Evaluation method of the saturation level of a railway line

MAZEN FARES
Evaluation method of the saturation level of a railway line

Mazen Fares

Master Thesis
February 2016

Department of Transport Science
KTH Railway Group
KTH Royal Institute of Technology
Table of contents

Contents

Acknowledgment .............................................................................................................. 5
Abstract ............................................................................................................................ 6
Index of figures ................................................................................................................. 7
Index of tables .................................................................................................................. 8
1. Introduction ............................................................................................................... 9
  1.1. Background .......................................................................................................... 9
  1.2. Aim and scope of the Master Thesis ................................................................. 9
  1.3. Methodology ...................................................................................................... 10
2. Objective ................................................................................................................... 13
  2.1. Problem description ......................................................................................... 13
  2.2. Definition of saturation .................................................................................... 13
3. Theoretical study ..................................................................................................... 15
  3.1. Compression method ....................................................................................... 15
    3.1.1. Aim ............................................................................................................... 15
    3.1.2. Framework ................................................................................................... 15
    3.1.3. Implementation ............................................................................................ 16
    3.1.4. Grey areas .................................................................................................... 26
    3.1.5. Critical assessment ...................................................................................... 27
  3.2. Robustness method ......................................................................................... 27
    3.2.1. Aim ............................................................................................................... 27
    3.2.2. Framework ................................................................................................... 27
    3.2.3. Implementation ............................................................................................ 28
    3.2.4. Grey areas .................................................................................................... 30
    3.2.5. Critical assessment ...................................................................................... 31
  3.3. Regularity method ........................................................................................... 32
    3.3.1. Aim ............................................................................................................... 32
    3.3.2. Framework ................................................................................................... 32
    3.3.3. Implementation ............................................................................................ 32
    3.3.4. Grey areas .................................................................................................... 33
    3.3.5. Critical assessment ...................................................................................... 33
4. Application to a case study ....................................................................................... 35
  4.1. Introduction to the case study ......................................................................... 35
  4.2. SAMURAIL model .......................................................................................... 36
  4.3. Capacity results and analysis ......................................................................... 38
    4.3.1. Compression on a line section ................................................................. 38
4.3.2. Compression of a node .................................................................................................. 44
4.3.3. Summary .................................................................................................................... 48
4.4. Robustness results and analysis .................................................................................. 50
  4.4.1. Methodology ........................................................................................................... 50
  4.4.2. Results and analysis ............................................................................................... 52
4.5. Regularity results and analysis ................................................................................... 59
  4.5.1. Methodology ........................................................................................................... 59
  4.5.2. Results and analysis ............................................................................................... 61
5. Results analysis ............................................................................................................. 65
  5.1. Relevance of the methods to study saturation .......................................................... 65
    5.1.1. Capacity method .................................................................................................. 65
    5.1.2. Robustness method ............................................................................................. 65
    5.1.3. Regularity method ............................................................................................... 66
  5.2. Another method: path quality method ...................................................................... 66
    5.2.1. Theoretical study ................................................................................................ 66
    5.2.2. Results and analysis .......................................................................................... 71
    5.2.3. Relevance of the method ................................................................................... 75
  5.3. Method proposal ........................................................................................................ 75

6. Discussion and Conclusion ........................................................................................ 79
  6.1. Further study ............................................................................................................. 79
  6.2. Summary ................................................................................................................... 80
7. References .................................................................................................................... 81
Acknowledgment

This master thesis was performed from September 2015 to February 2016 at the railway functionalities and operations department of INGEROP, a French engineering company.

I would like to thank my supervisor at INGEROP, Vincent Mahuteau, for giving me the opportunity to do this master thesis in his department, and for all the very helpful advice and excellent guidance. I also thank all the people at INGEROP for their warm welcome and for making me feel at ease. Special thanks to my officemates Eliel, Jordan, Yann, Thibaud and Raphael for all the help and making work fun, it has been an absolute pleasure working with you.

I also would like to thank my supervisor at KTH, Anders Lindahl, for accepting to be my supervisor on this project, for his guidance and his help despite the distance. I am also very grateful to my advisor at KTH, Jennifer Warg, for her very kind and precious comments regarding my master thesis.

I am also grateful to Pauline Lamotte for her help in my master thesis search and being my opponent during the final presentation.
Abstract

Saturation is becoming more and more of an issue for infrastructure owners, but there is no existing method to measure it. This master thesis aims at suggesting a method in order to evaluate the saturation level of a railway line. Saturation has an ambiguous definition. It deals with capacity issues, timetable stability and robustness, and with delay issues. Three methods are mainly studied, each one defining saturation from a different angle, and meeting a different definition of saturation. These methods are the compression method, defining saturation as a capacity issue, the robustness method, and the regularity method, i.e. delays analysis. A fourth method is created and studied in order to complete the previous three. The idea is to find the relevant indicators to evaluate saturation. These methods are first studied from a theoretical perspective before being applied to a study case to choose the relevant indicators. This study case involves a statistical analysis and a dynamic simulation of the graphical timetable. The results show that the regularity method is irrelevant to study saturation. The method suggested by this master thesis in order to evaluate saturation is a two-step method. The first step is the diagnosis based on the compression method and the traffic heterogeneity. The second step is the comparison between different scenarios to reduce saturation: this step is based on the compression method, the robustness method and the traffic heterogeneity. This method can later be used for an economic study or a multi-criteria analysis.
Index of figures

Figure 1: Determination of significant interlockings ................................................................. 17
Figure 2: Visual distance definition in a block section .............................................................. 17
Figure 3: Visual distance definition in a block section .............................................................. 18
Figure 4: Journey time of occupied block section ................................................................. 18
Figure 5: Journey time of the following block section .......................................................... 19
Figure 6: Definition of the block section clearing time .......................................................... 19
Figure 7: Example of graphical timetable before compression ............................................... 20
Figure 8: First step of the graphical timetable compression .................................................. 21
Figure 9: Second step of the graphical timetable compression ............................................. 21
Figure 10: Compression of a graphical timetable ................................................................. 22
Figure 11: Occupancy time after compression ................................................................. 22
Figure 12: Definition of capacity consumption ................................................................. 23
Figure 13: Example of incompatible routes in a node (4) ...................................................... 24
Figure 14: Example of the influence of interlockings choice ............................................... 26
Figure 15: Graphical timetable before introducing a disruption ........................................... 28
Figure 16: Example of a robustness test ............................................................................. 28
Figure 17: Example of indicators calculation for the robustness method ............................. 29
Figure 18: Example of robustness test choice ..................................................................... 30
Figure 19: Robustness test choice issues ........................................................................... 31
Figure 20: Relocation of the saturation effects from the regularity approach ...................... 33
Figure 21: Major stations of the case study line .................................................................. 35
Figure 22: Graphical timetable of the line for the studied day ............................................. 36
Figure 23: Example of a station modeled on SAMURAIL .................................................... 37
Figure 24: Example of a traction force graph depending on the speed (Source: http://www.twoof.freeserve.co.uk/motion1.htm) ................................................................. 37
Figure 25: Graphical timetable for the studied peak hour up way ...................................... 38
Figure 26: Graphical timetable for the studied peak hours down way ................................ 39
Figure 27: Implementation of the compression method ....................................................... 39
Figure 28: Implementation of the compression method ....................................................... 40
Figure 29: Implementation of the compression method ....................................................... 40
Figure 30: Available infrastructure time between the trains on the Rac – Cur ELS up way ...... 41
Figure 31: Occupancy rates of the ELS .............................................................................. 42
Figure 32: Number of freight trains running during evening peak hours for the studied week 42
Figure 33: Capacity consumption on Tiv – Cur TPLS .............................................................. 43
Figure 34: Capacity consumption on Cyv – Cur TPLS .............................................................. 43
Figure 35: Capacity consumption on Tiv – Rac TPLS .............................................................. 43
Figure 36: Capacity consumption on Cyv – Rac TPLS .............................................................. 43
Figure 37: Capacity consumption on Zid – Nec TPLS .............................................................. 44
Figure 38: Exclusion time calculation area for switch zones ................................................. 45
Figure 39: Track occupancy rate in Rac station ................................................................. 46
Figure 40: Track occupancy rate in Pis station ..................................................................... 47
Index of tables

Table 1: Additional times depending on the traffic type (4) ................................................................. 23
Table 2: Occupancy limit for good service quality (4) ........................................................................... 24
Table 3: Example of a simultaneity matrix ............................................................................................ 24
Table 4: Example of a node occupancy calculation table ........................................................................ 25
Table 5: Additional times in for switch and track areas (4) .................................................................... 25
Table 6: Example of a switch area occupancy rate calculation table ........................................................ 45
Table 7: Influence of switch zones on line occupancy rates .................................................................. 48
Table 8: Average number of trains activating the beacons on waypoints of the line .................. 60
Table 9: Service quality results for each origin-destination route up way ............................................ 73
Table 10: Service quality results for each origin-destination route down way .................................... 73
1. Introduction

1.1. Background

The current railway network is currently quite developed in Europe and France. Many countries in Europe had their first railway lines for several decades now, and these lines kept changing throughout the years in order to meet the evolving needs of society. Being able to evaluate the state of the railway network in terms of capacity is essential in order to meet the demand and anticipate the future requirements.

This is especially true since transportation infrastructure requires high investments and resources, while some European countries, such as France, have very limited budgets regarding these issues. Some investments are made to create and develop new transportation infrastructure, while the others are, in order to maintain the existing ones that could be worn or that need a higher capacity. When it comes to capacity issues, the State and the infrastructure owners need a mean to prioritize the projects in which to invest [1]. Indeed, some lines are congested, some in terms of number of users, some in terms of train allocation plans, and some for both [2].

With the deregulation of the railway in the European Union, the infrastructure owners are responsible for providing different railway operators with some paths. The directive 2001/14/EC [3] of the European Council requires the infrastructure owners to declare that a railway line is saturated if they are not able to satisfy the infrastructure needs of the operators. Then, the owner has 6 months to present a plan to improve the capacity on the line. That is why, SNCF Réseau, the infrastructure owner in France, would like to anticipate the congestion and saturation of its lines. However, the notion of saturation is not precisely defined and can have several interpretations [1], leading to different solutions. As a consequence, it would be interesting to give a better definition and understanding of the saturation of a railway line. This would give a better understanding of the causes creating this situation, in order to solve the congestion issues.

In order to do so, several methods involving different indicators will be studied to give a better understanding of the capacity issues and to attempt to give a more precise definition of the notion of saturation. This will be done from a theoretical point of view, as well as implemented on a study case.

1.2. Aim and scope of the Master Thesis

The aim of this master thesis is to define more precisely what the saturation of a railway line is and what parameters or indicators are relevant to measure it. This will allow us to define a methodology in order to measure this phenomenon. The idea would be to create an opposable method, built on relevant indicators, which could be applied later by the infrastructure owners as a standard method to determine the saturation level of a railway line. However, it is important to understand that this
method will not be used to solve directly the capacity issue: it will help the infrastructure owners measuring the saturation level and analyzing its causes. This will lead them to set up an action plan to improve the capacity of the line.

The method focuses on regional, inter-regional and long-distance railway lines. It could be applied to suburban or commuter train lines but this would require a few adaptations of the methods. However, urban systems such as metro lines are excluded from this study since they have very different properties from the lines studied with this method.

For the moment, saturation will only be studied in France, according to the French standards. This is why the study case will be carried out on a French railway line. However, the method could be adapted to other countries.

### 1.3. Methodology

The methodology used for developing the project follows these steps:

- **Search of information and theoretical analysis**

  This step is essential for the project. In this step, a comprehensive search is done among existing literature, rules and laws regarding saturation and capacity issues. The methods studied should be related to the different definitions and interpretations of the concept of saturation. Three main definitions, therefore, three existing methods will be studied during the project. A search among the existing literature will be done for each one of these methods. This search will lead to a first theoretical approach of the 3 methods in order to understand how they could be relevant for the project, and what elements need to be taken carefully into account.

- **Preparation of a study case simulation model**

  In order to apply these methods, a dynamic simulation model needs to be created. This will be done using simulation software, an equivalent to Railsys called SAMURAIL. The model will be created using data provided by SNCF Réseau. This operation model will be used for capacity, robustness, and stability simulations.

- **Application of the 3 methods on the study case**

  After having prepared the model, all the data and simulations will be done and the results will be analyzed for each method, in order to understand the results and do more accurate or relevant simulations to the case.
• Analysis and comparison of the methods

With the results of the previous analysis, it will be possible to compare the methods and to understand what relevant information they can give about the saturation level. The methods will be compared and analyzed together to understand how they can be used to complete each other. This will help us to give a better method using the previous ones.

• Path quality method

A fourth method will be studied in order to complement the three others. This method is studied separately since it does not exist yet and its indicators aim at giving a deeper understanding and analysis of saturation. This method will also be applied to the study case. In the end, all the methods will help us define the relevant indicators to measure the saturation level and give a better method using the complementarity of all the studied methods.
2. Objective

2.1. Problem description

Some railway lines are currently getting congested, or about to. However, there is no existing method to objectively determine the saturation level of such a line. Indeed, different indicators have been used to declare a line as saturated: sometimes, the capacity consumption is used while others, the regularity or the punctuality on the line is presented as the relevant indicator. Yet, using one indicator only might lead to mistakes regarding the level of saturation. Two indicators might present different results, or sometimes contradictory results. Which one should be used? Until now, no method has been determined. This is why the idea of this master thesis is to compare three different methods and to analyze them, in order to understand why they would be relevant to evaluating the saturation level of a railway line. The final aim is to define a method and relevant indicators that would give relevant information regarding saturation. The methods will be studied theoretically and then applied to a study case. A fourth method, which is quite new, will be studied separately first, and then compared to the others. It aims at completing the results given by the other methods to give a deeper analysis of saturation.

2.2. Definition of saturation

Saturation is commonly perceived as an overload, a limit that cannot be exceeded. If one considers a glass, one would say it is saturated once it gets full. However, this notion also refers to the inability to meet an additional demand.

Although railway and roadway have similarities, the notion of saturation is easier to define in the latter case. Indeed, a road is defined as saturated once the demand level is higher than the flow capacity of the considered road. At this level, the road is congested and the flow on this road decreases, resulting in a decreasing speed for car users. However, railway is different since a railway system works with a planned traffic and trains are expected to follow a schedule, with specific times to respect. This means that the capacity consumption of a train does not only depend on its characteristics and the infrastructure, but also on the other trains performances and nature. This is why measuring the saturation level of a line through the number of trains that can be run by hour for instance is irrelevant.

Furthermore, many stakeholders are involved in a railway project, whatever it is and whatever the step of the project: infrastructure owners, operators, transport organizer authorities and users are all related to the project, have different interests and their own vision and insight into what makes a railway line saturated.

The infrastructure owner is bound by the European directive 2001/14/EC [3]. This directive gives a definition of saturation: “Where after coordination of the requested paths and consultation with applicants it is not possible to satisfy requests for infrastructure capacity adequately then the
infrastructure manager must immediately declare that element of infrastructure on which this has occurred to be congested. This shall also be done for infrastructure which it can be foreseen will suffer from insufficient capacity in the near future.” [3] As a consequence saturation from the infrastructure owner perspective could be seen as a difficulty to open new paths, or issues with the existing paths, a strain between infrastructure maintenance and path service as well as growing issues regarding capacity allocation. If the directive is considered, saturation would be perceived mainly as an inability to create new paths, a capacity issue [1].

Operators, on the other hand, will not have the same definition of saturation, since they have different interests. Some might say that saturation is reached when the maximum allowed traffic is run on a line, depending on the properties of the trains, infrastructure and network. However, if we run as many trains as possible, one behind the other, as soon as an issue occurs on one of them, it will be spread throughout the whole network, making it unstable. If we tie this to the previous definition, it is possible to understand that adding new paths might in some cases create an unstable network. This shows that saturation is also related to robustness and stability [1].

Transport organizer authorities pay attention to the service development and quality. As a consequence, they will consider that a railway line is saturated when the quality of the paths does not reach some objectives defined in advance [1]. For example, running times, headways, or distribution patterns of the paths along a day are defined in advance, and if the objectives are not met, the line is considered a saturated according to them.

Last but not least, passengers consider that a line is saturated as soon as they encounter problems, such as delays, cancellations, crowds or lack of comfort because of the crowd [1]. As far as freight is considered, saturation could be defined as a difficulty to meet delivery deadlines because of delays and too long running times for example [1]. Saturation could be defined as a regularity issue in this case.

The adopted perspective defines saturation: this means that there is not a definition of saturation, but several ones. They are related to capacity issues, robustness, regularity and quality of paths. Saying that a line is saturated is not enough to understand its issues. What kind of saturation are we talking about? Each of these definitions matches one of the saturation evaluation methods that are described later in this report.
3. Theoretical study

To begin with the study of an evaluation method of the saturation level of a railway line, three methods have been studied separately from a theoretical aspect first, and then applied to a study case. The objective behind this study is to understand which indicators, properties and results can be relevant to evaluate saturation in order to compare them later on. In this theoretical study, the method will be analyzed in standardized way. As mentioned previously, each method has been chosen because it corresponds to a definition of saturation.

3.1. Compression method

The compression method is presented below. The International Union of Railways (UIC) described it in a leaflet [4] [5]; however, the leaflet is elusive on some aspects. As far as this thesis is concerned, hypotheses and choices regarding the elusive aspects are made and explained below. The reader can refer to the original leaflet to get the full description of the method.

3.1.1. Aim

The compression method can be implemented to evaluate the saturation level using two indicators:

- The occupancy rate
- The capacity consumption and the unused capacity

These indicators are calculated thanks to this method which implementation is detailed later in this thesis. Earlier in this report, several definitions of saturation were mentioned; through its outputs, this method considers saturation as a capacity issue. This means that the element that will determine the saturation level of a railway line is its occupancy level.

3.1.2. Framework

The idea of the compression method is to determine the unused capacity by compressing the paths on a specific calculation area and during a time period. In order to do so, graphical timetables are used. For each indicator, the calculation is made at a different scale:

- Occupancy rates are calculated by compressing paths on smaller line sections that are determined from an operational perspective. Theses elementary line sections (ELS) can be represented as tubes in which the arrangement of the trains does not change. The determination of these elementary line sections is described later in this report.
- Capacity consumption and unused capacity are calculated by compressing paths on commercial line sections, e.g. commercial line sections where trains are operated by for passengers and freight traffic. These line sections will be called train path line sections (TPLS) from now on. Its determination is presented later in this report.
It is important to notice that both kinds of line sections do not have the same purpose. TPLS have a commercial purpose while ELS have an operational one. That is why capacity demands are usually expressed for TPLS and not ELS. Therefore, it would be irrelevant to calculate capacity consumption on an ELS. However, occupancy rates can be calculated on TPLS.

3.1.3. Implementation

3.1.3.1. Definition of calculation areas

As previously mentioned, calculation is run both on train path line sections and elementary line sections. TPLS are defined from a commercial perspective and actually correspond to the main stations and nodes of the lines. This makes the TPLS quite easy to identify. On the other hand, ELS are more difficult to identify. An ELS is defined between two interlockings: to be more accurate, the identification of the interlockings is more difficult and requires a rigorous identification method. It is one of the major elements to consider while applying the compression method. Indeed, the occupancy rate can greatly vary depending on the defined ELS, which might lead us to making mistakes. Interlockings are only mentioned in the UIC leaflet and no definition is actually given. However, two criteria help defining them:

- The possibility for a train to cross or overtake another one. When this first criterion is met, the infrastructure element (station, node, junction...) can be considered as a significant interlocking. However, a theoretical possibility for a train to overtake or cross another one is not enough to define an interlocking. Some junctions might, in theory, allow trains to cross or overtake; nevertheless, if they are not used for that purpose, it would be irrelevant to consider them as significant interlockings. They have to actually be used that way in order to be significant interlockings. This one criterion, when met, is enough and there is no need to check the second one.

- The fact that trains begin or end running. This criterion on its own is not enough to define a significant interlocking. Some parts of a railway network are owned by private companies and are actually inactive, or slightly active. This means that the number of trains running on these sections is not high enough to influence the rest of the network. So, in order to define a significant interlocking, the considered infrastructure element needs to have enough trains running on it and ending or beginning their service.

When analyzing saturation on a line, the infrastructure and signaling maps are studied in order to determine all the infrastructure elements that could be significant interlockings. Then, using the completed timetables, it is possible to determine whether or not one of the criteria is met.
3.1.3.2. Definition of block section

The compression method defined by the UIC is defined for space-based signaling systems. This means that the line is divided into block sections for safety reasons. On a block section, only one train at a time can be running, in order to avoid collisions. If we come back to the aim of the compression method, this means that each train takes an occupancy time for itself; while a train is running through a block section, no other train can use this block section. This block section, defined in terms of space, can also be represented with a time representation, the block time. This block time is dependent on the signaling system as well as on the rolling stock.
In order to determine the block time, one needs to consider the fact that the driver needs to stop the train before entering a block section in case of a red signal. Therefore, the communication system needs to inform the driver beforehand of the color of the following signal. In France, this time is usually equal to 35 seconds for passenger trains and 45 seconds for freight trains since they are heavier [6]. This is a margin of security since trains usually need less than 35 seconds to brake and stop. This “time for visual distance” is part of the occupancy time of a train.

Figure 3: Visual distance definition in a block section

Once a train has run this visual distance, if the signal is green, it enters the block section. The journey time of the occupied block section is then considered. Once again, it depends of the rolling stock performance.

Figure 4: Journey time of occupied block section
Once the train leaves the block section, the signal located at the entrance of the block section, turns yellow. This means that the block section is not cleared yet, since the next block section is occupied. In order to turn green, the considered train needs to leave the following the block section.

![Figure 5: Journey time of the following block section](image)

To free the block section, a route release time is considered. This time includes the time for the full length of the train to leave the second block section and the time needed for the signaling system to indicate that the block section is free.

![Figure 6: Definition of the block section clearing time](image)
The block time calculation needs to be done for each block section and each train, since it depends on the signaling system, the length of block sections and the rolling stock. These calculations will be done on SAMURAIL software and described in part 4. Once they are done, the following graphical timetable is drawn, which is used to compress the paths.

![Figure 7: Example of graphical timetable before compression](image)

### 3.1.3.3. Calculation of time period

In order to perform the compression method, the calculation time period needs to be defined as well. Indeed, only the paths included in the calculation time window will be compressed and phenomena occurring outside this time window are not considered. This time window is used to determine the occupancy rate and the capacity utilization. Theoretically, there is no restriction regarding the time length of the window. However, the UIC recommends not going below two hours. For the occupancy rate, two consecutive peak-hours will be considered, at the busiest time of the day, since the aim is to evaluate the maximum occupancy rate. However, the capacity consumption can be calculated both on two peak-hours and on a whole day to have a better idea of the unused capacity on a commercially relevant line section.

### 3.1.3.4. Compression

The aim of the compression is to move the train paths closer to each other until the blocks are in contact, without changing the order on the considered ELS or TPLS in the chosen calculation time period. Once the compression is done, occupancy rates and capacity consumptions can be determined. This is applied quite simply on a line, but the method is a bit different for a node. Both methods are presented below.
3.1.3.4.1. Compression on a line

The compression is done using the graphical timetable with the block time’s representation. After having chosen the calculation time and area (ELS or TPLS), the paths are simply moved closer to each other so that the blocks are in contact. In the following example, a 24-hour graphical timetable is presented. A two-hour calculation time period is considered, and then the paths are compressed on an ELS (between stations C and E).

![First step of the graphical timetable compression](Image)

*Figure 8: First step of the graphical timetable compression*

The following graph (*Figure 9*) is obtained by zooming in on the previous graph.

![Second step of the graphical timetable compression](Image)

*Figure 9: Second step of the graphical timetable compression*
The paths are then compressed and moved closer to each other, without changing their order. We do not pay attention to what happens outside the ELS and the calculation time period, even if the paths collide.

Figure 10: Compression of a graphical timetable

Then, the calculation can be done; on an ELS, the occupancy rate is determined and on a TPLS, the occupancy rate, capacity consumption and unused capacity. In order to calculate the occupancy rate, a fictitious path is added (in white and green in Figure 11) which corresponds to the first path of the calculation time period. The occupancy time corresponds to the time between the beginning of the calculation time period and just before the fictitious path; indeed, the compression method is defined for a timetable with a repetition pattern of the paths.

Figure 11: Occupancy time after compression
To get the occupancy rate, the following formula is used:

\[
\text{occupancy rate} = \frac{\text{occupation time}}{\text{calculation time period}}
\]

The occupancy rate can be calculated both on an ELS and a TPLS: in both cases, the calculation is the same. However, capacity consumption and unused capacity should only be calculated on TPLS, since they are relative to commercial operation (Figure 12). In order to determine the capacity consumption additional times are taken into account. A part of these additional times is given by the UIC leaflet as a percentage of the calculation time period; these additional times correspond to buffering times required for a good operation service and are presented in the following table (Table 1) [4]

\[
\begin{array}{|c|c|c|}
\hline
\text{Type of line} & \text{Peak hour} & \text{Daily period} \\
\hline
\text{Dedicated suburban passenger traffic} & 18 \% & 43 \% \\
\text{Dedicated high-speed line} & 33 \% & 67 \% \\
\text{Mixed-traffic lines} & 33 \% & 67 \% \\
\hline
\end{array}
\]

There is another kind of additional times that are determined for each line and compression. They take into account maintenance work on the infrastructure, the rolling stock and the crossings between two trains.

![Figure 12: Definition of capacity consumption](image-url)
According to the UIC, the saturation levels are obtained for the following occupancy rates [4]:

<table>
<thead>
<tr>
<th>Type of line</th>
<th>Peak hour</th>
<th>Daily period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dedicated suburban passenger traffic</td>
<td>85 %</td>
<td>70 %</td>
</tr>
<tr>
<td>Dedicated high-speed line</td>
<td>75 %</td>
<td>60 %</td>
</tr>
<tr>
<td>Mixed-traffic lines</td>
<td>75 %</td>
<td>60 %</td>
</tr>
</tbody>
</table>

### 3.1.3.4.2. Compression on a node

The method is applied a bit differently for nodes, although the idea is still to get the paths closer to each other. The method will be described with an example.

At a node, there are incompatible routes, routes that cannot be run by trains simultaneously. For instance, the route from V to B (vB in red) and the route from A to V (aV in blue) cannot be run simultaneously, since some switching operations must be done to allow a train to run after the other did. This is why a simultaneity matrix is defined, in which exclusion times for a train following an itinerary incompatible with the previous train are defined. An example of such a matrix is presented below.

<table>
<thead>
<tr>
<th>Excluded trip</th>
</tr>
</thead>
<tbody>
<tr>
<td>vA 1,7 1,4 1,7</td>
</tr>
<tr>
<td>vB 1,4 1,7 1,4 1,4 1,4 1,7 1,4</td>
</tr>
<tr>
<td>aV 1,5 1,8 1,3 1,3 1,8</td>
</tr>
<tr>
<td>aF 2,4 2,2 2,9 2,4 2,4 2,9 2,4</td>
</tr>
<tr>
<td>fB 2,4 2 2,4 2,4 2</td>
</tr>
<tr>
<td>fA 2,4 2,1 2,1 2,2 2,4 2</td>
</tr>
<tr>
<td>bF 2,3 2,3 2,3 1,7</td>
</tr>
<tr>
<td>bV 1,8 1,5 1,5 1,5 1,5 1,8</td>
</tr>
</tbody>
</table>
For instance, a train following the vA route will have to wait 1.7 minute behind a train running the same route. A train following vB will have to wait aV to be able to go.

As for the compression of a line, one needs to determine the calculation time period. All the trains running through the node during this time window are considered, and keep their order unchanged. Once the train order at the node is determined, this matrix is used to calculate occupancy times. The matrix helps completing the occupancy time table below. Occupancy times are calculated by adding the exclusion times.

<table>
<thead>
<tr>
<th>Actual trip</th>
<th>Excluded trip</th>
</tr>
</thead>
<tbody>
<tr>
<td>vA</td>
<td>1.7</td>
</tr>
<tr>
<td>vB</td>
<td>1.4</td>
</tr>
<tr>
<td>aV</td>
<td>1.5</td>
</tr>
<tr>
<td>aF</td>
<td>2.4</td>
</tr>
<tr>
<td>fB</td>
<td>2.4</td>
</tr>
<tr>
<td>fA</td>
<td>2.4</td>
</tr>
<tr>
<td>bF</td>
<td>2.3</td>
</tr>
<tr>
<td>bV</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Table 4: Example of a node occupancy calculation table

In order to determine the occupancy rate, a fictitious path is also added at the end. It corresponds to the first train running during the considered time period. This is the same process as for the compression on a line. The occupancy rate is calculated by dividing the occupancy time by the calculation time period. The UIC leaflet defines the following occupancy rates as limits for saturation [4]:

Table 5: Additional times in for switch and track areas [4]

<table>
<thead>
<tr>
<th>Type of node area</th>
<th>Concatenated Occupancy Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Switch area</td>
<td>60 % 80 %</td>
</tr>
<tr>
<td>Track area</td>
<td>40 % 50 %</td>
</tr>
</tbody>
</table>
3.1.4. Grey areas

The major issue that one could face with this method is getting wrong results because of a wrong identification of interlockings, leading to calculating occupancy rates on wrong ELS. Indeed, it is possible to get very different results, as the following example shows. It is a line with one station at both ends, and two junctions in the middle of the line. This leads to 4 different possible cases, 3 were studied. For the first case, the junctions were not considered as significant interlockings so there was one ELS. For the second one, one junction was considered as a significant interlocking, leading to 2 ELS. For the third case, both junctions were considered significant interlockings, leading to 3 ELS. Occupancy rates are calculated for the 3 cases and the results were as follows:

<table>
<thead>
<tr>
<th></th>
<th>1 ELS</th>
<th>2 ELS</th>
<th>3 ELS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><img src="image1" alt="Diagram" /></td>
<td><img src="image2" alt="Diagram" /></td>
<td><img src="image3" alt="Diagram" /></td>
</tr>
<tr>
<td>1</td>
<td>80%</td>
<td><img src="image4" alt="Diagram" /></td>
<td>10%</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td><img src="image5" alt="Diagram" /></td>
<td>80%</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td>10%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>30%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>45%</td>
</tr>
</tbody>
</table>

*Figure 14: Example of the influence of interlockings choice*

We get 3 completely different results, leading to very different interpretations. For the first situation, which makes sense from a commercial aspect, since there is a capacity demand for trains running from a station to the other, one would say that the line is saturated. For the second, one would say the same thing, and would get a more precise idea of the location of the saturation. However, according to the last case, there is no saturation; in this case, a junction was considered as a significant interlocking although it was not. Through this example, two things can be understood; the importance of the definition of interlockings and the difference between an ELS and a TPLS and the sake of each one. ELS will help us localize saturation, while TPLS will help us determine if it is possible to add new trains on relevant lines from a commercial perspective. In the example, it would make sense to study cases 1 and 2. Case 1 would help us from a commercial point of view; the second case would not do that because no train would run from a station to a junction and just stop to leave the passengers there. The second case helps us understand that the line is saturated before the junction.
3.1.5. Critical assessment

This method can be applied quite rapidly and easily once the interlockings have been thoroughly defined. It is also a method that can be applied to any line.

However, it is a one-dimensional approach to saturation that is considered only as a capacity issue. Stability and reliability of the timetable, infrastructure and rolling stock are absolutely not considered. The characteristics of each line are not considered. Moreover, paths cannot be tested or modified, and are all considered the same way, although there are many differences between a high-speed train and a freight train.

3.2. Robustness method

The robustness method is defined in reference documents [7] [8] and is intended for infrastructure owners. It is often applied during preliminary studies.

3.2.1. Aim

This method aims at evaluating the resilience of a couple infrastructure/service i.e. the ability of such a couple to absorb disruptions. It is also a way to evaluate the stability of the timetable. For this method, saturation is not defined only as a capacity issue as it is for the compression method. Indeed, depending on the results of an analysis, the network will be declared saturated in case of instability or if the network is not efficient enough in absorbing the disruptions.

3.2.2. Framework

The idea is to simulate the reaction of the network to a disruption on a specific time at a specific place. The indicators that are mostly used to describe the robustness of a line are:

- The number of trains impacted on top of the train where the disruption occurs.
- The time for the network to get back to its regular working state; this will be measured at the disruption location in order to evaluate local effects. The regular situation will be considered as the moment when the track is cleared at the disruption location, after the last affected train has passed through.
- The total number of minutes lost locally, i.e. the delays for each train affected by the disruption and running through the disruption location, is added.

This method is more efficient when several infrastructure/service couples are compared rather than just applied in absolute terms since the thresholds of the method are not constraining enough.
3.2.3. Implementation

According to the reference documents that need to be respected, for a timetable to be robust, it needs to absorb a 10-minutes disruption in less than 60 minutes, without any intervention (changing the trains’ order or making trains stay longer in stations for example). Also, in order to be robust, there should not be any major delay and no snowball effect (increase of the initial disruption). The implementation is presented with a theoretical example (Figure 15). Suburban trains are represented in yellow and high-speed trains are in red.

To apply the method, one considers a timetable and tests each kind of train by applying a 10-minutes disruption. For the presentation of the implementation, only a suburban train will be disrupted, as shown on the following graph (Figure 16). In blue is represented the route of the train without the disruption. A place, a time and a train to disrupt, are chosen in order to study the worst case possible.
After simulating the timetable, using SAMURAIL program for example, it is possible to see how the other trains are affected by the disruption and how much time the network needs to get back to its regular working situation. In Figure 17, the planned paths are thicker than the simulated paths.

During the simulation, the disrupted train can consume all the available margins in order to catch up with the planned timetable. Indeed, paths are usually created including a 4.5 minutes' margin per 100 km. This margin is supposed to be defined for other purposes such as construction work on the line for example, but the assumption in the study is that they can be consumed during the simulations. The effects of the disruption are analyzed locally; the blue line ends quite early, even though the disruption still has impacts on other places of the line, because the disruption no longer has impact at the disruption point after the blue line ends.

If the method is applied to the previous example, the results are as follows:

- Number of trains impacted on top of the train where the disruption occurs: 2. In the previous example, the disrupted train also disrupts a high-speed train (in red) and another suburban train.
- Total number of minutes lost locally: 13 minutes (10 minutes for the disrupted train, 2 minutes for the high-speed train and 1 minute for the suburban train)
- Time for the network to get back to its regular working state: 17 minutes (15 minutes between the beginning of the disruption and 2 minutes to clear the track)

This means that the infrastructure/service couple seems to be robust, but one would need to disrupt a high-speed train to be able to declare that it is actually robust.
3.2.4. Grey areas

There are some aspects that are somehow unclear, or that at least require a special attention:

- Test location: the simulations must be done at a dimensioning point (dense traffic, nodes...)
- Disrupted train: at least one train for each type of train (High-speed, suburban, freight, express trains, omnibus trains...) during peak-hours. Otherwise, some stability problems might be missed.

However, this last point can be tricky. Below is an example to show the issues that can be faced, when choosing the test. There is a graphical timetable which robustness should be tested. Each kind of train is represented by a color. If one wants to test the orange trains, in this case, the choice is quite obvious. There is quite some time between the second orange train and the following trains: testing this train would be irrelevant since the disruption would be very small for the other trains. On the contrary, the first orange train could disturb the network in a major way, so it should be tested. In this case, the choice is quite obvious.

![Figure 18: Example of robustness test choice](image)
However, if one wants to test the blue trains, it is rather unclear. In this case, both trains should be tested.

Figure 19: Robustness test choice issues

3.2.5. Critical assessment

This method gives a good understanding and representation of reality. The dynamic simulations help getting a realistic representation of the network behavior. It is also quite simple to implement, especially since many simulations can be done rapidly once the model is built.

However, the usual indicators with the robustness method are not sufficient to evaluate all the robustness criteria. Indeed, with the previously introduced indicators, only the network response to a 10-minute disruption is tested, the idea is then to check if it is absorbed within 60 minutes. The snowball effect and the major delay criteria are not tested. The snowball effect criterion would require redefining the limit of the studied line section: instead of considering only local effects, global effects would also be included. This will be added to the method for the rest of the thesis; disruptions will be analyzed on the whole studied line. As a consequence, two other indicators will be added to this method: the total delays and the time for the network to get back to its regular working situation, for the whole considered line.

Moreover, the disruption absorption criterion is too easy to respect, and makes comparison between different situations harder. That is why, other tests will be performed with more restrained limits for the disruption absorption time. What is more, it would be more realistic to take into account the possible regulation when a disruption occurs, which was not the case with the initial method. These tests will be performed on top of the initial method.
3.3. Regularity method

3.3.1. Aim

This method is used to analyze the performances of the network using the actually carried out timetables by the trains on a line. These elements are analyzed in order to determine where delays are created and how these delays are spread. The difference with the previous method is that past data and timetables are used to perform the study, while the robustness method is done as preliminary study. Moreover, the reliability issues are identified with this method, which is not the case for any other method. For this method, saturation is not defined as a capacity or stability issue, but as a delay issue.

3.3.2. Framework

For this method, the required data are actually the carried out timetables by the trains on the considered line, for a significant period of time, since a statistical analysis will be performed and the aim is to have a relevant tendency. A lot of data is needed in order to carry out this method:

- Incident reports; in order to identify the kind of incident and its cause.
- Statistics regard delays at every remarkable point of the line.

The most interesting indicators to study saturation with this method are:

- Regularity rate at a remarkable point (5-minutes regularity or 1-minute regularity)
- Average delay at a remarkable point
- Delay growth rate on a line section

3.3.3. Implementation

The statistical analysis will be made at remarkable points or by section, using the data from the database in order to follow each train and its delay. This will allow us to calculate average delays for each individual train path instead of calculating them only on the all the trains as a group.

Since the aim is to compare the results of all the methods, we will work on the same elementary line sections as those used in the previous methods and at the same peak hours. The results will also be compared at different time of day to evaluate the impact of traffic density on the delays.

The most interesting indicator with this method is the delay growth on a line section, especially if the rate is calculated on the same elementary line sections (ELS) as for the compression method. This would help us compare the results between these methods. The idea would then be to find, for each train, the delay when entering the ELS and when leaving it. By doing this for each train, it would be possible to use a linear regression in order to determine the average delay growth on each ELS. This would help us identify the most saturated sections.
3.3.4. Grey areas

This method is based on a statistical analysis on data extracted from database. This database is completed by beacons located all along the line, but some information can be wrong. This method, as any other statistical analysis, can therefore include some errors and we need to have an idea of the margin of error for this study.

Another aspect that needs to be taken care of is the consideration of trains arriving early or on time. In this thesis, are included trains arriving on time for the calculation of average delays and statistical calculations, while trains arriving early, i.e. with negative delays, will be considered as arriving on time.

3.3.5. Critical assessment

One of the strengths of this method is that it is applied on past data, which gives a very realistic diagnosis of the situation. Moreover, it is a very simple method, with very few elusive aspects.

However, it is important to pay attention to the reliability of the data, since the method is based on a lot of data that need to be processed (removal of wrong data, removal of technical movements...). As any other statistical analysis, there can also be irrelevant or insignificant results. It is also important to be aware of the fact that major delays can happen at different places than the saturated sections. The example below shows a junction; trains have major delays before the junction but their regularity is better on the common track, which is actually the saturated line section.

![Figure 20: Relocation of the saturation effects from the regularity approach](image)
4. Application to a case study

In order to adapt and improve the indicators used to evaluate the saturation level of a railway line, the previously mentioned methods are performed and studied on an actual line. For confidentiality reasons, the names of the stations and the results have been modified; however, the conclusions that can be drawn from these results are not altered.

4.1. Introduction to the case study

The studied line is about 200 kilometers long and the major stations are presented Figure 21. This line is studied since some issues related to saturation are appearing little by little. The characteristics of the line make it very interesting to study. Indeed, the traffic on the line is very heterogeneous; regional trains, long-distance trains, freight trains and high-speed trains run on the line. All the trains have different performances and run at different speeds, which is not optimal in terms of capacity. Although high-speed trains run on the line, the infrastructure is not designed for high-speed trains, so they cannot run at their maximum speed. Moreover, several elements can create incidents on the line, especially the high number of cross levels on the line.

This line is studied for several reasons: for the past few years, the traffic has been increasing quite quickly. There are more and more reliability issues on the line, which might be related to saturation. Besides, the traffic increase is also accompanied by increasing travel times; this does not satisfy local authorities and passengers. Moreover, local authorities would like to increase the number of regional trains per hour, but the existing transport system does not allow it. Currently, it is not possible to have four regional trains per hour both ways.
The graphical timetable shows that the line is quite congested:

Figure 22: Graphical timetable of the line for the studied day

4.2. SAMURAIL model

In order to use the compression and robustness methods, it is needed to establish a model for the line and to simulate it. In order to do so, SAMURAIL (Software to Analyze and Maximize Use of RAIL) will be used, simulation software and alternative to Railsys. It has been created by a French software company called Corys.

In order to create a model on SAMURAIL, many information need to be provided regarding:

- The infrastructure: this includes the signaling system with the signals location, information given by the signals, conditions for a track to be available, possible tracks for a train, the track position, the speed limits all along the line depending on the train type...
- The rolling stock: all the physical characteristics of the rolling stock (mass, length, drag resistance, traction performance...)

The infrastructure is modeled thanks to the layouts showing how the tracks are positioned, giving the signaling system and the maximum speed allowed by the infrastructure. The software provides a high level of accuracy since results are given with a split-second and split-meter precision. Moreover, it is quite easy to modify the infrastructure if needed. All the signals on the line are modeled. For our study, only the tracks where trains actually run are modeled. Altimetry is not considered in the
model, although it would be possible to include it, since it is not very really relevant to our study, it does not vary a lot. An example of a modeled station on SAMURAIL is given in Figure 23.

Figure 23: Example of a station modeled on SAMURAIL

The rolling stock characteristics are also an input for the model; for each train type, data about the rolling stock are available, including the weight of the trains, their length, their drag resistance, traction performance and speed limit. An example of traction performance of a train is presented below.

Figure 24: Example of a traction force graph depending on the speed
(Source: http://www.twoof.freeserve.co.uk/motion1.htm)

Once the infrastructure and rolling stock are modeled on SAMURAIL it is possible to simulate the timetable. In order to have the most accurate model, the graphical timetable is needed, which has been extracted from database with all the trains running on the line. Moreover, track occupation graphs are provided in order to know how the trains are distributed on the tracks within the stations. It is possible to simulate the actual route followed by the trains: once the infrastructure is created, it is possible to pick which track the train will follow all along the line and at each station. This gives a higher accuracy to the model.
4.3. Capacity results and analysis

Now that the SAMURAIL model is built and running, it is possible to apply each method starting with the compression method previously introduced. The idea is here to determine the occupancy rate of the line in both up and down ways on each of the elementary line section, and then the capacity consumption on each train path line section. On top of that, the occupancy level of the track and switch zones at each node of the line will also be determined. Therefore, 3 different calculations are run here. The calculations will now be introduced as well as the results.

4.3.1. Compression on a line section

4.3.1.1. Methodology

The idea here is to compress the train paths together on each elementary line section to begin with. The choice of the ELS and the time period has been explained previously. In the up way, an assumption is made to consider that the studied time period is one evening peak hour, since there are not two consecutive hours that are really busy for all the line.

![Figure 25: Graphical timetable for the studied peak hour up way](image-url)
In the down way, it is equal to two evening peak hours, since this way is more used during two full hours.

In order to determine the occupancy level, the idea is to determine the minimum block section clearing time between two train paths on the studied ELS. This way, it is possible to determine for how long the infrastructure will not be occupied.

Here is an example of how this is done. We will consider the up way and the ELS between the stations Rac and Cur.

![Figure 26: Graphical timetable for the studied peak hours down way](image)

![Figure 27: Implementation of the compression method](image)
Between two consecutive train paths the area in which the block section clearing time is probably the lowest is determined. In the following example, this area is represented by the blue bubble. For each signal, the simulation gives the elements to calculate the time between the moment the signal is cleared by the first train and the moment the second train crosses the signal. This time is calculated for each signal as shown in the following example.

Then, the calculation of the block section clearing time is run by subtracting the visual distance time (equal to 35 seconds for passenger trains and 45 seconds for freight trains) to the gap time previously calculated.

In the previous example, this visual distance time is equal to 35 seconds.
By doing so for all the train paths, the results for the ELS between Cur and Rac in the up way are the following:

![Figure 30: Available infrastructure time between the trains on the Rac – Cur ELS up way](image)

One can notice that the green train path is not a constraint for the occupancy when compressing the train paths: this means that the maximum occupancy is given by the blue train ahead of it and red train behind it.

In order to calculate the occupancy rate, the following formula is then used:

\[
\text{occupancy rate} = \frac{\text{time period} - \text{sum of the minimum block section clearing times}}{\text{time period}}
\]

In the previous example, the occupancy rate is equal to 69.7%.

In order to determine the capacity consumption on a TPLS, we need to use this compression methodology on the studied TPLS. It has to be done for each TPLS since the combination of trains creating the higher occupancy depends on the considered TPLS. Then, the occupancy rate is calculated and multiplied it by 4/3 in order to get the capacity consumption. This additional time is needed to have a reasonable service quality.
4.3.1.2. Results and analysis

After doing that on all the line sections, the results for the occupancy rates on ELS are:

We notice that the occupancy is higher down way. There are two explanations to this; first, there are generally more freight trains during evening peak hours going down way (Figure 32). Freight trains are slower so they consume more occupancy. Secondly, there is an asymmetry between the transport services in both ways: indeed, there are regional trains going down way between Rac and Cyv or Tiv, which do not exist up way. This is due to the fact that demand is higher this way during the evenings.

The Rac – Cur and Pis – Rac ELS are really congested, since they are very close to the limit rate to get a good service quality (defined equal to 75% by the UIC [4]), while the Pis – Cyv and Cyv – Tiv ELS are moderately congested. This does not mean that it would be easy to add trains on these sections. Indeed, when the occupancy rate on an ELS is calculate, neighboring sections are not considered, so...
if a train runs on several ELS, we will not be able to see all the constraints that exist on this train. This can be observed thanks to the train path line sections, which results follow:

**Figure 33: Capacity consumption on Tiv – Cur TPLS**

**Figure 34: Capacity consumption on Cyv – Cur TPLS**

**Figure 35: Capacity consumption on Tiv – Rac TPLS**

**Figure 36: Capacity consumption on Cyv – Rac TPLS**
Results on the Cur – Tiv TPLS show that the capacity consumption on the line is equal to the limit rate for the up way, while it is well over the limit for the down way. This means that the service quality is probably affected on this section. These results show that it will not be possible to add train paths going from Cur to Tiv or the other way around.

The results show that the capacity consumptions on Cur – Cyv and Cur – Tiv are the same; this shows that trains running on Cyv – Tiv do not create any constraint on the other sections. All the constraints are gathered on the Cyv – Cur section.

![Figure 37: Capacity consumption on Zid – Nec TPLS](image)

The results on the Zid – Nec TPLS show that the capacity consumption is below the limit given by the UIC. Therefore, one might say that it is possible to add train paths on this TPLS without damaging the service quality. Theoretically, one additional average train path per hour represents approximately 7% of capacity consumption, which would make it possible to add one train path per hour on this TPLS in both ways. However, this depends on the kind of train and the capacity consumption of a freight train would be quite different. In this case, demand for additional trains relates to regional trains.

However, this estimation does not include the compatibility of this additional train path with the existing train paths. Elements such as timing, train reversals, track occupancy at terminus stations should be considered. Since the compatibility of such train paths has not been tested, it is not possible to confirm whether adding train paths is possible. This possibility is not excluded, but cannot be confirmed at the moment, with the current data.

### 4.3.2. Compression of a node

#### 4.3.2.1. Implementation in switch zones

The idea is the same here as for the line compression on line section, but the methodology is a bit different. In switch zones, some train routes are incompatible, which means that they cannot be run simultaneously. Therefore, the incompatibility between two routes creates infrastructure occupancy. The methodology to calculate the occupancy rate of a switch zone with the simultaneity matrix was previously introduced. In order to fill such a matrix, we need to consider the structure of a switch zone.
On SAMURAIL, exclusion times are calculated during the dynamic simulation, each train is followed. The exclusion time is taken between the moment a train crosses the entry signal and the moment it frees the route of another train. To that time, the visual distance time and a time for the switch to change its position (12 seconds in our study) are added. These times are calculated by simulation of the SAMURAIL model and then the simultaneity matrix (Table 3) can be filled.

Using this matrix, a VBA program is created on Excel in order to calculate the exclusion times and the time at which each train starts occupying the infrastructure: the beginning of occupancy is calculated as if the train had to go one after the other without any margin in between.

An example of the table resulting from the Excel VBA program is given Table 6:

<table>
<thead>
<tr>
<th>Train Number</th>
<th>Itinerary</th>
<th>Occupancy beginning</th>
<th>Ca1-D</th>
<th>Pe2-C</th>
<th>A-Ca2</th>
<th>Dp-H</th>
</tr>
</thead>
<tbody>
<tr>
<td>###</td>
<td>Ca1-D</td>
<td>0,00</td>
<td>2,58</td>
<td>0,00</td>
<td>0,00</td>
<td>0,00</td>
</tr>
<tr>
<td>###</td>
<td>Pe2-C</td>
<td>0,00</td>
<td>2,58</td>
<td>1,93</td>
<td>1,78</td>
<td>0,98</td>
</tr>
<tr>
<td>###</td>
<td>A-Ca2</td>
<td>1,78</td>
<td>2,58</td>
<td>4,15</td>
<td>4,62</td>
<td>3,22</td>
</tr>
<tr>
<td>###</td>
<td>Dp-H</td>
<td>3,22</td>
<td>3,22</td>
<td>4,58</td>
<td>6,12</td>
<td>3,22</td>
</tr>
</tbody>
</table>

The third column corresponds to the moment at which the train can engage on its route. In order to calculate the occupancy rate, the beginning of occupancy of the last train is considered and the following formula used:

\[
\text{occupancy rate} = \frac{\text{occupancy beginning of last train}}{\text{time period}}
\]
In our example, the last train can depart after 47.4 minutes and a 2-hour time period is considered. Therefore, the occupancy rate is equal to 39.5%.

It is important to notice that for each node, there are two switch zones in our study, one on the north side of the node and the other on the south side. This means that this compression method has to be applied twice for each node, since they are passing nodes, and not terminus stations.

4.3.2.2. Implementation track zones

In order to compress the train paths in a track zone, a track occupation graph is needed. This way it is possible to know where the trains go and stop in a node. The method is the same as for the compression on a line section: the occupancy begins when a train crosses the entry signal and ends when the end of the train crosses the first exit signal. This makes the calculation of the occupancy rate for each track possible by dividing the sum of occupancy times by the studied time period.

4.3.2.3. Results and analysis

Rac and Pis are not major nodes, they are only passing stations. Therefore, only track occupancy rates will be shown for these stations. Cyv is a major node which is the junction between the studied line in the master thesis, and another line: both track and switch zones track occupancy will be shown for this station.

There is no real feedback regarding the limit occupancy rates for track and switch zones; the limits given by the UIC are arbitrary and some researchers are still trying to define these limits. The limit will be considered equal to 60% for both track and switch zones [9] [10].

The track occupancy rates at Rac station are shown in Figure 39. We notice that the occupancy rates on some tracks, especially track A, are quite high. On the whole, this station is moderately congested.

---

```
To Cur

F 33%
E 29%
D 20%
C 36%
B 37%
A 58%

Average: 35.5%

To Pis
```

Figure 39: Track occupancy rate in Rac station
The track occupancy rates at Pis station are shown in Figure 40. It is a very dimly congested station.

![Figure 40: Track occupancy rate in Pis station](image)

Results for the Cyv node are shown in Figure 41. It is quite congested. Some tracks are very congested, almost reaching the 60% limit. Switch zones are also quite congested.

![Figure 41: Track and switch occupancy rates in Cyv node](image)
4.3.3. Summary

Until now, results at nodes and on ELS were presented separately. The compression method was done on ELS excluding stations and nodes used to define the ELS. However, some constraints within the nodes might actually involve higher occupancy rates, especially the Cyv node. It is possible to use the compression method by including the switch zones in the calculation on ELS and to go until the track section. The only interesting switch zones in our study are at the Cyv node; it will be the only one considered. In order to include the switches in the occupancy calculation, the free time, e.g. the time for which the infrastructure is not occupied, is verified between two trains so that it is not smaller in the switches than for the rest of the line. The new occupancy rates are calculated on two ELS: Tiv – Cyv and Cyv – Pis. The results are presented in Table 7.

Table 7: Influence of switch zones on line occupancy rates

<table>
<thead>
<tr>
<th></th>
<th>Without the Cyv switch zones</th>
<th>With the Cyv switch zones</th>
</tr>
</thead>
<tbody>
<tr>
<td>Occupancy rates Pis - Cyv up way</td>
<td>30,8%</td>
<td>34,3%</td>
</tr>
<tr>
<td>Occupancy rates Pis - Cyv down way</td>
<td>53,1%</td>
<td>58,7%</td>
</tr>
<tr>
<td>Occupancy rates Tiv - Cyv up way</td>
<td>47,5%</td>
<td>52,0%</td>
</tr>
<tr>
<td>Occupancy rates Tiv - Cyv down way</td>
<td>59,5%</td>
<td>59,5%</td>
</tr>
</tbody>
</table>

The differences do not change the analysis previously made but they should not be neglected. An illustration of the results presented of the same figure for the ELS, track and switch zones is presented in Figure 42.
We notice that the occupancy rates are higher down way than up way. The sections Pis – Rac and Rac – Cur present higher occupancy rates than the limit (75%). The results show that Rac and Pis stations are not congested, while Cyv node is quite used since it is at the intersection of two lines. From these results, a detailed picture of the infrastructure occupancy and of which sections are most occupied appears; however, these results do not mean that it is possible to add trains between Cyv and Pis because the results are given by ELS and do not take into account the constraints of the other ELS.
4.4. Robustness results and analysis

4.4.1. Methodology

In order to study the robustness of the line, its response to disruptions is studied in the worst case scenario, during peak hours. This way, it is possible to make sure that the line is robust if the results indicate it, provided that the chosen tests are relevant. Two different kinds of tests will be run:

- **3-minute disruption tests without any operational regulation**: these tests are run in order to observe the reaction of the transportation system to small disruptions that often occur. The idea is to check that the disruption can be absorbed rapidly enough, without affecting many trains if possible.

- **10-minute disruption test with operational regulation**: these tests are more realistic since human beings are intervening whenever there is a problem on the line. Therefore, taking decisions and intervening in order to reduce the impact of disruption should be taken into account at some point.

In order to simulate these disruptions, simulation software is studied, in our study, SAMURL. For each test, the train is actually delayed only at the test point and is supposed to follow the planned timetable anyway. The simulation will then make the train use its margins to keep following the planned timetable. As previously explained, each type of train will be tested: so at each test point, a freight train, a high-speed train, a regional train and a long-distance train will be disrupted. The tests will be run at the entrance station of each elementary line section, in both ways, in order to observe the system’s response on each ELS and to be able to compare the results with the other methods. For each test point and each train type, the train that is the most likely to create the biggest impact on the system is chosen. On the following graphs, each dot represents a test. Each test is run individually, meaning that only one train is disrupted at a time. For each dot, a 3-minute and a 10-minute disruption test are run. For the up way, the tests are presented Figure 43:
Figure 43: Robustness tests up way

In the down way, the following tests will be done:

Figure 44: Robustness tests down way
The following indicators will be measured by reading the simulated graphs on SAMURAIL for each test:

- Number of trains affected by the original disruption
- Cumulative local delays: all the delays created by the original disruption at the test point are added.
- Cumulative global delays on the ELS: the delays created by the original disruption at the end of the ELS are added.
- Cumulative global delays on the line: the delays created by the original disruption at the end of the line are added. This is calculated in order to evaluate the spreading of delays on other lines.
- Spreading rate of the original delay, which is the ratio between the cumulative delay at the end of an ELS and the original delay.
- Time to get back to the regular working state locally, on the ELS and on the line

These indicators are measured manually on the simulated paths.

### 4.4.2. Results and analysis

We will start by introducing a robustness test with a 10-minutes disruption in order to see an example of operation regulation and understand more practically the methodology. The results of all the tests will then be introduced.

A 10-minute disruption test on a high-speed train and study its impact on the other trains is performed.
Since the high-speed train leaves ahead of a freight train (in green) and a regional train (in blue), its delay will have an impact on these trains. If these trains leave on time, since they are slower than the high-speed train, either they will need to be overtaken at some point, or the high-speed train will be stuck behind them, in which case its delay will keep increasing along the way. Therefore, it seems preferable to keep both trains longer at the initial station and let the high-speed leave ahead of them. This is better since all the trains can go at their own pace in order to absorb their delay without being constrained by another train. That’s the first operational regulation: both trains will stay longer in Cur station. This can be observed in the graph below: bold lines correspond to the planned timetables whereas light lines correspond to the results of the simulation. SAMURAIL is not able to take regulation decisions so this has to be done manually, by implementing the most efficient regulation measure. These regulation measures are applied according to the rules dispatchers actually implement on a daily basis.
Instead of leaving the station before the freight train, the regional train actually stays in the station and leaves after. This is due to the number of stops the regional train has to make: if it left just before the freight train, the latter would increase its delay. Moreover, the freight train will have a long stop a few stations later, where it can easily be overtaken by the regional train.

A second freight train has to park longer in a station as presented in the following figure. In the initial timetable, without the disruption, the freight train was supposed to park there so that the high-speed train could overtake it. However, since the high-speed train is late, it is better to keep the freight train in the station while the high-speed train passes through it.
Once these operational regulation measures are taken, the relevant indicators can be calculated and the results are:

- **Number of additionally affected trains**: 3.
- **Cumulative local delay**: 21 minutes (10 for the TGV, 8 for the regional train and 3 for the freight train).
- **Cumulative global delay on the ELS**: 17 minutes (7 for the TGV, 5 for the regional train and 5 for the following TGV).
- **Cumulative global delay on the line**: 0 minute.
- **Local time to regular working state**: 19 minutes
- **Time to regular working state on ELS**: 56 minutes.
- **Time to regular working state on the line**: 65 minutes.
- **Local spreading rate**: 210%
- **“Snowball effect” on the ELS**: -14%. The delays decrease throughout the ELS by 14%.
- **“Snowball effect” on the line**: -100%. The delays are totally absorbed within the studied line.
For the 3-minute tests, the results are as follows:

**Figure 48:** Average amount of additionally affected trains for 3-minute robustness tests

**Figure 49:** Average cumulative local delays for 3-minute robustness tests

**Figure 50:** Average cumulative delays on ELS for 3-minute robustness tests

**Figure 51:** Average time to regular working state on ELS for 3-minute robustness tests
For the 10-minute tests, the results are as follows:

These results are difficult to analyze. There is no real common conclusion that can be drawn from these results. Each indicator seems to give different results and it is difficult to explain why; understanding saturation through these indicators is difficult and seems inappropriate. It seems that the chosen indicators are not relevant to this study case. Indeed, the three-minute tests are better suited for very frequent and close train paths, such as suburban or metro systems, which is not our case. As a consequence, it has been decided to study new indicators, using the results of the ten-minute tests with regulation:

- **Local spreading rate**: it is the ratio between the cumulative secondary delays and the primary incident duration (10 minutes in this case). A 50% local spreading rate means that the primary incident created a total delay of 5 minutes on the other train at the incident point.
- **Damping factor on the ELS**: it is the ratio between delays at the incident point and the delays at the exit of the ELS for the affected trains. It represents the proportion of delays that has been made up along the ELS.
The results for these indicators are as follows:

![Figure 56: Average local spreading rate](image)

4.4.2.1. Up way

We notice, as it was the case for the previous method, that the results are better up way than down way. This can be explained by the lower density of trains; there is only one freight train and three regional trains per hour up way, but two freight trains and four regional trains per hour down way.

The local spreading rate at the Pis station up way is higher than at the other stations, despite a total cost of incident at almost the same level on the Pis – Rac ELS as on the other ELS. This is due to the configuration of the train paths at Pis station: they have a funnel configuration, meaning that over an hour, trains paths are gathered only into half an hour. However, the density of train paths is not very high on the ELS ahead the incident point.

4.4.2.2. Down way

If we consider total cost of an incident, Rac – Cur present the worst results: it is also the ELS with the highest train paths density. It is also noticeable that the local spreading rate ahead of Cur down way is also the highest. It is equal to 108%, meaning that a 10-minute delay creates 10.8 minutes of additional delay on other trains. This shows the density effect on this section: trains are very close together at Cur station, and all along the Cur – Rac ELS.

The results on other ELS are consistent with the results given by the previous method. The denser the traffic, the higher the total cost of an incident and the local spreading rate. The only ELS on which this does not apply is Rac – Pis; indeed, the cost of an incident and the local spreading rate are
surprisingly low although this section has a very high occupancy rate. An explanation of this phenomenon can be given by the damping factor on this section. It is equal to 0.3, twice to four times lower than on the other sections. This means that 70% of the original delay at Pis is caught up on the section. Despite a high occupancy rate on this section, trains have lower constraints on this section since they are able to make up for their delay quite significantly.

4.5. Regularity results and analysis

4.5.1. Methodology

This method is different than the previous ones as it uses past data and helps analyzing an existing situation while the previous methods were more used in order to anticipate. This method uses a statistical analysis using data collected in databases. The data is collected by beacons located at waypoints along the line. The data is collected and saved in an excel file where many information appear: the train identifier number, the train number, the origin and destination of the train, the line on which the train is running, the kilometric point of the beacon, the time at which the train actually activated the beacon, and the scheduled time of activation. The first thing to do is sorting the data. This is done using an Excel VBA program.

In order to evaluate the evolution of delays, only working days are considered while holidays are excluded. This represents around 220 days. Since the aim is establishing comparisons between the results of all the methods, the evolution of delays will be studied on ELS: since the focus point is studying the saturation of the line, only the evolution of delays on the links between the major stations of the line will be analyzed. Therefore, it is necessary to pick the kilometric points where the evolution of delays will be calculated. The criteria to choose them are their closeness to the major stations of the line and how many trains have activated the beacon at the kilometric point. Indeed, some beacons do not record all the trains that pass. A VBA program on Excel is used in order to determine the yearly average number of trains activating each waypoint: the results are presented in Table 8. Each station has several beacons identified by a code. This table is then used to choose the relevant waypoints between which the evolution of delays is calculated. These waypoints are represented in Figure 58. There was no waypoint between Cyv and Pis where enough trains activated beacons, therefore the evolution of delays will be studied on the whole line section.

![Figure 58: Sections of which the evolutions of delays is measured](image-url)
Table 8: Average number of trains activating the beacons on waypoints of the line

<table>
<thead>
<tr>
<th>Station</th>
<th>Kilometric point</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kyz</td>
<td>147</td>
</tr>
<tr>
<td>Vuh</td>
<td>110</td>
</tr>
<tr>
<td>Zyz</td>
<td>181</td>
</tr>
<tr>
<td>Tiv</td>
<td>147</td>
</tr>
<tr>
<td>Ynf</td>
<td>1</td>
</tr>
<tr>
<td>Hey</td>
<td>141</td>
</tr>
<tr>
<td>Kan</td>
<td>91</td>
</tr>
<tr>
<td>Cuz</td>
<td>44</td>
</tr>
<tr>
<td>Cyv</td>
<td>4</td>
</tr>
<tr>
<td>Nie</td>
<td>133</td>
</tr>
<tr>
<td>Tav</td>
<td>95</td>
</tr>
<tr>
<td>Mve</td>
<td>233</td>
</tr>
<tr>
<td>PIs</td>
<td>200</td>
</tr>
<tr>
<td>Zyu</td>
<td>196</td>
</tr>
<tr>
<td>Cur</td>
<td>150</td>
</tr>
<tr>
<td>Lva</td>
<td>150</td>
</tr>
<tr>
<td>Huk</td>
<td>176</td>
</tr>
<tr>
<td>Hen</td>
<td>176</td>
</tr>
<tr>
<td>Rys</td>
<td>150</td>
</tr>
<tr>
<td>Pyu</td>
<td>176</td>
</tr>
<tr>
<td>Hui</td>
<td>8</td>
</tr>
<tr>
<td>Nec</td>
<td>241</td>
</tr>
<tr>
<td>Zid</td>
<td>151</td>
</tr>
<tr>
<td>Rac</td>
<td>141</td>
</tr>
<tr>
<td>Hiz</td>
<td>259</td>
</tr>
<tr>
<td>Taz</td>
<td>141</td>
</tr>
</tbody>
</table>

Once these waypoints were determined, a VBA program on Excel was created to evaluate the evolution of delays. Each train is tracked all along the line and its delay at each selected waypoint is recorded. For each section, we only consider the train that ran through the whole section. If a train does not reach the end of the section (e.g. registration disappeared), it is not taken into account in the calculation of the evolution of delays. Since freight trains have specific operation rules, they will not be considered in the part; indeed, they are irrelevant to study saturation using delays. Freight trains offer more flexibility during operational issues since it is difficult for passengers to accept being held too long during their trip. Moreover, trains that undergo an increase of delays higher than 60 minutes are not considered either; they represent a very small ration of the sample but their influence is consequent. Most of the time, these delays are related to reliability or exceptional incidents; this is why, they are excluded from our study.

All the previously mentioned indicators for this method have been calculated. However, only one seems to be relevant and will be presented: the ratio between the evolution of delays and the scheduled travel time. This ratio is calculated for each train according to its theoretically scheduled travel time. This indicator is interesting as it takes into account the length of the section.
4.5.2. Results and analysis

The results are presented at peak hours and off-peak hours:

The first conclusion we can draw is the irregularity of the results: they seem to be better most of the time during off-peak hours since trains seem to make their delay up or at least limit their delay increase at off-peak hours. However, it can be noticed that this is not true between Cyv and Pis: indeed, results are better during peak hours. The effects due to the flow density are not always observable. Therefore, this method results should be analyzed cautiously.

Another element that is noticeable is the troubles around the Cyv node, especially at peak hours. Trains going to this station seem to increase their delay, which confirms what was observed with the compression method.

The oddest results are on the Rac – Pis section in the down way. Delays increase quite significantly on this section (at least by 3% of the scheduled travel time) in the down way. This is true for both peak hours and off-peak hours. A deeper analysis has been led on this section in order to understand the reasons for such results. A closer examination of the evolution of delays has been done on this section and in both ways.
These results show an increase of delays between Lva and Ymf in both ways. Nevertheless, delays tend to decrease between Lva and Hen. The results during off-peak hours confirm this (Figure 62). An asymmetry between the results in both ways is noticeable. Indeed, a train running in up way starts by the difficult section where it increases its delay, and then arrives in a favorable section where it can consume all the margins to make up for its delay. On the contrary, a train running down way will increase its delay after Lva and have no margin left before the end of the ELS to catch up. That is why trains decrease their delay up way and increase it up way. This is to analyze with the map of crossing levels; indeed, several crossing levels are located between Ymf and Lva while there is none between Lva and Hen. This could be an explanation since cross levels can create operational issues; however, the link between these facts has not been established.
It seems difficult to analyze saturation using this method. Indeed, it seems better suited to analyze operational issues and to identify their causes than to analyze saturation. The results, as a whole, do not seem related to saturation issues.
5. Results analysis

5.1. Relevance of the methods to study saturation

5.1.1. Capacity method

This method helps analyzing the saturation level of a railway line both from a micro and macro perspectives regarding the infrastructure occupancy. Occupancy rates of the TPLS help evaluating the capacity that could be available for new train paths for each origin-destination line. Moreover, it provides an evaluation of saturation in major stations and nodes, therefore helping the identification of bottlenecks on a line. It is the only method that provides a defined limit; 75% for elementary line sections and 100% for train path line sections. It is the only approach that can be used absolutely, meaning that there is no need for comparison, results are self-explanatory. It is possible to draw conclusions from this method with the one situation only. Nevertheless, it is necessary to keep in mind that the results have to be considered cautiously; indeed, the limits for occupancy levels and capacity consumptions have been evaluated empirically. Therefore, they may be subject to discussion: this is especially true for capacity consumption since the used additional times and introduced previously can be discussed and give quite different results. Moreover, the limits for occupancy rates on the track and switch zones of a station or a node are not well defined. The limit is defined equal to 60% in our study, but could be higher than that since there is almost no feedback regarding this limit. In order to have a better idea of the limit, nodes that are clearly known as congested should be considered. Their occupancy level should be calculated in order to have an idea of what a congested node is regarding its occupancy level.

As a conclusion, this method is always implemented the same way once the ELS are defined, helping therefore to have a fair comparison between several lines. It is completely relevant to the study of saturation: however, it is not sufficient alone to qualify the saturation. It is not possible to make the difference between a line saturated because of the heterogeneity of the line and one saturated because of the very high traffic density.

5.1.2. Robustness method

The robustness method does not appear as fit to evaluate saturation. Indeed, there is no real constraining criterion to actually notice a difference between several lines. In our case study, the line was always robust according to the regulations [7].

The other indicators introduced in our study, e.g. local spreading rate and damping factor, give a deeper analysis of the line regarding traffic flow, operating schedule tracks occupancy but there is no criteria to define saturation. It is better suited to compare two different scenarios and decide which transport infrastructure, or transport plan is better. It becomes interesting to evaluate the feasibility and benefit of a project by comparing it to the existing situation.
5.1.3. Regularity method

The reasons to study this method are quite natural: it is supposed to help diagnose a line using the paths completed by trains with the idea that saturation would involve delays. However, the case study shows that this density effect is not clearly noticeable through this method. Indeed, there is a lot of statistical noise: the variations of delays are not directly related to traffic density. Moreover, when the density effect clearly appears, it is not located where the traffic is denser, but in the adjacent sections. This leads to difficult results to interpret as far as saturation is concerned.

This method is not suited to study saturation but if combined with other approaches, it can be very efficient to identify operation issues regarding the reliability of the railway subsystems.

5.2. Another method: path quality method

The previous results showed that the capacity method was absolutely relevant to evaluate saturation. However, it is lacking information alone in order to qualify and to properly understand saturation. Indeed, there is no difference between a very dense line, such as a commuter train line (RER A in France for example), where almost all the trains follow the same path with the same travel time, and a railway line with a heterogeneous traffic. Both could be saturated but with very different characteristics. Another method should therefore be studied in order to help qualify the kind of saturation of a railway line.

5.2.1. Theoretical study

5.2.1.1. Aim

This method presents a different approach to the saturation issue compared to the previous ones. While the previously mentioned methods evaluate the transportation plan as a whole, this method focuses on each train path individually. This meets in a more obvious way the saturation definition given by the European directive [3], which defines saturation as the inability for the infrastructure owner to meet the train paths demand.

Actually, the capacity allocation is decided after discussions between the different operators and the infrastructure owner. Instead of refusing allocating capacity, it is possible to compromise by modifying the initial demand: the train path can then be modified in order to meet the operator’s demand while being compatible with the rest of the traffic. In this case, the train path is “damaged” compared to the original demand: it is however interesting to understand to what extent it is damaged and to quantify it. The main idea is that the closer we are to saturation, the more compromises are made, and as a result, the more train paths are damaged. From this method perspective, saturation could be defined as an unsatisfactory or a poorly satisfactory service compared to the initial demand. There is no existing methodology or directive for this method. The idea is therefore to build this method with relevant indicators.
5.2.1.2. Framework

As previously mentioned, this method deals with the train paths at several stages in the planning: the theoretically optimal train path, the theoretical train path and the actually completed train path. The relevant indicators that are suggested for this method are:

- **Speed**
  - Commercial theoretical maximum speed.
  - Planned speed.
  - Completed speed.
  - Absolute subjugation (in minutes) and relative subjugation (in percentage of travel time) of the train paths.
  - Amount and duration of over-parking for freight trains.

- **Service quality**
  - **Timing:** a regular timing provides a lower waiting time for passengers.
  - **Train stop policy:** express trains, semi-express trains, omnibus trains...

- **Traffic heterogeneity:** trains with different travel times and stopping policies create higher constraints on the infrastructure occupancy.

5.2.1.3. Implementation

All the indicators will be calculated on the elementary line sections previously introduced in order to compare the results given by this method to the others. We will only consider train paths at peak hours. The indicators will be calculated depending on their typology:

- Speed and subjugation indicators
- Service quality indicators

5.2.1.3.1. Speed and subjugation indicators

These indicators are calculated by comparing the train path shapes given by the theoretical optimum, the theoretical path and the completed path. The theoretical optimum corresponds to a train running at the maximum speed allowed by the infrastructure all along the way. The theoretical optimum corresponds to a train running at the maximum speed allowed by the infrastructure all along the way. The theoretical optimum corresponds to the theoretical optimum path, to which margins are added in order to able the train to get back on time in case of a small delay. The completed path corresponds to the actual path of a train, which is measured by the beacons.

In order to do so, the following data are necessary:

- Data from simulations software (i.e. SAMURAIL) for the theoretical optimum
- Graphical timetables for the theoretical paths
- Data given by the beacons for the completed paths
In order to calculate the subjugation and over-parking of the paths, a simple comparison between the theoretical optimum path and the theoretical path is made.

### 5.2.1.3.2. Service quality

The service quality is associated with the timing and can be described with 2 indicators that we can calculate using the theoretical train paths:

- Maximum time gap between two trains
- Timing quality coefficient:

  \[
  \text{timing quality coefficient} = \frac{\text{Minimum } (l_i)}{\text{Average } (l_i)}
  \]

  Where \( l_i \) is the headway between two trains

  When the headway between the trains is always the same, the coefficient is equal to 100%.

  It is equal to 0 when two trains leave one behind the other as shown on the example Figure 64.
Below is an example of these indicators:

- Maximum time gap between two trains: 20 minutes
- Timing quality coefficient: 47%.
5.2.1.3.3. Traffic heterogeneity

Evaluating the traffic heterogeneity of a railway line can help identify the kind of saturation of a line. Indeed, some lines can be saturated because there are a lot of trains doing exactly the same trip with the same traveling time, while others have fever trains running, but with very different traveling times, creating additional constraints. In order to calculate traffic heterogeneity, we will calculate the ratio between the faster and slower trains on the line using the following formula:

$$\text{traffic heterogeneity} = \frac{\text{longest travel time}}{\text{shortest travel time}}$$

This will be done for each ELS.

5.2.1.4. Grey areas

There are some aspects that require paying attention. The construction of the theoretical optimal path will depend on the software used to calculate it. Therefore, it can change from software to another, leading to different results. Moreover, in the theoretical optimal path, regularity margins are taken into account. Since this is not a high-speed line, this margin has to be equal to 4.5 minutes every 100 km.

This method can be limited by the lack of data; indeed, in order to be fully accurate, it is necessary to know the local operations instructions as well as the train paths.

5.2.1.5. Critical assessment

The main strength of this method is that it is the only one that compares the planned train paths to the theoretical optimum train paths since the three other methods take the graphical timetable as a group that cannot be modified. Therefore, it is able to compare the gap between what is actually done and what could be done in terms of performance without considering the operations’ constraints.

However, the major issue with this method is that there are no directives or norms that are common to everyone. Moreover, the values of the indicators are not limited by any text, which makes their interpretation variable. If we consider freight trains, subjugation will not be a major issue; it will prefer being slowed down that having to park longer than planned at some point. This is not the case for passenger trains. Besides, the subjugation does not only depend on its value, but also on the moment trains are given more time to reach their destination. It is usually better to add a few minutes at the end of the trip in order to improve the punctuality at the final destination.
5.2.2. Results and analysis

5.2.2.1. Speed and subjugation

The aim is to calculate the travel time difference between the planned timetable (theoretical path) and the travel time if the train was always running at the maximum speed allowed by the infrastructure (theoretical optimum path). The work will only be done for passenger trains as it is not relevant for freight trains.

The theoretical optimum path is given by the infrastructure and the rolling stock performance. Regularity margins are added to that theoretical optimum path: they are equal to 4.5 minutes every 100 kilometers [8]. On top of regularity margins, it is possible to add some additional margins. The idea here is to evaluate the additional margins thanks to simulations on SAMURAIL. The first step is to grade the SAMURAIL model in order to have the same theoretical optimum path on SAMURAIL as the ones given by transport planners. In order to do so, more precise information regarding the rolling stock characteristics are added to the model on SAMURAIL. In our case, there were only minor changes to do regarding the number of cars of a train.

Once this is done, it is possible to calculate the additional margins by calculating the travel time difference between the scheduled train path and the theoretical optimum, for each train path, on each elementary line section. On the following figures, the margins are represented as a percentage of the travel time on each ELS.

The results show that the travel time margins are quite high on this line in both ways. This is done in order to prevent faster trains from catching up slower ones to often as this would result in delays for passengers. Moreover, this is done to prevent delays due to reliability issues, especially for regional trains: indeed, the contracts between the operators and local authorities give objectives to reach in terms of delays, especially 5-minute delays.

We notice that two sections have higher additional margins than the others in both ways: Pis – Rac and Tiv – Cyv. This confirms and explains the results of the robustness tests. Indeed, trains have a lot of margin on these sections which helps recovering from a disruption quickly.

These results show that trains run quite slower than what could be expected: this can be due to connection constrains with other trains, or saturation. However, it is difficult to conclude about saturation with this indicator, as it is difficult to fully explain the results.
Figure 66: Subjugation results up way for each ELS

Figure 67: Subjugation results down way for each ELS
5.2.2.2. Service quality

The service quality is studied depending on the origins and destinations of each train. The timing quality coefficient is calculated over one peak hour. In the following tables, the number of trains per hour going from one station to another is given, and the timing quality coefficient is given in parentheses. This service quality is given for the passengers to know how long they have to wait before getting on the train they want to. If the headway varies a lot, e.g. the coefficient is low, passengers can be confused as it is more difficult to understand the schedule. The results are given for each way in the following tables:

Table 9: Service quality results for each origin-destination route up way

<table>
<thead>
<tr>
<th>From</th>
<th>To</th>
<th>Tiv</th>
<th>Cyv</th>
<th>Pis</th>
<th>Rac</th>
<th>Cur</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tiv</td>
<td>1 (93%)</td>
<td>1 (93%)</td>
<td>1 (93%)</td>
<td>1 (93%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cyv</td>
<td>2 (62%)</td>
<td>2 (62%)</td>
<td>2 (57%)</td>
<td>3 (35%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pis</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rac</td>
<td>2 (57%)</td>
<td>2 (57%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cur</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 10: Service quality results for each origin-destination route down way

<table>
<thead>
<tr>
<th>From</th>
<th>To</th>
<th>Cur</th>
<th>Rac</th>
<th>Pis</th>
<th>Cyv</th>
<th>Tiv</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cur</td>
<td>3 (20%)</td>
<td>2 (100%)</td>
<td>2 (100%)</td>
<td>1 (100%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rac</td>
<td>3 (45%)</td>
<td>3 (45%)</td>
<td>1,5 (47%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pis</td>
<td>3 (60%)</td>
<td>2 (77%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cyv</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tiv</td>
<td>1,5 (70%)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

We notice that the timing quality coefficient is very low for trains going from Cur to Rac. This can be explained by the heterogeneity of the trains between these stations. Indeed, there are 2 fast trains and one slow train linking these stations. The slower one has to leave behind the fast one in order to avoid a fast train being stuck behind a slow train. The same phenomenon exists between those two stations up way.

On the whole, we notice that there are some issues to get a very regular service with a perfect timing. Traffic heterogeneity seems to be an explanation; however, the results given by this indicator cannot be directly related to saturation.
5.2.2.3. Traffic heterogeneity

In order to evaluate traffic heterogeneity, the travel time of all the trains running on the chosen day for the study will be considered. By comparing all the travel times, it was possible to calculate the traffic heterogeneity for each ELS and each way. The results are presented in Figure 68.

![Figure 68: Traffic heterogeneity coefficient for each ELS of the line](image)

We notice that the coefficients are very high, since the travel times on some sections since the slower trains take more than twice the time needed by faster trains on some sections. This shows the traffic heterogeneity on this line. Indeed, there are passenger trains and freight trains running on the same line although they present very different characteristics. Moreover, passenger trains have different stopping policies leading to more acceleration and deceleration phases for some than for the others. Freight trains have very different travel times since some are almost as fast as some passenger trains, while others are very slow, more than twice slower than the fastest trains.

We also notice that there is some kind of relation between the traffic heterogeneity and the occupancy rates previously calculated: this is true except for the Čyv – Pis. Indeed, the results on this ELS are due to its length: it is a very short section compared to the others (about 25km against at least 50km for the others); therefore the travel time is very short compared to the others. The traffic heterogeneity is quite sensitive on this section: a small difference in travel times can create quite high traffic heterogeneity coefficients.

From all the results, it appears that this line is saturated. The traffic is density is moderately high compared to other types of lines (such as commuter trains lines) but the traffic heterogeneity creates constraints on the infrastructure and the operation resulting in high occupancy rates. So, despite the quite moderate number of trains running on the line, their very different travel times create saturation.
5.2.3. Relevance of the method

While the first three studied methods were interesting in terms of results for the infrastructure owners, the path quality method is especially relevant to transport authorities or operators that would like to ask for new paths. Transport authorities can use these results to analyze the existing transport service, understand the waiting time issues for passengers if the timing quality is not satisfactory and if needed, ask for new paths in order meet a specific demand and improve the timing quality. Besides, in the study case, transport authorities are complaining about the increasing travel times on the line. The subjugation indicator is a good way to analyze where this increase comes from and to try to fix it with the infrastructure owner. As for the operators, they can analyze the current service to evaluate the possible improvements in terms of number of trains running on the line and time at which they run.

Nevertheless, two of the three indicators studied with this method are hardly relevant to directly study saturation. Indeed, there is no explicit relation between saturation and subjugation or timing as shown by the results. There are several reasons to explain these phenomena: regarding subjugation, it is interesting to slow down trains compared to their performance in order to prevent delays, to prevent faster trains catching slower ones and also commercial issues such as connections that need to be possible for passengers at some stations. Therefore, this indicator does not help revealing specifically saturation. As far as service quality is concerned, the study case did not reveal any relation to saturation.

The major indicator that seems relevant to study saturation is the traffic heterogeneity coefficient. It helps qualify the saturation type of a line: is the line used by a variety of trains, running at different speeds, with different stopping policies? In that case, the heterogeneity creates high constraints increasing the infrastructure occupancy. Or, on the contrary, are we in the case of a very homogeneous traffic? This would involve that the high traffic density explains why the line is saturated. This indicator gives a deeper understanding of the saturation of a railway line.

5.3. Method proposal

Now that four methods have been studied and implemented on a study case to analyze their relevance to saturation, it is possible to formulate the method that should be used to determine whether a railway line is saturated.

As previously explained, although it is an interesting tool, the regularity method should not be considered to study saturation. The original idea was that if a line was saturated than delays would appear on the line, due to the traffic density. As the study case results showed, the density effect is only partially observable and the high statistical noise would make it a mistake to interpret the delays as the effects of saturation exclusively. Problems such as reliability issues or operational issues have an influence on the results given by this method. Therefore, this method can be very effective
in order to identify operational issues, their origin and to find solutions to fix this kind of problems. It should be considered as a check-up tool to daily operation of a railway line.

Two study levels appear to study saturation: the first level corresponds to the analysis of the existing line in order to determine whether the line saturated or not, while the second level corresponds to a deeper analysis that would be led later on, once projects are studied to fix saturation issues. For the first level of analysis, the following indicators should be used:

- Occupancy rates on the elementary line sections, track and switch areas of the stations on the line;
- Capacity consumptions of each commercial train path line section;
- Traffic heterogeneity coefficient.

These indicators help evaluating the infrastructure occupancy and qualify the nature of saturation. It is also possible to determine where it would be possible to add new paths. The compression method is very interesting since occupancy rates should not be higher than limit values that exist, although some of them need to be confirmed with more experience feedback. If train paths cannot be added on the relevant TPLS, e.g. the ones where demand exists, then the line is saturated. The occupancy rate gives more detailed information as to what are the most congested sections. The traffic heterogeneity helps determining the origin of saturation.

---

**Figure 69: Flow chart of the evaluation method of the saturation level of a railway line**
Once this first step is done, if a line is declared as saturated, the infrastructure owner can decide to launch new projects in order to fix saturation. Then, on top of the previous indicators, the robustness method is a good complement in order to compare the existing situation with the impacts of the project, or the impacts of several projects in a multi-criteria analysis. The compression method would help to see to what extent the occupancy of the infrastructure decreases and the robustness would give information regard the operation of the line, in particular regarding its response to disruptions. The study case showed that the robustness method applied for only one scenario was difficult to interpret and conclusions could hardly be drawn regarding saturation through this approach. However, it is particularly efficient to study specific issues by comparing situations. As a consequence, for the second level of saturation analysis, the following indicators should be considered:

- Occupancy rates on the elementary line sections, track and switch areas of the stations of the line;
- Capacity consumptions of each commercial train path line section;
- Average damping factor on each elementary line section;
- Evolution of delays after a 10-minute disruption;
- Traffic heterogeneity coefficient.

In order to calculate these factors, a projected timetable of the future transport service should be realized. This second level of analysis might be a bit time consuming, especially if the projected transport service is very different from the existing service, as the SAMURAIL model should be recreated and the occupancy calculations on SAMURAIL take some time and are not automated for the moment.
6. Discussion and Conclusion

6.1. Further study

The method created in the thesis is a first step towards accurately evaluating the saturation level of a railway line. However, it can be improved by pushing further the elaboration of this method. The study was led on SAMURAIL, especially for the compression method. The determination of the block section on SAMURAIL was led manually, which is fine although time-consuming for only one line. Nevertheless, it would be too time-consuming when comparing several scenarios or projects; therefore, in order to make the method less time-consuming, it would be interesting to work on the automation of this process. This way, it would be fast and easy to calculate the occupancy rates and capacity consumptions. With the same automation process in mind, it would be possible to improve the method by developing a stochastic method to combine the regularity and robustness analyses. The idea would be to analyze existing delay data to determine patterns: then, these patterns would be used to determine the probability of a train being delayed and combined to robustness tests.

Besides, the method has been formulated based on one case study. It was interesting but the final method is somehow biased since the choice of indicators was done based on the characteristics of the studied line. It would be interesting to study other lines with different characteristics in order to improve the method and make it more accurate and applicable to almost all the railway lines. It is also important to keep in mind that the method was created for French railway lines; since the operation rules are not the same in other countries, this method could be completed with the study of railway lines from other countries.

As far as the method itself is concerned, the compression method should be further investigated. Indeed, although there is enough feedback and distance to define the occupancy rates limits, other elements need to be defined more accurately. Indeed, the feedback to define accurately the occupancy rates limits for track and switch areas is unsatisfactory and needs to be completed. Therefore, the results analysis depends highly on those limits that might evolve in the future. Moreover, the additional times given by the UIC in order to determine the capacity occupation are empirical; it would be interesting to evaluate their accuracy and their influence from a socio-economic perspective.
6.2. Summary

This thesis was a study of a method to evaluate the saturation level of a railway line. Saturation is a concept that started being studied only very recently as some networks present a high traffic density. It is becoming an issue for infrastructure owners, especially in Europe where the EU requires them to be able to meet new train paths demand. If the infrastructure owner is unable to do so, the infrastructure owner has 6 months to suggest a plan to fix the problem or the infrastructure is declared saturated.

Although everyone gets the general concept of saturation, it has several meanings when it comes to railway. Therefore, three methods, each one referring to a definition of saturation, were studied. They were studied from a theoretical point of view first, to know their strengths and limitations and then applied to a study case. The compression method considers the capacity issue related to saturation: if the infrastructure occupancy is over a certain value, then the infrastructure is saturated. This method was given by the UIC in a leaflet [4] but was rather unclear. Therefore, the hypotheses of the method have been clarified for the implementation in the case study. The robustness method considers the stability of graphical timetables as an aspect of saturation. The graphical timetable is tested to see how it responds to a disruption. However, the tests should be relevant and chosen carefully for them to be meaningful. The regularity is a statistical analysis to analyze the creation and evolution of delays on the line. From this method perspective, saturation involves an increase of delays.

These methods were then implemented to a study case on an actual railway line. A SAMURAIL model was created in order to calculate the indicators for the compression and robustness methods. The results for the regularity methods were calculated using Excel, Excel VBA and data extracted from a database. The results showed that the regularity method was not suited to study saturation. The robustness method can be used as a mean to compare two situations, but not to initially establish the saturation level of a railway line.

Another method was then studied: the path quality method. This method was studied separately since it has been created along the way in order to complement the results given by the other methods. This method revealed the relevance of studying the traffic heterogeneity in order to qualify the nature of the saturation of a line. The case study showed that the line is saturated since the occupancy rates and capacity consumptions are above the limits; this is due to the traffic heterogeneity creating high constraints between different trains, resulting in higher infrastructure occupancy.

A two-step method has been created to evaluate saturation. The first step is the diagnosis and involves the compression method coupled with the traffic heterogeneity study. The second step is the evaluation of the projects; to the previous methods, the robustness method is added in order to compare the current service with the project, or several projects in a multi-criteria analysis.
7. References

1. **Ourliac, Jean-Paul.** *Recommendations du conseil scientifique des observatoires de la saturation ferroviaire.* 2015.
5. —. *Capacity Management (Capman Phase 3).* December 2004.
10. **Armstrong, John and Preston, John.** *Developing and Calibrating capacity utilisation measures for nodes.*
16. **Laroche, Florent.** *Exploration de la congestion ferroviaire : proposition d’une méthode pour estimer le taux d’occupation d’une infrastructure.*
20. **Landex, Alex.** *Methods to estimate railway capacity and passenger delays.* 2008.
22. **Rodriguez, Joaquin.** *Débat public "Réseau Express Grand Lille" : Gestion du trafic ferroviaire.*
23. **Knight Merz, Sinclair.** *Assessment of capacity allocation and utilisation on capacity constrained parts of the GB rail network.*
25. **Krause, Christoph.** *Simulation of dynamic station dwell time delays on high frequency rail transport systems.* 2014.

26. **Coviello, Nicola.** *The influence of ECTS and traffic composition on daily capacity of single track lines.* 2013.

