free UIC-adapted)-(Potthoff-adapted)	24.3%	26%	21.7%
(Timetable-free UIC-adapted)-(SNCF-adapted)	65.6%	66.3%	11%
(Potthoff-adapted)-(SNCF-adapted)	54.9%	55.2%	3.2%

Table 4.4.2.2: Relative differences for total delays indicators

Regarding capacity utilisation, it can be noticed the relative difference between the timetable-free UIC-adapted indicator and Potthoff's shows a low standard deviation (2.3%), meaning that the relative difference between Potthoff's and timetable-free UIC-adapted's capacity utilisation indicators are well centred around a mean difference of 16.6%. Thus, it can be observed that the indicators produced by these methods differ by a steady multiplicative factor. This research does not further investigate the reason for this difference, but the following comments and recommendations for complementary investigations can be made. The occupation time calculated by the Potthoff method results from the multiplication by an average headway of an average number of trains belonging to a virtual critical sequence. Thus, further complementary research could try to determine which of these two factors differs in the Potthoff method compared to those in the timetable-free UIC-adapted method. The number of trains belonging to the critical sequence in the timetable-free UIC-adapted can be retrieved in the UIC 406 algorithm as the "number of concatenations" presented in *UIC, 2013* [18], while an average headway could be calculated based on the headways between the trains of this critical sequence. Average values of these two factors could then be calculated over the arrival sequences tested by the timetable-free UIC-adapted method.

Finally, the comparison with SNCF-adapted's capacity utilisation shows that the difference with the timetable-based UIC-adapted and Potthoff's capacity utilisations is high on average and dispersed. It is hard to define a link between SNCF-adapted's capacity utilisation indicator and the timetable-based UIC-adapted and Potthoff's indicators.

Concerning total delays, it can be noticed that the difference between SNCF-adapted and Potthoff-adapted's total delays indicators shows a low standard deviation (3.2%), meaning that the difference is well centred around a mean relative difference of 54.9%. This is consistent with the similar trends observed in the graphs. This could be expected as both methods work on a similar principle, that is estimating a probability of conflict between trains on conflicting routes and multiplying it by an average consecutive delay based on the first train's occupation time. The difference lies in the way the probabilities of conflicts are estimated in both methods.

Then the comparison with the timetable-free UIC-adapted total delays indicator shows that the difference with Potthoff'-adapted's and SNCF-adapted's indicators is high on average and dispersed (high means and standard deviation of the relative differences). This is consistent with the previous observations on the graphs which showed that the increase rates of SNCF-adapted and Potthoff-adapted's total delays indicators were higher than the one of the timetable-free UIC-adapted method. Therefore, it is hard to define a relation between the timetable-free UIC-adapted total delays indicator and SNCF-adapted and Potthoff-adapted's.

4.5. Validation against recorded performance data

This section presents the results of the validation process described in section 3.2.2. First, the trends and magnitude of the values taken by the methods' indicators are compared to those of the real values. Then, the difference between each method's indicators and the real values is investigated.

For the timetable-free methods, the headways between trains are calculated using the percentages of each train types per route given in the planned timetables. For the timetable-based methods, knowing the type of each train in the planned timetable allows to precisely use the right headway depending on the train types. More detail is given in Appendix C.

The following figures present the values taken by the different methods' capacity utilisation indicators, as well as the real capacity utilisation. For each method, the traffic variation on the three branches are presented separately. It must be noted that two observations were removed from the data sample, due to outlying real total delays values.

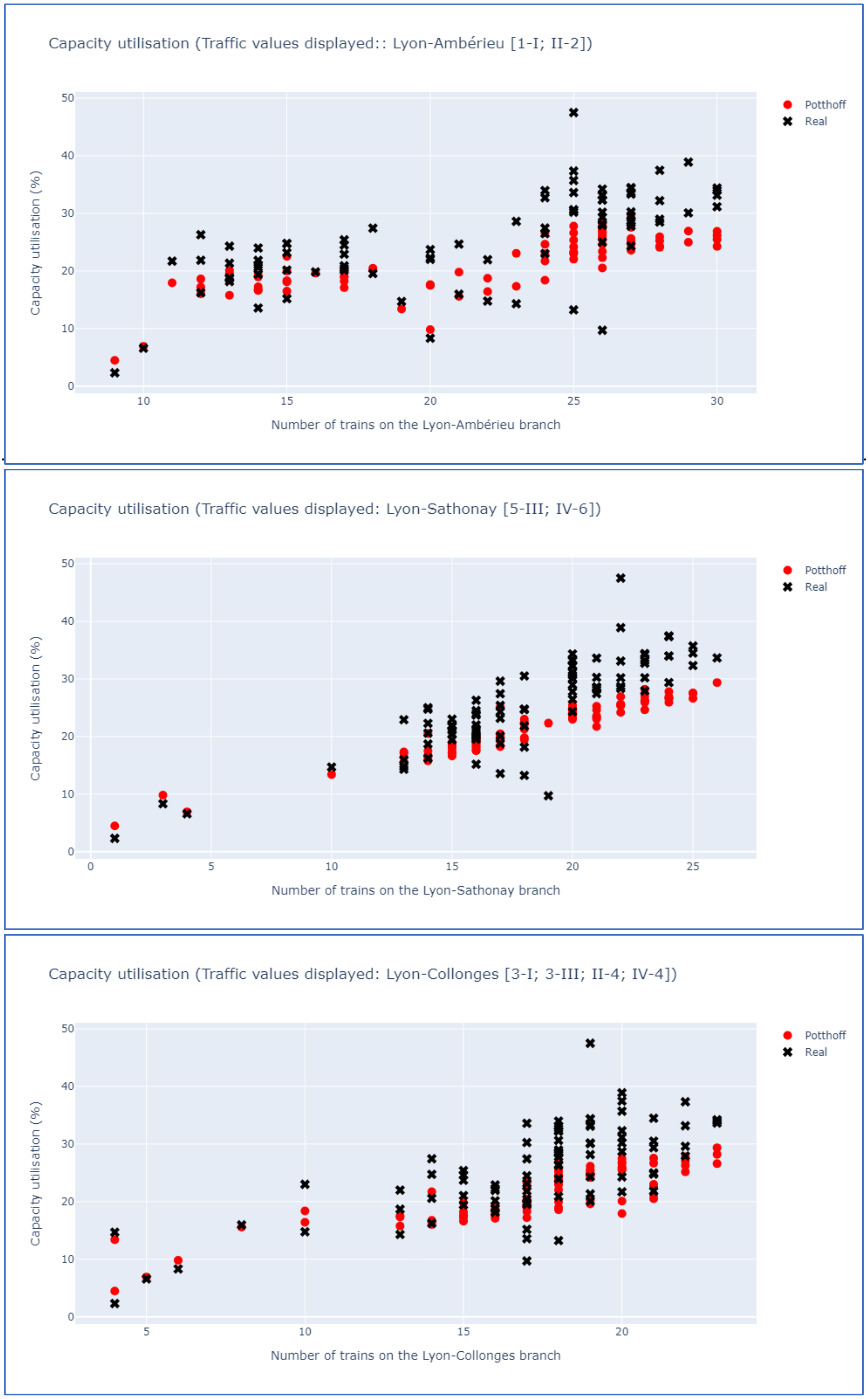


Figure 4.5.1: Potthoff's capacity utilisation indicator and real capacity utilisation

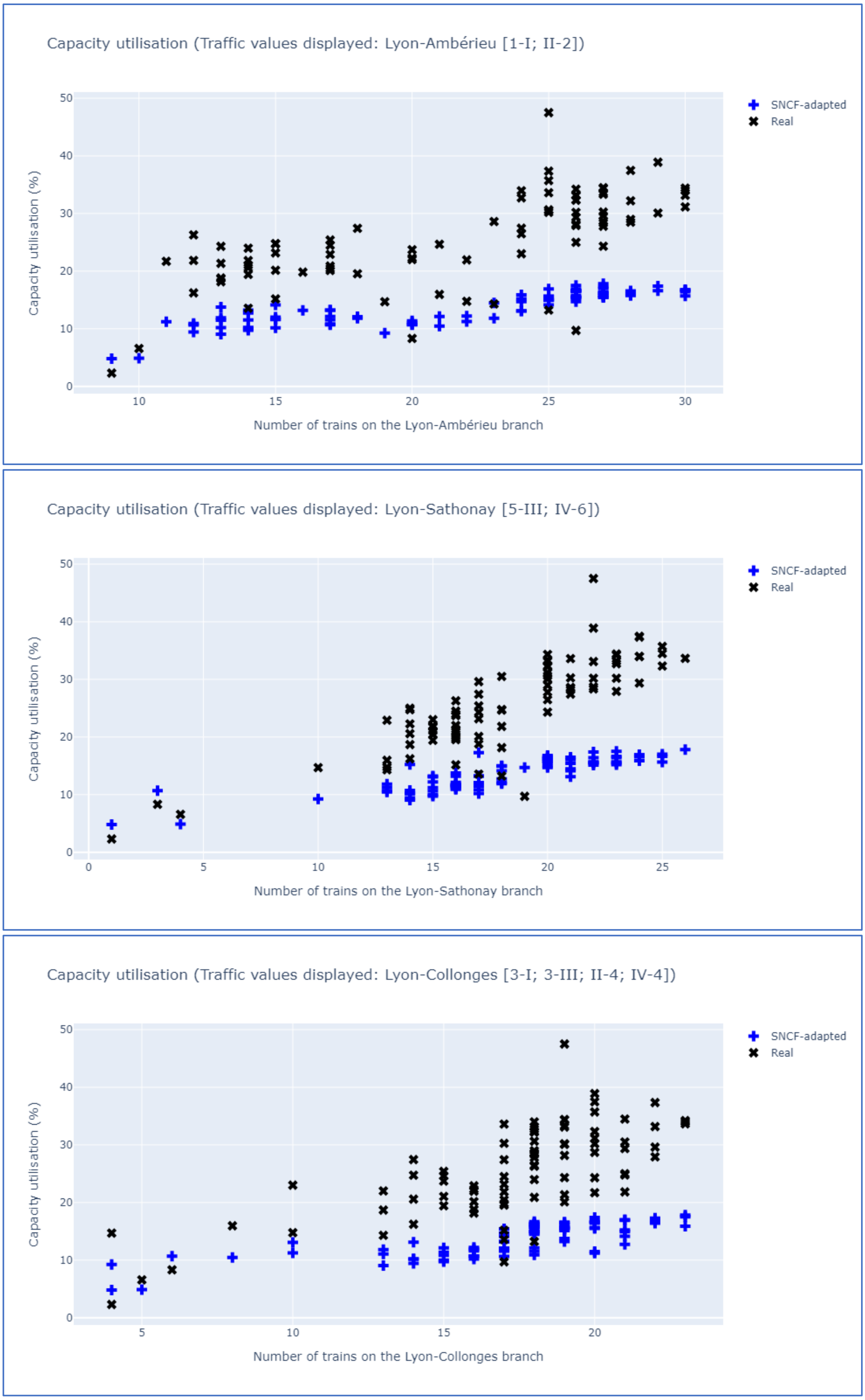


Figure 4.5.2: SNCF-adapted's capacity utilisation indicator and real capacity utilisation

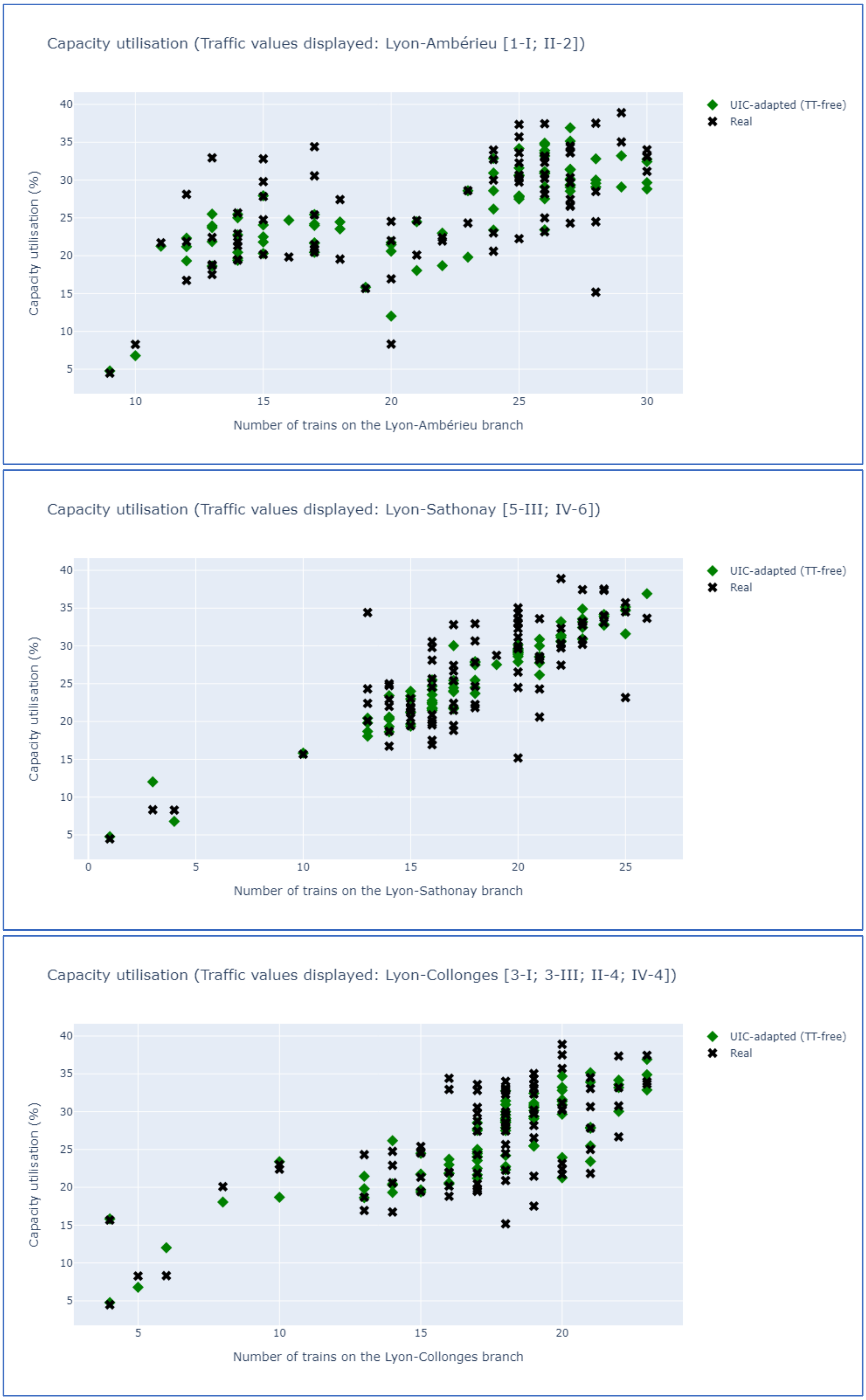


Figure 4.5.3: Timetable-free UIC-adapted capacity utilisation indicator and real capacity utilisation

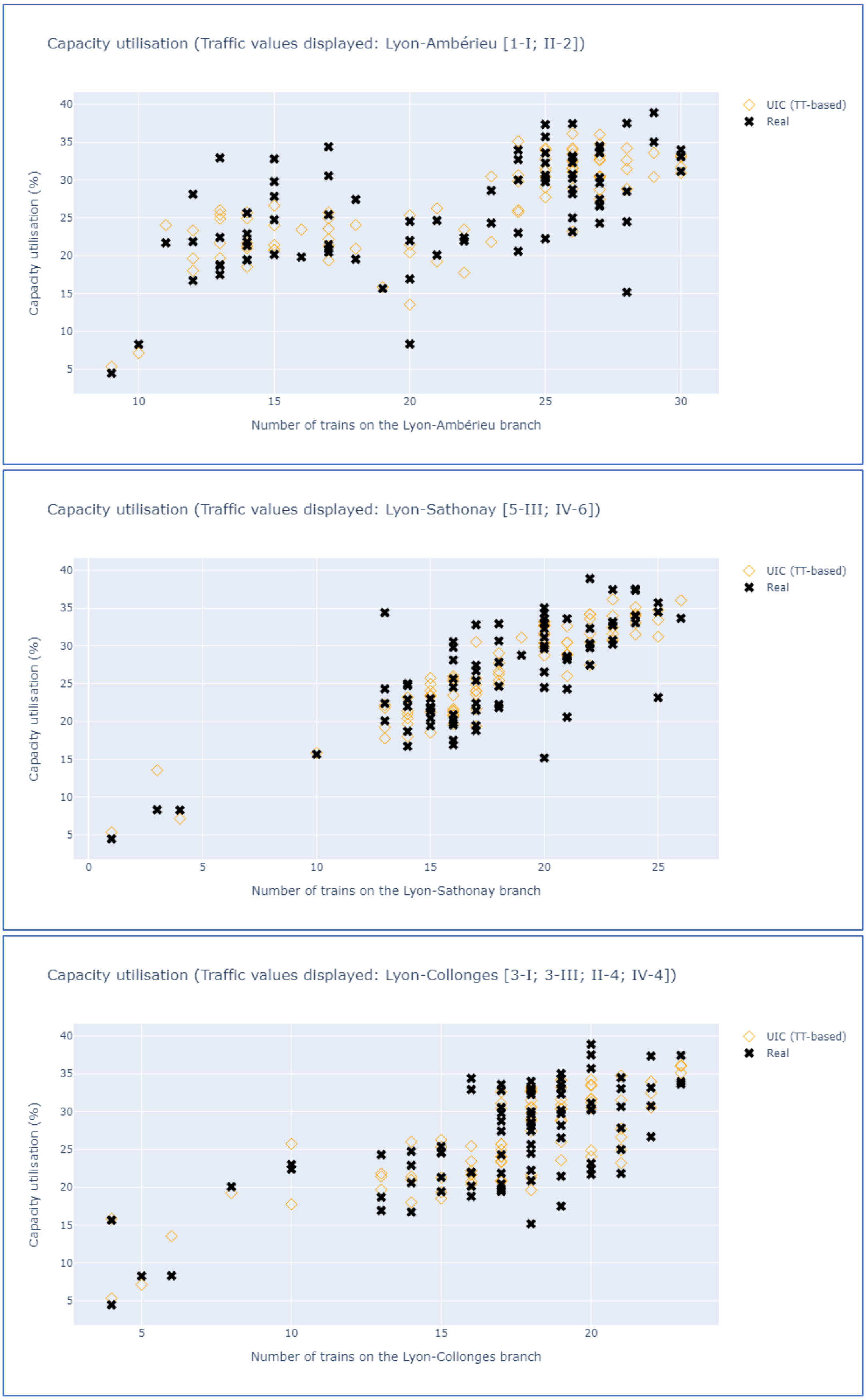


Figure 4.5.4: Timetable-based UIC 406 capacity utilisation indicator and real capacity utilisation

The following comments can be made regarding the overall trends and magnitude of each method's capacity utilisation indicators, in comparison to the real ones:

- Potthoff method's capacity utilisation values are on average slightly lower than the real values
- SNCF-adapted method's capacity utilisation values are clearly lower than the real ones
- The values taken by the timetable-free and timetable-based UIC-adapted methods' indicators seem to be closely intertwinded with the real values.

Then, the next figures show the values taken by the different methods' total delays indicators, as well as the real total delays.

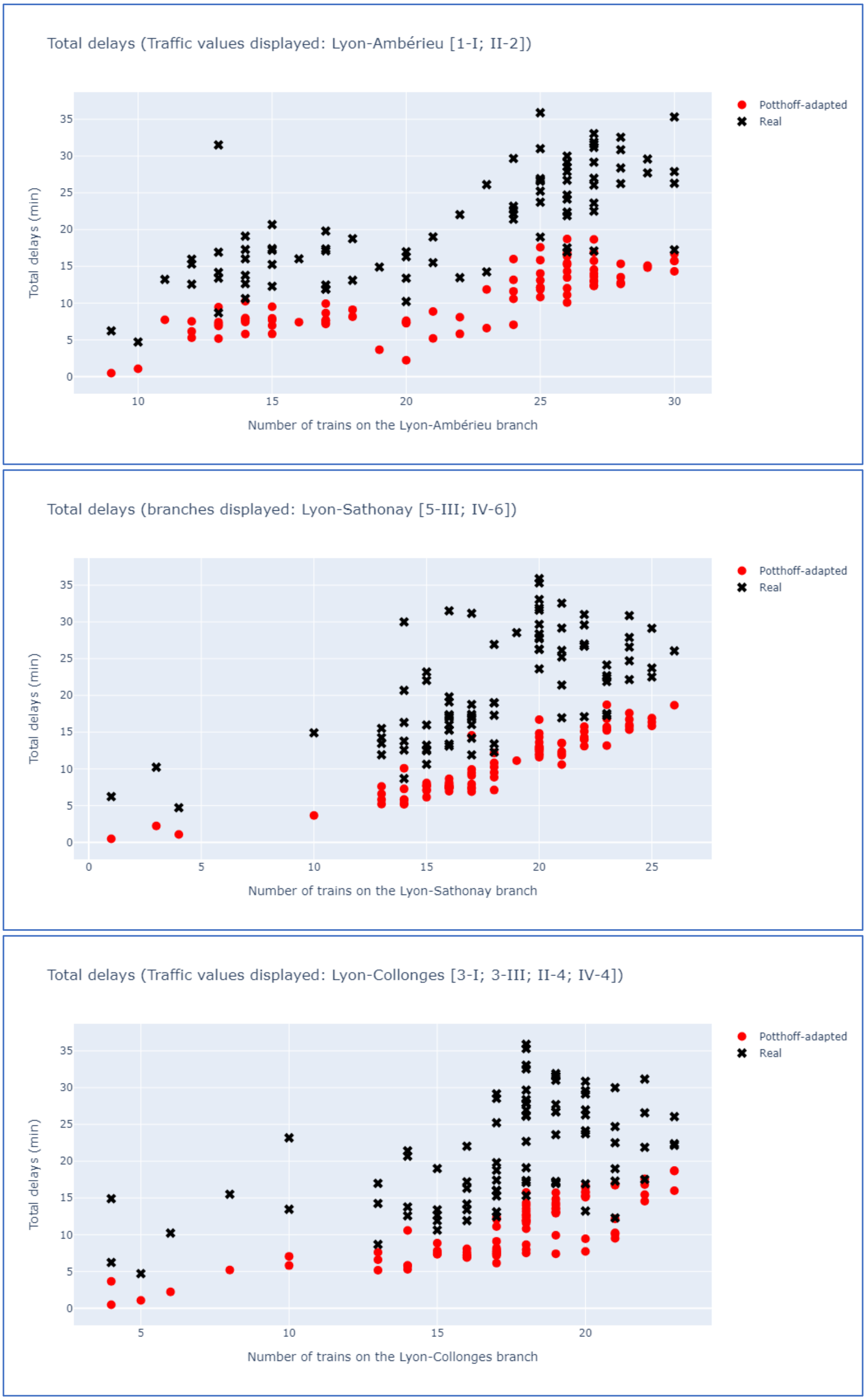


Figure 4.5.6: Potthoff-adapted total delays indicator and real total delays

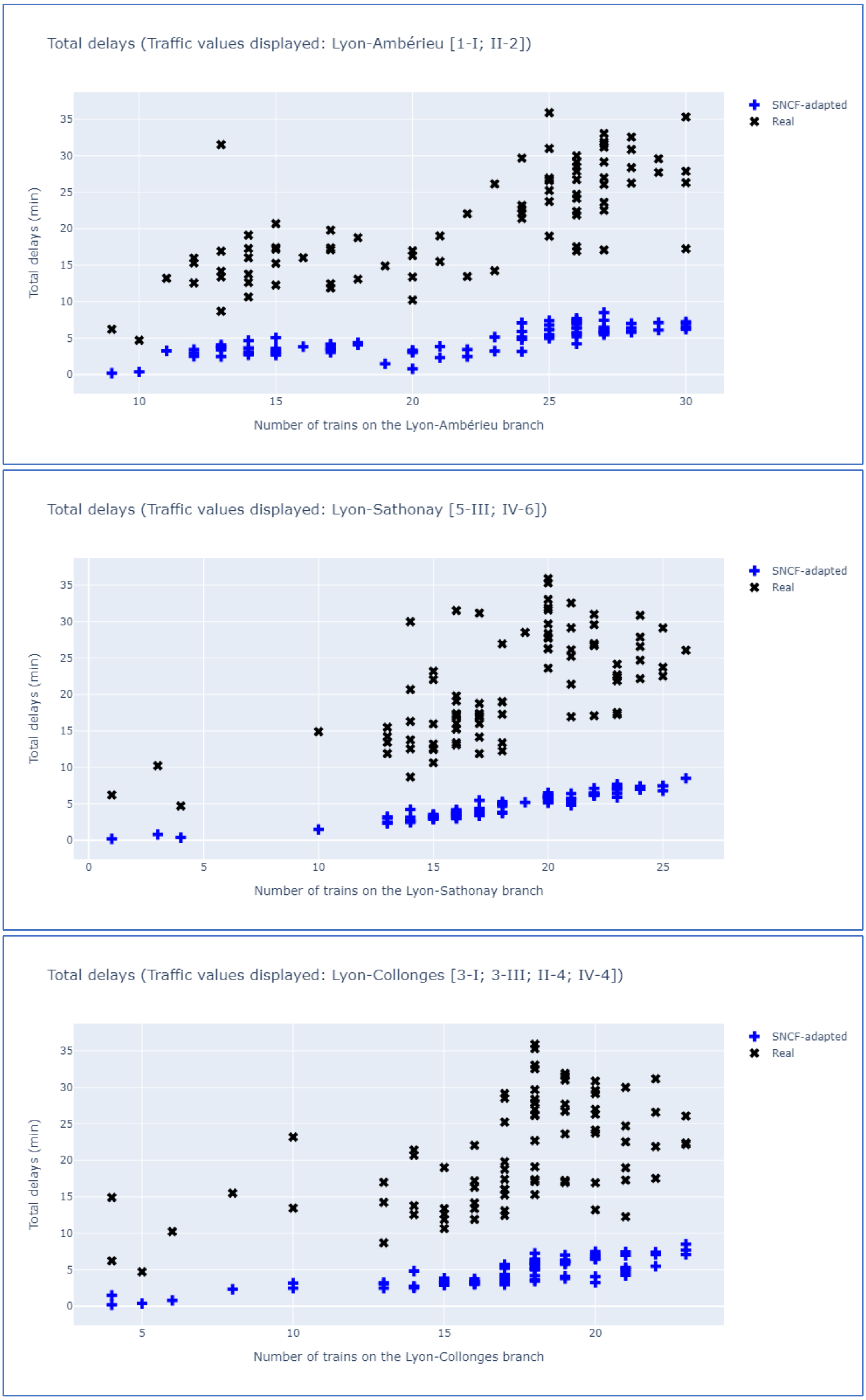


Figure 4.5.7.: SNCF-adapted total delays indicator and real total delays

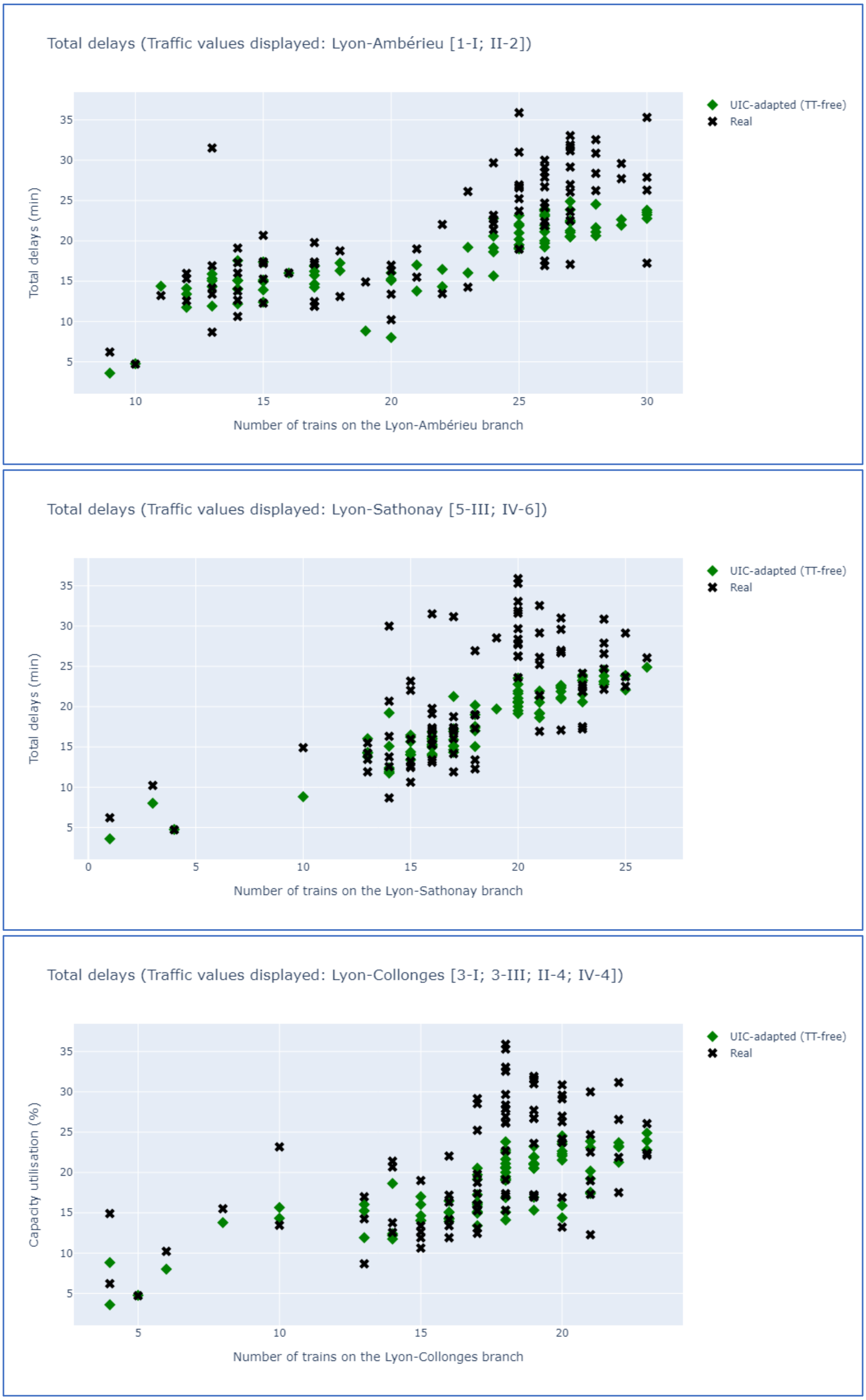


Figure 4.5.8: Timetable-free UIC-adapted total delays indicator and real total delays

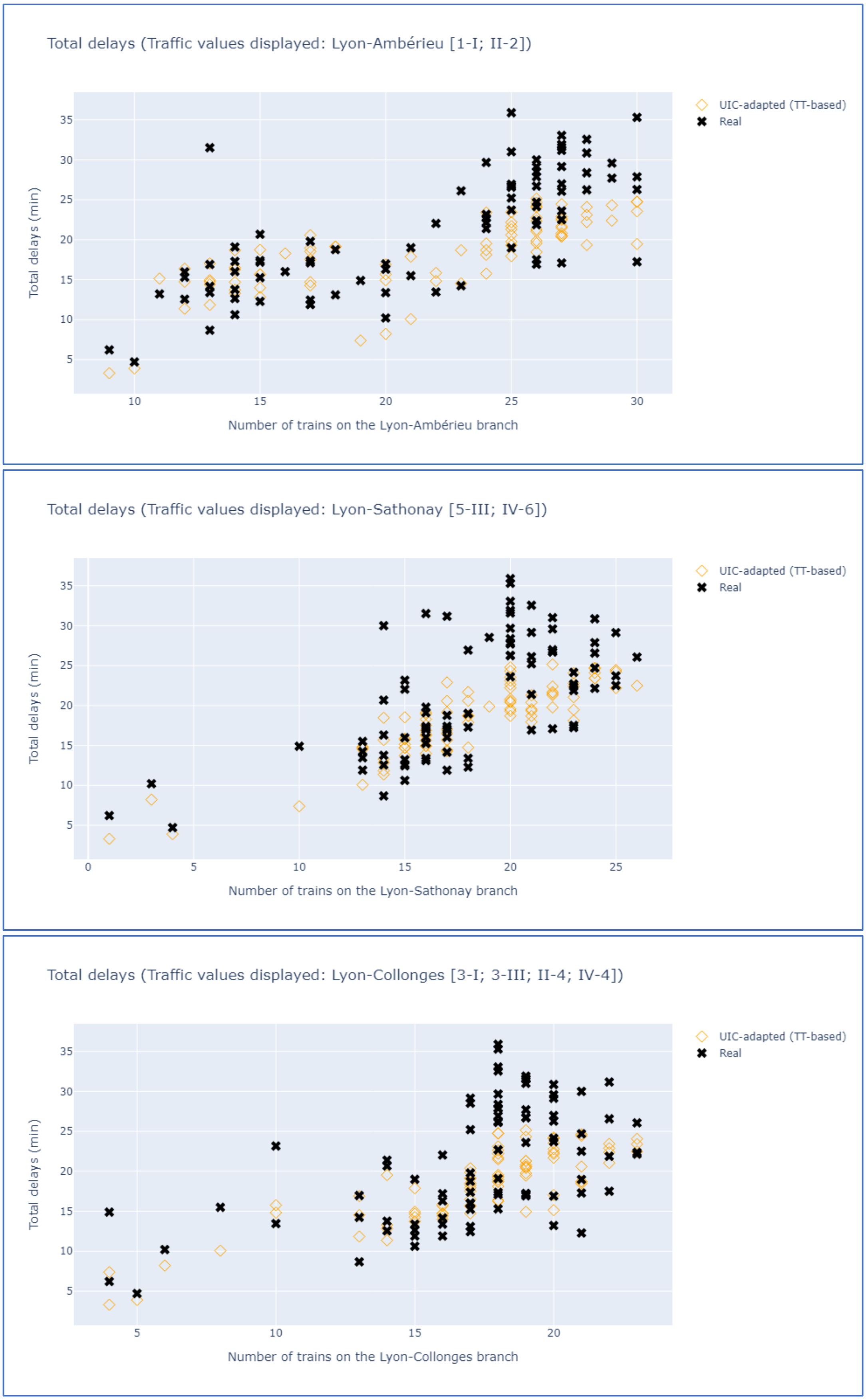


Figure 4.5.9: Timetable-based UIC-adapted total delays indicator and real total delays

The following comments can be made regarding the overall trends and magnitude of each method's total delays indicators, in comparison to the real ones:

- Potthoff-adapted method's total delays values are on average slightly lower than the real values, and the overall trends are similar
- SNCF-adapted method's total delays values are clearly lower than the real ones, yet the overall trend of the method's indicator seems to be consistent with the one of the real values
- The values taken by the timetable-free UIC-adapted method's indicator seem to be closely intertwined with the real values for moderate traffic volumes, but then appear to be lower for higher traffic volumes
- Similarly to what can be observed for the timetable-free approach, the values taken by the timetable-based UIC-adapted total delays indicator seem to be closely intertwined with the real values for moderate traffic volumes, but then appear to be lower for higher traffic volumes.

The relative differences (in percentages) between real and methods' indicators are computed so as to provide more accurate analyses. The real values are taken as reference. The following formulas are used.

$$Difference(indicator)_{Real-Potthoff}(\%) = 100 \times \frac{indicator_{Real} - indicator_{Potthoff}}{indicator_{Real}}$$

$$Difference(indicator)_{Real-SNCF}(\%) = 100 \times \frac{indicator_{Real} - indicator_{SNCF}}{indicator_{Real}}$$

$$Difference(indicator)_{Real-UIC\_free}(\%) = 100 \times \frac{indicator_{Real} - indicator_{UIC\_free}}{indicator_{Real}}$$

$$Difference(indicator)_{Real-UIC\_based}(\%) = 100 \times \frac{indicator_{Real} - indicator_{UIC\_based}}{indicator_{Real}}$$

These relative differences are calculated for each observation. The results are shown in the tables below, where mean, median and standard deviation values of each relative difference are presented.

$Difference(Capacity\ utilisation)(\%)$	**Mean**	**Median**	**Standard deviation**
Real-(Potthoff)	16.5%	19.3%	15.2%
Real-(SNCF-adapted)	45.9%	49.2%	14.4%
Real-(Timetable-free UIC-adapted)	-1.2%	1.3%	19.3%
Real-(Timetable-based UIC-adapted)	-3.7%	-1.8%	20.1%

Table 4.5.1: Relative differences for capacity utilisation indicators

$Difference(Total\ delays)(\%)$	**Mean**	**Median**	**Standard deviation**
Real-(Potthoff-adapted)	49%	51.2%	15.6%
Real-(SNCF-adapted)	77.2%	77.3%	7.1%
Real-(Timetable-free UIC-adapted)	9.4%	11%	21.5%
Real-(Timetable-based UIC-adapted)	7.9%	9.7%	23%

Table 4.5.2: Relative differences for total delays indicators

Concerning capacity utilisation values, all relative differences between real capacity utilisation methods' indicators show a moderate dispersion (standard deviations between 14.4% and 20.1%) in general. This can be linked to how the real capacity utilisation is computed. Indeed, the real capacity utilisation takes into account the moment from which route is locked for an incoming a train, which is usually done around 1 to 2 minutes prior to the train arrival. The methods' capacity indicators, however, consider the minimum technical time needed to set an itinerary and time supplements to the minimum headway. This difference could lead to variability in the results. Therefore, the dispersion observed in the differences between real and methods' capacity utilisation indicators could be linked to the numerical values used and the assumptions taken in the headway's calculation (common to all methods), rather than to the methods' assumptions and calculations themselves.

The timetable-based UIC 406 method provides a good approximation of the real capacity utilisation values, with a slight overestimation (negative relative difference)of 3.7% on average. Then, among the timetable-free methods, the timetable-free UIC-adapted method performs best in anticipating the real capacity utilisation values, with a slight overestimation (negative relative difference) of 1.2% on average. Actually, it even performs better than the timetable-based UIC 406 method in terms of average relative difference, which was unexpected. The reason can be that the timetable that is executed can slightly differ from the planned one, and the timetable-free UIC-adapted method can take these slight variations into account by evaluating different random train orders, while the classic timetable-based UIC 406 method can only consider the planned timetable. The Potthoff method's indicator is also performing quite correctly, with a mean relative difference of 16.5%. However, the SNCF-adapted method's capacity utilisation indicator appears to be inappropriate for estimating the real capacity utilisation, with a high mean relative difference of 45.9%.

To conclude, the timetable-free UIC-adapted method and Potthoff seem appropriate to perform timetable-free evaluation of capacity utilisation, while the timetable-based UIC 406 method seems appropriate if timetables can be used.

Regarding the total delays values, the timetable-based UIC-adapted method shows the lowest relative difference on average (7.9%), but also the highest standard deviation value (23%), denoting a high dispersion and thus a lack of reliability. Conversely, the timetable-free Potthoff-adapted and SNCF-adapted methods show much higher mean relative differences (respectively 49% and 77.2%), but with much lower standard deviation (respectively 15.6% and 7.1%). The timetable-free UIC-adapted method shows a low mean relative difference (9.4%) but at the expense of a high standard deviation (21.5%).

It can be argued that the UIC-adapted methods for delay propagation (both timetable-based and timetable-free) do not offer satisfying results in terms of reliability (high dispersion). This could come from the way the initial delays are generated for these methods. As mentioned during the description of these methods in chapter 3, the definition of the time interval used for initial delays generation is still exploratory and certainly requires more investigation.

Then, the Potthoff-adapted and SNCF-adapted methods do not provide accurate total delays values on average (high underestimation in mean relative difference). Yet, they show better results in terms of reliability (low dispersion). These methods might correctly estimate the number of conflicts in the node area (leading to a low dispersion in relative difference) but then underestimate the magnitude of the delays generated in each conflict (leading to a high underestimation in mean relative difference). The explanation for this underestimation may lie in the fact that the calculation of the delays does not take into account a train order sequence. Thus, it does not grasp the interdependencies that may lead to the propagation of delays between routes that are not directly in conflict, via common intermediate conflicting routes.

To conclude, even though none of the methods seems to directly provide a correct assessment of the total delays, it appears that the low dispersion of the relative difference between Potthoff-adapted and SNCF-adapted methods' delays and the real ones could be further exploited to correct these methods' indicators with a correction factor. However, this has to be properly investigated with a calibration and a validation of such a factor. This will be the topic of the next part, where the possibility to correct the SNCF-adapted method is investigated, as it showed the lowest dispersion in relative difference with the real values (standard deviation of 7.1%).

4.6. Investigating the possibility to correct the SNCF-adapted method for delay propagation

In this section, the possibility to correct the SNCF-adapted method with a certain corrective factor is investigated. First, the dataset of the validation phase is split into a calibration dataset and a test dataset. Then, a corrective factor is estimated with the calibration dataset. Finally, the values of the SNCF-adapted total delays indicator in the test dataset are corrected with the estimated corrective factor and compared to the real total delays.

The dataset is first randomly split in half, into a calibration dataset, containing 50% of the observations, and a validation dataset, containing the other 50% of all observations. In the calibration dataset, the mean value of the relative difference between the real total delays and the SNCF-adapted's total delays is equal to 76.6% and the standard deviation value is equal to 7.2%. (in the full dataset, these values were respectively 77.2% and 7.2%). Then, a corrective factor β is estimated in the calibration dataset, as:

$$\beta = \frac{1}{1 - mean(Difference(Total\ delays)_{Real-SNCF})} = \frac{1}{1 - 0.766} \simeq 4.27$$

This corrective factor is then applied to the values of the SNCF-adapted method in the test dataset. Corrected SNCF-adapted total delays values are obtained by multiplying the original SNCF-adapted total delays values with the corrective factor β. The following figures show the real and corrected SNCF-adapted total delays values of the test dataset, plotted on each branch.

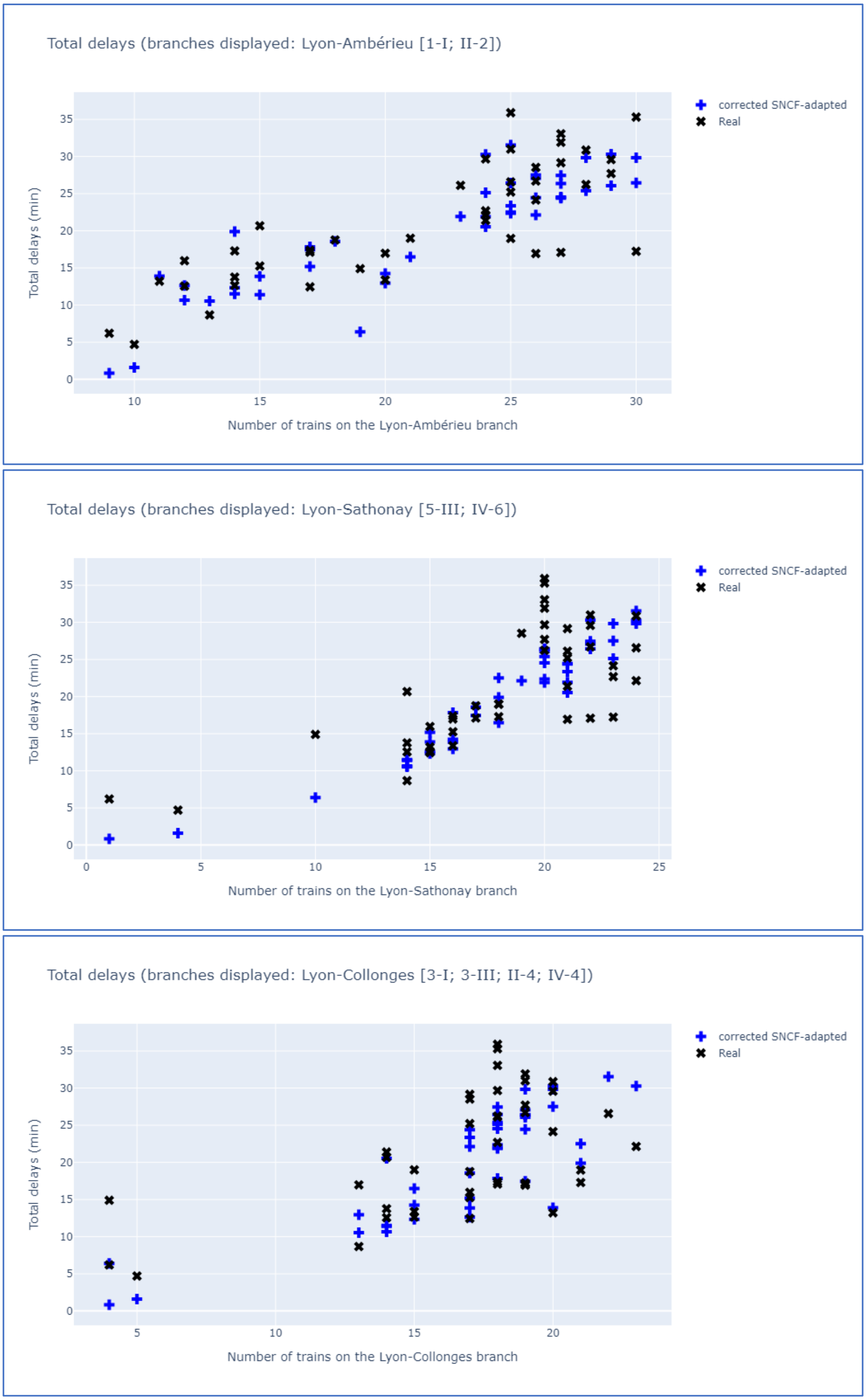


Figure 4.6.1: Corrected SNCF-adapted total delay indicator and real total delays

Overall, a good correspondence seems to be achieved. Now, in the test dataset, the mean relative difference is only about 5.3%. Therefore, it is chosen to calculate corrected SNCF-adapted total delays values by multiplying the method's total delays with β.

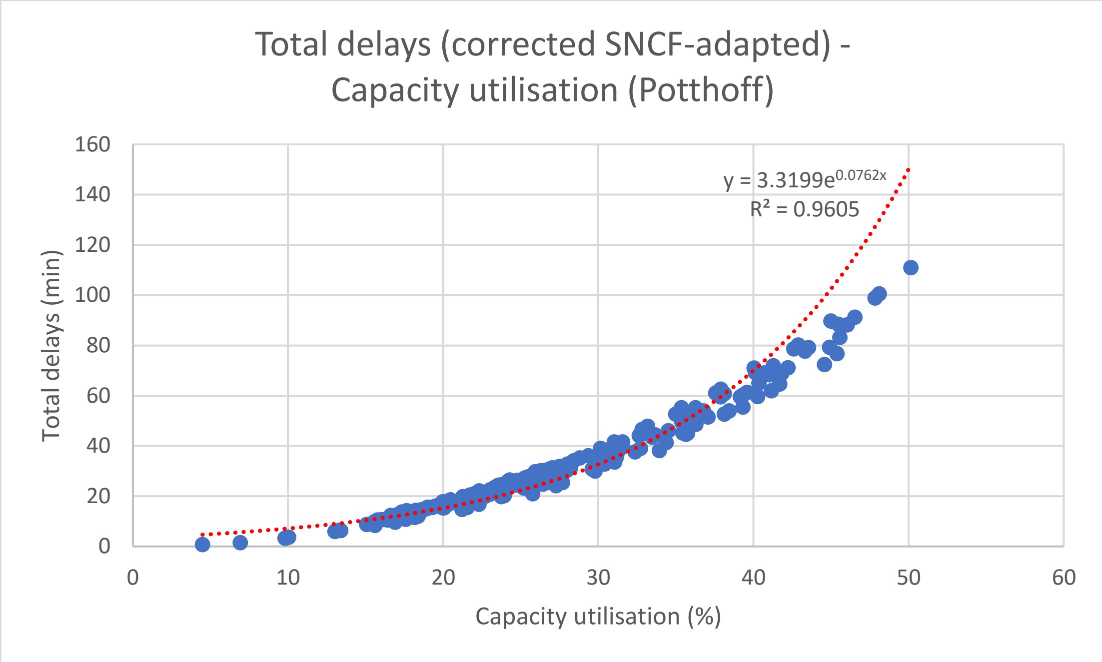
4.7. Investigating the capacity utilisation – total delays relationship

This section builds upon the results obtained in the verification and validation steps in order to study the relation between capacity utilisation and total delays. From the analysis of the observations made previously, the following choices are made:

- For capacity utilisation assessment, the timetable-free UIC-adapted method and the Potthoff method are further studied in this section. Indeed, they provide capacity utilisation values that proved to be good estimates of the real capacity utilisation. Here, only timetable-free methods are investigated, in order to take advantage of the large number of unobserved traffic configurations used in the verification dataset. It can already be expected that the findings obtained for the timetable-free UIC-adapted method will be applicable to the timetable-based UIC 406 method, as the analysis in the validation phase showed that they produced capacity utilisation values of close magnitudes.
- For delay propagation assessment, the corrected SNCF-adapted method is used with the corrective factor β estimated in 4.6. ($\beta \simeq 4.27$).

These methods are used to calculate capacity utilisation and total delays values from an enlarged set of traffic configuration, containing both the observed traffic configurations of the validation phase, and the unobserved traffic configurations used in the verification phase.

The following figures are obtained:



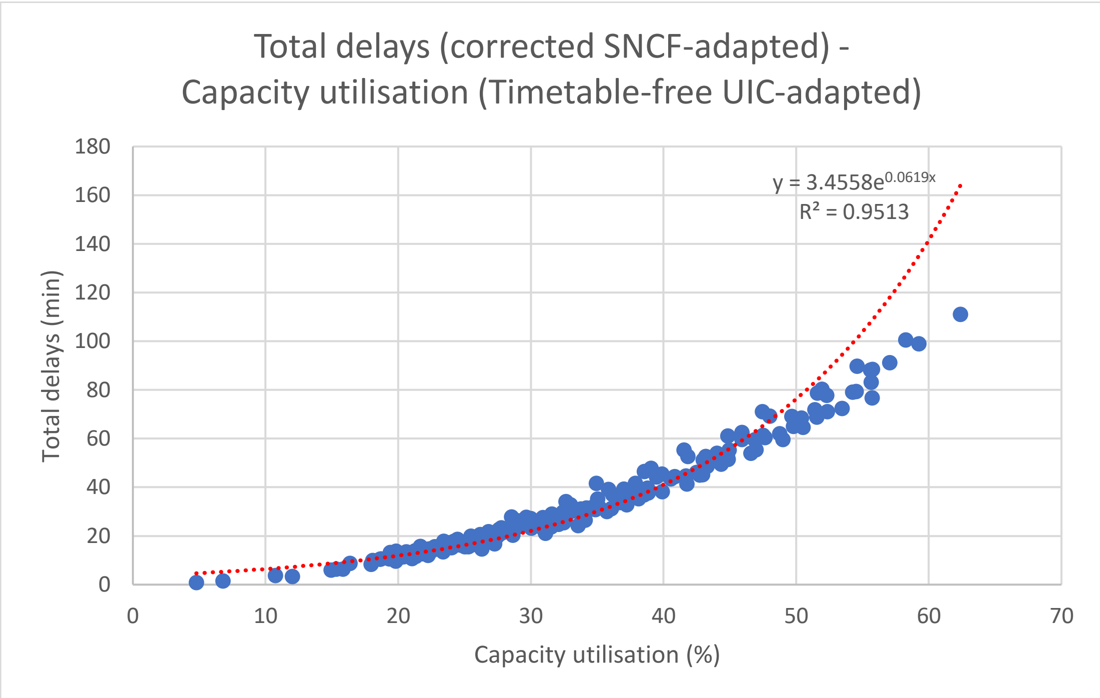
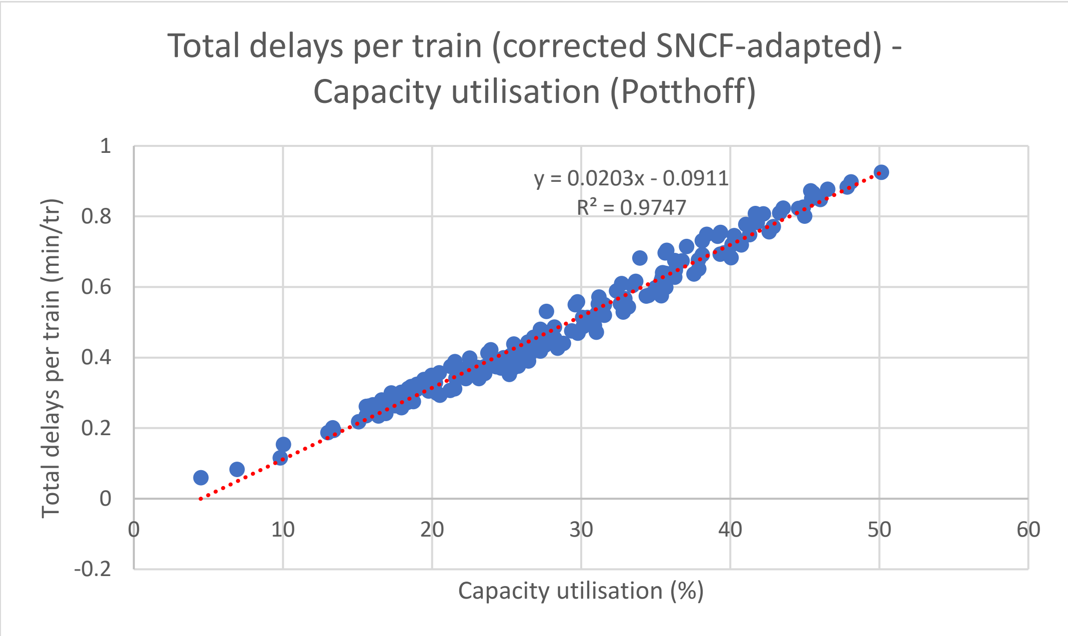


Figure 4.7.1: Total delays – capacity utilisation relationships

It can be observed that the relationships between capacity utilisation and total delays for both methods take the expected form of an exponential function. This finding is in line with the results found in *Armstrong & Preston, 2017* [3]. The results show that when the capacity utilisation value increase by 1%, the total delays can be expected to increase by 6.4% in the case of the timetable-free UIC-adapted capacity utilisation indicator ($e^{0.0606} = 1.064$) and by 7.9% in the case of Potthoff's capacity utilisation indicator ($e^{0.0762} = 1.079$). Yet these are preliminary results, and these values should be later confirmed by additional research over more traffic configurations and different infrastructure layouts.

The infrastructure manager can be interested in knowing critical thresholds of capacity utilisation. While the total delays indicator is difficult to interpret alone, using the ratio between total delays and the number of trains (total delays per train) allows to detect when critical situations are reached more easily. The following figures are obtained when plotting the total delays per train against capacity utilisation values.



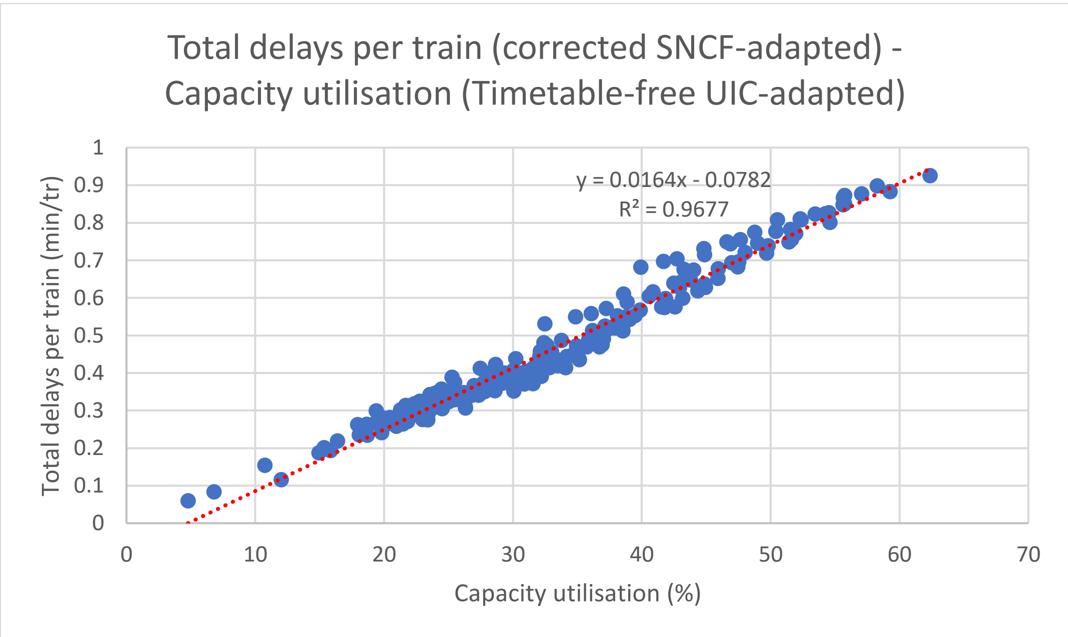


Figure 4.7.2 Total delays per train – capacity utilisation relationships

This time, a strong linear relationship can be observed between capacity utilisation and total delays per train. Using the equations of the regression curves (red dot lines), it can be calculated that a critical total delays per train value of 1min/tr is obtained when Potthoff's capacity utilisation reaches 53.7%, or when the timetable-free UIC-adapted's capacity utilisation reaches 65.7%. These values match with the capacity utilisation for which the total delays increase rapidly (*Figure 4.7.1.*). It can be noted that the capacity utilisation thresholds are lower than the thresholds recommended by the UIC for railway line track sections (*UIC, 2013* [18]). Actually, the difference is even greater as the methods studied in this research use headways containing the minimum technical headways plus headway supplements, while *UIC, 2013* [18] only uses minimum technical headways. This finding is also in line with the conclusions of *Armstrong & Preston, 2017* [3] that noted lower capacity utilisation thresholds for railway nodes, albeit with a different capacity utilisation assessment method.

These thresholds are to be considered preliminary findings. Further investigations should be conducted by the infrastructure manager to check their validity over an extended range of traffic configurations and different infrastructure layouts.

5. Application of the methods for supporting the long-term planning and design processes of a railway node

In this section, the results obtained regarding the methods during the evaluation process are reflected upon and analysed in order to support the long-term planning and design process of a railway node. In the first subsection, the timeline of a railway project at SNCF Réseau is analysed, and the positioning of the railway operation studies department is identified in relation with the other stakeholders. Then, a reflection on the methods' strengths and weaknesses is conducted, and the benefits they can bring to the different stakeholders is analysed. Based on the preceding information, the ideal positioning of the methods in a generic study's timeline is described. After this, a small case study is conducted to determine when the methods could be employed during the redesigning of Bordeaux station, whose operation under increasing future traffic is currently questioned.

5.1. Timeline of a railway project at SNCF Réseau and involved stakeholders

5.1.1. Origin and timeline of railway project at SNCF Réseau

A railway project at SNCF Réseau can originate from a new service development, such as when local or national services' traffic is increased, or from the need to correct or increase the performance of the existing system. An infrastructure project is structured in different steps:

- Emergence of the project (definitions, conceptual designs): *around Y-15 to Y-10* (Y: year of operations)
- Pilot designs: *around Y-10 to Y-05*
- Final design and construction phase: *around Y-05 to Y*
- Commissioning and feedback processes: *after Y*

However, the timeline of the definition of the timetable is different:

- Definition of the timetables used in the studies (capacity engineering department):
- Long-term traffic projections: *before Y-15*
- Emerging timetable plan: *around Y-10*
- "Reference" timetable plan: *around Y-05*
- Two-hours detailed timetable pattern: *between Y-05 and Y-03*
- Definition of the actual timetable (train path allocation department):
- Construction of the timetable in cooperation with the railway undertakings: *from Y-03 to Y*

The timelines for infrastructure design and timetable design differ slightly. The consequence is that the timetable is defined in detail (two-hours timetable pattern and construction of the actual timetable) only after the infrastructure has been planned. Therefore, projects have to rely on timetables plans that can only have a limited degree of reliability.

5.1.2. Involved stakeholders and positioning of the railway operation studies department

In France, the coordination and decision-making regarding railway projects is conducted within the framework of the "Service and infrastructure platforms" ("*Plateformes services et infrastructure*" later abbreviated "PS&I") that regroup representatives from the railway infrastructure manager SNCF Réseau, local transport authorities (mainly "Régions", equivalent of "Provinces" in the Netherlands) of a given geographical area, and the national government. These work platforms aim to coordinate the action of these stakeholders in terms of medium to long-term railway service development and infrastructure upgrades and mitigate possible conflicts of use, within their geographical perimeter. Within the framework of these "PS&I" work platforms, service and infrastructure studies can be ordered jointly, or separately by one or several stakeholders, to support the decision-making process. In case of diverging positions between stakeholders, the presence of representatives from the national government can help settle the issues and reach a decision.

Within that overarching organisational framework, the representatives of SNCF Réseau aim to coordinate the planning and design process of the railway project, but they usually require additional expertise to assess its operational performance. For a project involving the modifications of operations at a station, the assessment of a track layout is usually conducted after the design of the infrastructure and operations at the line level. In that context, a study can be conducted to assess:

- The relevance of different track layout designs, combined with different traffic scenarios (rather at a long-time horizon)
- The performance of a track layout under different timetables (rather towards the shorter term)

Once a decision has been made within the "PS&I" framework to launch an infrastructure project, this project still has to be improved by higher instances of the SNCF Réseau. Thus, the agreement of the "National committee for investments and commitments" ("*Comité national des investissments et engagements",* later abbreviated "CNIE") of SNCF Réseau is mandatory. This committee analyses the various aspects of a project, and in particular its operational and socio-economic relevance, as well as its schedule and financial feasibility.

The railway operation studies department of SNCF Réseau can be asked to conduct feasibility assessment studies of the traffic and infrastructure development projects envisaged by the stakeholders taking part in the "PS&I" work platforms. Yet, since this can also be done by other external consultancy firms, depending on the stakeholders' choice, the railway operation studies department also intervenes during the examination of the project by the "CNIE", by providing a formal opinion about the feasibility of the railway operations.

The stakeholders taking part in the "PS&I" work platforms and in the decision-making process within the "CNIE" generally aim to optimise the project so that it satisfies their own interest. For instance, a local transport authority will try to prioritise an increase in the regional trains traffic, while limiting the infrastructure expenses, together with the financial department of the infrastructure manager. Yet, these stakeholders may lack a comprehensive vision of the whole railway system and thus they will not necessarily grasp the negative consequences that their preferences may bring upon other involved parties.

In that context, the goal of the railway operation studies department is to make the decision-makers aware of the consequences of their choices on the whole railway system, and to support design choices that might lead to a better overall performance of the system for all involved stakeholders. Yet, in the case of railway nodes assessment, the railway operation studies department is lacking methods to perform medium to long-term analyses, and therefore it can hardly intervene and exchange with other stakeholders in the early emerging phases of a railway node project.

5.2. Reflection on the methods' strengths and weaknesses, and interest for the involved stakeholders

5.2.1. Methods' strengths and weaknesses

The railway node capacity and performance analysis methods studied in the previous sections of this report work on the basis of different hypotheses and requirements (timetable-free methods and timetable-based methods). They have different strengths and weaknesses, which are summarised in the table below.

		Strengths	Weaknesses
Capacity utilisation methods	Timetable-based UIC 406 method	The capacity utilisation indicator of this method can accurately estimate the real capacity utilisation. Since a train arrival sequence is required, sources of deviation and effects of individual trains on the capacity utilisation can be studied.	A timetable (more specifically, an arrival sequence) is required to apply the method, making it vulnerable to timetable uncertainty. Moreover, the real capacity utilisation can still be subject to changes due to slightly different train arrival sequences in the real operations.
	Timetable-free UIC-adapted method	The capacity utilisation indicator of this method can accurately estimate the real capacity utilisation. Since the method does not rely on a fixed train arrival sequence, it can be applied more easily than the traditional timetable-based UIC 406 method, and is not vulnerable to timetable uncertainty.	No timetable can be examined by this method. Thus, it cannot investigate the effects of different arrival sequences. The computation time of the timetable-free UIC-adapted method is higher than those of the other timetable-free capacity utilisation methods. This is due to the usually high number of train sequences that must be analysed before convergence is reached.
	Potthoff method	The capacity utilisation indicator of this method can estimate the real capacity utilisation with a moderately good accuracy. Compared to the timetable-free UIC-adapted method, the computation time is much lower.	No timetable can be examined by this method. Thus, it cannot investigate the effects of different arrival sequences.
	SNCF-adapted method	-	The SNCF-adapted method for capacity utilisation estimation provides highly underestimated capacity utilisation values. In its current formulation, it does not provide valid evaluation of the capacity utilisation at a node.

Delay propagation methods	Timetable-based UIC-adapted method	The method can provide on average a good approximation of the magnitude of the total delays.	The dispersion of the values provided by the method in comparison with the real ones proved to be high, making the method unreliable.
	Timetable-free UIC-adapted method	The method can provide on average a moderately good approximation of the magnitude of the total delays.	The dispersion of the values provided by the method in comparison with the real ones proved to be high, making the method unreliable.
	Potthoff-adapted method	The method can provide total delays values that are moderately dispersed in terms of relative difference with the real values. Further research can be performed in order to correct the total delays values produced by the method accordingly.	The method's values are underestimating the real total delays on average and their magnitude cannot be exploited immediately.
	SNCF-adapted method	The method can provide total delays values that are moderately dispersed in terms of relative difference with the real values. Further research can be performed in order to correct the total delays values produced by the method accordingly (*a first attempt has been performed in this research*). Furthermore, additional analyses can be conducted by looking at the probabilities of conflicts between each pair of conflicting routes on the node. That way, critical bottlenecks of the investigated switch area can be identified more easily.	The method's values are strongly underestimating the real total delays on average and their magnitude cannot be exploited immediately.

Table 5.2.1.1. Strengths and weaknesses of the railway node capacity and performance analysis methods studied in this research

5.2.2. Interest for the involved stakeholders

The railway operation studies department is primarily interested in tools for the long-term analyses of railway node performance, that can allow it to intervene early in the emerging design and decision-making processes of railway node infrastructure and operations. Then, the department is also interested in having tools that can be easy and quick to apply in the shorter-term horizon, to support already used but more time and resource demanding methods such as stochastic tests. In that regard, the railway node capacity and performance analysis methods studied in this research can help fulfil both railway operation studies department's objectives. The timetable-free approaches are applicable early on in a project as they do not require detailed timetables. Conversely, with more detailed timetable patterns, timetable-based methods can be used to support already used methods, while being quicker to implement and less resource and time consuming.

The other stakeholders involved in a railway project (in particular, those of the "PS&I" work platforms) are frequently asking for a comparison of different traffic and infrastructure scenarios. For railway line projects, the railway operation studies department often offers to make comparison between capacity utilisation rates. Additionally, it has been observed in past project that the various stakeholders working on railway line projects tend to agree upon the relevance of the infrastructure occupation thresholds provided in the *UIC, 2004* [17] leaflet. Therefore, it can be expected that the utilisation of capacity utilisation indicators in the analysis of railway nodes will be understood by stakeholders, and even those that may not be necessarily familiar with capacity engineering otherwise. The railway node capacity and performance analysis methods studied in this report could allow to perform such comparative analyses at the node level, to provide insight in the evolution of the node's capacity utilisation rates under different scenarios.

Yet, sometimes, these other stakeholders do not necessarily ask for particular indicators but would rather seek the advice of the railway operation studies department on a particular situation. In this case, capacity utilisation and delays indicators for railway nodes could be used by the railway operation studies department to support its early qualitative analyses with quantitative figures, and therefore intervene in the emerging discussions surrounding railway node projects. It could then communicate its solutions for better performing nodes to the other stakeholders.

The department is aware that other factors than the operation performance of the railway system will be taken into account and even possibly favoured by the other stakeholders during the planning and design phases. Such factors include financial aspects, for instance regarding infrastructure developments, or also political aspects, for instance when deciding upon increasing the frequency of train services. Furthermore, it is often perceived within the department that the other stakeholders do not always properly interpret the results and the recommendations given in the railway operation studies. This is because these stakeholders may lack knowledge or experience in railway operations. In that context, the ability to provide early quantitative figures in support of qualitative arguments appears to be crucial for the railway operation studies department to defend their arguments and convince the other stakeholders.

5.3. Ideal positioning of the application of the methods within the timeline of a generic project

Based on the description of a project's timeline and the timetable definition process, as well as the analysis of the methods' strengths and weaknesses, the railway node capacity and performance analysis methods studied in this report can be positioned within the timeline of a generic project.

The timetable-free methods (specifically, the timetable-free UIC-adapted method for capacity utilisation assessment and the SNCF-adapted method for delay propagation assessment, with a correction factor) could be utilised in the assessment of emerging and pilot infrastructure and traffic plan designs, at a time horizon ranging from Y-15 to Y-05, using emerging and reference traffic plans. With these methods, the railway operation studies department could provide early quantitative figures to support the design of the infrastructure in the early phases of the project or identify potential issues with the existing or planned infrastructure that would not be detected until later in the project otherwise. Its qualitative arguments could be supported by quantitative figures and could therefore be reinforced in the discussions with the other stakeholders.

Furthermore, it can be noted that using these methods early in the project might suit the other stakeholders, as the broad assumptions taken by the methods (no timetable pattern, only traffic volumes) are more plausible in the long-term horizon, and easier consensus is achievable among stakeholders regarding traffic volumes inputs.

Then, the timetable-based approach (specifically, the timetable-based UIC 406 method for capacity utilisation assessment) could be used in the shorter-term horizon, when more detailed reference timetable plans or even two-hours timetable patterns are available. With this method, the effects of specific timetable scenarios could be studied in more details, which is something that is not possible with the timetable-free methods. Additionally, it can be recommended to use this method for preliminary capacity utilisation assessment of final project designs, prior to performing stochastic tests, around Y-05. Indeed, the interest of such a method for the railway operation studies department and the other stakeholders is also that it is less time and resource demanding than more advanced stochastic tests, and therefore quicker to yield results. Regarding delay propagation assessment, no satisfying timetable-based method was found in this research. Hence, it can be recommended to either continue using the timetable-free method (specifically the SNCF-adapted method for delay propagation assessment, with a correction factor) for the short-term assessment, or rely directly on more detailed methods such as stochastic tests.

It can be noted that applying the timetable-based approach might be favoured by some involved stakeholders that may want to test the effects of specific timetable patterns on the node's capacity and performance. For instance, a local transport authority might be interested in assessing the effects of adding some of its additional train services at specific moments in the timetable.

Yet, it is important to emphasise that the criteria of use of each approach (timetable-based or timetable-free) should not strictly be the time horizon of their application, but rather the level of confidence surrounding the infrastructure and timetable data that is available. If infrastructure data and train arrival patterns at a node can already be estimated with a good level of confidence even in the long-term horizon, then timetable-based methods could be applied already. On the contrary, if train traffic patterns remain uncertain even in the shorter time horizon, then timetable-free methods can be applied to provide first estimates of capacity utilisation and performance, while waiting for more accurate timetable patterns to be fixed.

However, precautions must be taken for this last proposition, as some stakeholders could argue that the timetable-free assumptions (no timetable pattern, only traffic volumes) may be less relevant towards the short-term, especially if some timetables are already being debated.

Finally, as noted before, stakeholders tend to agree upon the validity of the infrastructure occupation thresholds provided in the *UIC, 2004* [17] leaflet for railway line track sections. Therefore, it can be recommended that the railway operation studies department communicates thresholds values of capacity utilisation for railway nodes (found in this research or in a future project) to the other involved stakeholders prior to the start of a study. That way, the analysis of the results will be made on a reference shared and understood by all stakeholders.

5.4. A case study: Bordeaux station

In this subsection, the case study of Bordeaux station is investigated, to observe how the methods could be integrated in the processes of a concrete study.

5.4.1. Description of the situation

The railway network south of Bordeaux Saint-Jean station comprises two branches, towards the cities of Dax (western branch) and Toulouse (eastern branch).

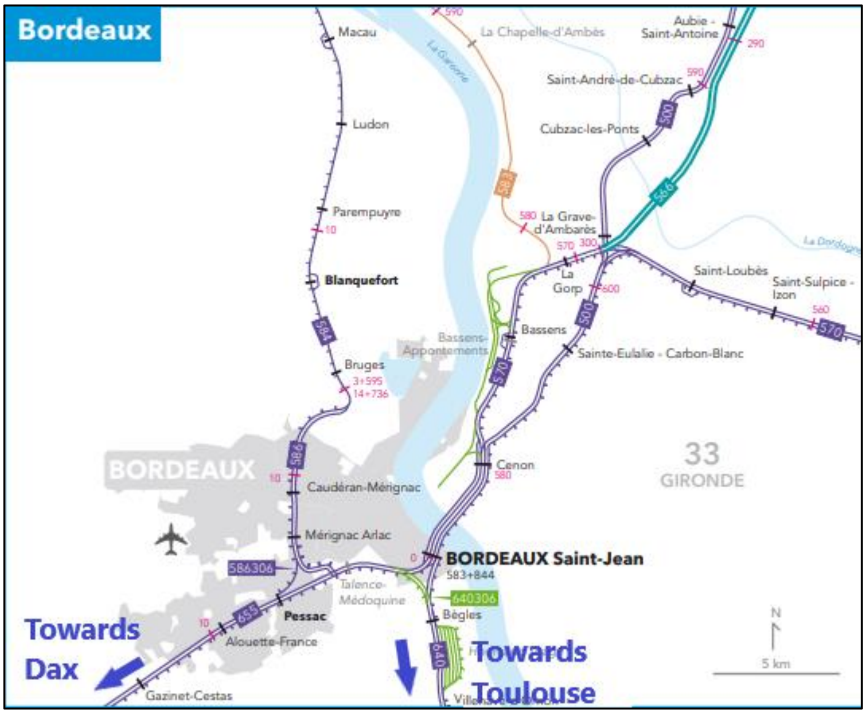


Figure 5.4.1.1. Railway map of Bordeaux

Two major sources of traffic increase in this area are expected in the coming years:

- The implementation of an Express Metropolitan Service (regional equivalent of Paris' RER service) around 2030
- A traffic increase due to the new high-speed lines between Bordeaux and Toulouse, and Bordeaux and Dax (a project that is called "*Grand Projet ferroviaire Sud-Ouest*" – "GPSO")

In that context, infrastructure developments have been planned in the south of Bordeaux Saint-Jean, to support the traffic increase. This infrastructure project is called "AFSB" (*"Aménagements Ferroviaires du Sud de Bordeaux",* literally "railway works south of Bordeaux"). The project aims to add a third track to the line towards Toulouse, in the first kilometres after Bordeaux. Preliminary strategic studies for "AFSB" were launched in 2016, and the infrastructure construction is scheduled to start around 2022-2023. The commissioning of the new infrastructure is expected around 2032.

Two project management structures of SNCF Réseau are working in this area:

- The local territorial directorate of SNCF Réseau, that supervises the implementation of the Express Metropolitan Service
- A national project management structure of SNCF Réseau created for and dedicated to the "AFSB" project

The railway operation studies department was asked by these structures to conduct several studies:

- Starting in 2016: preliminary strategic studies were conducted (socio-economic, environmental assessment, etc.) (outside the railway operation studies department)
- September 2021: selection of the final infrastructure design out of different scenarios, using macro simulation to model the track occupation diagram and the timetable in the southern area of Bordeaux
- Between September 2021 and March 2022: a stochastic study was conducted to assess the robustness of different timetables using the selected infrastructure scenarios.
- Since April 2023: several studies are conducted: analysis of the shunting movements across the southern switch area of the station; studies on lines to and from Bordeaux; etc.

In the recent months, concern has been arising regarding the available capacity of the switch area south of the station. The concern is shared by local stakeholders, that have witnessed difficulties arising in Strasbourg station after the implementation of an Express Metropolitan Service in that city. The railway operation studies department at SNCF Réseau also shares this concern.

Weaknesses in the operation of the southern switch area were already detected during the stochastic study from September 2021 to March 2022. Track layout modifications were proposed to the project management organisation for "AFSB", but they were not chosen for the final infrastructure design. Since then, another study has been launched to assess the feasibility of new shunting movements through the switch area generated by a new maintenance centre in the vicinity of the station.

5.4.2. Positioning of the methods in the study process

It seems that the issues regarding the operation of Bordeaux Saint-Jean station's southern switch area were identified late in the project (that is, almost near the start of the construction of the "AFSB" project, scheduled around 2022-2023). This late warning can be the reason why the recommendations of the railway operation studies department regarding modifications of the track layout were not chosen for the final design of the project. Therefore, it may be argued that quicker analyses conducted earlier in the process could have been beneficial, particularly before launching the stochastic study, to raise the stakeholders' awareness about the issues in the southern switch area of the station.

Additionally, the infrastructure construction phase in this project takes around 10 years. Consequently, only emerging timetable plans could be used to evaluate the final infrastructure design, or reference timetable plans at best (which are usually slightly more reliable). Therefore, it can also be noted that timetable-free methods remain relevant in this case to evaluate the final design of the infrastructure.

Based on these observations and the preceding observations and recommendations in 5.1., 5.2. and 5.3. regarding the methods studied in this report, the following recommendations can be given.

- First analyses with timetable-free methods (the timetable-free UIC-adapted method for capacity utilisation assessment and the SNCF-adapted method for delay propagation assessment) could be conducted early in the project, as soon as emerging timetable plans are available. The quick implementation of the methods could enable the railway operation studies department to provide analyses that can raise the other involved stakeholders' awareness about the criticality of the operations in the southern switch area early in the project, and therefore justify the study of infrastructural designs aimed at fixing potentially expected issues.
- Given the uncertainty still surrounding the timetable plans at the later stages of the infrastructure design, timetable-free methods could still be relevant to assess the later designs of the infrastructure.
- During the assessment of the final design of the infrastructure, using the timetable-based UIC 406 method for capacity utilisation assessment could be relevant to provide first analyses prior to the use of stochastic tests. This could enable the railway operation studies department to provide early analyses to be communicated quickly to the other stakeholders, while waiting for more detailed analyses from the stochastic tests.

As previously mentioned, priority should be given to explaining the values of the indicators produced by the methods, and especially the capacity utilisation thresholds. This is necessary to ensure that the other involved stakeholders do not make misleading interpretations of the results. In a tensed situation such as in Bordeaux (important expected traffic increase, limited infrastructure modifications and deadlines), this aspect appears to be even more crucial, as there is a significant risk of deliberate misinterpretation by some stakeholders that may try to avoid additional infrastructure expanses or deadlines extension, for financial or political reasons. Hence, the railway operation department should make sure that sufficient explanation is given about the methods to the other stakeholders.

6. Conclusion

This conclusion chapter is divided into three parts. First, the subquestions and main research questions formulated at the beginning of the research are answered. Then, reflection on the results of the research is given. In the last part, recommendations to SNCF Réseau are provided.

6.1. Answering the research questions

The objective of this research was to study capacity analysis methods that can enable to assess the relationship between railway node capacity utilisation and performance, with the goal of determining capacity utilisation thresholds associated with levels of performance. The main research question was formulated as:

Which methods can be effectively used to improve the capacity and performance assessment of railway nodes in the long-term planning stages?

A set of subquestions were defined in order to structure the answer to the main research question. The first subquestion was related to the literature and the practitioners' processes.

SQ1. Which methods have been developed in the literature and used by practitioners to study railway node capacity and approach operational performance, and what limitations can be found?

The scientific literature mainly provides line track capacity analysis methods, but several methods to study the capacity and performance of a railway node have also been proposed. These methods can be based on simulation, operational research or more simple analytical approaches, and can be classified on their reliance on a timetable, or not. Yet, the research to assess the link between capacity utilisation values and performance levels is still limited, and so is the comparison between timetable-free and timetable-based approaches. In France, the infrastructure manager SNCF Réseau has mainly been relying on extensive simulation and stochastic studies to assess the performance of railway nodes operations. A few attempts to use capacity utilisation indicators on the routes of a node took place, but these remained limited as little reference was available to interpret these capacity utilisation values. Nowadays, the absence of analytical approach to study railway nodes in the railway operations department's set of methodologies and tools prevents it from taking part in the long-term design and decision-making process of railway nodes. This is particularly true when timetables have a high degree of uncertainty.

SQ2. Which methods can assess the relationship between capacity utilisation and performance indicators in order to identify capacity utilisation thresholds that are critical in terms of performance?

To answer these limitations, this research studied a set of four methods to calculate capacity utilisation indicators for railway nodes, and four methods to assess their performance through the calculation of the delay propagation generated by conflicts between incompatible movements (expressed as "total delays"). These methods have been taken and sometimes adapted from the literature and SNCF Réseau's practices, for the purpose of this research. Among the capacity utilisation assessment methods, the Potthoff method, SNCF-adapted method and timetable-free UIC-adapted method do not require a timetable in their input data, while the original timetable-based UIC 406 method does. Concerning the delay propagation method, the Potthoff-adapted method, SNCF-adapted method and timetable-free UIC-adapted method for delay propagation work without a timetable, and the timetable-based UIC-adapted method for delay propagation necessitates a timetable.

These methods were studied on the case study of the Lyon Saint-Clair junction in Lyon, France. The timetable-free methods were first compared in a verification phase that used artificial traffic data, and then assessed together with the timetable-based methods in a validation phase against indicators calculated from real traffic data.

The result of the verification phase showed that the Potthoff method's capacity utilisation indicator showed a steady average relative difference of 16.6% with the capacity utilisation from the timetable-free UIC-adapted method, for this case study. Potential sources for this difference were outlined and recommendations provided for further investigations. On the other hand, the SNCF-adapted capacity utilisation indicator was more difficult to relate to the other indicators, as it showed low values and dispersed differences with the other methods' indicators. Then, the total delays indicators form Potthoff-adapted and SNCF-adapted methods could be clearly related as their relative difference was around a steady 54.9% on average, for this case study. This could be expected as the methods work on similar principles, with a difference lying in the way the probabilities of conflicts are estimated in each method. The timetable-free UIC-adapted for delay propagation provided values of higher magnitude but varying less rapidly with respect to the increase in traffic.

The comparison with indicators calculated from real traffic data in the validation phase showed that the timetable-free UIC-adapted method, Potthoff method and timetable-based UIC 406 method provided indicators that were close to the real capacity utilisation values. In particular, both timetable-based and timetable-free UIC methods showed low relative differences with the real values on average. This was expected concerning the original timetable-based UIC 406 method, but not for the timetable-free UIC-adapted method. The SNCF-adapted method's capacity utilisation indicator showed a high relative difference with the real values, making it inappropriate for estimating the real capacity utilisation. The relative differences with the real values are moderately dispersed for all methods, but this could be due to differences in the way the recorded headways and the theoretical headways are calculated, and not the methods' processes themselves. To conclude, the results obtained for this case study suggest that the timetable-free UIC-adapted and Potthoff methods seem appropriate to perform timetable-free evaluation of capacity utilisation, while the timetable-based UIC 406 method seems appropriate if timetables can be used.

Then, regarding total delays, the results of this case study showed that the timetable-free and timetable-based UIC-adapted methods gave total delays that were close in magnitude to the real observed values, but also highly dispersed in terms of relative difference, thus diminishing their reliability. The definition of the time interval used for initial delays generation in these methods is still exploratory and requires more investigation. Conversely, the Potthoff-adapted and SNCF-adapted methods gave results that had a low dispersion in relative difference (thus, a better reliability) but a high underestimation in terms of magnitude, compared to the real total delays. This underestimation in magnitude may be due to the methods not taking into account the train arrival sequences, and thus the interdependencies between routes that could lead to delays being propagated between two routes that are not directly in conflict, via common intermediate conflicting routes. To conclude, the results obtained in this case study suggest that none of the method can be used directly to perform delay propagation assessment, but the low dispersion with the real values in the Potthoff-adapted and SNCF-adapted methods can be exploited in an attempt to apply a corrective factor.

The total delays indicator of the SNCF-adapted method showed the lowest dispersion in relative difference with the real values, and therefore the possibility to correct it with a corrective factor has been investigated. This corrective factor is based on the mean relative difference of the method's indicator with the real delays. It is calibrated and validated using two randomly generated halves of the original dataset. The validation of the corrective factor appeared to be satisfactory, and this factor is applied to correct the values of the SNCF-adapted method for the whole dataset.

Then, the relationship between capacity utilisation and total delays is investigated. The study is conducted on an enlarged spectrum of traffic configuration, containing both the observed traffic configurations and the unobserved ones built during the verification phase. For delay propagation assessment, the corrected SNCF-adapted method is used. For capacity utilisation, the timetable-free UIC-adapted method and the Potthoff method are studied. The results obtained for this case study seem to confirm the exponential trend of the functional relationship between capacity utilisation and total delays which was observed in *Armstrong & Preston, 2017* [3]. Finally, a preliminary attempt to study capacity utilisation thresholds was conducted by looking at total delays per train. For this case study, a threshold of 1min/tr is reached at a capacity utilisation of 53.7% for the Potthoff method, or 65.7% for the timetable-free UIC-adapted method. These thresholds for a railway node are lower than the thresholds suggested for railway line tracks in *UIC, 2013* [18], which is also in line with the findings of *Armstrong & Preston, 2017* [3].

SQ3. How can these methods be used to improve the long-term planning of railway nodes?

The timetable-free methods (specifically, the timetable-free UIC-adapted method for capacity utilisation assessment and the SNCF-adapted method for delay propagation assessment, with a correction factor) could be utilised in the assessment of emerging and pilot infrastructure and traffic plan designs, when timetables are still not precise enough or subject to further changes. This would allow the railway operation studies department to provide early assessment on a railway node project and reinforce qualitative arguments with quantitative figures. In that process, potential weaknesses in the emerging plans of the project could already be detected.

The timetable-based method (specifically, the timetable-based UIC 406 method for capacity utilisation assessment) could then be used in later phases of a project, when timetable designs are more reliable, in order to assess final (or close to final) project designs. Compared to timetable-free approaches, the timetable-based approach enables to compare the effects of different timetable arrival sequences on the capacity utilisation level. This kind of capacity utilisation assessment could for instance take place before applying more time and resource-demanding assessment methodologies, such as stochastic studies. That way, assessment of the utilisation of capacity of a railway node could lead to first quantitative analyses before more detailed results are produced. No satisfying timetable-based method was found in this research, therefore it is recommended to use a timetable-free approach (the SNCF-adapted method for delay propagation with a corrective factor) also in the short-term assessments, or use more detailed methods such as stochastic tests.

Yet the decision to use one approach or another should primarily rely on the data that is available. The timetable-based UIC 406 method for capacity utilisation assessment could already be used in the long-term horizon if the confidence surrounding the timetable is high. Conversely, the timetable-free approaches can be used even close to the final steps of the project's design, if uncertainty regarding the timetable remains high.

The last subquestion referred to recommendations that could be provided to SNCF Réseau and other infrastructure managers that may want to use these assessment methods. These recommendations will be summarised in 6.3, after reflection is given in the next paragraph, 6.2.

Finally, the main research question "*Which methods can be effectively used to improve the capacity and performance assessment of railway nodes in the long-term planning stages?*" can be synthetically answered as follows. The timetable-free methods (timetable-free UIC-adapted method for capacity utilisation, Potthoff method for capacity utilisation, corrected SNCF-adapted method for delay propagation) can provide results that are relevant in the magnitude and trends for the long-term assessment of railway node capacity utilisation and performance. Then, if timetables are available in the long-term, or if there is the need to study the effects of different timetable patterns on capacity utilisation and performance, timetable-based approaches can be used. No satisfactory timetable-based delay propagation method was found in this research. Hence it is recommended to continue with the currently used simulation approach or use the timetable-free corrected SNCF-adapted method for delay propagation if quick evaluation is needed. Concerning capacity utilisation, the original timetable-based UIC 406 method can be used to provide relevant capacity utilisation values and study different timetable patterns.

6.2. Reflection

All in all, the results of this research must be considered preliminary results that should be reinforced by further studies before the methods are incorporated in the infrastructure manager’s set of tools for the evaluation of railway nodes capacity utilisation and performance.

The findings of this study should further be reinforced by analyses performed on more extensive traffic data. The available real data was limited, and furthermore only available for June 2021, when the COVID-19 pandemic still imposed a limited traffic. Therefore, only a limited range of traffic situations could be observed in this study, and these were usually of lower densities than the ones that have been operated after 2021. In particular, more extensive data would be required to better assess the functional relationships between capacity utilisation and total delays, as well as critical thresholds of capacity utilisation. More precisely, the capacity utilisation and total delays indicators resulting from more recent denser traffic configurations should be evaluated.

Moreover, the findings of this study could be further developed and enriched by studying different track layouts. The case study of Lyon Saint-Clair was appropriate for this study because it gave an interesting layout situation with available data on a prolonged period of one month. The absence of stops in the immediate vicinity of the area made it possible to observe delay values that were only related to train conflicts. Yet, several other track layouts should be studied to assess the functional relationship between capacity utilisation and total delays more in depth, and to see if there are differences in the values observed for different track layouts.

6.3. Recommendations

The ideal positioning of application of the different methods was outlined in the prior paragraphs. Yet, further work might be needed prior to implementing them in real studies.

As mentioned before, a first necessary step is to continue the study of the methods on different track layouts and with more varied real traffic data. This will enable a more precise assessment of the methods, for different infrastructure settings and denser traffic. This step seems mandatory before applying the methods in real studies. Such further studies could preferably be performed on railway nodes with extensive available traffic data. Yet, if data sources are lacking, it can also be envisaged to perform first additional analyses using simulation software with models that were deemed to realistically represent the observed train operations in previous studies.

Further studies could also try to improve the formulation of the UIC-adapted methods for delay propagation. The results of the case study of Lyon Saint-Clair showed that these methods could interestingly provide total delays indicators of magnitude close to the real values, but unfortunately with a high dispersion. Attempts could be made to improve the definition of the time intervals from which the initial delays are drawn.

Other knowledge that could be brought by additional studies is linked to the perimeter taken for the assessment of the delays engendered by train conflicts at the node. In this research, the perimeter where delays were generated due to conflicts with other trains was taken as the block prior to the signal protecting the switches. This does not allow to capture delays that might be accumulated on upstream blocks due to the queuing of trains, and on downstream blocks due to the trains having to reaccelerate after a conflict and thus run under their scheduled speed. Yet, observing these delays could help achieve a better definition of critical capacity utilisation thresholds. To solve this issue, the perimeter taken for the collection of real delays could be extended to a few blocks prior to the protecting signal, and to a few subsequent ones. However, it must be noted that collecting delay data that way will not make it comparable with the outputs of the delay propagation methods. Indeed, these methods are defined to calculate the delay occurring on the last block prior to the junction. Therefore, collecting real data on this extended perimeter would only be useful to better assess the capacity utilisation thresholds with real delay data.

Once the previous items have been completed, the methods can be incorporated within the railway operation studies department’s set of tools and methodologies to assess railway nodes. It is then recommended to communicate a brief description of the methods to the stakeholders using their outputs in the design of railway node projects. More specifically, communicating on the different capacity utilisation thresholds seems important to ensure a good understanding of their meaning, and avoid misinterpretation of the results.

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Cover picture: switch area in front of Lyon Perrache station (Lyon, France), retrieved from https://patrimoine.auvergnerhonealpes.fr/dossier/IA69000834

The railway maps presented in this document are published by SNCF Réseau, and can be found at https://www.sncf-reseau.com/fr/carte/carte-reseau-ferre-en-france

Appendix

Appendix A: Scientific paper

Improving the capacity and performance assessment of railway nodes on the French network

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Abstract. Capacity and performance (evaluated through delay propagation) analysis methods have mostly focused on railway line track sections, but less attention has been given to nodes. Still, a few analytical methods for the capacity and performance assessment of the switch areas between station platform tracks and line tracks can be classified upon their reliance on a timetable ("timetable-based" methods) or not ("timetable-free" methods). The relation between capacity utilisation and performance has rarely been tested for railway nodes, and critical capacity utilisation thresholds remain to be investigated. The comparison of timetable-based and timetable-free methods also needs to be conducted. Filling these knowledge gaps will help the French infrastructure manager SNCF Réseau improve its analyses of nodes capacity utilisation and performance in the long-term planning stages. This paper investigates a small set of timetable-based and timetable-free methods either taken and adapted from the literature, such as the Potthoff and UIC 406 methods, or developed for the need of this research, such as adaptations of the UIC method and a method developed from SNCF Réseau's previous works. The methods are applied on a case study on the French network, first evaluating their indicators' magnitude and trends with artificial traffic data, and then comparing their outputs to real data. It is found that the Potthoff method and a timetable-free UIC-adapted method for capacity utilisation evaluation and an SNCF-adapted method for delay propagation provided results that are relevant in terms of magnitude and trends for long-term assessment. The timetable-based UIC 406 method for node capacity utilisation assessment can be used to study specific timetables. No satisfactory timetable-based delay propagation method was found in this paper. The timetable-free methods are further used to study the capacity utilisation – delay propagation relationship, which takes the form of an exponential function. Attempts to determine capacity utilisation thresholds are also conducted. It is recommended to perform further research with extended traffic data on different node layouts to consolidate these preliminary findings before applying them in real studies.

I. Introduction

Railway networks can be conceptualised as sets of railway nodes (that are, railway stations or junctions) linked together by railway track sections. With increasing demand, infrastructure saturation tends to arise. Thus, assessing railway node capacity is critical as they tend to be the bottlenecks of the network. While most capacity analysis methods have focused on railway line track sections, nodes have been given less attention. Still, a few analytical methods have been developed for railway nodes assessment, and in particular for the assessment of switch area capacity. In this paper, and unless stated otherwise, *railway nodes* will designate these switch areas that link the platform tracks of stations with the line tracks. These analytical methods can be classified depending on their reliance on a timetable ("timetable-based" methods) or not ("timetable-free" methods). Yet it is not clear how timetable-based and timetable-free methods compare when assessing railway nodes capacity utilisation and performance in the long-term planning horizon. The term *performance* here refers to the delay propagation happening at a node. Furthermore, it appears the relation between capacity utilisation and performance has rarely been tested for railway nodes, while capacity utilisation values are better linked to performance thresholds for railway line track sections thanks to shared reference values, such as the ones proposed in *UIC, 2004* [16]. In that context, the railway operation studies department of the French railway infrastructure manager SNCF Réseau currently lacks knowledge and tools to provide first evaluations of the capacity utilisation and quality of train operations at a railway node in the long-term planning process. Additionally, its analyses can be hindered by the uncertainty surrounding the actual realisation of the timetable patterns available in the long-term horizon. This paper aims to analyse and compare a small set of timetable-based and timetable-free methods in order to determine which ones could be effectively used to improve the capacity and performance assessment of railway nodes in the long-term planning stages. The methods are either taken and adapted from the railway operations science literature or developed for the purpose of this research. The methods are evaluated on a case study node of the French railway network in a two-step process. First, a verification process is set to assess the methods' outputs using artificial traffic data inputs. Then, the methods are compared based on their ability to reproduce indicators obtained from real traffic data, and the best performing methods are further used to study the capacity utilisation – performance relationship as well as capacity utilisation thresholds. The remainder of this paper is structured as follows. Chapter II reviews the scientific literature on railway node capacity utilisation and performance assessment. Then, in chapter III, the methods are described in detail and the evaluation process is outlined. Chapter IV presents the results of this evaluation process, and finally chapter V gives a conclusion and reflection perspectives on the subject.

II. Literature review

The definition of the capacity of a railway infrastructure can vary depending on the sources. The definition of a "practical" capacity is given in *Hansen & Pachl, 2008* [8] as the maximum number of trains that can use the infrastructure while respecting operation constraints such as timetable structure. Then, *capacity utilisation* can be defined as the extent to which the maximum capacity of a railway infrastructure is being used. *UIC, 2004* [16] calculates capacity utilisation as the ratio between the occupancy time of the train paths, to which are added time supplements, divided by the duration of the studied time period. Most methods investigate the capacity of railway line track sections, while not necessarily being applicable to railway nodes (*Lindner, 2011* [11]). Although less numerous than methods focusing on line track sections, several node capacity and performance analysis methods have been applied and developed in the literature. *Crenca et al., 2005* [6] and *Bažant et al., 2018* [3] distinguish analytical methods that rely on the application of formulas and provide general information for network planning, and simulation methods that give detailed outputs through a replication of the dynamics of the real systems. *Weik et al., 2020* [18] introduces another classification, differentiating methods that rely on a timetable ("timetable-based" methods") and those that do not ("timetable-free" methods) and instead use coarser information such as traffic volumes. While timetable-based methods tend to be more adapted for short-term assessment when reliable timetables are available, timetable-free methods can be used at medium or long-term horizons to perform strategic planning analyses.

Most timetable-based methods for capacity analysis rely on the principle of timetable compression. In particular, the publication of UIC Code 406 (*UIC, 2004* [16]) led to a widespread sharing and usage of the timetable compression approach for railway capacity analysis. Yet, UIC 406 was mostly focused on the analysis of line track sections, and discussions emerged on its applicability to railway nodes. In 2013, a second edition of UIC Code 406 was published (*UIC, 2013* [17]) adding to the previous version an adaptation of the timetable compression method for station and junction areas. This adaptation takes into account the incompatibility between conflicting routes. Other timetable compression approaches for railway nodes have been developed, such as in *Bešinović & Goverde* [4] where the authors use a max-pls automata model to assess the capacity utilisation of railway node.

In parallel to the development of capacity methods relying on timetable patterns, other methods using coarser timetable-free input data have been created. Potthoff's method (*Potthoff, 1963-1972* [14]) enables a global quantitative analysis of a node's capacity utilisation. The method assumes a random arrival of trains over the studied period and uses the matrix of headways between incompatible routes and the traffic volumes per routes to calculate an average number of simultaneous train movements and an average headway between incompatible routes. This leads to the calculation of a capacity utilisation indicator. The method of *Corazza & Musso, 1991* [5] shares similarities with Potthoff's, as it follows the same process. However, in this method the estimation of the average number of simultaneous movements and average headway between incompatible routes is made differently and takes into account the probability of occurrence of different combinations of simultaneous movements. More recently, *Landex & Jansen, 2013* [10] presented a set of methods that can be used to analyse a railway node with "track complexity" indicators. Their methods range from the sole consideration of the routes' topology to the inclusion of train traffic volumes and finally timetable patterns. Timetable-free analytical models also entail queuing theory models. In that area, *Niessen, 2008* [13] studied the capacity of route nodes via a multiresource queue approach, modelling the route nodes as multichannel systems where two or more trains could run simultaneously, and computing their theoretical capacity by maximising the arrival throughput in a linear programming approach.

Besides capacity utilisation analysis, methods can also aim to assess the performance of a node through its tendency to propagate delays between trains. The Potthoff's timetable-free method presented previously incorporates an estimation of the total delay produced conflicting interactions of trains and was further improved by the Deutsche Bahn (*Deutsche Bahn, 1979* [7]) which incorporated a priority hierarchy between routes. When the only purpose lies in assessing performance, other tools can be used such as the queinuing theory's Pollaczek & Chintschin formula to compute the mean waiting time at a route node (*Hansen & Pachl, 2008* [8]. Regarding timetable-based approaches, *Yuan & Hansen, 2006* [20] proposed a detailed modelling of the propagation of knock-on delays of trains at a station in order to optimise the utilisation of its capacity. Finally, outside the scope of analytical methods, it is interesting to mention simulation-based approaches with tools such as RailSys (*Radtke & Hauptmann, 2004* [15]) or OpenTrack (*Nash & Huerlimann, 2004* [12]) that allow to reproduce the dynamics of the system and evaluate delay propagation.

Finally, several sources support the relevance of a link to be made between capacity utilisation and performance. *UIC, 2013* [17] suggested some capacity utilisation limits for switch areas analysis, that still need to be thoroughly investigated in follow-up studies. A link is made between capacity utilisation at node and the knock-out delays in *Armstrong & Preston, 2017* [2]. Using an adapted version of the British's CUI capacity analysis methodology for nodes (*Armstrong & Preston, 2012* [1]), the authors found an exponential relationship between capacity utilisation and delays, for several stations in the United Kingdom. Finally, in *Yuan & Hansen, 2006* [20] an exponential relationship was also found between modelled knock-out delays propagated a railway node and the buffer times set between conflicting trains.

III. Methodology

III.1. Description of the methods

This paper studies four capacity utilisation analysis methods and four delay propagation analysis methods for railway nodes. The methods are reviewed and adapted from the literature and SNCF Réseau's previous studies or developed for the need of this research.

III.1.1. Capacity utilisation methods

III.1.1.1. Timetable-free Potthoff method for capacity utilisation analysis

The Potthoff method for capacity utilisation analysis does not require a timetable and assumes trains can arrive at any moment of a studied time period of duration T. The method requires the matrix of incompatible routes on the node, the minimum headway $t_{min,ij}$ between incompatible routes i and j and the traffic volumes n_i per route i. In this research, headway supplements b_{ij} are added to the minimum headways, and headways $t_{ij} = t_{min,ij} + b_{ij}$ are used. The procedure starts by calculating an average number of simultaneous movements n_{mean}, which is calculated as $n_{mean} = \frac{N^2}{\sum_i \sum_{j\ conflicting\ with\ i}\ n_i n_j}$. Then, an average headway between conflicting routes t_{mean} is calculated as $t_{mean} = \frac{\sum_{i,j} n_i n_j t_{ij}}{\sum_{i,j} n_i n_j}$. A number of trains belonging to a virtual critical sequence of paths is further calculated as $\frac{N}{n_{mean}}$, and the occupation time over the studied B period equals $B = \frac{N}{n_{mean}} \times t_{mean}$. Finally, the capacity utilisation rate U is calculated as $U = \frac{B}{T}$.

III.1.1.2. Proposed timetable-free SNCF-adapted method for capacity utilisation analysis

A railway node analysis method punctually used at SNCF Réseau consists in estimating the probabilities of conflicts of trains running over the conflicting routes of a node. This research further adapts this approach by proposing a method that calculates a capacity utilisation indicator. The overall process is similar to Potthoff method, as an average number of simultaneous movements n_{mean} and an average headway between conflicting routes t_{mean} are calculated. However, their formulation differs, as it is based on the average number of conflicts $E(X_{ij})$ that can occur between incompatible routes i and j (if i and j are compatible, then $E\left(X_{ij}\right) = 0$). Here, X_{ij} is a random variable that counts the number of conflicts k that can occur between trains on incompatible routes i and j. X_{ij} follows an hypergeometric distribution, and thus the probability of k conflicts occurring between i and j is calculated as: $P\left(X_{ij} = k\right) = \frac{\binom{n_j}{k}\binom{N_{ij}-n_i}{n_i-k}}{\binom{N_{ij}}{n_i}}$, where $N_{ij} = \frac{\bar{t}_{min,ij}}{T}$ is the total number of paths that can use the conflicting section shared by i and j over the course of T. $\bar{t}_{min,ij}$ is the weighted average of the minimum headways $t_{min,ij}$ and $t_{min,ji}$: $\bar{t}_{min,ij} = \frac{n_i}{n_i+n_j} t_{min,ij} + \frac{n_i}{n_i+n_j} t_{min,ji}$. The average number of simultaneous movements is equal to $n_{mean} = \frac{N}{\sum_i n_i \times \frac{\sum_j E\left(X_{ij}\right)}{\sum_i \sum_{j \geq i} E\left(X_{ij}\right)}}$, and the average headway between conflicting routes is $t_{mean} = \frac{\sum_{i,j} E(X_{ij}) t_{ij}}{\sum_{i,j} E(X_{ij})}$. Finally, the occupation time over the studied B period equals $B = \frac{N}{n_{mean}} \times t_{mean}$, and the capacity utilisation rate U is calculated as $U = \frac{B}{T}$.

III.1.1.3. Timetable-based UIC 406 method for capacity utilisation analysis

The railway node capacity utilisation assessment method described in this section has been published in the second edition of UIC Code 406 (*UIC, 2013* [17]) which presented a timetable compression method for railway nodes. In this paper, the procedure presented for analysing switch areas' capacity is used. The required data are made of the route compatibility matrix over the studied node, the headways between incompatible routes and the sequence of arrivals of the trains given by the timetable. In this paper, the headways comprise both the minimum headways and headway supplements. An iterative process is used to determine a critical sequence of paths between the beginning and end of the studied time period. Each train path is allowed to start at a minimum starting time calculated based on the preceding trains and the headways they impose on following trains. When all trains of the timetable sequence have been added, *UIC, 2013* [17] recommends repeating the first train of the sequence at the end. This is relevant for cyclic timetables, in which the first train of a sequence is indeed the first train of the sequence of the next time period. Yet, the timetables used on the French network are mainly acyclic. Therefore, following the recommendation of *Jensen et al., 2017* [9], no train is repeated at the end of the sequence, and the occupation time is calculated as the maximum of all starting times in the compressed timetable. Finally, the capacity utilisation is equal to the ratio of the occupation divided by the duration of the studied time period. A detailed example of the application of the method can be found in Appendix A of *UIC, 2013* [17].

III.1.2. Delay propagation methods

III.1.2.1. Proposed timetable-free Potthoff-adapted method for delay propagation assessment

The Potthoff method introduced in *III.1.1.1.* also performs a delay propagation assessment, by calculating a total delays indicator $R_{tot} = \sum_i \sum_{j\ conflicting\ with\ i} R_{ij}$. Here, R_{ij} is the total delays of trains on route j conflicting with trains on route i. R_{ij} is calculated as $R_{ij} = \frac{n_i t_{min,ij}}{T} \times \frac{t_{min,ij}}{2} \times n_j$, where $\frac{n_i t_{min,ij}}{T}$ is the probability for a train running on route j to be hindered by a train on route i over the course of T. If a conflict occurs, the train on j can wait for a time ranging from (almost) 0 to $t_{min,ij}$. Given that trains arrival is assumed to be random, a conflict will lead to j waiting on average for $\frac{t_{min,ij}}{2}$.

In this paper, an attempt is made to improve Potthoff's approach by adapting it to take into account the longer headways due to trains having to restart after a stop at a red signal. Trains on a route i can also conflict with other trains on different routes. If this occurs, they will impose longer headways $t_{restart,ij}$ to the trains after them, due to their lower speed after restarting. In this research, these $t_{restart,ij}$ are computed assuming the trains start at a null speed after stopping due to a red signal. Therefore, the idea in this adapted version of the Potthoff method is to change $t_{min,ij}$ in the R_{ij} formula by a weighted minimum headway $t_{mix,ij}$ that balances $t_{min,ij}$ and $t_{restart,ij}$. This weighted minimum headway is calculated as $t_{mix,ij} = P_i t_{restart,ij} + (1 - P_i) t_{min,ij}$, where P_i is the probability for a train on i to suffer at least one conflict: $P_i = \sum_{j \; in \; conflict \; with \; i} \frac{n_j t_{min,ji}}{T}$. Finally, R_{ij} is rewritten as $R_{ij} = \frac{n_i t_{mix,ij}}{T} \times \frac{t_{mix,ij}}{2} \times n_j$.

III.1.2.2. Proposed timetable-free SNCF-adapted method for delay propagation assessment

The SNCF-adapted method introduced in *III.1.1.2.* is further developed to calculate a total delays indicator $R_{tot} = \sum_i \sum_{j \; conflicting \; with \; i} R_{ij}$. Here, $R_{ij} = E(X_{ij}) \frac{t_{mix,ij}}{2}$. The idea is the following. Given a pair of conflicting routes i and j, the use of the hypergeometric distribution leads to the calculation of an average number of conflicts $E(X_{ij})$ occurring between trains on i and j. This average number of conflicts is then multiplied by the average waiting time resulting from a conflict. Similar to the assumption taken in the Potthoff-adapted method, the average waiting time of a train on j conflicting with a train on i is taken as $\frac{t_{mix,ij}}{2}$. Here again, $t_{mix,ij}$ is a weighted minimum headway that balances $t_{min,ij}$ and $t_{restart,ij}$: $t_{mix,ij} = P_i t_{restart,ij} + (1 - P_i) t_{min,ij}$. However, the calculation of P_i is different: $P_i = 1 - \prod_{j \; in \; conflict \; with \; i} P(X_{ij} = 0)$.

III.1.2.3. Proposed timetable-based UIC-adapted method for delay propagation assessment

This section presents a method built for the purpose of this research, that aims to compute the total delays generated by conflicts at a node, knowing the arrival sequence of trains given by a timetable. The difficulty of building such a method lies in defining initial delays in such a way that the method can still compared with the Potthoff-adapted and SNCF-adapted methods. It is chosen to follow a mixed approach to formulate a timetable-based delay propagation procedure, that will account for the knowledge about the train arrival sequence while still incorporating some random initial delays. The procedure consists of four steps:

- Step 1: a basic timetable is constructed by spacing the trains in the planned arrival order specified in the timetable, according to the headways between conflicting routes (taking into account the minimum headways plus supplements).
- Step 2: Each train can suffer an initial delay. This initial delay is drawn from a uniform distribution over a restricted time interval the train's arrival time in the basic timetable. The restricted time interval is defined such that the initial delays are not too large in magnitude while still being able to lead to conflicts between trains and thus delay propagation. The restricted timetable interval for a given train is defined with:

- Lower bound: minus half the headway separating the train from its first conflicting preceding train
- Upper bound: plus the headway separating the train form its first conflicting following train.

This definition allows a train to arrive early, but to a lesser extent than late. At the end of step 2, a delayed timetable is obtained.

- Step 3: The delayed timetable is rectified. Each train's starting time is checked in the initial arrival order and corrected so that minimum headways between conflicting trains are respected again. Furthermore, if the starting time of a train on a route i is modified (that is, if it has to stop and gets delayed due a conflict with a preceding train), this train will further impose a minimum headway $t^*_{min,ij} = t_{restart,ij}$ to any following train on a conflicting route j. Otherwise, this minimum headway stays at $t^*_{min,ij} = t_{min,ij}$. Formally written, for a given train numbered l in the arrival sequence, the starting time $T_{rectified,m}$ of any of its successors $m > l$ has to verify the following condition: $T_{rectified,m} \geq t^*_{min, \; route(l),route(m)} + T_{rectified,l}$. If it is not the case, then

$T_{rectified,m}$ has to be increased (i.e., train m is delayed) so that the condition holds again. This delay propagation process works on the assumption that no regulation rules are applied, and that the trains are processed according to their scheduled arrival order.

- Step 4: Finally, the total delays are computed as the sum over all trains of the difference between a train's starting time in the delayed (step 2) and rectified (step 3) timetables.

Steps 2 to 4 are repeated over a certain number of draws of initial delays. An average total delays value over all draws is then computed. Taking inspiration from *Jensen et al., 2017* [9], the number of draws of initial delays is successively increased in an iterative process until convergence is achieved, that is when the averaged total delays over all draws does not significantly change anymore.

The definition of the basic timetable in step 1 and the restricted time interval used in step 2 are primary attempts to achieve a functioning method. It can be argued that spacing the trains in the basic timetable according to the headways between conflicting routes (minimum headways plus supplements) could lead to overestimating the number of conflicts as in reality time spacing can be bigger. On the other hand, the restricted time interval from which the initial delays are drawn in step 2 is also defined based on these headways, thus the initial delays' magnitude is limited and adapted to the initial time spacing. Therefore, it can be expected that a balance is achieved: the initial time spacing is smaller than in reality, but the initial delays' magnitude is also limited.

III.1.3. Proposed timetable-free adaptation of the UIC methods

The timetable-based UIC 406 method for capacity utilisation analysis and UIC-adapted method for delay propagation assessment are expanded with a timetable-free version. Thus, two additional timetable-free methods are obtained: a "timetable-free UIC-adapted method for capacity utilisation assessment", and a "timetable-free UIC-adapted method for delay propagation assessment". This paragraph describes the functioning of both adaptations, which are similar.

The methods are adapted into timetable-free methods: no timetable is required anymore, but instead random train arrival sequences are generated and given as inputs to the algorithm of each timetable-based methods. Then, an average indicator (capacity utilisation or total delays, depending on the method) is calculated. Taking inspiration from *Jensen et al., 2017* [9], this process is generated for an increasing number $n_{sequence}$ of random arrival sequences, until convergence in the averaged indicator value is achieved. Convergence is considered to be achieved when the averaged indicator does not vary significantly over a certain number of $n_{sequence}$ increase. By "random train arrival sequences", it is meant that the sequences are created by randomly selecting train orders permutations. Thus, this generation process does not guarantee the representativeness, nor the realism of each drawn sequence taken individually, but the utilisation of a convergence criterium for calculating the averaged indicator value aims to compensate for this.

III.2. Description of the evaluation process

The evaluation of the studied methods is conducted in two steps, on a selected case study described in chapter IV. The first step of the evaluation process is the verification step, where the timetable-free methods are tested using artificial traffic data. The objective of this verification step is to assess and compare the magnitude and trends of each methods' indicator. Then, the second step of the evaluation process is the validation step: timetable-free and timetable-based methods are compared on their ability to reproduce capacity utilisation and total delays indicators computed with real traffic data. The relative differences between the methods and the real values are assessed to determine which methods can best estimate the real values. Finally, the best performing methods are used to assess the total delays-capacity utilisation relationship. Critical thresholds of capacity utilisation are investigated according to the corresponding levels of total delays dived by the number of trains (total delays per train). These total delays per trains can be calculated with one the methods or with the real total delays if no method could reliably forecast the real total delays.

IV. Application and results

IV.1. Description of the selected case study

The chosen case study must allow to observe the delays occurring due to conflicting trains. Choosing a switch area located in front of a station's platform tracks would not allow to distinguish the delays generated to conflicts between trains from delays occurring because of external causes at a station (such as late crew members, overcrowding on the platforms, etc). Thus, the case study shall be a switch area far enough from platform tracks, but still in the vicinity of a station so that the results obtained can be relevant for such areas. Based on these requirements, the selected case study is the level junction of Lyon Saint-Clair, that marks the northern entrance of the station area of Lyon Part-Dieu station.

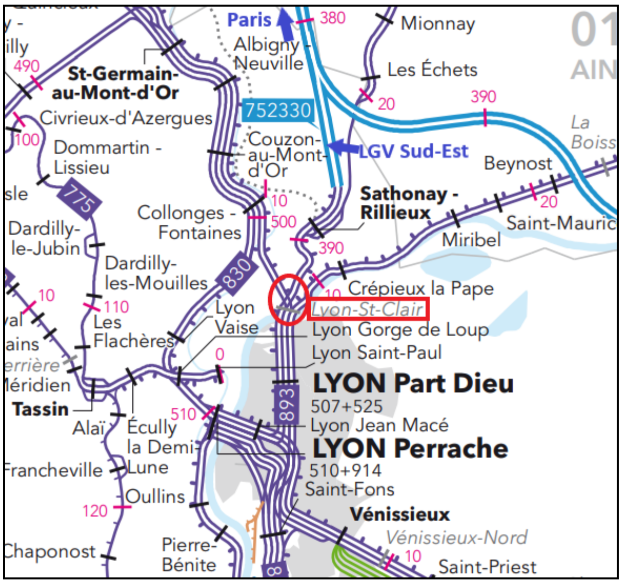


Figure IV.1.1. Location of the Lyon Saint-Clair junction

This junction is at the crossroad of three major lines: the historical line "Paris-Lyon-Marseille" line, the "LGV Sud-Est" high-speed line towards Paris, and the line towards Geneva, Switzerland. Due to the significant traffic to and from Lyon Part-Dieu, it is considered a major bottleneck of the regional network around Lyon. Figure IV.1.2. depicts the routes on the studied area and Table IV.1.1. gives the route compatibility matrix.

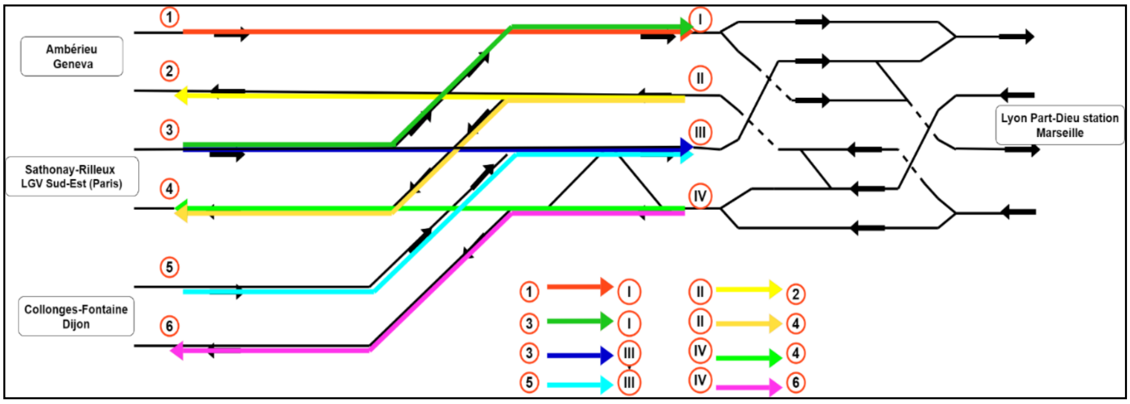


Figure IV.1.2. Studied area and conflicting routes

	1 - I	3 - I	3 - III	5 - III	II - 2	II - 4	IV - 4	IV - 6
1 - I	a	c	.	.	.	.	.	.
3 - I	c	a	d	.	x	.	.	.
3 - III	.	d	a	c	.	x	.	.
5 - III	.	.	c	a	.	.	x	.
II - 2	.	x	.	.	a	d	.	.
II - 4	.	.	x	.	d	a	c	.
IV - 4	.	.	.	x	.	c	a	d
IV - 6	.	.	.	.	.	.	d	a

Table IV.1.1. Route compatibility matrix (a: same route; c: converging routes; d: diverging routes; x: crossing routes)

IV.2. Data used

IV.2.1. Data sources

The infrastructural data (tracks, switches, signalling, speed) was collected from SNCF Réseau's technical documentation. The minimum headways are calculated on SNCF Réseau's technical norms for the BAL signalling system ("*Block automatique lumineux"*, 3-aspects block signalling system). Realised traffic data was collected from the track occupation data recorded by the local computerised control unit, from 31st May to 30th June 2021. Three time periods were considered for each day, each lasting three hours: morning peak (6:30-9:30), evening peak (16:30–19:30) and off-peak period (10:15-13:15). Data could not be collected for the 5th, 13th, 24th and 27th in the morning peak. Off-peak data was not available on 24th June either. In total, the dataset of real values contained 88 observations.

IV.2.2. Headways calculation

The minimum headways between conflicting routes are calculated with SNCF Réseau's technical norms from the entry signals of each route, that are, the signals protecting the switches. The restarting headways used in the delay propagation methods are calculated by assuming a null speed of the trains at the entry signals.

Three types of trains are considered: high-speed TGV passenger train; regional TER passenger train; freight train. Their characteristics are given in Table IV.2.1.1. below. Constant deceleration and acceleration factors are considered for simplification.

	TGV	TER	Freight trains
Length	200m	100m	750m
Acceleration rate	0.5m/s²	0.5m/s²	0.15m/s²
Braking rate	0.6m/s²	0.6m/s²	0.5m/s²

Table IV.2.1.1. Rolling stock technical data

Headway supplements are calculated according to SNCF Réseau's practices as: $Headway\ supplements = \chi + m$, where χ is a timetable margin at SNCF Réseau ($\chi = 30s$) and m is a rounding margin that depends on the train types ($m = 15s$ if the first and second trains are passenger trains, $m = 30s$ if at least one of them is a freight train).

In the verification phase, the timetable-free methods use headways and headways supplements that are calculated based on the assumption of 75% of passenger trains traffic and 25% of freight traffic. Furthermore, regarding the passenger trains, the traffic on the Lyon-Ambérieu and Lyon-Collonges branch is assumed to be made of TER trains, while the traffic on the Lyon-Sathonay branch is made of TGV trains. In the validation phase, the timetable-based methods make use of the type of each train given in the planned timetables, while the timetable-free methods use the percentages of train types on each route given in the planned timetables.

IV.2.3. Real indicators calculation

Recorded delay data of each train is computed as the variation of the differences to the scheduled passing times at the edges of the block preceding the entry signal. Realised total delays are the sum of each train's delay. Then, taking inspiration from *Yuan & Hansen, 2004* [19], the real capacity utilisation is computed by compressing the realised timetable to the minimal headways between trains, obtained with the realised blocking times, plus the time during which the routes were set and reserved for an incoming train. The occupation time is the maximum starting time in the compressed timetable. These realised capacity utilisation and real total delays are computed for each observation point.

IV.2.4. Computational parameters

The "UIC" methods make use of the following parameters:

-Timetable-based UIC-adapted method for delay propagation assessment: the increase step of draws of initial delays is equal to 5; the calculation process stops when the total delays averaged over all initial draws has not changed for more than 10% after 3 successive increases in the number of initial delays draws.

-Timetable-free UIC-adapted method for delay propagation assessment: the increase step of draws of arrival sequences is equal to 10; the calculation process stops when the total delays averaged over all arrival sequences draws has not changed for more than 10% after 3 successive increases in the number of arrival sequences draws.

-Timetable-free UIC-adapted method for capacity utilisation assessment: the increase step of draws of arrival sequences is equal to 10; the calculation process stops when the total delays averaged over all arrival sequences draws has not changed for more than 5% after 3 successive increases in the number of arrival sequences draws.

The methods are implemented using Python 3.9.13. The Python scripts are run on a Windows 10 laptop with an Intel Core i5-10210U processor and 8GB of RAM.

IV.3. Results of the verification step

IV.3.1. Artificial traffic data

A range of traffic volumes is tested, as summarised in Table IV.3.1.1. below. In total, 125 traffic combinations are tested.

	Lyon-Ambérieu	**Lyon-Sathonay**	**Lyon-Collonges**
Routes	1-I ; II-2	3-I ; 3-III; II-4; IV-4	5-III; IV-6
Traffic variation per route	From 4 to 20 (increase steps: +4)	From 2 to 10 (increase steps: +2)	From 4 to 20 (increase steps: +4)
Traffic variation on the whole branch	From 8 to 40	From 8 to 40	From 8 to 40
Average traffic on the whole branch	24	24	24

Table IV.3.1.1. Set of traffic combinations used in the verification step

IV.3.2. Results

<u>IV.3.2.1. Assessment of the timetable-free capacity utilisation analysis methods</u>

Figure IV.3.2.1.1. displays the capacity utilisation indicators of the three timetable-free methods with respect to the level of a traffic of the Lyon-Ambérieu branch. The two other branches are kept at their average traffic values (24). Similar figures are obtained showing the variation of the traffic on the other two branches.

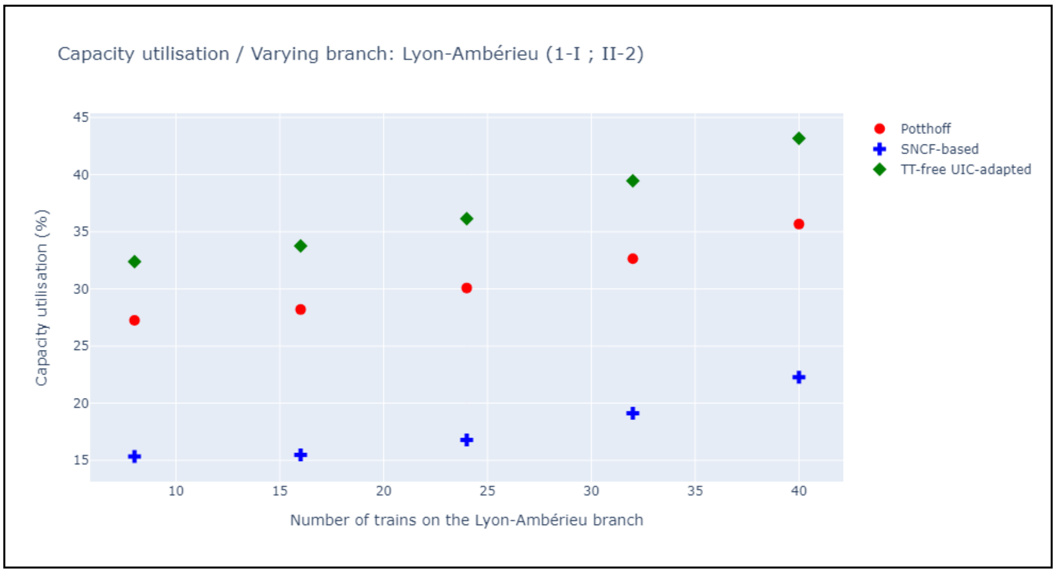


Figure IV.3.2.1.1. Capacity utilisation of the three timetable-free methods

The magnitude of the different indicators is ordered as follows. First, the timetable-free UIC-adapted method provides the highest values; Then, Potthoff's capacity utilisation values are close to those of the timetable-free UIC-adapted method. Finally, the SNCF-adapted method provides low capacity utilisation values.

In order to further compare the methods, their relative differences are computed. The timetable-free UIC-adapted method is taken as reference when comparing with Potthoff and SNCF-adapted methods. Potthoff method is taken as reference when comparing with SNCF-adapted method. Table IV.3.2.1.1. gives the mean, median and standard deviation of each relative differences.

Capacity utilisation indicators' relative differences (%)	Mean	Median	Standard deviation
(Timetable-free UIC-adapted)-(Potthoff)	16.6%	17.1%	2.3%
(Timetable-free UIC-adapted)-(SNCF-adapted)	47.5%	51.2%	9%
(Potthoff)-(SNCF-adapted)	37.1%	40.9%	10.6%

Table IV.3.2.1.1. Relative differences of the different capacity utilisation indicators

It can be observed that the relative difference between Potthoff's and timetable-free UIC-adapted's capacity utilisation indicators is well centred around a mean 16.6%, as the standard deviation is low (2.3%). This difference could come from Potthoff method's estimation of the number of trains in the critical sequence of paths, or its evaluation of the average headway between conflicting routes. Then, the comparison with SNCF-adapted's capacity utilisation indicator shows that the relative differences are high on average and dispersed. It is hard to define a link between SNCF-adapted's capacity utilisation indicator and the indicators of the other methods.

IV.3.2.2. Assessment of the timetable-free delay propagation assessment methods

Figure IV.3.2.2.1. displays the total delays indicators of the three timetable-free methods with respect to the level of a traffic of the Lyon-Ambérieu branch. The two other branches are kept at their average traffic values (24). Similar figures are obtained showing the variation of the traffic on the other two branches.

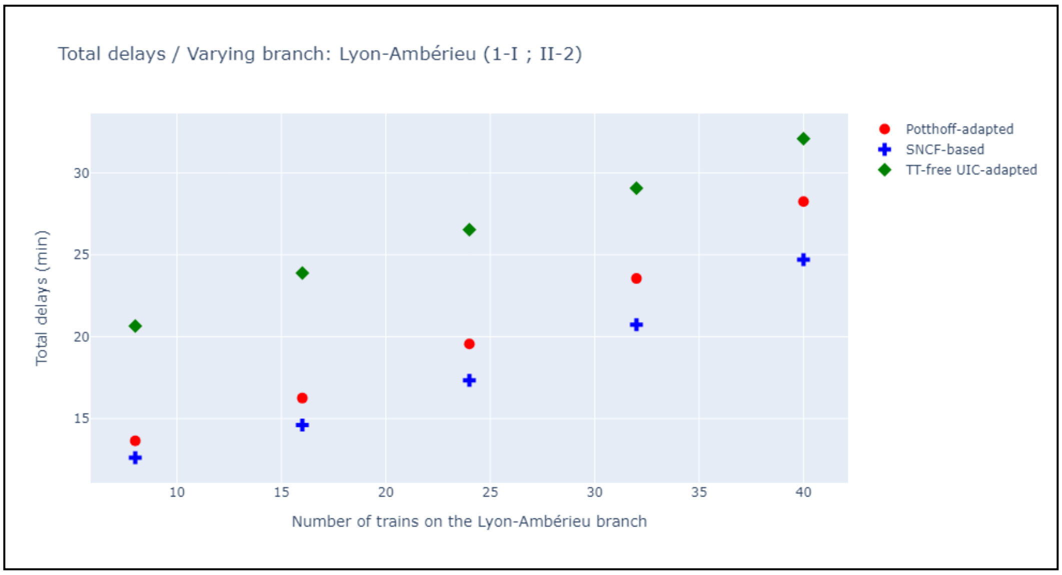


Figure IV.3.2.2.1. Total delays of the three timetable-free methods

The magnitude of the different indicators is ordered in the same way as for the capacity utilisation indicators: first, the timetable-free UIC-adapted indicator, then the Potthoff-adapted indicator, and finally the indicator of the SNCF-adapted method. Potthoff-adapted and SNCF-adapted's total delays are close and follow a similar trend. Furthermore, their increase rate is greater than the one of the timetable-free UIC-adapted method.

The relative differences between the indicators are computed. The timetable-free UIC-adapted method is taken as reference when comparing with Potthoff-adapted and SNCF-adapted methods. Potthoff-adapted method is taken as reference when comparing with SNCF-adapted method. Table IV.3.2.2.1. gives the mean, median and standard deviation of each relative differences.

Total delays indicators' relative differences (%)	Mean	Median	Standard deviation
(Timetable-free UIC-adapted)-(Potthoff-adapted)	24.3%	26%	21.7%
(Timetable-free UIC-adapted)-(SNCF-adapted)	65.6%	66.3%	11%
(Potthoff-adapted)-(SNCF-adapted)	54.9%	55.2%	3.2%

Table IV.3.2.2.1. Relative differences of the different total delays indicators

It can be seen that the relative difference between SNCF-adapted and Potthoff-adapted methods' total delays indicators shows a low standard deviation (3.2%) which confirms the observation of similar trends made with the graph. This similarity could be expected as both methods work on a similar principle, that is estimating a probability of conflicts for trains on conflicting routes and multiplying it by an average consecutive delay based on the first train's occupation time. The difference thus lies in the way the methods evaluate the probabilities of conflicts. Then, the comparison with the timetable-free UIC-adapted method shows a high on average and dispersed relative difference, which is consistent with the lower increase rate observed for this method on the graph. Hence, it is hard to define a relation between the timetable-free UIC-adapted method and the other methods.

IV.4. Results of the validation step

IV.4.1. Capacity utilisation assessment

In Figure IV.4.1.1. the different methods' capacity utilisations are plotted, as well as the real capacity utilisation, for the various observed traffic combinations. Traffic variation is presented for the Lyon-Ambérieu branch, but similar results are observed when plotting the figure with the traffic variation on one of the other branches.

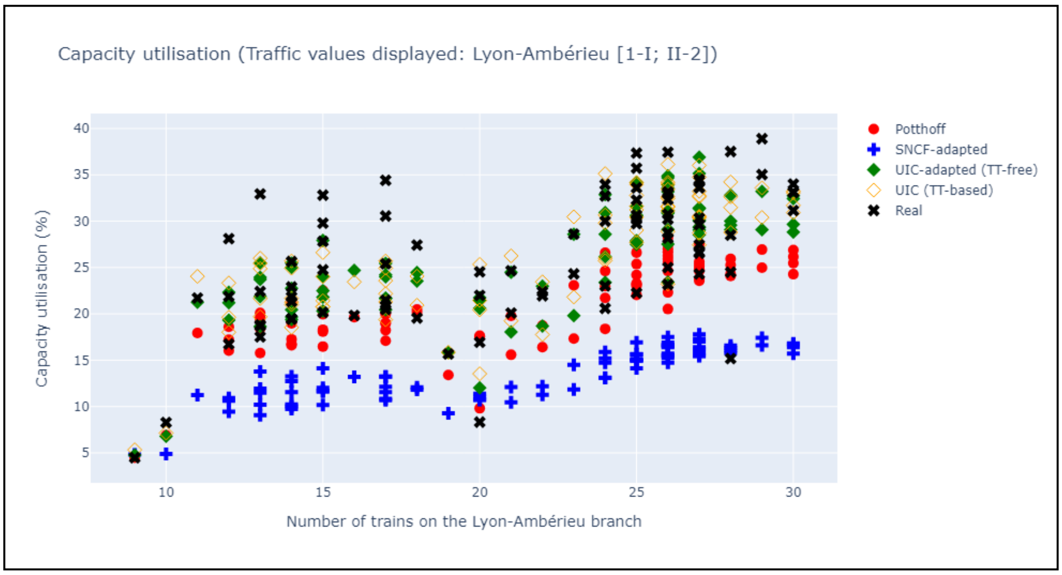


Figure IV.4.1.1. Capacity utilisation indicators of the methods and real capacity utilisation

Overall, Potthoff method's capacity utilisation is slightly lower than the real values, while both UIC methods (the timetable-free and the timetable-based methods) produce capacity utilisation values that are closely intertwined with the real ones. However, the SNCF-adapted method's capacity utilisation is clearly lower than the real values.

The relative differences between the methods' indicators and the real values are computed, and their mean, median and standard deviation are shown in Table IV.4.1.1. The real capacity utilisation values are taken as reference.

Capacity utilisation indicators' relative differences (%)	Mean	Median	Standard deviation
Real-(Potthoff)	16.5%	19.3%	15.2%
Real-(SNCF-adapted)	45.9%	49.2%	14.4%
Real-(Timetable-free UIC-adapted)	-1.2%	1.3%	19.3%
Real-(Timetable-based UIC-adapted)	-3.7%	-1.8%	20.1%

Table IV.4.1.1. Relative differences of the methods' capacity utilisation indicators with the real capacity utilisation

All relative differences show a moderate dispersion (standard deviations between 14.4% and 20.1%. Yet this could be linked to the way the real capacity utilisation is calculated. Indeed, it takes into account the moment from which route is locked for an incoming a train. However, the methods consider the minimum technical time needed to set itinerary and time supplements to the minimum headway. This difference could lead to variability in the results. Therefore, these moderate dispersions could be linked to the numerical values used and the assumptions taken in the theoretical headways' calculation (common to all methods), rather than to the methods' assumptions and calculations themselves.

The timetable-based UIC 406 method provides a good approximation of the real capacity utilisation values, with a slight overestimation (negative relative difference) of 3.7% on average. Then, the timetable-free UIC-adapted method performs best in anticipating the real capacity utilisation values, with a slight overestimation of 1.2%. It even performs slightly better than the timetable-based UIC 406 method, which was unexpected. The reason could be that the timetable-free method is able to consider multiple train arrival sequences and thus cope with small variations of the timetable in the real operations, while the timetable-based method can only assess the planned timetable. Then, the Potthoff method is also performing correctly, with a mean relative difference 16.5%. However, the SNCF-adapted method's capacity utilisation indicator appears to be inappropriate for estimating the real capacity utilisation, with a high mean relative difference of 45.9%, which confirms the observation made on the graphs.

To conclude, the timetable-free UIC-adapted method and Potthoff seem appropriate to perform timetable-free evaluation of capacity utilisation, while the timetable-based UIC 406 method seems appropriate if timetables can be used.

IV.4.2. Delay propagation assessment

Figure IV.4.2.1. shows the different methods' total delays, as well as the real total delays, for the various observed traffic combinations. Traffic variation is presented for the Lyon-Ambérieu branch, but similar results are observed when plotting the figure with the traffic variation on one of the other branches.

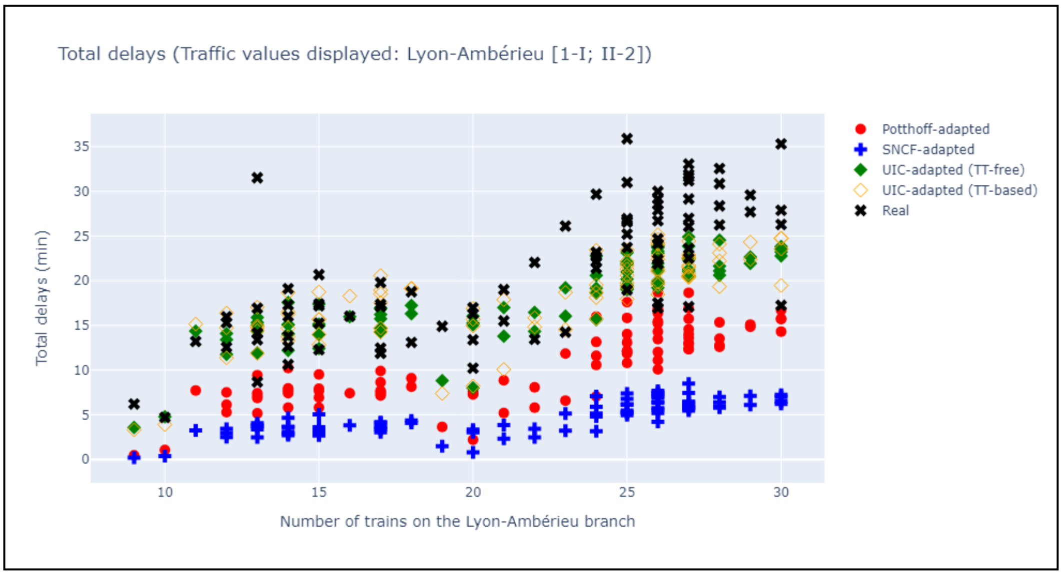


Figure IV.4.2.1. Total delays indicators of the methods and real total delays

It can be observed that both UIC-adapted methods (the timetable-free and timetable-based versions) produce indicators that tend to be close to the real values for low to moderate traffic volumes, but then tend to be lower for higher traffic volumes. Potthoff-adapted's total delays are on average slightly lower than the real values but with a trend that matches the real total delays, and the SNCF-adapted method produces total delays that are clearly lower than the real ones, yet with a trend seemingly consistent with the real total delays.

The relative differences between the methods' indicators and the real total delays values are computed, and their mean, median and standard deviation are shown in Table IV.4.2.1. The real total delays values are taken as reference.

Total delays indicators' relative differences (%)	Mean	Median	Standard deviation
Real-(Potthoff-adapted)	49%	51.2%	15.6%
Real-(SNCF-adapted)	77.2%	77.3%	7.1%
Real-(Timetable-free UIC-adapted)	9.4%	11%	21.5%
Real-(Timetable-based UIC-adapted)	7.9%	9.7%	23%

Table IV.4.2.1. Relative differences of the methods' total delays indicators with the real total delays

It can be argued that the UIC-adapted methods (both timetable-based and timetable-free) do not offer satisfying results in terms of reliability, as their relative differences with the real values show high dispersions (respectively 23% and 21.5%). Yet they provide indicators that are close in magnitude with the real total delays. Further work is required in order to improve the definition of these methods. The definition of the time intervals used to draw the initial delays is still exploratory and requires more investigation. Then, the Potthoff-adapted and SNCF-adapted methods do not provide accurate total delays on average (high underestimation in mean relative difference) but they show better results in terms of reliability (low dispersion). The reason might be that the methods correctly estimate the number of conflicts in the node area (leading to a low dispersion in the relative differences) but underestimate the magnitude of the delays generated by each conflict. The explanation for this underestimation could be that the methods do not take into account the train order sequence, thus they do not grasp the interdependencies that may lead to the propagation of delays between routes that are not directly in conflict, via common intermediate conflicting routes.

All in all, none of the methods studied in this paper seems to be immediately adequate for estimating the delay propagation at a node. Yet, the low dispersion of the relative differences between the real total delays and Potthoff-adapted and SNCF-adapted methods' total delays could be further exploited to estimate a steady factor that could correct their magnitude.

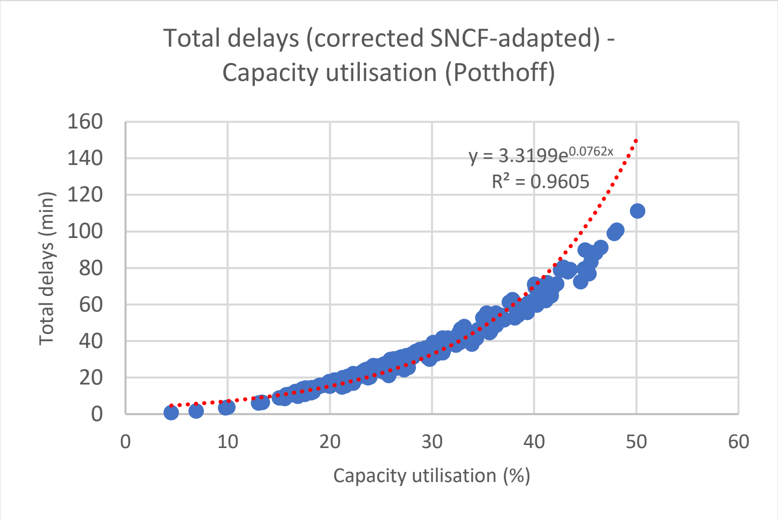
IV.5. Investigating the total delays – capacity utilisation relationship

In this section, the total delays – capacity utilisation relationship is further investigated, using the best performing methods found previously. Methods are applied on an enlarged traffic configurations dataset containing the traffic configurations observed in reality (validation phase) as well as the traffic configurations generated in the verification phase.

For capacity utilisation assessment, the timetable-free UIC-adapted method and the Potthoff method are further studied. Only timetable-free methods are studied to take advantage of their applicability on unobserved traffic configurations. Yet it can be expected that the findings obtained for the timetable-free UIC-adapted method are applicable to the timetable-based UIC 406 method, as the results of the validation showed they produced values of close magnitude.

For total delays assessment, a "corrected SNCF-adapted method" is used. This consists in applying a fixed factor to correct the method's total delays magnitude. This factor is estimated on a calibration dataset, which is a random half of the validation dataset, and verified on a test dataset, which is the other random half of the validation dataset. The factor, called β, is calculated as $\beta = \frac{1}{1-(mean\ Total\ delays\ relative\ \ difference_{Real-SNCF})}$. In the calibration dataset, it is found that $\beta \simeq 4.27$, and the application of β in the test dataset shows that the mean total delays relative difference with the real values is now only 5.3%. Hence, this calibration factor $\beta = 4.27$ is used to multiply the total delays produced by the SNCF-adapted method.

The application of the SNCF-adapted method corrected with β for total delays calculation, and the Potthoff and timetable-free UIC-adapted methods for capacity utilisation assessment yields the following results.



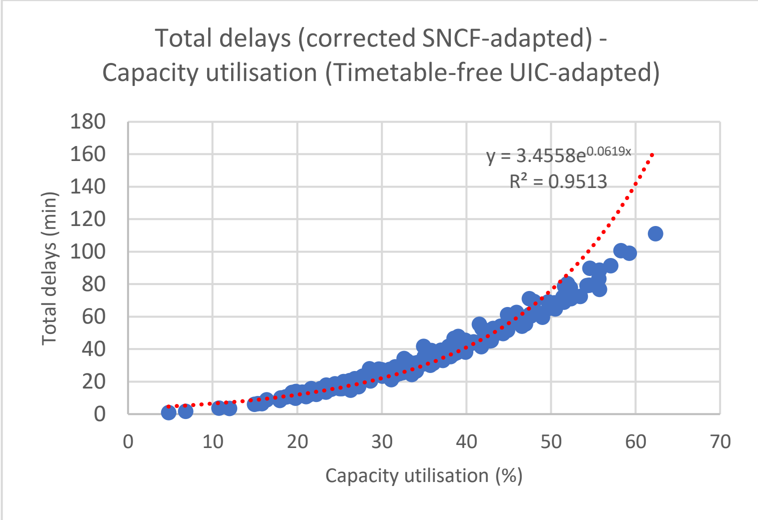
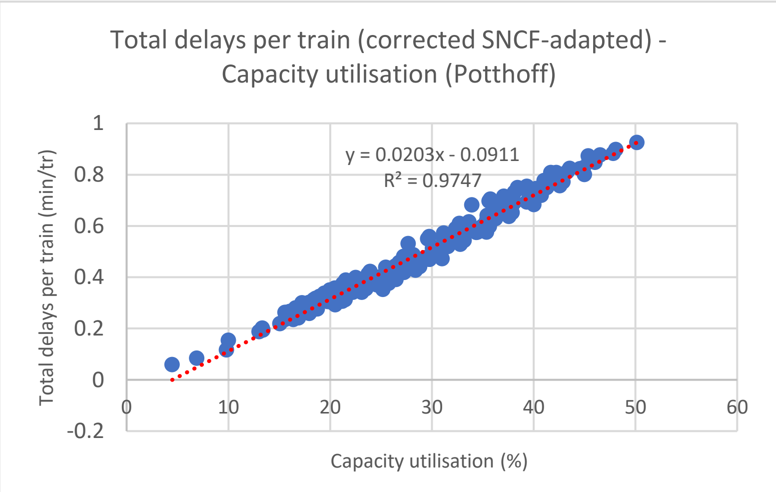


Figure IV.5.1. Total delays – capacity utilisation relationships

For both capacity utilisation methods, the relationship shows an exponential trend, which is in line with the findings of *Armstrong & Preston, 2017* [16]. The infrastructure managers can be interested in knowing critical thresholds of capacity utilisation. As the total delays indicator is difficult to interpret alone, using the ratio between the total delays and the number of trains allows to detect when critical situations are reached. The following figures are obtained when plotting the total delays per train against capacity utilisation values.



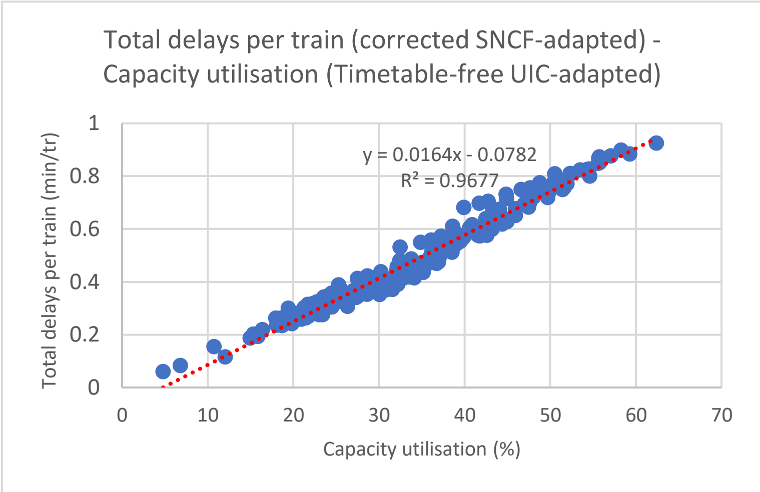


Figure IV.5.2. Total delays per train – capacity utilisation relationships

A strong linear relationship can be observed between capacity utilisation and total delays per train. Using the equations of the regression curves, it can be found that a critical total delays per train value of 1 min/tr is reached when Potthoff's capacity utilisation is at 53.7%, or when the capacity utilisation of the timetable-free UIC-adapted method is at 65.7% These thresholds are lower than those recommended in *UIC, 2013* [17] for railway line track sections. Actually, the difference is even greater as this paper made use of headways containing the minimum headways plus headway supplements for the compression of the train paths, while *UIC, 2013* [17] only used compression with minimal headways. *Armstrong & Preston, 2017* [2] had also obtained lower capacity utilisation thresholds for railway nodes, albeit with a different capacity utilisation assessment method. These thresholds should be considered preliminary findings that need to be further studied and validated over an extended range of traffic and infrastructure configurations.

V. Conclusion and recommendations

This paper aimed to determine methods that could be effectively used to improve the capacity and performance assessment of railway nodes in the long-term planning stages. It has been found that among the timetable-free methods, the timetable-free UIC-adapted and Potthoff methods for capacity utilisation evaluation, and SNCF-adapted method with a correction factor for delay propagation assessment were able to provide results that are relevant in terms of magnitude and trends for the long-term assessment of railway nodes capacity and performance. Then, if timetables are available, or if there is the need to study particular timetable patterns, the timetable-based UIC 406 method for railway node capacity utilisation assessment can be used. No satisfactory timetable-based delay propagation method was found in this paper, hence it is recommended that the infrastructure manager continues using the current simulation approaches, or use the timetable-free corrected SNCF-adapted method for delay propagation if quick evaluation is needed.

This paper provided preliminary results regarding capacity utilisation thresholds that are critical in terms of delay propagation. These thresholds appear to be lower than the ones recommended for railway line track sections. Yet, these results need to be further confirmed and detailed on different infrastructure layouts and with more varied traffic configurations, before they are applied in the infrastructure manager's set of tools for the evaluation of railway nodes' capacity and performance. In particular, using more varied traffic data appears essential as the analyses presented in this paper relied on traffic data from June 2021, when the COVID-19 pandemic still imposed a limited traffic. More recent denser traffic configurations could help study critical capacity utilisation thresholds in more details. Then, further studies could attempt to improve the formulation of the UIC-adapted methods for delay propagations proposed in this research. Specifically, the definition of the time intervals from which the initial delays are drawn could be adapted and calibrated by comparing the methods' total delays with real total delays. Another possible continuation of this research could consist in better assessing capacity utilisation thresholds by collecting total delays data on an extended perimeter, ranging from a few blocks prior to the protecting signal to a few blocks after. The loss of time due to deceleration and reacceleration could be better captured, and capacity utilisation thresholds might be better identified. Once the previous items have been completed, the methods can be incorporated within the infrastructure manager's set of tools. It is then recommended to communicate on the different capacity utilisation thresholds, so that the other stakeholders involved in the planning processes have a good understanding of their meaning and avoid misinterpretation.

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Appendix B: SNCF's method: adaptation of the hypergeometric distribution's formula when N_{AB} is not an integer

- Case 1: A and B are distinct routes: it can be shown that:

$$P(X_{AB}=k)=\sum\nolimits_{(c_1,c_2,\dots,c_n)}\frac{n_A}{N_{AB}-c_1}\frac{n_A-1}{N_{AB}-c_2}\dots\frac{n_A-(k-1)}{N_{AB}-c_k}$$
$$\times\prod_{i=0}^{c_1-1}\frac{N_{AB}-n_A-i}{N_{AB}-i}\prod_{i=c_1+1}^{c_2-1}\frac{N_{AB}-n_A-(i-1)}{N_{AB}-i}\dots\prod_{i=c_{k-1}+1}^{c_k-1}\frac{N_{AB}-n_A-(i-(k-1))}{N_{AB}-i}\prod_{i=c_k+1}^{n_b-1}\frac{N_{AB}-n_A-(i-k)}{N_{AB}-i}$$

with $(c_1, c_2, \dots, c_n)$ the combinations of drawing ranks of the k conflicts over the n_b drawings.

- Case 2: A and B are the same route: it can be shown that:

$$P(X_{AB}=k)=\sum\nolimits_{(c_1,c_2,\dots,c_n)}\frac{n_A-c_1}{N_{AB}-2c_1}\frac{n_A-(c_2+1)}{N_{AB}-2c_2}\dots\frac{n_A-(c_k+(k-1))}{N_{AB}-2c_k}$$
$$\times\prod_{i=0}^{c_1-1}\frac{N_{AB}-n_A-i}{N_{AB}-2i}\prod_{i=c_1+1}^{c_2-1}\frac{N_{AB}-n_A-(i-1)}{N_{AB}-2i}\dots\prod_{i=c_{k-1}+1}^{c_k-1}\frac{N_{AB}-n_A-(i-(k-1))}{N_{AB}-2i}\prod_{i=c_k+1}^{n_b-1}\frac{N_{AB}-n_A-(i-k)}{N_{AB}-2i}$$

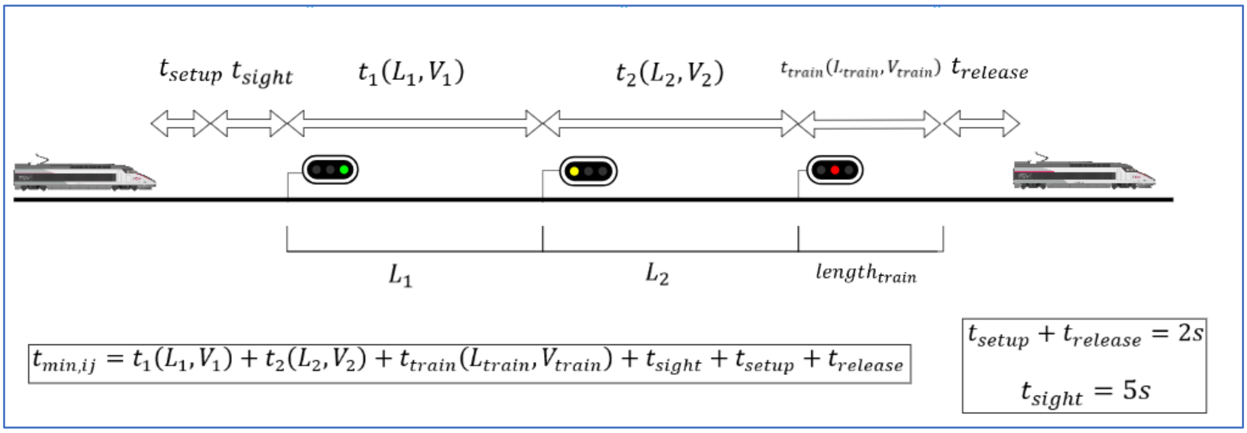
Appendix C: Headways calculation

Minimum headways

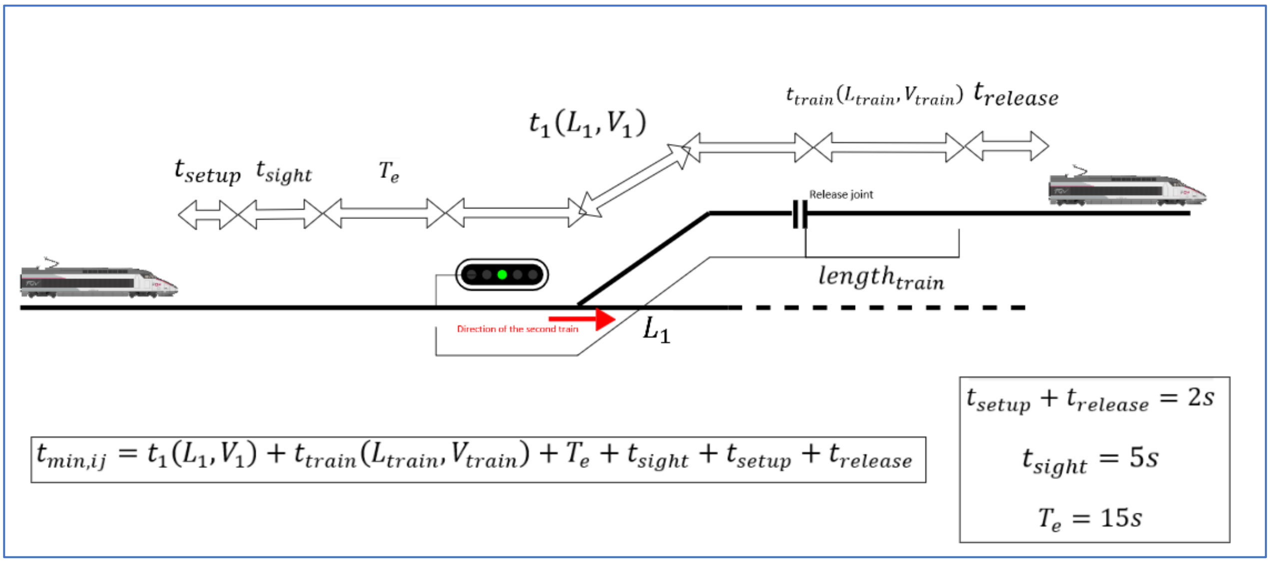
Minimum headways calculation (basic case)

For the case study on the Lyon Saint-Clair junction, the calculation of the minimum headways between conflicting routes is performed following the guidelines published in SNCF Reseau's technical documentation. The headways are calculated from the moment a train passes an entry signal to the area (that is, a signal protecting the switch area, see figure IV.2.1). In the basic case, the trains are assumed to run at the maximum allowed speeds. The signalling system at this junction works according to the sectional release principle.

The figures below illustrate the different cases that can be encountered. Then, the formulas are detailed.



Calculation of the minimum headway between two following (or converging) trains



Calculation of the minimum headway between two diverging (or crossing) trains

The general formula of the minimum headway between two following/converging trains is:

$$t_{min,ij} = t_1(L_1, V_1) + t_2(L_2, V_2) + t_{train}(L_{train}, V_{train}) + t_{sight} + t_{setup} + t_{release}$$

The general formula of the headway between two diverging/ crossing trains is:

$$t_{min,ij} = t_1(L_1, V_1) + t_2(L_2, V_2) + t_{train}(L_{train}, V_{train}) + t_{sight} + t_{setup} + t_{release}$$

Where:

L_k is the length of a block section k (or the length of the train if $k = train$);

V_k is the speed of the train on a block section k (or over the length of the train if $k = train$);

$t_k(L_k, V_k)$ is the time needed for a train to run over a block section k of length L_k at speed V_k;

t_{sight} is the minimum sighting time for the driver to see the signal ($t_{sight} = 5s$);

t_{setup} and $t_{release}$ are the technical times needed to respectively set and release the route ($t_{setup} + t_{setup} = 2s$);

T_e is the technical time needed to move the switches ($T_e = 15s$).

These general formulas formed the base of the calculations. Additionally, track sections were modelled in more details by adding the locations where trains have to change speed. Thus, acceleration and deceleration times were taken into account in the calculation of $t_k(L_k, V_k)$. Constant acceleration and deceleration factors were considered, in order to simplify the calculations (these are given below in the *"Rolling stock data"* table in the "*Minimum headways: numerical values"* paragraph). The following formulas were used to compute the acceleration (or deceleration) time under a constant acceleration (or deceleration) factor a:

- Time $t_{v_1 \to v_2}$ to accelerate from v_1 to v_2 ($v_1 < v_2$): $t_{v_1 \to v_2} = \frac{v_2 - v_1}{a}$ $(a > 0)$
- Time $t_{v_2 \to v_1}$ to decelerate from v_2 to v_1 ($v_1 < v_2$): $t_{v_2 \to v_1} = \frac{v_1 - v_2}{a}$ $(a < 0)$
- Distance $d_{v_1 \to v_2}$ to accelerate from v_1 to v_2 ($v_1 < v_2$): $d_{v_1 \to v_2} = \frac{{v_2}^2 - {v_1}^2}{2a}$ $(a > 0)$
- Distance $d_{v_2 \to v_1}$to decelerate from v_2 to v_1 ($v_1 < v_2$): $t_{v_2 \to v_1} = \frac{{v_1}^2 - {v_2}^2}{2a}$ $(a < 0)$

Minimum headways imposed by restarting trains

The minimum headways imposed by trains starting after a stop at the signal protecting the switch area, called $t_{restart,ij}$, were also considered in the delay propagation assessment methods. These $t_{restart,ij}$ were calculated using the same formulas as for the minimum headways in the basic case (when the trains run at the maximum allowed speed), but this time imposing a null speed for the restarting trains at the signals protecting the entry to the switch area (that is, the starting points of the routes).

Minimum headways: numerical values

Three types of trains were considered in the case study of the Lyon Saint-Clair junction:

- Passenger trains: “TGV” trains (high-speed trains) and “TER” trains (regional trains)
- Freight trains

The following data were used (taken from SNCF Réseau’s database).

	TGV	**TER**	**Freight trains**
Length	200m	100m	750m
Acceleration rate	0.5m/s²	0.5m/s²	0.15m/s²
Braking rate	0.6m/s²	0.6m/s²	0.5m/s²

Rolling stock technical data

The results of the calculations of the minimum headways imposed by each train type are given in Appendix D.

Headway supplements

The methods make use of the following headway supplements, set in accordance with SNCF Reseau’s practices.

$$Headway\ supplements = \chi + m$$

With:

χ=30s : timetable margin used at SNCF Réseau

$m = \begin{cases} 15s \text{ if both trains are passenger trains} \\ 30s \text{ if at least one train is a freight train} \end{cases}$: rounding margin

Calculation in the verification and validation steps

Calculation of the minimum headways

In the verification step, the minimum headways are calculated using the percentages of each train type per route. **The headways for freight and passenger trains are calculated and then weighted according to their respective percentages**. The traffic is assumed to be made of 75% of passenger trains and 25% of freight trains on all routes. Passenger train types are split as follows:

- Lyon-Ambérieu branch (1-I; II-2) and Lyon-Collonges branch (5-III; IV-6): TER trains
- Lyon-Sathonay branch (3-I; 3-III; II-4; IV-4): TGV trains

In the validation step (comparison of the methods' outputs against real data), planned timetables are used in the timetable-based methods. These planned timetables also provide the train types, therefore **for the timetable-based methods the headways are set specifically according to each train's type.** Regarding the timetable-free methods, their headways in the validation step are computed as a weighted average with the planned percentages of each train type per route.

Calculation of the headway supplements

In step 1 of the evaluation process (verification), artificial traffic data is used to study the timetable-free methods. There are 25% freight trains and 75% passenger trains on all branches.

Therefore, on all branches there are 56.25% of train pairs with only passenger trains, and (100-56.25) = 43.75% of pairs with at least one freight train. The average m value is calculated accordingly: $m = 0.5625 \times 15 + 0.4375 \times 30 = 21.56s$, for all branches.

In step 2 of the evaluation process (validation), the pairs of trains observed in the planned timetable are used to determine m for the timetable-based, while for the timetable-free methods the planned percentages of train types are used to calculate a weighted average m value.

Appendix D: Minimum headway matrices

The minimum headway matrices calculated for the case of the Lyon Saint Clair junction are given below for each train type.

	1 - I	3 - I	3 - III	5 - III	II - 2	II - 4	IV - 4	IV - 6
1 - I	74.9	74.9	0.0	0.0	0.0	0.0	0.0	0.0
3 - I	76.4	76.4	40.3	0.0	43.9	0.0	0.0	0.0
3 - III	0.0	33.5	64.2	64.2	0.0	36.8	0.0	0.0
5 - III	0.0	0.0	80.6	80.6	0.0	0.0	50.8	0.0
II - 2	0.0	45.0	0.0	0.0	84.6	41.4	0.0	0.0
II - 4	0.0	0.0	52.5	0.0	49.5	128.5	128.5	0.0
IV - 4	0.0	0.0	0.0	41.7	0.0	112.0	112.0	41.2
IV - 6	0.0	0.0	0.0	0.0	0.0	0.0	47.3	107.8

Minimum headways imposed by TGV trains (in seconds)

	1 - I	3 - I	3 - III	5 - III	II - 2	II - 4	IV - 4	IV - 6
1 - I	72.9	72.9	0.0	0.0	0.0	0.0	0.0	0.0
3 - I	74.4	74.4	36.3	0.0	39.9	0.0	0.0	0.0
3 - III	0.0	31.5	62.2	62.2	0.0	34.8	0.0	0.0
5 - III	0.0	0.0	78.6	78.6	0.0	0.0	48.6	0.0
II - 2	0.0	43.0	0.0	0.0	84.0	39.4	0.0	0.0
II - 4	0.0	0.0	48.5	0.0	45.5	126.5	126.5	0.0
IV - 4	0.0	0.0	0.0	39.7	0.0	110.0	110.0	39.2
IV - 6	0.0	0.0	0.0	0.0	0.0	0.0	44.1	105.3

Minimum headways imposed by TER trains (in seconds)

	1 - I	3 - I	3 - III	5 - III	II - 2	II - 4	IV - 4	IV - 6
1 - I	110.4	110.4	0.0	0.0	0.0	0.0	0.0	0.0
3 - I	117.1	117.1	75.3	0.0	78.9	0.0	0.0	0.0
3 - III	0.0	61.3	97.7	97.7	0.0	65.0	0.0	0.0
5 - III	0.0	0.0	116.3	116.3	0.0	0.0	82.3	0.0
II - 2	0.0	74.8	0.0	0.0	129.0	70.8	0.0	0.0
II - 4	0.0	0.0	87.5	0.0	84.5	175.3	175.3	0.0
IV - 4	0.0	0.0	0.0	71.1	0.0	152.2	152.2	70.6
IV - 6	0.0	0.0	0.0	0.0	0.0	0.0	77.5	139.6

Minimum headways imposed by freight trains (in seconds)

	1 - I	3 - I	3 - III	5 - III	II - 2	II - 4	IV - 4	IV - 6
1 - I	101.9	101.9	0.0	0.0	0.0	0.0	0.0	0.0
3 - I	87.5	87.5	58.9	0.0	62.5	0.0	0.0	0.0
3 - III	0.0	58.8	91.2	91.2	0.0	63.0	0.0	0.0
5 - III	0.0	0.0	103.2	103.2	0.0	0.0	73.2	0.0
II - 2	0.0	72.0	0.0	0.0	113.0	68.2	0.0	0.0
II - 4	0.0	0.0	71.2	0.0	68.2	147.1	147.1	0.0
IV - 4	0.0	0.0	0.0	68.6	0.0	139.0	139.0	68.0
IV - 6	0.0	0.0	0.0	0.0	0.0	0.0	68.7	129.9

Minimum headways imposed by restarting TGV trains (in seconds)

	1 - I	3 - I	3 - III	5 - III	II - 2	II - 4	IV - 4	IV - 6
1 - I	97.4	101.9	0.0	0.0	0.0	0.0	0.0	0.0
3 - I	93.5	93.5	52.9	0.0	56.5	0.0	0.0	0.0
3 - III	0.0	52.9	87.2	87.2	0.0	57.8	0.0	0.0
5 - III	0.0	0.0	98.1	98.1	0.0	0.0	68.0	0.0
II - 2	0.0	67.8	0.0	0.0	109.0	63.7	0.0	0.0
II - 4	0.0	0.0	65.2	0.0	62.2	141.1	141.1	0.0
IV - 4	0.0	0.0	0.0	64.0	0.0	135.0	135.0	63.5
IV - 6	0.0	0.0	0.0	0.0	0.0	0.0	63.6	124.8

Minimum headways imposed by restarting TER trains (in seconds)

	1 - I	3 - I	3 - III	5 - III	II - 2	II - 4	IV - 4	IV - 6
1 - I	184.4	184.4	0.0	0.0	0.0	0.0	0.0	0.0
3 - I	172.7	172.7	130.8	0.0	134.4	0.0	0.0	0.0
3 - III	0.0	130.8	172.4	172.4	0.0	135.7	0.0	0.0
5 - III	0.0	0.0	182.5	182.5	0.0	0.0	147.3	0.0
II - 2	0.0	138.7	0.0	0.0	203.1	142.2	0.0	0.0
II - 4	0.0	0.0	143.1	0.0	140.1	230.8	230.8	0.0
IV - 4	0.0	0.0	0.0	142.7	0.0	226.2	226.2	142.0
IV - 6	0.0	0.0	0.0	0.0	0.0	0.0	142.0	204.9

Minimum headways imposed by restarting freight trains (in seconds)