

Metro traffic regulation and quality of passenger service

Performance analysis of the new operational control centre at RATP



Front page:

- (up, left) line 6 of the Paris metro network;
- (up, right) a platform of line 13 at peak hour;
- (down, left) inside the modernised operational control centre of line 13;
- (down, right) waiting time indicator for passengers on line 9.

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Master thesis

**Metro traffic regulation and quality of passenger service:
performance analysis of the operational control centre at RATP**

Graduation project conducted at RATP (Paris) under the supervision of

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Preface

This thesis is the result of a graduation project to obtain a Master's degree in Transport, Infrastructure and Logistics from Delft University of Technology. It has been carried out at RATP, Paris metro company.

Having been interested in a long time in land management and transport issues in urban areas, I chose to join the TIL master after I finished my engineering school in France. Not only did I want to experience life abroad, in such a welcoming country as the Netherlands had been often described to me, I had also heard a great many praises about TU Delft, and more particularly about the TIL master.

I dare say I was not disappointed at all, for the education I received in this master was exactly what I was looking for, and even more. I had the opportunity to learn about transport engineering from the various points of views of my teachers and of my fellow classmates, and to do so in a truly interdisciplinary environment. The multi-disciplinary organisation of the TIL master taught me among other things to always keep my mind open to all the aspects of a project which I think is a key point for all transport-related issues. For this, and for all the education I received, I would like to thank all my teachers and the people involved in the organisation of the TIL master.

In this regard, I would also like to thank my fellow classmates, especially those who participated in various classes and projects with me, and Dispuut Verkeer who not only provided much needed coffee at all time of day between classes, but also offered various activities, both for leisure and for additional education on transport, that were always welcome!

When I started thinking about graduation projects, I decided I would try to conduct it within a transport company in order to get a more direct contact with the actual field of operations. I also preferred to find a project back in France for as much as I liked life in the Netherlands, I wanted to see how things were done in the transport field in my own country. I was also more confident, and probably more interested, in studying a transport environment that I was familiar with. I was lucky to have several companies offer me a position to conduct my research with them, and with the advice of my teachers, I chose the one offered by RATP, not only because the subject was the most appealing to me, but also because I was eager to learn more about operations in the Paris metro for it has been a part of my life since I was born.

I would thus like to thank Laurent Fourtune, the deputy director of RATP's engineering department, who offered me this position and always kept a high interest in my research.

Guillaume le Mandat, head of the PCC modernisation project, took up on the task of being my supervisor at RATP. His help, support and advice for my research and on more general topics regarding the PCC project and RATP were numerous and always useful and I truly enjoyed working with him those 6 months. I hope that he enjoyed my working with him as well for I dare say I have found in him more than a supervisor but also a great friend who proved to be of very good company around a cup of coffee, and of very good advice for the decisions I have to make regarding my future life as a transport engineer.

Many other people at RATP are to be thanked for their contribution to my research, and especially Michel Monteil who first introduced me to the regulation principles at RATP, Hervé le Gall and all the operators of line 3 that I had the opportunity to meet, and William Charenton who gave me access to all the software and data I needed, as well as very good advice on how to use them.

I would also like to thank the members of my graduation committee at TU Delft who were very helpful and supportive during all stages of this project and who always seemed truly interested in it. My only regret is that since I was conducting this project abroad, I was not able to meet with them as often as I wanted to discuss the advances of my work which could have benefited from such feedback meetings even more.

Paul Wiggenraad was the first person I contacted to discuss this graduation project, and from the very first moment, he provided some much needed advice, and was very helpful to calm me down and make me be more organized when I sometimes have a tendency to panic and get overcome by unexpected events.

Rob Goverde provided some much needed references on the subject and always insisted on my being really precise on technical features, which forced me not to settle for what I could do, but try and do even better.

John Baggen particularly insisted on my keeping a more open view on the subject and to try and detach myself from technical features, and more importantly from RATP, which really helped me see things in a different light.

Finally, Prof. Hansen manifested a true interest in my project from the very beginning, which really encouraged me to go as far as I could in my research and not disappoint his expectations. I would like to especially thank him for this, for his constructive and systematic supervision of the project, and for always finding ways for me to improve it and go even further.

I would of course also like to thank my friends and family for their support during this project. A special thank goes to Lili for her help, advice and friendship during this project, and more generally during the two years of our master, and to Charles who took the time to proof-read this report for me.

Finally, I would like to express my most sincere gratitude to my parents for supporting me in my education my whole life, and to my fiancé who patiently listened to my explanations of my research almost every day for the last 6 months without complaint, and apparently with a genuine interest in the subject, and actually provided some helpful advice when I most needed them.

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Summary (English)

The Paris metro network operated by RATP is well-known all over the world for its complexity and high level of efficiency. Since most of its equipment dates back from the 1970's, it is undergoing an important modernisation plan, among which the renewal of all the equipment involved in traffic control, both on the lines and in terminals, within the Operational Control Centres (PCC). This new PCC system has now been implemented on lines 13 and 3, and although the operators of those lines are generally pleased with the technical features of the new PCC, they remain somewhat doubtful regarding its efficiency on automatic traffic regulation. The objective of this project was to detect if indeed those mixed feelings were founded by studying the specifications of the new system as well as its impact on operations through an analysis of the operational data. Although it was not a primary objective of the PCC project, it is hoped that this new system can help improve traffic regulation performance, and through this the overall quality of passenger service which is very much related to how regular the traffic of a metro line is.

Public transport in Ile-de-France is governed by the public authority STIF. Every four years, a new contract is signed between STIF and RATP regarding operations in the metro network. This contract defines the total number of kilometres that need to be produced every day of the year on each line, but it also sets quality indicators among which two are directly related to traffic regularity: passenger waiting time and production during peak hours, the latter having been introduced in 2008. Production and quality of service are rewarded or penalized financially. RATP therefore has strong incentives to both produce the contractual number of train*kilometres, but also to ensure a regular traffic on their line. In order to operate the lines according to those contracts, theoretical timetables are built according to a number of constraints such as headways to be implemented, running times, dwell times, buffer times at terminals. Although those timetables are never communicated to the passengers who are only given the maximum waiting time depending on the time of day, they are the basis of operations in the metro lines. In reality, it is almost impossible for the metro lines to respect those theoretical timetables because of all the incidents, but also because it is very difficult to predict the time needed to be spent at stations. With more passengers, the trains need to stay longer in stations, thus creating additional delay on the whole line. The later a train is, and thus the more space there is between it and the previous train, the more passengers will be waiting for it, and the more time it will have to stay in the stations.

The traffic on a metro line as busy as the ones in the Paris metro network are therefore highly unstable and a single incident can completely disrupt the traffic on the whole line for a very long time. This is especially true of lines where trains are running very close to each other (down to 95s at peak hours on line 13). Because of this, it is very important to implement the appropriate regulation strategies. At RATP, the main objective of the regulation actions is to maintain a regular interval between trains at departure and on the lines while still trying to recover from delay in terminals. Before the new PCC system was implemented, traffic on the line was overseen by the traffic controllers who were all located in the Bourdon building and used button-control panels, while departures from terminals was overseen by the departure chief in the terminals. In the new system, not only have the equipment been renewed, operations on the line have also been re-organised and the regulation strategies are now the responsibility of the computerized system. Traffic regulation on the line is still the responsibility of the traffic controller, but he is now located at the decentralised PCC, closer to the lines. With him are also the two terminal managers who now oversee all train movements in their terminals from the PCC. As for the calculation of departure times, whereas it was before the role of the departure chief, it is now the computer that calculates them according to the general decision made by the terminal manager who can

choose between a no-regulation mode, a constant headway mode and a recovery mode. The latter is based on the former strategy that consisted in distributing the delay among trains in order to ensure regular departures in the line when there was a disruptive train causing delay at departure, and headway reduction in order to recover from the delay when the disruption has disappeared. When it is not possible anymore to recover from delay with those re-calculation methods, namely because the accumulated delay is too important, the last resort of the terminal manager is to cancel some departures, thus leading to the so-called “lost laps for schedule compensation”. After studying the specifications of the algorithm for the calculation of departure times, it was concluded that they were in line with RATP’s requirements. However, those requirements date back from almost ten years ago, and the needs of the line operators have evolved ever since then, especially with the introduction of the “production during peak hours” criteria, which might already explain the mixed feelings of the operator regarding the system’s regulation functions.

Although the operators are not completely satisfied with the system’s performance, it needs to be stressed out that they are overall quite happy with the new equipment. Furthermore, the new organisation ensures a much better communication between the various actors of traffic regulation which is much appreciated. However, traffic controller do feel a loss at being now separated from the other lines, and the terminal managers at being separated from their terminals for they do not have direct communication with the drivers anymore. As for the actual impacts of the system on operations, it was possible to conduct a performance evaluation using the operational data provided by the IGT and OSIRIS software, specifically developed for RATP. Among the various methods that were considered for this data analysis, the most efficient one was to assess the number of lost laps for schedule compensation as opposed to the number of incidents, or to the total delay on the line per day. Indeed, on days with the same amount of delay, more cancelled departures mean that the system is not able to recover from delay alone, and is therefore less efficient. Various periods before and after the implementation of the new system were thus compared. The first conclusion of this study was overall that the situation on the lines had not particularly been improved with the implementation of the new system, neither had it worsened. Although this conclusion is already quite satisfactory, as it was never an objective to improve the operational results of the lines, it still needs to be taken into context. Indeed, the operational environment of the lines nowadays are very different from what they were even 5 years ago for the passenger flows and the number of scheduled trains have increased, and other modernisation project have been or are being implemented at this time. It is very likely that the old system would not have been capable of handling those changes, and would not have had as good operational results as the ones observed with the new system. Unfortunately, this is only a guess that can never truly be verified.

It was also observed on both lines 13 and 3 than the implementation of the new system was always followed by very difficult periods for the operators and that problems regarding parameterization had occurred quite often, especially on line 3. A simple model of the calculation of the algorithm on line 3 was thus built in order to try and study the impact of parameter changes. The outcome of this study was not only that a more precise calibration of parameters was necessary to improve the efficiency of the system, but also that the main calculation of the algorithm could very well be modified in order to better fit the evolving needs of the lines. A first recommendation for the improvement of the system is therefore to conduct a more extended study on this option. Furthermore, the specific characteristics of the lines and the evolving needs and structures should be better taken into account. Finally, another improvement could come from a better training and support of the operator who, as it is, does not have a good enough level of understanding of the system, which leads to misinterpretations and misuse on his part.

Résumé (Français)

Le métro parisien est renommé à travers le monde pour son efficacité et son niveau de complexité. Cependant, une grande partie de ses équipements date encore des années 70, et afin de parer à leur obsolescence technique, la RATP a engagé une politique de renouvellement des installations nécessaires à la production de l'offre de transport, parmi lesquels les Postes de Commande Centralisés (PCC) qui assurent la supervision du trafic en ligne et dans les terminus. Le PCC modernisé a maintenant été déployé sur les lignes 13 et 3, et bien que les unités opérationnelles soient globalement satisfaites des nouvelles installations, les opérateurs émettent des réserves sur les performances offertes par le système en terme de régulation du trafic. L'objectif de ce stage était donc de vérifier si ces impressions mitigées étaient fondées, et ce à travers d'une part une étude des spécifications du nouveau système et d'autre part une analyse des données opérationnelles qui a permis de mettre en valeur son impact sur l'exploitation. Par ailleurs, si ce n'était pas un objectif explicite du projet de modernisation des PCC, on pourrait espérer que ce nouveau système mène à une amélioration des performances de régulation du trafic, et à travers cela, de la qualité de service au voyageur qui dépend fortement de la régularité du trafic.

L'autorité organisatrice des transports en Ile-de-France est le STIF. Tous les quatre ans, un nouveau contrat est signé avec la RATP pour chacun de ses réseaux, et notamment pour l'exploitation du métro. Ce contrat définit le nombre de kilomètres à produire sur chaque ligne pour chaque jour de l'année, ainsi que des indicateurs de qualité parmi lesquels deux sont en lien direct avec la régularité du trafic : l'attente des trains et la production en heures de pointes, ce dernier critère ayant été introduit en 2008. La production et la qualité sont récompensées ou pénalisés financièrement, incitant la RATP à assurer la production du nombre contractuel de kilomètres, tout en maintenant un trafic régulier. Afin d'exploiter les lignes selon les exigences contractuelles, des horaires théoriques sont construits prenant en compte un certain nombre de contraintes supplémentaires tels que l'intervalle à assurer et l'intervalle minimal, les temps de parcours, les temps de stationnement, les temps de retournement et de battement en terminus. Si ces horaires ne sont jamais communiqués aux voyageurs à qui l'on communique uniquement le temps d'attente maximum entre les rames selon l'heure de la journée ainsi que les premiers et derniers passages de train, ils sont à la base de l'exploitation des lignes de métro. En réalité, il est quasiment impossible de respecter ces horaires théoriques à cause des nombreux incidents plus ou moins importants, mais également parce qu'il est très difficile de prévoir exactement le temps nécessaire à passer en stations. S'il y a plus de passagers, les trains doivent rester plus longtemps, créant ainsi des retards supplémentaires sur la ligne. Plus un train est retardé, et donc plus il y a d'écart avec le train précédent, plus il y aura de passagers attendant aux stations, et donc plus longtemps encore il devra attendre et être retardé par la suite.

Le trafic de lignes de métro aussi chargées que celles du métro parisien est donc fortement instable et un incident même mineur peut perturber tout le trafic de la ligne. Ceci est particulièrement le cas sur les lignes où les trains circulent très rapprochés les uns des autres (95s d'intervalle à l'heure de pointe sur la ligne 13 par exemple). Ainsi, il est absolument nécessaire d'appliquer des stratégies de régulation adaptées aux contraintes des lignes et aux situations en temps réels. A la RATP, l'objectif principal de la régulation est de maintenir un intervalle régulier entre les trains au départ et sur la ligne tout en essayant de rattraper le retard occasionné sans réduction de l'offre de transport. Sur les lignes non modernisées, le trafic en ligné est supervisé PCC centralisé de Bourdon par le chef de régulation au travers de postes à boutons, tandis que les départs des terminus sont la

responsabilité des chefs de départ en terminus. Avec les PCC modernisés, d'une part les installations ont été renouvelées, et d'autre part l'exploitation des lignes a été réorganisée. Les stratégies de régulation sont maintenant gérées par un système informatisé. La régulation du trafic en ligne est toujours placée sous la responsabilité du chef de régulation qui agit maintenant depuis le PCC décentralisé au plus près des lignes. Les deux gestionnaires de terminus supervisent depuis le PCC tous les mouvements des trains dans leurs terminus respectifs depuis le PCC décentralisé également. Le calcul des heures de départ, qui était la fonction principale du chef de départ, est maintenant effectué et constamment réactualisé par le système informatisé selon les décisions prises par le gestionnaire de terminus qui peut choisir entre un mode « hors régulation », un mode « intervalle constant » et un mode « récupération ». Ce dernier reprend les anciennes stratégies de régulation qui consistent à répartir le retard causé par un train perturbateur en ligne entre les trains en amont afin d'assurer un intervalle régulier, et à minorer l'intervalle des trains en aval afin de rattraper ce retard. Lorsqu'il n'est plus possible de récupérer le retard par ces méthodes, principalement lorsque le retard est trop important, le dernier recours du gestionnaire de terminus est de supprimer des départs, occasionnant ainsi des « tours perdus pour compensation d'horaire ». L'étude des spécifications a mené à la conclusion que cet algorithme de calcul des heures de départ était en accord avec les exigences de la RATP. Cependant, ces exigences ont été définies il y a bientôt 10 ans et les besoins des exploitants ont évolué depuis, avec notamment l'introduction du critère de production aux heures de pointes. Ceci pourrait fournir une première explication au mécontentement des exploitants quant aux performances de régulation.

Si l'exploitant n'est pas pleinement satisfait des performances du système, il faut néanmoins signaler que les nouveaux locaux, outils et équipements sont quant à eux très appréciés. De plus, la nouvelle organisation de l'exploitation permet une meilleure communication entre les différents acteurs de la régulation. Cependant, les chefs de régulation ressentent comme une perte le fait d'avoir été séparés des autres lignes, et les gestionnaires de terminus le fait d'avoir été séparés des terminus, en particulier parce qu'ils n'ont plus de contact direct avec les conducteurs. Pour ce qui est des conséquences sur la production du transport, l'utilisation des données d'exploitation fournies par IGT et OSIRIS a permis de mener une évaluation chiffrée des performances du système. Parmi les différentes méthodes qui ont été envisagées pour cette analyse, la plus pertinente est d'étudier le nombre de tours perdus pour compensation d'horaire par rapport au nombre d'incidents ou au retard cumulé par jour sur les lignes. En effet, pour des jours présentant le même retard cumulé, un nombre plus important de tours perdus est la preuve que le système en place n'a pas su rattraper le retard seul. Différentes périodes avant et après déploiement du PCC sur les lignes 13 et 3 ont été comparées avec cette méthode. La première conclusion de cette étude est que la situation globale sur la ligne 13 n'est pas particulièrement meilleure que ce qu'elle était avant le PCC modernisé, mais pour autant, elle n'est pas pire. Si cette conclusion est déjà satisfaisante en soi, puisque l'amélioration des performances de régulation du trafic ou de la qualité de service au voyageur n'était pas un objectif explicite du projet de modernisation des PCC, il faut néanmoins la replacer dans son contexte opérationnel. En effet, l'environnement d'exploitation aujourd'hui est très différent de ce qu'il était il y a seulement 5 ans puisque d'autres projets de modernisation ont été menés sur la ligne 13, et parce que l'offre de transport a été renforcée sur la ligne 13 en 2007 pour faire face à l'augmentation constante du nombre de passagers. Il est fort probable que l'ancien système n'aurait pas été capable de prendre en charge ces évolutions et n'aurait pas eu d'aussi bons résultats d'exploitation que ceux produits par le nouveau système. Ceci n'est bien sûr qu'une supposition qu'il n'est malheureusement pas possible de vérifier.

On a également observé sur les lignes 13 et 3 que le déploiement du nouveau système, était toujours suivi de périodes très difficiles pour l'exploitation et que des problèmes de paramétrage étaient survenus dans les premiers temps de l'utilisation, particulièrement sur la ligne 3. Un modèle simple du comportement de l'algorithme sur la ligne 3 a donc été construit afin de comprendre l'impact des changements de paramètres sur ses calculs. Le résultat de cette étude est non seulement qu'une calibration plus précise des paramètres est nécessaire pour améliorer l'efficacité du système, mais également que les formules de calcul de l'algorithme pourraient être modifiées afin de mieux prendre en compte le besoin évolué de l'exploitant. Une première recommandation pour l'amélioration du système est donc de pousser cette étude plus loin afin d'arriver à une formulation optimale de l'algorithme. De plus, les caractéristiques des lignes et les évolutions des structures et des besoins devraient être mieux intégrées dans le déploiement du système. Enfin une amélioration supplémentaire pourrait venir d'une meilleure formation et d'un meilleur accompagnement de l'exploitant qui, aujourd'hui, n'a pas une compréhension suffisante du système, menant à des erreurs d'interprétation et parfois à une mauvaise utilisation des outils du système.

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Variables

Variable	Definition	Defining equation
b	Irregularity coefficient	(18.2)
BT_{driver}	Compulsory buffer time allocated to drivers between two laps	
BTF	Incompressible buffer time	
BTT (n,A)	Theoretical buffer time of train n in terminal A	(3)
coef_{MI}	Multiplying coefficient to apply to the headway reduction, manually chosen by the operator	
Cor (l)	Overall correction induced on train l	(8.2)
Cor (n/l)	Correction induced by train n over train l	(8.1)
CV(i,X ->Y,m)	Running time of trains in direction i from station (or terminal) X to station (or terminal) Y in modal type m	
d	Average deviation from theoretical headway	(18.1)
DTT (m)	Theoretical (minimum) duration of a lap in modal type m	(1)
DUR_{man.ret} (A, i)	Duration of turn-over maneuver i in terminal A	
HAC (n,X,i)	Calculated arrival time of train n in station (or terminal) X in direction i	(5)
HDC (n,X,i)	Calculated departure time of train n from station (or terminal) X in direction i	
HDC_{h&s}	Calculated departure time of train n from station (or terminal) X in direction i in headway and schedule regulation mode	(16)
HDC_{headway}	Calculated departure time of train n from station (or terminal) X in direction i in headway regulation mode	(15)
HDC_{IC}	Calculated departure time of train n from station (or terminal) X in direction i in constant headway mode	(12) (17)
HDC_{recovery} (n,X,i)	Calculated departure time of train n from station (or terminal) X in direction i in recovery mode	(10)
HDC_{schedule}	Calculated departure time of train n from station (or terminal) X in direction i in schedule regulation mode	(14)
HDP (n,X,i)	Earliest possible departure time of train n from station (or terminal) X in direction i	(4) (6) (13)
HDR (n,X,i)	Real departure time of train n from station (or terminal) X in direction i	
HDT (n,X,i)	Theoretical departure time of train n from station (or terminal) X in direction i	
H_{not}	In the recovery mode, time calculated applying the respect of the theoretical headway (line 3)	
H_{rec}	In the recovery mode, time calculated applying the recovery principle (line 1)	
H_{tech}	In the recovery mode, time calculated applying the respect of the minimum headway (line 4)	

IC	Constant headway chosen manually by terminal manager	
I_{min}	Minimum technical headway	
I_{real_i}	Realized headway between trains i and i-1	
I_{th (n)}	Theoretical headway between train n and n-1	
I_{th_av}	Average theoretical headway during a defined period	
Mi (n)	Possible headway reduction on train n	(9.1)
N(n)	Theoretical number of trains in the same group as n (number of trains needed to run the line with the same buffer time and theoretical headway as applied on train n)	(9.2)
Ret (n)	Contribution of train n to the general delay	(7)
SM (A,i)	Minimum stay in terminal A with turn-around maneuver of type i	(2)
τ	Multiplying coefficient to apply to the evolved headway reduction method	
T_{arrival (A)}	Time to spend at arrival quay in terminal A	
TBC	Evolved calculation of possible headway reduction	(19)
T_{departure (A)}	Time to spend at departure quay in terminal A	
T_{el}	Quay constant corresponding to the opening of the signal	

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Introduction

Created in 1949 to be the only operator of the Paris public transport system, RATP has now spread its activities in many other countries while still improving its network and services in Ile-de-France. They are implementing solutions for modern transportation systems according to the future's needs all over the world, such as automatic metro lines, silent tramways or BRT systems. Yet, however innovating those flagship projects are, it appeared at the end of the 1990's that the Paris metro network needed a modernization plan for most of its equipment. Part of this plan is to decentralise and upgrade the operational control centres of the metro lines (in French, PCC: poste de commande et de contrôle centralisé), radically transforming the operation's organisation and methods.

Since the 1970's, the PCC of a metro line is the operational organ in charge of regulating traffic. The traffic of metro type railways is intrinsically unstable in that a delay of sometimes even less than a minute on one of the train can cause an increasing delay in the whole line, but also increasing passenger charge in the delayed trains, leading to even more delay. In times of traffic disruption, the trains operating the lines must stay united in following regulation methods that will ensure an acceptable headway between trains at all time and optimal allocation of passengers on the different trains, especially at peak hours. In the 1970's, it became obvious to RATP that only on-train and in-station supervision was not sufficient to ensure a regular traffic and accommodate the increasing passenger flows in the network. The PCCs were therefore implemented, leading to a great improvement in metro operations. At the time, they were composed of state-of-the-art technologies, but nowadays, those PCCs are still in place and operating the lines, much as they were thirty years ago, and they have become technically obsolete.

The department of engineering of RATP is therefore conducting a project to implement modernised PCCs on the different lines of the network. This has already been completed on two lines and is under implementation on two others. This new system, designed to be a generic one to be adapted and implemented on any line but the fully automated ones, not only updates the equipment on a technical level, it also changes the organisation of operations and the methods they use. Those evolutions thus have important impacts on the way operations are being conducted on the metro lines, especially on the strategies for regulating the metro traffic, which has direct repercussions on the quality of passenger service. As part of a feedback analysis, RATP was willing to have a study conducted on the performances of the system. As the priority of the metro lines should always be to offer the best quality of service to passengers, it was even more interesting to try and evaluate the advantages and drawbacks that it led to regarding operations and impact on passenger service. Therefore, they agreed to participate in this graduation project that could provide them with a new vision on their system and its performances, even more so as it was being conducted from an external point of view.

This research project required prior knowledge of public transportation systems, but also an ability to perceive complex systems with an interdisciplinary perspective, since this project involves technical features, but also human management and organisational problems for example. Therefore, this subject was considered appropriate for a TIL student with specialisations in public transport systems and systems engineering, and moreover, a good continuation of the master TIL and a very suitable transition from the academic master education to working in the field of transport engineering.

This report is divided into four main parts. The first part entitled Project Background includes a more extended presentation of the project as well as an overview of the transport market in Ile-de-France and of the way operations are organised and managed in the metro network of RATP. Part II on metro traffic regulation could be seen as the theoretical part of this study, as it describes the various methods of regulation, first generally speaking over the world and throughout history, then specifically at RATP before and after the implementation of the new PCC system. The last chapter of this part gives an evaluation of the new system on paper, validating that it is indeed in line with the requirements and expectations that were set for its development. At the same time as this theoretical study was being conducted, a practical performance analysis was carried out, that is to say an assessment of the operator's impression on the new system, and a data analysis regarding the impacts that the implementation of the modernised PCC already has on the lines where it is operating. This is the object of the third part of this report entitled performance analysis. As the conclusion of this analysis is that the system still needs to be improved, the last chapter of this performance analysis explains how this could be conducted, with a simple model of the calculating algorithm of the system. The overall conclusions of this study are drawn in part four along with some discussions and questions that were raised throughout the course of this project.

Part I – Project background

Chapter 1 – Project presentation and approach

Chapter 2 – Transport market in Ile-de-France

Chapter 3 – Operating the metro network

Part II – Metro traffic regulation

Part III – Performance analysis

Part IV – Conclusion

This part of the report gives most of the information needed to understand the background of this project. First, an overall presentation of the project is given, including the context in which the problem arose, the research objectives that were set in collaboration with RATP as the problem owner, and a reading guide for the consideration of the readers in a TIL master perspective. Chapter 2 gives an overview of the transport market in Ile-de-France with a description of the transport demand, an attempt at defining quality of passenger service in the metro network, and a description of the institutional framework for metro operations in Paris. This chapter is therefore mostly a technology and policy management-related chapter that sets the framework for metro operations. Finally, chapter 3 is a more technical one for it gives an overview of how operations are being conducted at RATP according to the demand and framework presented in chapter 2.

Chapter 1 – Project presentation and approach

When the author of this project was researching possible master thesis subject, RATP offered an opportunity to study a problem they were facing within the modernisation plan for the traffic control system of their metro network. This context is explained in this chapter, as well as the research objectives that were defined, both in the interest of RATP and of the graduation project itself. The way this research was conducted is then presented, and finally a reading guide to this report is provided in the last part of this chapter.

1.1. Context

1.1.1. RATP and the Paris metro network

RATP stands for “Régie Autonome des Transports Parisiens” and is a public institution with industrial and commercial purpose responsible for the majority of public transportation in Paris and its surroundings.

With sixteen metro lines, two regional express train lines, three tram lines, more than 300 bus lines, and shuttles to two major airports, the RATP-operated multimodal network in the Paris region is one of the world’s largest and densest mass transit systems. In a densely populated area (11 million people live in 12 000 square kilometres), RATP accommodates more than 3 billion passengers a year, among which 1.4 billion a year by metro. Dealing with such important and growing flows, RATP must keep innovating and finding new solutions to manage the saturation of the network.

When it comes to the metro system, a particularity of RATP, as opposed to other public transport companies in the world, is that they are both owner and operation manager of the transport infrastructure – although this status is going to evolve in the future because of the mandatory opening to competition. This, however, allows RATP to implement integrated solutions working in the same projects on the infrastructure, the equipment and the way they are being used. For the operations themselves, RATP is under contractual agreement with the now regional public transport authority in the Ile-de-France region STIF (“Syndicat des Transports d’Ile-de-France”). For each line operated by RATP, STIF sets a number of criteria regarding quality of service and day-to-day number of vehicle*kilometres to fulfil as explained in chapter 2 of this report.

The metro network of Paris is composed of 16 lines for a total of 200km of lines and over 380 stations. Each line runs on separate tracks (under or over ground) and is managed by its own operation team. At peak hours, the headway between trains is less than 2 minutes on most lines, which calls for very high efficiency operations and state-of-the art technologies. Therefore, RATP is continuously maintaining and trying to modernise the network. This so-called modernization plan is presented in the next paragraph. However, each line having different characteristics in terms of equipment, technology, geography or management, it is sometimes difficult to develop standardised solutions for the whole network. A map of the metro network and an overview of the main characteristics of all lines are given in Annex 1.

1.1.2. The modernisation plan

In the early 2000s, RATP initiated a policy for the renewal of the facilities necessary to the transportation supply. The two goals of this plan are to improve rail traffic safety and to increase the capacity for transport supply. This strategy for the renewal of metro facilities is

based on the implementation of the following industrial policy: each line is to be modernized through the deployment of generic products for

- Automatic and semi-automatic driving (CBTC system OURAGAN or OCTYS, SAET for fully automated lines);
- Supervisory systems (PCC);
- Signalling systems for in-line trains and terminal manoeuvring (PMI).

In particular, a new system for the operational control centre (PCC – Poste de Commande et de Contrôle) has been specified by RATP. Indeed, the ones in operation (centralised in the same place for all the lines) dated back from the 70s and there was a need for the renewal of this equipment, if only technically speaking. Further than this, it was decided to change the overall organisation of the PCC and to some extent of line operation and to some extent of the methods and responsibilities of the operators, as described in chapter 6. The deployment of modernized PCC for the metro network is part of the operation “Modernisation Générique du Métro” (Generic modernization of the Metro) and under the control authority of RATP who is the project owner. The realisation of three decentralised PCC was entrusted to the enterprise group (GE) THALES - STERIA.

The modernization of the PCC is controlled and monitored by a project team from the department of engineering at RATP (ING). One of the major specifications of the project was to develop a standardized tool that could be implemented and adapted to all the lines of the metro network (except for the automated ones, which have completely different modes of operation). To this date, two modernized PCC have been implemented, on line 13 and line 3. Two other lines are under implementation: line 5 and line 12. Finally, the costs of deployment of the modernized PCC on line 9 have been assessed (target commissioning more distant - 2018). Even though it was not specifically mentioned as one of the objectives of the project, there is a hope that this new organisation of the control system will help improve the quality of passenger service.

RATP is also conducting other projects that interact with the PCC deployment, such as extension of line 12, and more importantly for all the lines, the implementation of the CBTC system OCTYS (Open Control Train Integrated Interchangeable System) and of the PMI (Poste de Manoeuvre Informatisé - Computer-based manoeuvre control station). Although those projects are separated from the PCC project, they are both closely related to it during both implementation and operation, and their developments often interact.

1.2. Research objectives

This graduation project was conducted at RATP as part of a feedback analysis on the performance offered by the modernised PCC. Therefore, a problem statement was clearly identified by the problem owner, RATP, and led to the definition of several research questions for the completion of this study.

1.2.1. Problem statement

As previously mentioned, the main objective of the PCC renewal was the modernization of the equipment. On line 13 and 3, where the new system is now in operation, this objective has been fulfilled. However, the operators using those new systems have a mixed opinion on its performance. Indeed, their impression is that they do not meet the objectives that were set in the specifications. Especially, the effectiveness of the regulation algorithm that should allow the system to get back on time following an incident is being questioned.

Unfortunately, a rough measure of the performance of this type of complex system is not easy to conduct: so far, only the availability of the equipment can be measured and validated. Furthermore, if the level of satisfaction of the operation staff differs, it is difficult to assess whether this is related to the algorithm and methods of the system, or to the way it is being used and purely organisational aspects. It is important to mention here that what is referred to as the “PCC system” which will be studied in this research project is the overall system, that is to say everything and everyone interacting under the PCC organisation (hardware, software and wetware as well as interface between all of them and organisational principles). The problem to be addressed by this thesis is therefore the following:

Problem statement

Regarding its support function for real-time regulation of trains, the modernised PCC system offers a level of performance that is not in line with the requirements and expectations of the operation staff and that differs from one line to the other.

The reasons for this are yet to be identified, and this is one of the objects of this thesis. Indeed, this standardised system is a complex one, but is also supposed to be very efficient and of great help to operations. It is meant to be implemented on all the lines of the network (except for the fully automated ones) and if this problem of performance is not investigated, the legitimacy of this operation could be compromised.

The problem of lack of performance is a relatively subjective one. Indeed, if there is a lack, and this is yet to be proven, it is in comparison with something, whether it is with the specifications that preceded the elaboration of the system, or with the performances of the former system. Therefore, the objective of this project would be to identify the reasons for the observed gap between specifications or expectations and performance, and if possible to come up with recommendations on how to improve the performance of the new system. This lead to the following main research question:

Research question

What are the impacts (specified, expected and observed) of the new regulation system on operations and on quality of passenger service and how could its performance be improved?

1.2.2. Research questions

In order to answer this question, the project was divided into two main directions: a theoretical study of regulation methods, in general, at RATP and in this specific system, and an analysis of the observed and/or felt performance on line 13 and 3. Before those directions are addressed, a preliminary study is necessary for the comprehension of the subject from a master student point of view but not as part of RATP’s objectives. It can be summed up in the following question:

- *A – How are operations organised on the metro network at RATP? (Network operations)*

This question is answered through literature review, and with the help of several RATP operators that provided much needed information on the subject.

Once this question is answered, it is possible to get into the core of the subject. The study on regulation is a theoretical approach to the problem of regulation in a metro network, at RATP and in this new control system. It can be divided into the following secondary research questions:

- *B1 - How is regulation conducted on the metro lines of RATP?(Regulation methods)*

Part I – Project Background

Chapter 1 – Project Presentation and Approach

The different types of metro traffic regulation were studied in order to reach a good comprehension of their principles and implementation at RATP. This helped understand the requirements of the line operator regarding the PCC system.

- *B2 - How is regulation performed by the new PCC system?(Regulation with the new system)*

Since the new PCC software and hardware systems were delivered by an external party, it was important to study its methods to understand how it performs traffic regulation, and how it takes the RATP regulation principles into account.

- *B3 - Is the PCC algorithm consistent with the RATP regulation principle, with the requirements and with general regulation methods? (consistency)*

This question was answered after the previous two had been investigated. Their outcomes were compared, and the specifications of the operators studied in order to detect any difference between the product and the requirements and expectations of the operator (explicit and implicit).

- *B4 - How can the system be improved to approach the operators' expectations?(parameterization)*

To answer this question, it was necessary to study how the results change when some of its parameters are modified and how this influences operations. This part of the project required both a good understanding of the algorithm, but also an extended study of operational data to be used.

The second side of this project is more practical for it consists in an analysis of the actual performance of the system, observed and felt, to understand the actual gain introduced by the new system on line 3 and 13. The two secondary questions here are:

- *C1 - How do operators feel about this new system?(operators' impression)*

Out of all the research questions, this one can be viewed as the least technical one. It is also a very complex one for it requires to take into account the human factor and to try and make up a unified objective feedback from very subjective opinions and assessments. Furthermore, one would have to understand the difference between feelings about the fact that this system is new (which is often not welcomed by operators), about the new organisation of work, and about the performance of the system itself, all of which having to be taken into consideration. This question includes various aspects that do not seem directly related to the subject at first such as taking into account the human factor in highly computerized system, the difference in points of view between different actors (passengers, conductor, controller, project manager, etc ...) or the differences between nominal and effective use of a system, and leads the way to understand that even in such a high-tech system, not everything is technical, and human psychology remains very important.

- *C2 - How are operations impacted by the use of this new system?(Impact on operations and line behaviour)*

With this question, the goal was to perform a data analysis to come up with numbers that would corroborate, or on the contrary invalidate the subjective feedback from the operator. It is expected that if the operator says the system does not work, this will turn out in an analysis of the operational data, and vice-versa. This should also help validate, or improve the system and might also be used to answer the last of the previous set of questions on parameters, since there is still a need here to have a good understanding of the operational data.

1.2.3. Complementary research directions

In addition to those research questions, which are necessary to answer in order to fully address the problem at stake, other aspects were covered during this project.

On the one hand, the problem of regulation raises other questions that may be worth considering in addition to this study, such as those mentioned for question C1 (human factor, congestion, system utilization). It can also lead to a reflection on project management and the various factors that led to this late detection of problems in a project yet undertaken with great attention from beginning to end, or on the gaps associated with time management in a project (for example, as it is the case here, requirements may differ between the beginning of the project and its full implementation 5 to 10 years later). These aspects are not directly related to the subject of the study but may provide some interesting information for the discussion on improving the system and the project and are grouped under the following research direction: *D – Complementary research and ground for improvement.*

Furthermore, this project required taking many initiatives to get in contact with metro operators, technical centres, RATP project managers, systems and implementation engineers. It was interesting to take this opportunity to learn about different occupations and aspects of RATP and of project management in general. This was not always outside the scope of the study. For example, the first few weeks at the company were used to discover the PCC project as a whole, and more generally the engineering department which permitted among other things to truly understand the context and implications of this project.

1.2.4. Scientific contribution

From a scientific perspective, while there are many researches being conducted on railway traffic management and regulation, it is usually not specific, or even applicable to metro systems. Indeed, metro systems have characteristics that make their operations very different from other types of railway networks (high frequency of stops, very short headways depending on the time of day, high and irregular volumes of passengers, urban environment, equipment, control systems...). Furthermore, they generally differ from one network to the other, and it is not really possible to make up general theories and principles about them. Yet, in a commercial approach, the attempt of the industrial group is to develop a generic product that can easily be adapted to the various clients. The PCC system is no exception to this rule and this should be kept in mind during the study as this means that it can be compared with other metro networks, especially those equipped with a similar control system developed by THALES.

In this research, one of the goals is to understand how regulation is being performed in the case of the Paris metro and how new system have impacts on this. This is not a theoretical study, and its objectives seem to be mainly in the interest of RATP and anyone who would be interested in knowing more about this specific network – which truly is very interesting to study for it is a very complex and elaborate one. However, if similar researches were to be conducted for other metro systems in the world (preferably similar in size and volumes, such as London, Madrid or New York), it would be very interesting to compare them and to try and understand the differences and the similarities. Furthermore, an effort was made to put this research into perspective, especially since it was conducted as part of a TIL master education.

Finally, from an academic perspective, this research is being conducted as a graduation project, and as such, it is to be the gateway to a career in transport engineering. For someone who is interested in public transport, the Paris metro network offers a large numbers of captivating aspects. This research project in particular is a great opportunity to understand and observe how the theoretical concepts that were studied during the academic part of the TIL

master are implemented in practice, but also to discover this fascinating metro system and its various aspects and projects.

1.3. Research plan and reading guide

After defining the research questions, a clear research plan became obvious, as some parts needed the input of others. This adopted plan is presented in Figure 1 (see next page)

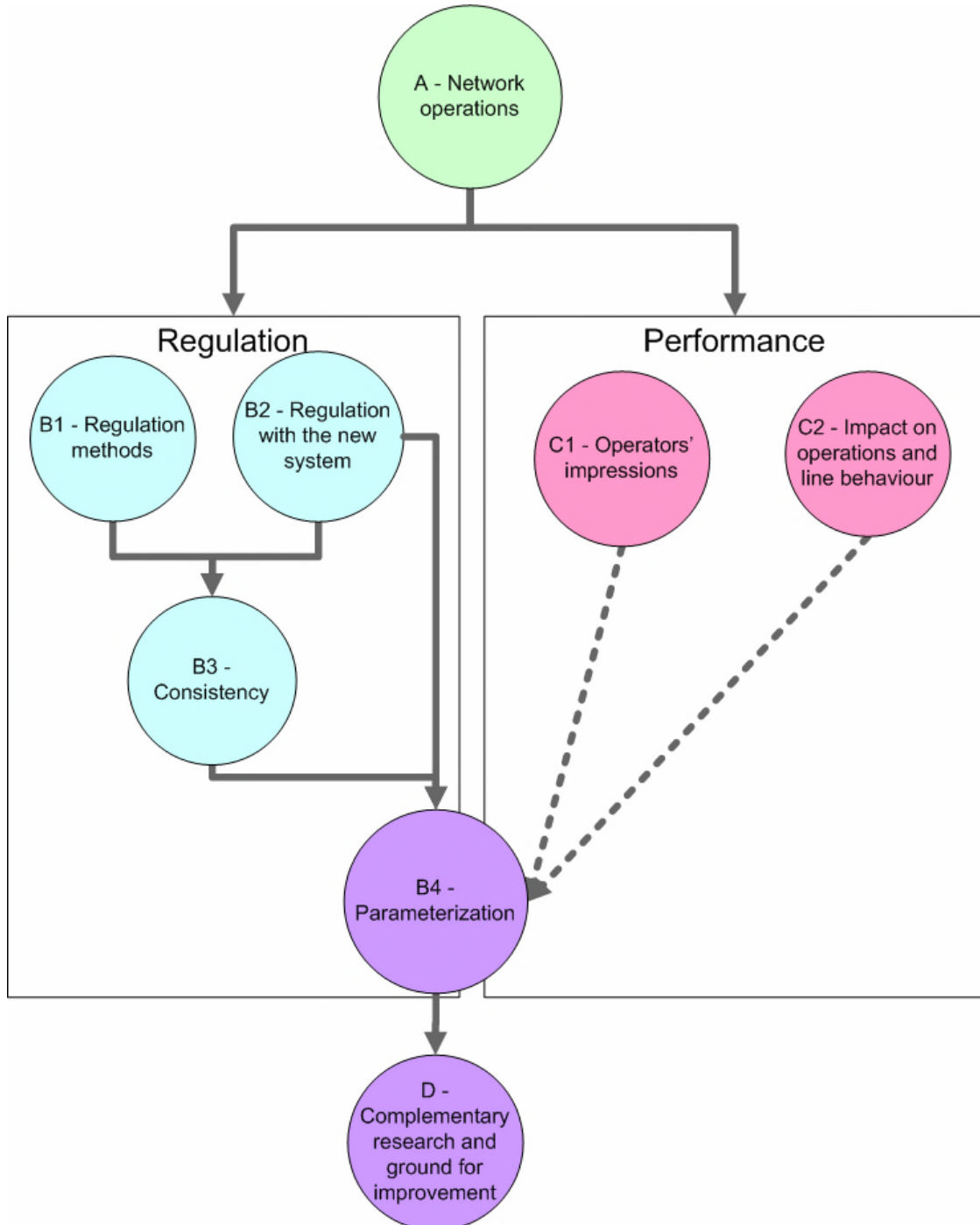


Figure 1 - Research plan

This leads to the following organisation of the report:

- **part 1 – project background** includes this chapter, and the two chapters describing the transport market in Ile-de-France and Operations of the metro network, thus answering research question A on network operations;
- **part 2 – metro traffic regulation** includes a state of the art of metro traffic regulation, which consists of the result of the literature review that was performed in order to have a good understanding of this subject and an overview of the different regulation methods in use around the world, a description of regulation principles at RATP, a description of the regulation methods in the modernised organisation of the PCC and finally a conclusion on the consistency of this system, thus answering research questions B1, B2 and B3.
- **part 3 – Performance analysis** includes a chapter on the operator facing the new system from a human experience perspective, as well as chapters on the data analysis (framework, observations and conclusion crossed with the human experience), thus answering research questions C1 and C2, and the result of the modelling work that was conducted in order to better understand the behaviour of the system (research question B4).
- **part 4 – Conclusion** gives the overall conclusion of this study with findings, recommendations and discussions, thus also exploring research question D on complementary directions.

The structure of the report is expanded on in Figure 2 to be used as a reading guide. The colours of the part refer to the ones used in Figure 1 to differentiate which research questions are being answered in which chapter. Since this project is part of the multidisciplinary master TIL, it includes both technical parts (that can be related to the education received from the Transport & Planning department in CiTG) and policy and management-related parts (to be related to the education received from the Transport & Logistics section in TBM). Indication on whether or not the aspects presented are technical, policy-related or both is given by means of red (technical) and yellow (policy) dots. The education received during the TIL master was indeed thoroughly used in the course of this project. A strong enough knowledge of operations and technical features of railway networks was needed to be able to address the subject at hand, but the policy-oriented and systems engineering knowledge gained through the TBM classes were also necessary to have a good understanding of the institutional environment. Furthermore, methods such as the TRAIL-layer model, stakeholders and requirement analysis or the performance criteria were very useful to this project, even if they do not always appear explicitly in this report.

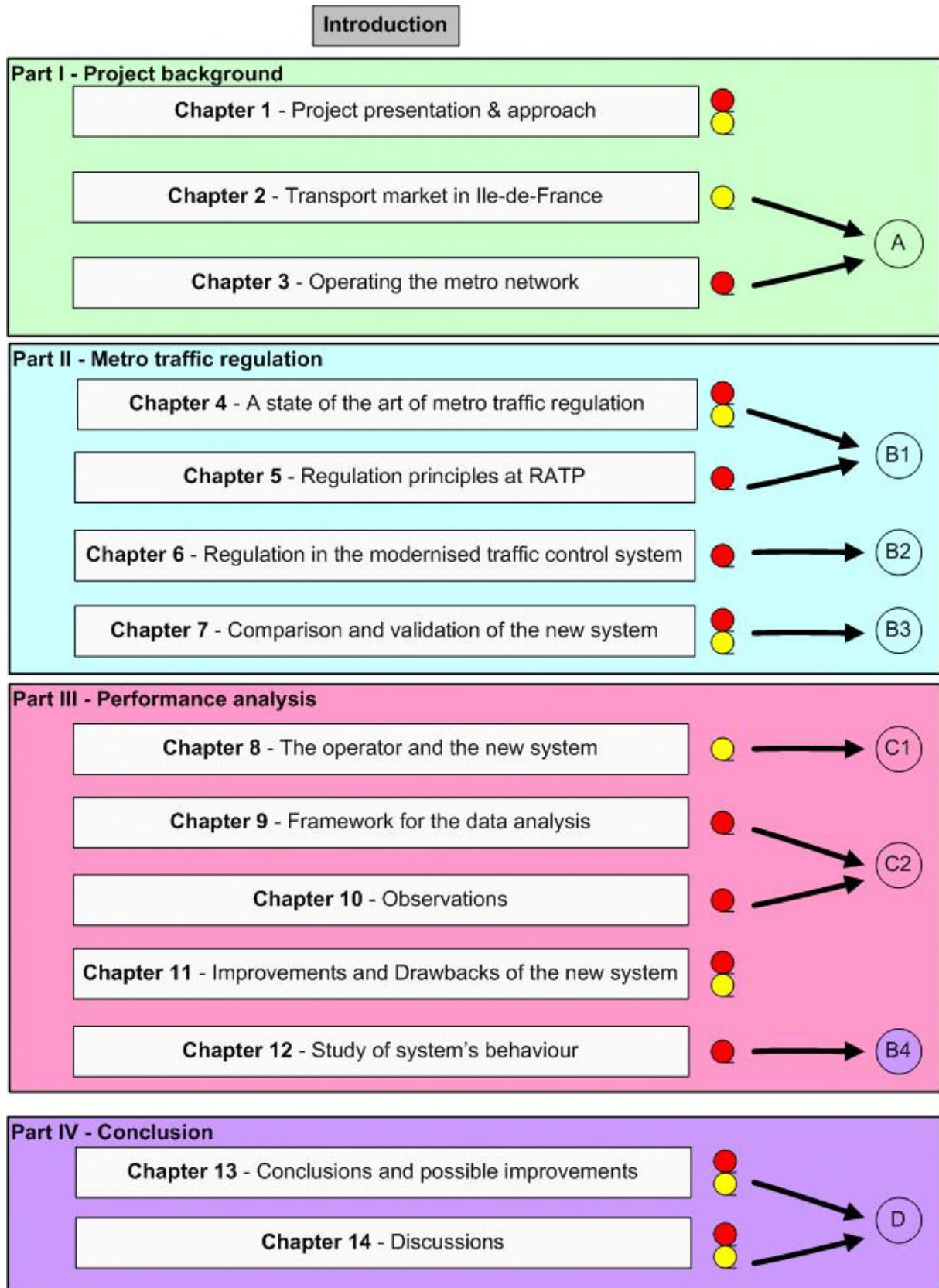


Figure 2 - Reading guide

Chapter 2 – Transport market in Ile-de-France

With around 11.8 million inhabitants, the region Ile-de-France, composed of Paris and its suburbs, is one of the most populated and dense areas in Europe. This leads to a very important transport demand, both in quantity and in quality. In this chapter, a brief description of the transport demand in Ile-de-France is first provided. The next part attempts to give a definition of quality of passenger service. According to this demand in quantity and quality, the public authority has developed an institutional framework for transport operations in the regions, mainly through the actions of the STIF. The description of this institutional organisation is given in the third part of this chapter.

2.1. Transport demand

In Ile-de-France, every eight to ten years, a large-scale study is being performed by the various transport actors in the region (mainly public authorities and transport companies), called the EGT (Enquête Globale Transport – Global study for transportation). This study tries and assesses the transport demand in the region. It is mostly based on surveys which list a number of details about all the trips being performed by the respondents (modal type, purpose, time, duration, length...). According to the last EGT (2001) on a business day, 35.2 million trips are performed in the region, among which 23 million are motorised trips (cars, buses, trains, metros, tram, motorbike...). Out of those, 30% are carried out through public transport. However, this is an average number on the overall region, and the modal split changes a lot depending on the origin and destination of the trips. Indeed, for example, when either the origin or destination of the trip is within the core city of Paris, the modal share of public transportation rises up to 60%. This might be explained by either the fact that using a car within Paris is made difficult by the high level of congestion in the city and the shortage of parking spaces, or by the high level of transport supply within the city, especially provided by the very dense metro network.

Another interesting fact in the results of the last EGT is the share between purposes in the trips which are presented in Table 1. The purposes are split between obligatory trips (commuting, business trip, education) and the non-obligatory trips (leisure and others).

	1976	1983	1991	2001
Commuting	6,8	6,4	6,4	6,6
Business	5,2	5,2	5,1	5
Education	4,3	4,8	5,3	5,4
Obligatory	53,6%	52,6%	50,8%	48,2%
Leisure	3,6	4,3	5,1	5,6
Other	10,5	10,5	11,2	12,7
Non-obligatory	46,4%	47,4%	49,2%	51,8%
Total	30,4	31,2	33,1	35,3

Table 1 - Daily amount of trips per purpose, in millions (EGT)

In this table, it can first be seen that the total amount of trips has been rising steadily ever since the first EGT, which was to be expected, since the population of Ile-de-France keeps increasing. However, a more interesting fact here is that the number of non-obligatory trips is increasing more importantly than the obligatory ones. When the latter used to be the majority before 2000, this trend was reversed in the last study. This fact is of importance, for depending on the purpose of the trip, transportation is not performed the same way, and

especially not at the same time. This means that in the last 35 years, traffic during off-peak hours and in the week-ends have increased more rapidly than that of the peak hour.

The difference in traffic depending on the time of day is very important for the definition of public transport supply. Figure 3 shows the number of people entering the metro network every half hour of a business day in 1996 and 2009.

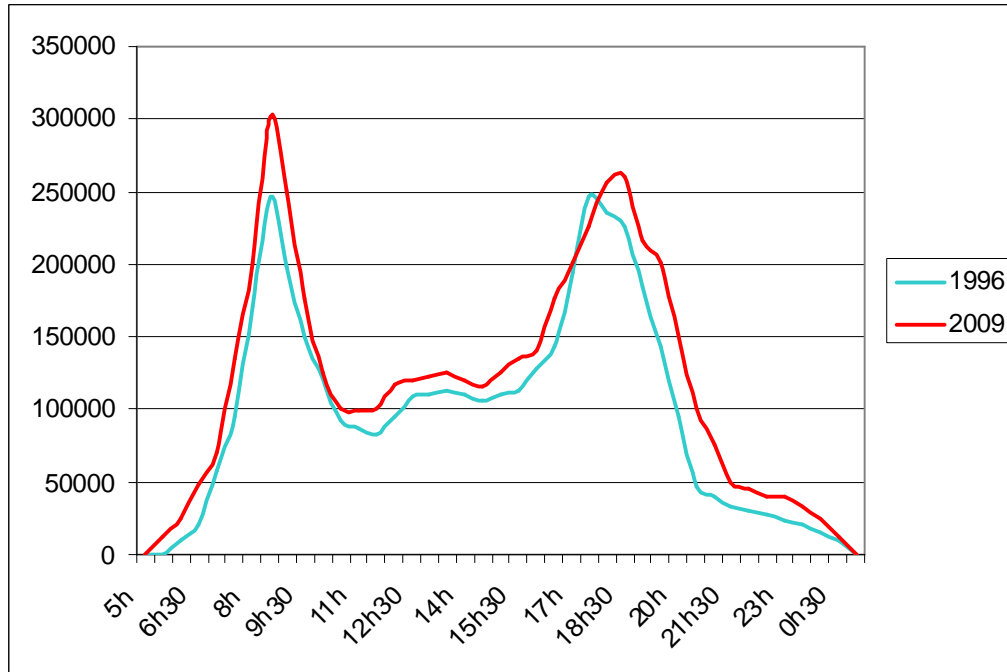


Figure 3 – Number of people entering the metro network every half hour on a business day (RATP)

As in any city, the transport demand is characterized by two peaks, in the morning and in the evening, due to commuters. In the comparison between 1996 and 2009, it can be seen that indeed, the total amount of trips has risen – in the metro, there was a daily number of passenger of 4.1 million in 1996, and 5.02 in 2009 on business days; yearly traffic in 1996 amounted to 1 091.6 million trips and 1 472.5 in 2009. Moreover, whereas the period of the morning peak has remained more or less the same (between 8 and 10), the evening peak is now longer (from 17 to 19:30 in 1996, and from 16:30 to 20:30 in 2009). Finally, the demand seems to be indeed higher during off-peak hours than it was before.

2.2. Quality of passenger service

The goal of any transport service is to provide a supply according to the demand in quantity, but also in quality. In this regard, one can wonder how to define quality of passenger service. This is a very subjective notion for the important factors differ from one person to the other. For some it is more important to have a short trip, whereas others prefer comfort. Most people regard waiting time as more inconvenient than time spent in vehicles, however, people feel very upset when vehicles stop for too long... As it is explained in the next part of this chapter, transport companies in Ile-de-France are compensated both for the amount of transport production and for their quality of service, which makes it important to have a clear definition of what is considered quality of service. In those compensation indicators, quality is split between six categories:

- regularity;
- passenger information;
- availability of equipment in the stations;

- reception and sales;
- cleanliness;
- perception of quality through passenger survey.

Whereas it is easy to understand how the last four are related to quality of service, and how they can be assessed, the aspect of regularity can be more puzzling.

When looking at a passenger's trip, he feels mainly two aspects that do not seem to be mentioned in the quality categories: the duration of the trip and the number of passenger travelling with him. However, in the case of passengers that use the network very frequently, which is the case of most metro passengers, the important feature is not actually the duration of the trip, but how close it is to what they expect, which means having to wait less than a certain amount of time, depending on the time of day (at peak hours, people are expecting less waiting time than in the middle of the day for example), and that the time spent in the vehicle (between stations and at stations) has to be constant. An adequate indicator of quality of service in this regard would actually be the "additional travel time", which is mostly caused by unreliable service (Van Oort, 2011). With a regular service, waiting times are equal from one train to the other, thus reaching the goal of quality of service from the passenger's point of view.

Moreover, to some extent, regularity is linked to the perception of comfort (Cortes & Loknar, 2008 & 2010). Indeed, if the traffic is irregular, the passenger loads will be uneven, leading to unequal impressions by the passenger. Some feel a very high level of discomfort related to the overload, while other do not notice any inconvenience. The problem is that if on average comfort seems to reach acceptable levels, the feelings of users who experience irregular traffic does not say so. This is simply explained in the following simplified example.

Considering three trains with a maximum capacity of 550 passengers each (limit of acceptable comfort) following each other on the line.

- *train 1 is loaded with 550 passengers*
- *train 2, running late, is loaded with 700 passengers*
- *train 3, running very close to train 2, is loaded with 400 passengers*

On average, the train load is of 550 passengers, which is within the comfort limit. However, the loads are felt differently by passengers from one train to the other:

- *550 passengers travel with 550 passengers*
- *700 passengers travel with 700 passengers*
- *400 passengers travel with 400 passengers*

leading to a load as felt by users of 577 which is not within the comfort limits.

As shown in the example, saturation of the trains and thus irregularity is felt by users as even worse than it is measured on average. Passengers are thus likely to feel irregularity even more than what the mere observation of operators might assess, which is an additional reason to try and ensure regularity between trains.

However, train overload is not only due to problem of regularity, but in general to the fact that in some critical parts of the network, the transport demand is too high. This can be solved by re-adjusting the supply and increasing the number of trains running a line at peak hour, but this is not always possible because of technical issues and social issues (increased frequency at peak hours means more rolling stock and more drivers). Indeed the two most congested axis of the metro network are the central east-west direction, covered by lines 1 and 14, and by RER A (among which line 1 is undergoing an automation project that should increase its

efficiency) and the north-south direction, mainly being covered by line 4 (already modernised since 2001) and RER B in the eastern part of Paris and line 13 in the western part, thus justifying the large investment that is being put on the modernisation plan for this line.

As for the general opinion of users regarding quality of passenger service, it differs a lot from one line to the other or from one person to the other for that matter. Accordingly with the problems of overload that were just mentioned, it is a well known fact among Parisians that line 13 is to be avoided whenever possible, for this line is always very crowded and often very irregular. Nevertheless, putting aside the general resentment about strikes that are very frequent in transport companies in France, especially in Paris, passengers are somewhat aware of the fact that their metro network is very well-developed and quite efficient, especially compared to other similar cities. However, they are very critical as soon as a difficulty occurs, and are tired of hearing that their train has to stop a little longer in the station “for regulation”. Indeed, those problems are recurrent, so much so that they overshadow other complaints that passenger could have about other aspects of quality of service, which is the reason why the focus of all transport companies in Ile-de-France needs to be set on resolving those regularity issues.

2.3. Institutional organisation

The transport demand is thus characterized by a passenger load depending on the time of the year, day of the week and the time of day and that differs from one line to the other. Any public transport operator is expected to meet this demand by providing a certain amount of traffic. In order to understand how operations on the metro network of Paris are organised, a TRAIL layer model is presented in Figure 4.

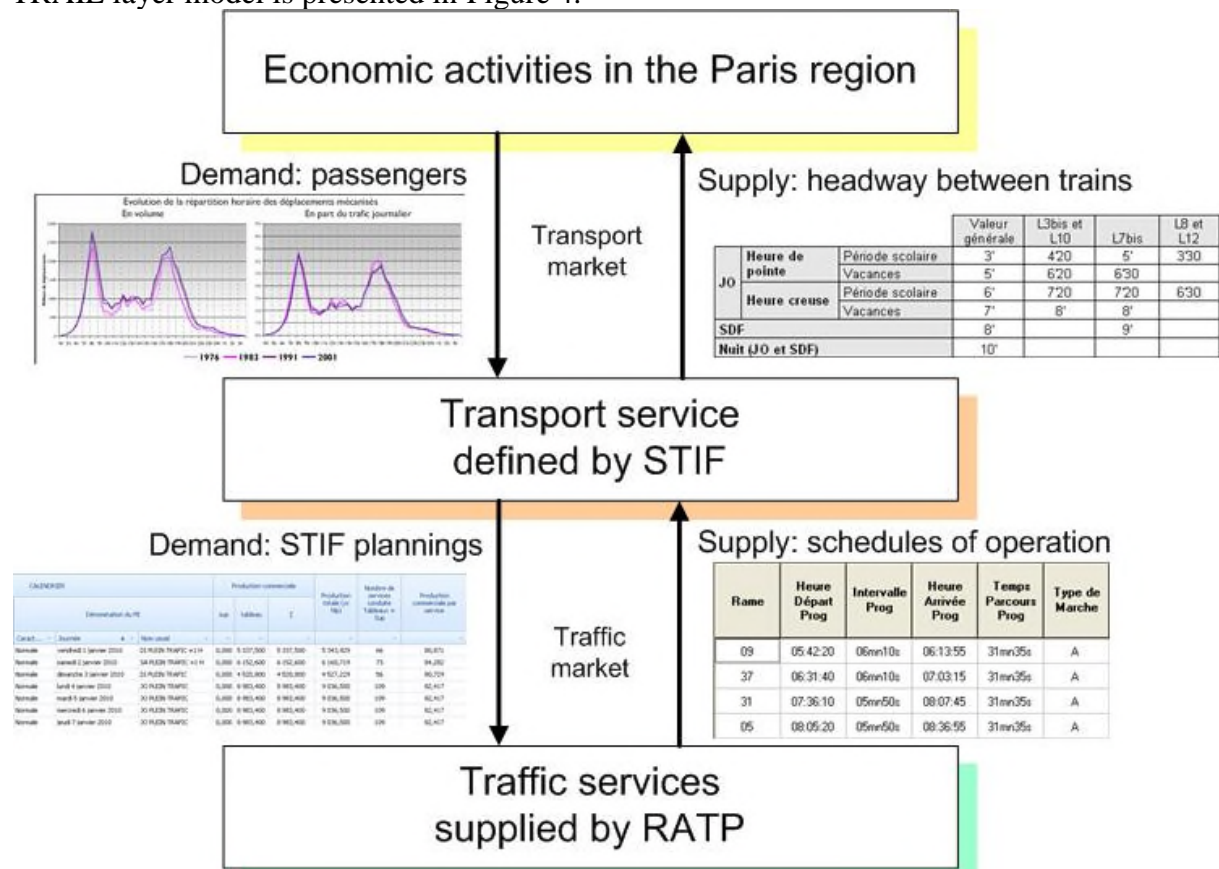


Figure 4 - Trail-layer model for the metro system in Paris

The three layers in the model are:

- the economic activities that create a need for transportation ;
- the transport service defined by STIF: operations of all public transport means in the Ile-de-France region are ruled and controlled by a regional public authority, the STIF (Syndicat des Transports en Ile-de-France – Union for transportation in Ile-de-France). Various companies operate public transport in Ile-de-France (RATP, SNCF, Veolia, Keolis...), those operation being ruled by contracts signed between them and STIF;
- the traffic service offered by RATP.

In between those three layers are the transport market, defined by the transport demand as described in part 2.1, and the traffic market.

In this part, the contract between STIF and RATP is presented in order to give a good overview of the institutional aspects that rule operations of the metro network. Based on the passenger flows, this contract describes the service that is asked of RATP both in quantity leading to the STIF yearly programs of operation and in quality, especially regarding frequencies between trains. A special attention is given in this part as to how regularity is accounted for in this definition of the production and in its remuneration.

Since the year 2000, public transport operations by public or private companies, including RATP, and their payment by the region Ile-de-France are defined in various contracts between STIF and the transport companies. Those contractual agreements ended the previous system based on compensatory allowance in which the transporters' accounts were automatically balanced at year end without there being any specific commitments in terms of quantity and quality of service.

A separate contract with the STIF is signed every four years for each of the networks operated by RATP (RER, metro, tram, bus...).

On the one hand, RATP is committed to producing a reference transport service defined in quantity (number of kilometres supplied for the transportation of passengers) and quality (through a set of quality indicators). On the other hand, the STIF is committed to a payment composed of a fixed standard compensation and a part based on direct revenue. After the first contract came to an end in 2003, various incentive mechanisms were added such as bonus or penalties, a share in the ales revenue...

2.3.1. Supply definition

For each one of the sub-networks operated by RATP, the transport supply is defined in terms of quantity and quality. For the metro network, the 2007-2011 contract defines the supply for each one of the 16 lines separately, leading to a more accurate assessment of the transport supply than in the previous contracts where only a global supply for the network as a whole was defined (thus allowing “good” lines to compensate for the “bad” ones which is not possible anymore).

Quantitative definition

For each line, STIF defines a total number of kilometres to produce yearly, accounted for in the unit TK (train*km). This total number of kilometres is the sum of the kilometres to produce each day of the year based on the passenger flows. Different types of days are defined along with a reference service as it can be seen in Table 2.

Types of operation table	number of days of the type in 2008	number of moves per direction	max. number of trains needed	headway between trains (min:s)			commercial TK (train*km)	total TK (train*km)
				min (peak hours)	daytime off-peak hours	max (night)		
JO lightened special	1	470	43	01:50	03:20	04:00	15 489	15 561
JO full traffic +1h	28	428	45	01:45	03:20	05:00	14 113	14 188
JO full traffic	106	398	45	01:45	03:20	07:45	13 128	13 203
JO lightened +1h	14	408	45	01:50	03:20	05:00	13 449	13 518
JO lightened	55	378	43	01:50	03:20	07:45	12 464	12 532
JO reduced +1h	6	346	35	02:15	03:35	05:00	11 392	11 439
JO reduced +1h	17	323	35	02:15	03:35	07:45	10 637	10 684
JO very reduced +1h	8	296	32	02:40	04:40	05:00	9 743	9 783
JO very reduced +1h	19	279	32	02:40	04:40	07:45	9 185	9 225
SA full traffic special	1	351	26	03:20	04:05	04:00	11 521	11 539
SA full traffic special	41	300	26	03:20	04:05	05:00	9 861	9 893
SA reduced	9	265	22	03:45	04:30	05:00	8 704	8 723
DF full traffic +1h	2	253	25	03:45	05:35	05:00	8 329	8 350
DF full traffic	48	229	25	03:45	05:35	07:45	7 541	7 662
DF reduced +1h	3	230	20	04:15	05:50	05:00	7 567	7 581
DF reduced	8	209	20	04:15	05:50	07:45	6 877	6 891
Total							4 128 168	4 152 662

Table 2 - Reference service on line 1 for the year 2008 (STIF)

The days of the year are categorised as either “JO” (standing for “Jour ouvré” – work day), SA (standing for “Samedi” – Saturday) and DF (standing for “Dimanche ou fête” – Sunday of holiday). They have different levels for the amount of traffic from very reduced (typically in August) to full traffic. On Fridays, Saturdays and days before a holiday, the service is extended of 1 hour at night, hence the +1h in some types of operation tables.

Detailed planning are issued by STIF indicating for each day of the year the type of days and number of kilometres expected, as long as exceptional reinforcements in some cases. The reference service table therefore gives all the indications needed to plan the traffic for each day of the year depending on its type and according to the contractual agreement. However, modifications to the reference service are allowed as long as they are agreed on by both RATP and STIF. This can lead either to a reduction of the service (due to work on the network, strikes...) or to an intensification of the service (for example due to a major event such as public demonstration or a concert) either for a specific line or for the entire network.

Qualitative definition

Quality indicators are defined for each sub-network along with an objective. Table 3 gives an overview of the indicators related to the metro network along with their goals. Not complying with those goals (in quality and in quantity) has consequences on RATP’s earnings that are described in the next sub-part. The indicator on regularity (here mentioned as “waiting time” is further explained in sub-part 2.3.3)

Indicator		average result	obj. Min	goal	obj max.
Line 1	Waiting time	98,9%	97,5%	98,0%	98,5%
Line 2	Waiting time	98,7%	97,5%	98,0%	98,5%
Line 3 & 3 bis	Waiting time	99,2%	97,5%	98,0%	98,5%
Line 4	Waiting time	99,1%	97,5%	98,0%	98,5%
Line 5	Waiting time	98,8%	97,5%	98,0%	98,5%
Line 6	Waiting time	98,7%	97,5%	98,0%	98,5%
Line 7 & 7 bis	Waiting time	99,0%	97,5%	98,0%	98,5%
Line 8	Waiting time	98,8%	97,5%	98,0%	98,5%
Line 9	Waiting time	98,5%	97,5%	98,0%	98,5%
Line 10	Waiting time	99,0%	97,5%	98,0%	98,5%
Line 11	Waiting time	99,7%	97,5%	98,0%	98,5%
Line 12	Waiting time	99,2%	97,5%	98,0%	98,5%
Line 13	Waiting time	98,9%	97,5%	98,0%	98,5%
Line 14	Waiting time	99,8%	97,5%	98,0%	98,5%
		99,0%			
	Reception at sales counter	95,0%	89,0%	92,0%	95,0%
	Reception at information desks	93,4%	89,0%	92,0%	95,0%
	<i>Delay before a passenger is assisted by an agent</i>	96,0%	89,0%	90,0%	
	Train cleanliness	95,5%	85,0%	90,0%	95,0%
	Station cleanliness	96,1%	86,0%	91,0%	96,0%
	Availability of escalators and moving walkways	96,2%	92,0%	94,0%	96,0%
	<i>Escalators and moving walkways repaired within 48h</i>	98,9%	89,0%	90,0%	
	<i>Escalators and moving walkways out of order with information on the time before returning to service</i>	57,0%	94,0%	95,0%	
	Availability of elevators	95,6%	90,0%	93,0%	96,0%
	<i>Elevators repaired within 48h</i>	98,4%	89,0%	90,0%	
	<i>elevators out of order with information on the time before returning to service</i>	34,9%	94,0%	95,0%	
	Availability of ticket selling\$ machines	98,4%	95,0%	97,0%	99,0%
	Availability of validating machines	98,7%	93,5%	96,0%	98,5%

The goal gives indication on the share of passengers that should be in « conformity situation ». For example, for the waiting time, 98% of passengers should wait less than the reference waiting time that is given for each line and each time of day.

Table 3 - Quality indicators for the metro network (RATP)

2.3.2. Financial compensation

The financial aspects of the contract are divided between direct traffic revenue, contribution from the STIF on operating expenses and a contribution to investments for the maintenance of assets. Moreover, it also includes a triple incentive mechanism:

- one that is linked to the sales volumes, motivating RATP to take an active part in ticket and subscription sales (the revenues of which used to go entirely to STIF);
- a possible reduction of the production contribution in case of failing to produce the agreed amount of transport supply (quantity);
- a bonus-malus system linked to the quality indicators.

As an example of the amounts at stake, the compensation from the year 2000 to 2004 are given in Table 4.

	2000	2001	2002	2003	2004
Fixed contribution paid by STIF & direct revenue	2 520,9	2 559,9	2 639,1	2 735,3	2 725,1
Payment of sales and commercial incentive	110,7	123,6	128,6	125,8	120,2
Payment for new services	0,0	0,8	4,6	11,2	2,9
Production contribution	718,5	717,7	707,6	699,2	677,1
Reduction of contribution due to non-production	0,0	0,0	0,0	0,0	0,0
Quality bonus/malus	9,6	9,0	7,9	7,8	7,7
Various	0,0	0,2	2,3	0,4	-22,5
Total	3 359,7	3 411,2	3 490,1	3 579,7	3 510,5

Table 4 - Yearly compensation from STIF to RATP (STIF) in million euros

Reduction of contributions due to non-production

For each line or network depending on the contract, a minimum amount of production for the year is agreed on, additional to the reference amount, in numbers of kilometres driven by all the vehicles of said network or line. As long as the yearly transport production is higher than this minimal amount, the payment of RATP by the STIF is not affected. However, if the minimal amount is reached, RATP incurs a risk of reduction in its payment by STIF for non-production. For the metro network, the reduction is calculated on the basis of 6.34€/non produced TK. The minimal amount of production is 96.5% of the reference production, thus allowing to a 3.5% loss in production. The reduction is capped for each network, reaching a maximum of 5.5 million € (out of around 700 million € of fixed contribution). This reduction mechanism is represented in Figure 5.

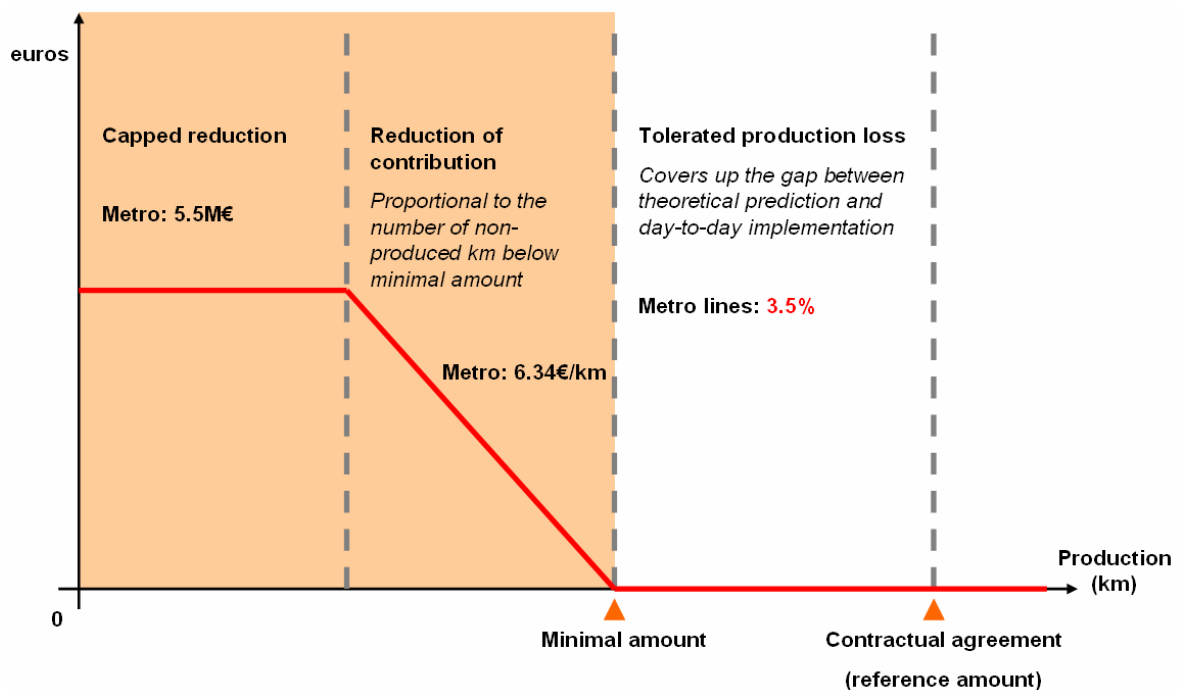


Figure 5 - Reduction mechanism in transport compensation by STIF (RATP)

The bonus-malus system linked to quality of service

Each one of the quality indicators that were introduced in the previous paragraph is defined by a way of measuring and an objective to reach. If the annual result is higher than the goal,

RATP is rewarded by a “bonus”. If it is lower, RATP is penalized by a “malus”. Along with the goal, a maximum and minimum are set. If the annual result exceeds those extrema (up or down), the maximum bonus or malus is applied and cannot grow anymore. This mechanism is represented in Figure 6, using the stations cleanliness indicator as an example.

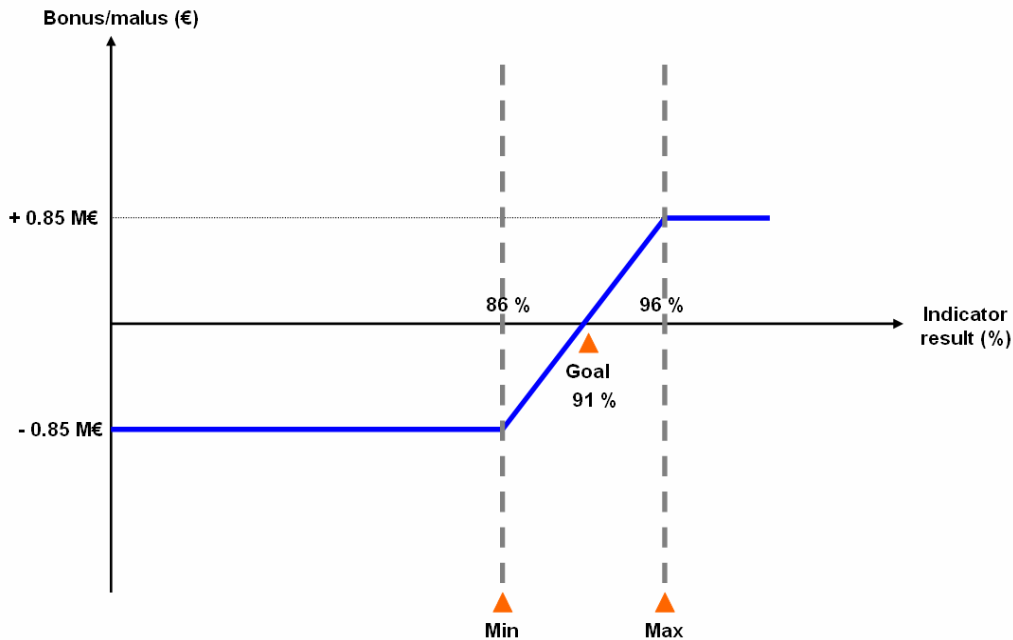


Figure 6 - The bonus-malus mechanism (RATP)

The overall amount of bonus-malus for all indicators is + / - 25 million. The quality indicators are defined and measured for each one of the networks operated by RATP, leading to the following distribution of maximum bonus/malus, which are set annually:

Metro	7,54 M€
RER A	5,40 m€
RER B	2,66 m€
BRT & tram	1,1 M€
Proximity buses	3,6 M€
Suburban buses	2,3 M€
Paris buses	1,3 M€
Night buses	0,9 M€
Quality perception by users	0,2 m€
Total	+/- 25 M€

Table 5 - Yearly distribution of maximum bonus/malus (STIF)

Those amounts are distributed between networks according to their importance, that is to say the number of passengers using the network or line in the case of RER A and B. In each network, the bonuses or maluses are distributed from the overall amount more or less as follows:

- regularity: 30%
- passenger information: 15%
- operational equipments: 15%
- reception and sales: 25%
- cleanliness: 9%
- perception of quality by passengers: 1%

2.3.3. Remuneration of regularity in the metro network

In the first two contracts (2000-2003 and 2004-2007), much like overall production, regularity was assessed by network, that is to say for the metro as an average between all the lines. As it was previously mentioned, bad results on some lines could therefore be caught up by good results on others. In the 2008-2012 contract, which focuses on decentralization of services, quantity and quality of service were defined separately for the 16 lines, which led to a more accurate assessment of performance, especially when it comes to regularity.

Furthermore, up until 2008, regularity in the metro network was only assessed through the time passengers had to wait for a train to arrive. Beginning in 2009, this criterion is completed by one that evaluates the amount of production during peak hours.

Waiting time

During a business day, there are three types of operational profiles: peak hours, off-peak hours and night. Business days are also classified between school time and vacation time. Saturdays, Sundays and holidays are only divided in two: day time and night time. The limits of those hours are defined depending on the line, which is expanded on later in this chapter. The reference service for regularity is defined by the STIF through the maximum time a passenger has to wait for his train for each type of hour. A general value is set that applies to all the metro lines, except in some cases for five of them for they usually experience passenger flows that are less important than the other lines.

This is represented in Table 6.

			General value	L3bis & L10	L7bis	L8 & L12
BD	Peak hour	School time	3'	4'20	5'	3'30
		Vacation time	5'	6'20	6'30	
	Off-peak hours	School time	6'	7'20	7'20	6'30
		Vacation time	7'	8'	8'	
Saturdays, Sundays & holidays			8'		9'	
Night time (BD & SSH)			10'			

In case of a branched line, to be applied to the common part.

Table 6 - Maximum waiting time allowed on the metro lines (STIF)

According to the goal of the waiting time indicator, 98 % of passengers should experience the reference service, with a lower bound of 97,5 %. In order to come up this measure, average platform occupation matrices are defined based on origin-destination surveys and regularly updated. For each station and direction of each line, those matrices give the average number of people waiting for a train depending on the type of day and the time (the days are divided in periods of half an hour). Those numbers are crossed with the data giving the hours of all train arrivals in all the stations for the whole year to give, which gives the assumed share of passengers who had to wait more than the maximum waiting time. However, it has to be mentioned that such a way to assess regularity is not so precise, especially since it is based on average number of waiting passengers that are on the one hand very difficult to assess, and on the other hand not representative of all situations, especially in critical times such as peak hours, or when disruption occurs in the network.

As it is the case for all the other quality indicators, the measures and calculation are performed by RATP. The STIF is free to perform audits on those values anytime they want. In practice, it is very rare that the annual result falls lower than the minimum goal, as it can be

seen in Figure 7 which presents the waiting time indicator results for all the metro lines in 2008, 2009 and 2010.

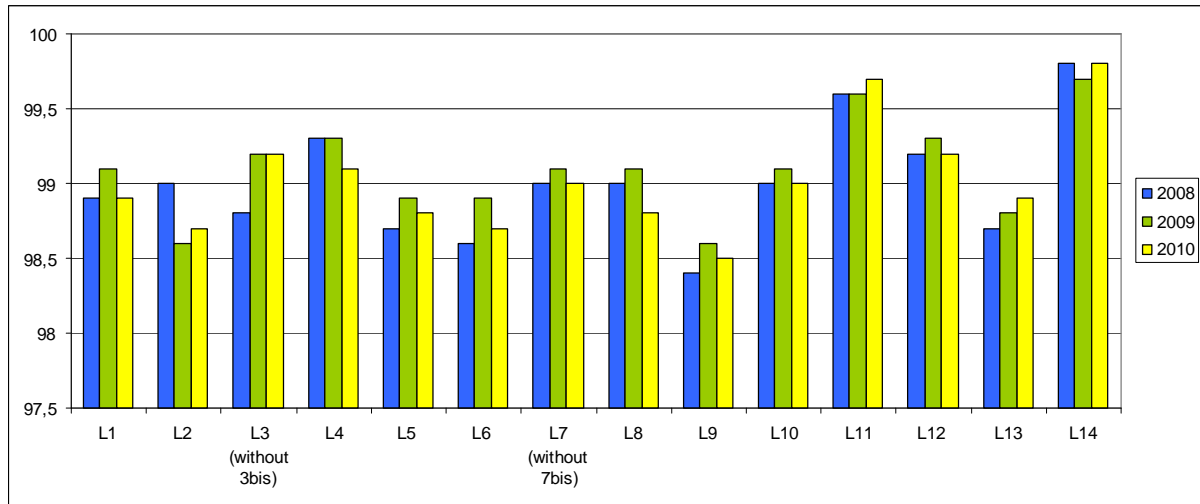


Figure 7 – Waiting time indicator in the metro network per line (RATP)

In the last three years, the indicator always exceeded its goal of 98%. This is however not at all consistent with the strong dissatisfaction of passengers in some lines. Therefore, this criterion is not enough to truly evaluate on its own the operation performances of the metro lines. Two explanations can be proposed for this:

- either the reference waiting time is too large (a goal of 3 minutes on lines that operate with a headway between trains of 100s is very easy to reach, even with disruption on the lines);
- or the periods when dissatisfaction is at its highest (usually, peak hours) are not represented enough in the calculation. That is to say that the weight given to the passenger loads through the platform occupation matrices is not sufficient to truly measure the importance of production during peak hours.

Because of this gap between passenger's negative impression and positive results on quality indicators, a new criterion on regularity was introduced in 2009 to come as an addition to the waiting time criterion.

Transport production during peak hours

The assessment of regularity in the metro is now completed by the indicator "transport production during peak hours". This measure gives the percentage of the actual amount of traffic produced against the reference service ordered by the STIF at peak hours. Figure 8 shows the results of this indicator for each line in 2009 when it was first implemented.

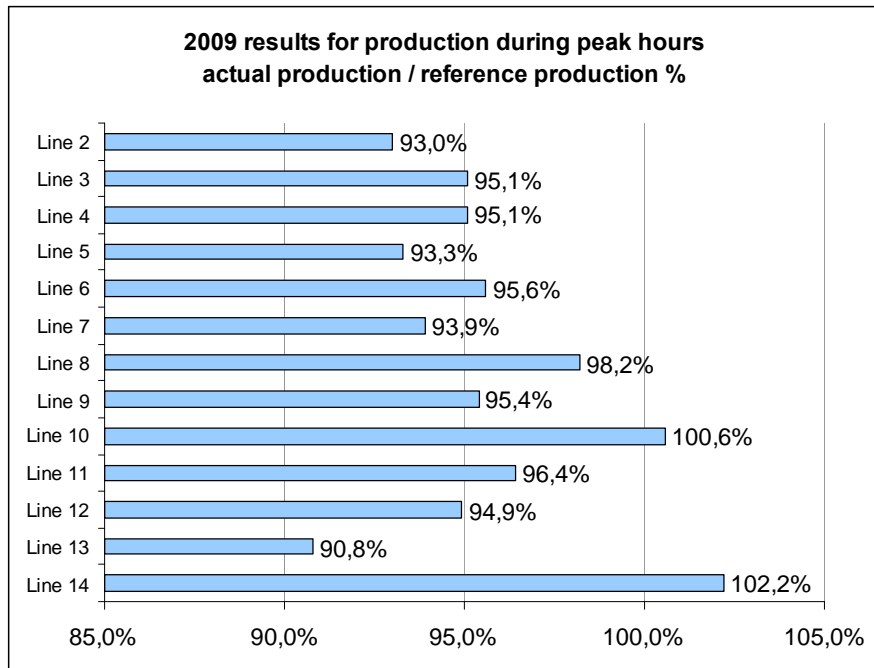


Figure 8 - Production during peak hour (RATP)

The goal of 97.5 % is only met by 3 lines. Those results are much less positive than for the waiting time indicator, and more in line with the passenger’s impression. Indeed, passengers’ bad impression on the service is strongly related to the saturation of the network. It is not that they had to wait too long for a train to come, it is usually either that they were packed up with too many people in the train, or in some cases, they had to see a train leave the station without being able to enter it due to the crowd of passengers, which is not accounted for in the waiting time criterion. Those problems are thus more related to transport production, and not so much to waiting time from a passenger’s perspective.

One conclusion that can be drawn from this is that the reference waiting time is obviously not in line with the reference production during peak hours. Whereas the operator has no problem with providing an acceptable headway between trains to passengers, the same headway is not sufficient to produce the reference amount of traffic.

Both indicators being complementary, they will be used simultaneously from now on. Indeed, if the indicator on production was to be kept alone, there would be a risk of highly irregular traffic with trains following each other very closely, and suddenly important gaps between groups of trains, which is not wanted by anyone anymore than the situation that is experienced now (that is to say apparently regular but insufficient traffic).

In 2008 and 2009, the total remuneration of regularity in the metro network was as follows (STIF):

	Max. bonus/malus on regularity for the metro	Result	%
2008	1 790 000 €	1 760 000 €	98%
2009	1 790 000 €	885 000 €	49%

Table 7 - Remuneration for metro regularity in 2008 and 2009 (STIF)

As we can see, the remuneration on regularity was divided by two with the introduction of the new criterion, which leads to believe that this new indicator helps provide an evaluation of

quality of service that is closer to reality, accounting for a better representation of passengers' impression in the remuneration.

2.4. Conclusion

In the case of the Paris metro, the transport demand is very high in quantity, but also very severe in quality, since users of the metro are very critical. Regularity in the traffic is the main factor in ensuring a good enough quality of passenger service, but is also the one that is the least satisfying as it is nowadays.

Ensuring a regular traffic is one of the commitments of RATP according to its contract with the public transport authority STIF but it is of course not the only one, and furthermore, it is a difficult criterion to assess. However, it is not only because of financial compensation that RATP needs to ensure a regular traffic on the lines, as explained later on in chapter 4. Moreover, it is important to understand that regardless of the institutional organization, passenger service is always to come first at all costs. Nevertheless, sometimes conflicts arise between transport production and quality of passenger service. The way RATP's commitments are being described, there is a risk that operators might lose their sense of priority which should be set on the latter, especially since in the remuneration, pure production seems to have so much more importance than quality of passenger service. Therefore, it could be that sometimes, operators are more driven by wanting to have trains running a line, rather than ensuring that every passenger receives the right level of service, thus leading to shortened waiting time at stations but irregular traffic.

Furthermore, the contractual agreement between STIF and RATP not being the same today as it was a few years ago, the objectives of operators have changed, which might lead to a different way of perceiving things, and to an evolution in their needs. This will be expanded on later in this report as it has indeed affected the assessment of operators over the new control system.

Nevertheless, before drawing any conclusion on the importance of a regular traffic, its link with passenger service, and the way it is taken into account by the operators, one needs to understand how, according to the demand defined by the STIF in the contractual agreement, RATP actually supplies the suitable transport production, which is the subject of next chapter.

Chapter 3 – Operating the metro network

RATP is bound to plan its operations in the metro network in order to provide the right amount of traffic and level of quality through the use of theoretical timetables and programs of operations that comply with the STIF requirements and are managed by different means and actors. However, the real transport service offered is limited by various constraints, and can be greatly modified by operations hazards, as presented in the third and fourth parts of this chapter.

3.1. Timetables

In order to provide the production demand that is defined by the STIF in terms of yearly planning and maximum headway between trains, a special unit at RATP called “Unité Spéciale Horaire et Trafic” (USHT - Special Unit for Schedules and Traffic) produces theoretical schedules for each metro line and each type of day. The schedules also take into account the various peak hours and characteristic times of the lines (driving time between stations, dwell time in stations, buffer time in terminals, break time for drivers...).

The peak hours are defined based on observations on the load of passengers of each line. This leads to the division of business days between several periods of time:

- Morning off-peak hours (from 5:30 until morning peak);
- Morning peak hour (1h between 8:00 and 9:30 depending on the lines);
- Daytime off-peak hours (between morning and evening peak);
- Evening peak hour (1h between 17:00 and 19:00 depending on the line);
- Evening off-peak hours (between evening peak and 20:30);
- Night time off-peak hours (between 20:30 and 1:15, 2:15 on Fridays and days before a holiday).

Saturdays, Sundays and holidays are divided in two periods: day time (from 5:30 to 20:30) and night time (from 20:30 and 1:15, 2:15 on Saturdays).

This division of the day is not only used to apply the right headway between trains according to the maximum waiting time defined by the STIF, but also to determine the duration of a journey from one terminal to the other.

Indeed, the duration of a journey depends on the time a train takes to go from one station to the next one but also on the dwell time at stations, which in turns depends on the load of passengers boarding and alighting the train at each station. Therefore, the reference dwell time is longer at stations with heavy loads than at others, but it also differs during the day in the same station, being longer during peak hours than during off-peak hours. Thus, depending on the time of day, different modes of operation are applied providing the reference dwell time for each station:

- Evening peak : mode A ;
- Morning peak : mode B ;

In reality, the periods during which the peak modes are applied are approximately of 2h30 around the actual peak hour.

- Morning, day time and evening off-peak : mode C ;
- Night time : mode D.

All the dwell times at each stations depending on the mode are represented for each line in a technical document called « marche-type pratique en service normale » (practical modal types

for normal service) which gives all the necessary indications to work out the operational schedules, but also to drive the trains in a timely manner.

The “marche-type pratique” also indicates the reference running times between all stations. Those times are calculated by graphical methods using the speed/distance diagrams of each sections of the line calculated according to the characteristics of the rolling stocks and of the line (curves, slope, stops, maximum allowed speed that varies up to 70 km/h), as well as driver’s typical behaviour. A more detailed explanation as to how those calculations are made is given in Annex 2. Although calculations exist for all possible configurations, the times indicated in the technical documents correspond to a load of 6 passengers per square meter (EL6 – considered as “normal load”) with a reduced breaking capacity. Because of this, drivers are actually expected to never run a section slower than the reference time, thus allowing for a little reserve time (up to 7s in some sections) that can be used in case of prolonged stay at a station. Nevertheless, this means that deviations from the reference running time are bound to happen. The modal type of line 3 is given in Figure 9 as an example with translation of most terms given in red.

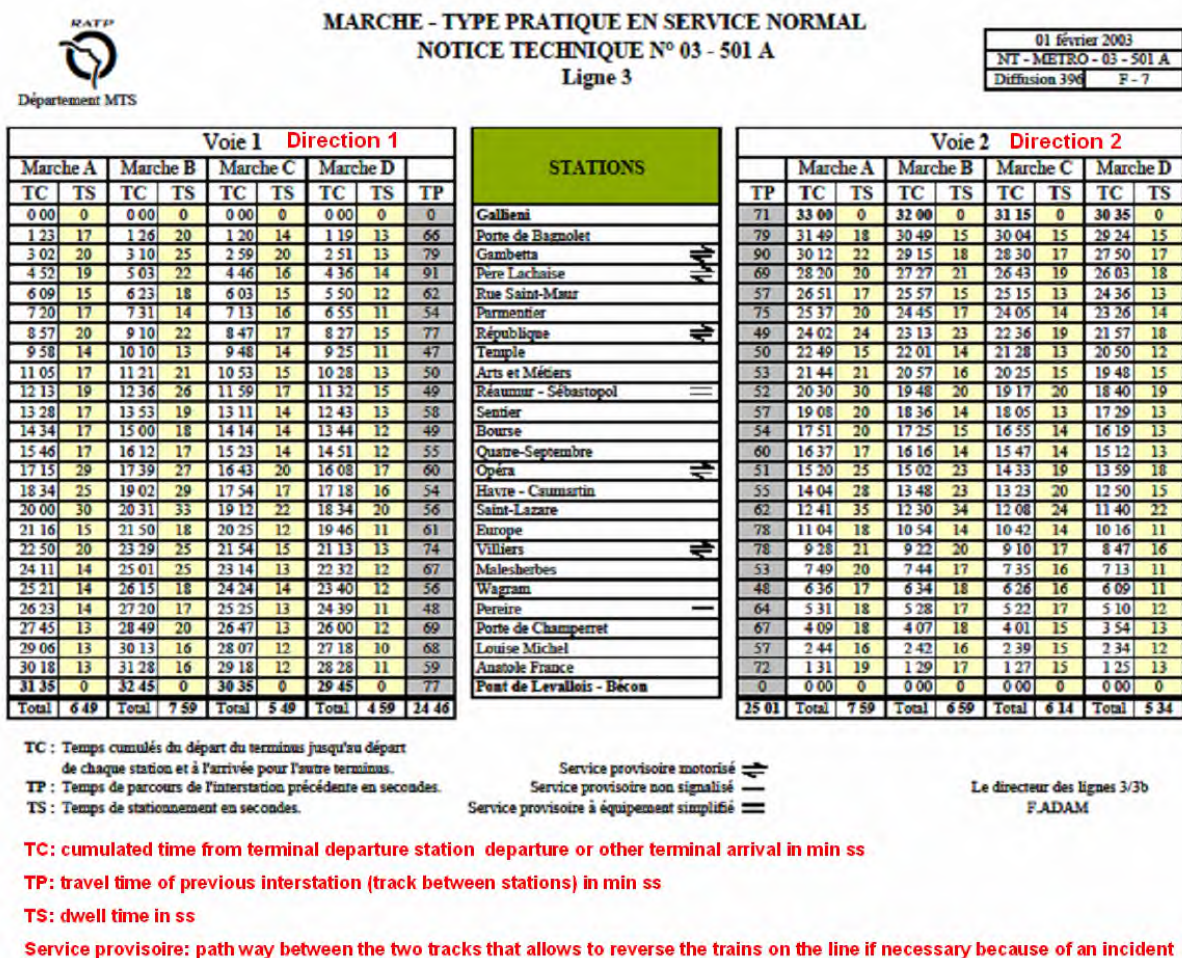


Figure 9 - Modal type for line 3 (RATP, 2003)

Based on the modal type, reference headways between trains and daily production, USHT works out theoretical schedules of operation which gives the time of departure and arrival of all trains at all stations and terminals, along with the drivers and the equipment they are to use. The operational unit of each line has the responsibility to carry out the transport service using the schedule as a reference for operations.

It is important to mention that those timetables are only given to the operators of the line and not to the passengers, who are actually not even aware of their existence. The passengers are

given information on the service by means of indication of the hours of the first and last train in the station and the reference headway between trains depending on the time of day. An example of this is given in the figure below.

M 3 Réaumur-Sébastopol

Direction: Pont de Levallois-Becon	
Premier métro First train	Time Horaires
Jusqu'à Pont de Levallois-Becon	05h39
Dernier métro	
Jusqu'à Pont de Levallois-Becon	00h56
Tranches horaires Time slot	Frequency Fréquences
Premier / 07h30	4 minutes
07h30 / 09h30	2 minutes
09h30 / 16h30	3 minutes
16h30 / 20h30	3 minutes
20h30 / Dernier	7 minutes

Direction: Gallieni (Parc de Bagnole)	
Premier métro First train	Time Horaires
Jusqu'à Gallieni (Parc de Bagnole)	05h49
Dernier métro	
Jusqu'à Gallieni (Parc de Bagnole)	01h03
Tranches horaires Time slot	Frequency Fréquences
Premier / 07h30	4 minutes
07h30 / 09h30	2 minutes
09h30 / 16h30	3 minutes
16h30 / 20h30	3 minutes
20h30 / Dernier	7 minutes

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Figure 10 - Passenger information for service in line 3 at station Réaumur-Sébastopol (RATP)

In stations, platform indicators give the real-time expected waiting time before the next two trains. This information is updated continuously.

3.2. Means and actors of operations

Within the RATP department in charge of metro operations (MTS – Metro Transport Service), each metro line is managed by a separate operational unit. Transport infrastructure and rolling stock are placed under their responsibility for operations (maintenance is the responsibility of other departments), and they are staffed by operators according to the operating needs.

3.2.1. Transport infrastructure

Each metro line runs on dedicated infrastructure. A typical line is composed of a single segment with two ways, one for each direction, although two lines are branched (line 7 and line 13). Stations are placed along the line, and passenger trains stop at all of them. The segment between two consecutive stations is called an “interstation”.

All the lines have terminals at both ends and may also have intermediary terminals due to historical reasons (extension of lines) or logistics (lack of place at some end stations). The line is separated in two geographical parts. If one of the parts has multiple terminals, one of them is declared the main one, and the operations at all the terminals of this part are placed under

the responsibility of this main terminal, which is not necessarily located at the end station of the line. All the lines therefore have two main terminals. In between the terminals, trains circulate to the right on separate ways dedicated to direction 1 and direction 2 as can be seen in Figure 11.



Figure 11 - Schematic of a metro line

A trip from one of the terminal to the other is called a journey; a round trip is called a lap. In some points of the line, the railway is equipped with special equipment that allows trains to switch directions and ways, called “temporary service” (in French “service provisoire”) for they are used mostly to establish a temporary service on parts of the line (for example when traffic is not possible in an interstation for a while because of an incident).

Traffic on the line is overseen by the operational control centre, the PCC (poste de contrôle centralisé). The organisation of the traffic control operations in the PCC (both old and modernised PCC) is described in chapters 5 and 6 of this report.

3.2.2. Rolling stock and drivers

Each line has its own trains, the number depending on its needs. RATP drivers are trained to drive all types of metro trains (rail or tire, semi-automatic or manual, CBTC or not) before being assigned to a particular line. Drivers are not bound to one train in particular and may be required to drive any of the trains of the line to which they belong. However, they are linked to one of the two terminals of the line where they always begin and end their service.

At the beginning of his daily service, a driver receives his programme of activity indicating his theoretical planning, which may have to change according to operational fluctuations. During a typical daily service of 7h, starting at different times according to the drivers, since continuous operations are required from 5am to 2am, a driver will usually spend 3 to 4 hours driving trains on the line (which corresponds to different number of laps along the lines: for example 3 on line 3, but 6 to 8 on the line 11), the remaining time being divided between maneuvers in the station and periods of availability during which he may be asked to replace another driver on a lap (thus changing his program of operations) or for manoeuvres.

When driving along the line, the driver can choose between manual or automatic driving. For the latter mode, if it is available, the role of the driver is limited to trigger the departure of the train from the stations. The traction effort (acceleration, speed) is then given automatically to the train by the autopilot program corresponding to the interstation where it is to be used. All drivers are required to make at least one complete lap per service driving manually in order not to lose their driving habits.

In terms of station dwell time, drivers are instructed to remain in the station until all the passengers on the platform were able to board the train, except in case of overcrowding. Mirrors and sometimes video cameras are placed at the head of all platforms to help drivers keep an eye on the movements on the platform.

Theoretical departure times from terminals are given to each driver, along with the identity number of the train they are to drive, but they are required to often check if any change has been made to the program of operations, especially since late departures often occur at peak hours, sometimes even leading to cancellations. However, when it comes to late departure, drivers have a right to refuse to leave on their last lap of the service if the departure time is

more than half an hour later than programmed because that would necessarily mean returning to their home terminal at least half an hour after the end of their service.

3.2.3. Maintenance, construction and modernisation

Maintenance of equipment and infrastructure is the responsibility of other departments. Maintenance of trains is planned so that it does not hinder operations. As for infrastructure, work can only be conducted at night when traffic is stopped, that is to say between 1:30 am and 5 am leaving a very short time for all that needs to be done.

When more substantial work on the line is needed, a project is defined. For example in the modernisation plan, several lines are to be reformed and equipped with new systems such as the new operational control centre or the computer-based train control system. For each system and each line, a project has therefore been defined according to the rules of the company. After the general budget is decided on, the project manager is designated. The project manager is assisted by functional managers from the MOT department (Maîtrise d’Ouvrage du Transport – transport projects owner) who are in charge of defining the needs of the client for this project, and in the case of a metro project, the line operators. They are usually former operators themselves and therefore have a good enough knowledge of operations to be able to formalise their needs. They consult the line operators and are helped by people from the operational department dedicated to assist the projects owner. After the needs have been specified, they are transmitted to the engineering department who is in charge of design, production and qualification of the systems.

3.3. Constraints on traffic operations

The theoretical schedules calculated by USHT generally indicate higher frequencies than those defined by the STIF requirements in order to produce the right amount of laps. In practice at peak hours, train departures are as close as it can possibly be done, and this “possible” situation is dependant on technical and human constraints.

3.3.1. Technical constraints

The main technical constraint that comes into account in the calculation of timetables is the incompressible technical interval. The driver-based lines of the Paris metro are physically separated into sections with fixed block signalling for security reasons. When a train enters a section, it is detected by a track circuit. Said section and the previous one are then denied access to other trains, both upstream signals appearing in red, as shown in Figure 12.

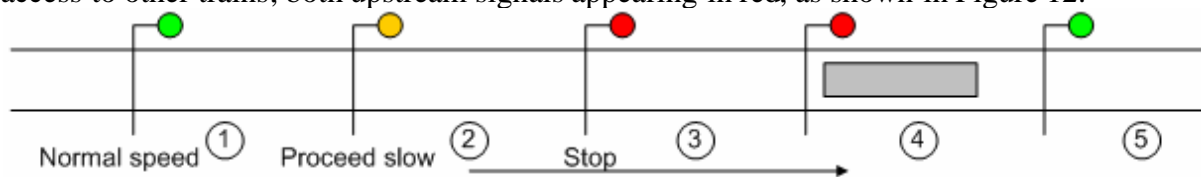


Figure 12 - Schematic of the signalisation on a metro line

Thus, the closest two trains can be is with one empty section between them. In the figure above, for example, the closest train downstream can be located in section 2 and will not be able to move forward until the train represented in section 4 has left it entirely. Those signals are placed along the line according to security distances calculated using the speed/distance diagrams of the interstations so that a driver always has time to break and stop between two signals even if he is running to the maximum allowed speed of this section.

This minimum distance translates into a minimum headway between trains at all signals of the line, called “temps de déblocage du signal” (release time of the signal). Since sections are of

different length along the line, the maximum release time has to be taken into account and considered as the minimum headway along the line. This reference time is called the incompressible technical headway (in French, “intervalle technique incompressible”, or sometimes “signal pendule”). More details on its calculation are also given in Annex 2. This technical headway is however a theoretical number. In reality, it is not possible to have trains running this close to each other, since there would be no margin left of even a few seconds for any error. However, the busiest lines tend to get as close as possible to this reference headway in their theoretical timetable. For example, line 13 has an incompressible technical headway of 90s and the theoretical headway applied at peak hours is of 95s, making it the world’s subway line with operations the closest to its technical limits. At the same time, this contributes greatly to the instability of its traffic, as expanded on in chapter 4.

3.3.2. Human constraints

If the technical constraints can always be taken into account, mostly because they relate to security reasons, it may be harder to do the same for human constraints which are of great importance in the operations of the metro network. Operating hazards related to human presence in the system are presented in the following paragraph. Nevertheless, there are human constraints that are very predictable and should be taken into account in developing the timetables and the operating programs of the lines as well.

First, it was already mentioned that passenger affluence in the network is obviously the first criterion to consider in organizing the operations of a public transport system. Thus, the irregular passenger load is taken into account both in preparing the STIF calendars, as well as in the development of corresponding timetables. The service is also lengthened in the evening on Fridays, Saturdays and eves of public holidays, and modified in the case of certain events to accommodate the additional passenger flows (fairs and exhibitions, sporting events, scheduled demonstrations...). Furthermore, the needs of passengers are also taken into account at the stations since the reference dwell times of the marche-type are based on stations affluence depending on the time of day.

Thus, the needs of passengers are taken into account at all stages of developing the program of operations, but they are also at the centre of all concerns related to operations in real time. As specific and detailed as the theoretical program is, passenger service remains the priority of the operations, even if this means changing what has been computed and planned.

The other type of human constraint is based on the fact that, with the exception of line 14, and in the very near future line 1, the metro lines of Paris are not fully automated and are managed by drivers. If the driver has a choice between manual operation and autopilot, he remains in all cases in charge of triggering the departure from stations, which may lead to deviations from the program of operations.

Furthermore, timetables and service programs must obviously take into account the working conditions of drivers, their availability, physical constraints ... For example, in terminals, train can change directions going through a loop, therefore the head of the train will remain the same and the manoeuvre can be performed by a single person. However, most terminals are not equipped with such convenient tracks for lack of space, and when only straight end-tracks are present, the manoeuvre can be performed either by a single person, who will therefore have to walk from one end of the train to the other (type 1), or by two drivers, one at each end of the train (type 2). In type 1, the computing of manoeuvre time must therefore take into account the walking time, whereas in manoeuvre two, this is not existent anymore. Even more so, some terminals (especially on line 13) are equipped with automatic turning where no driver at all is needed to perform the turning-over of the train. Finally, drivers’ schedules must

take into account a mandatory period of rest between journeys on the line. Therefore when there are enough drivers available, the allocation of drivers to trains follows a shift method: a driver does not leave the terminal with the train he arrived in, but with the next one (N+1 shift) or even the one after (N+2). This method tends to eliminate, or at least lessen the stress-related physical constraints.

3.4. Operations hazards

The practical realisation of the theoretical program of operations is obviously subject to random events for technical reasons (maintenance of equipment, failures, equipment availability, construction ...) but also for human reasons. Technical hazards are somehow easier to handle than human ones. Indeed, to some extent they can be predicted, and they are not in unknown territory for they apply to known technologies that can be fixed and maintained using pre-defined methods. However, human hazards are more difficult to handle. The first type of human-based hazard order is related to main actor in operations: the driver. Indeed, all the assumptions made on the timetables are based on the assumption that all drivers adopt a uniform conduct and full compliance with the instructions they are given. This is not a problem when it comes to safety since the drivers are trained and considered responsible enough not to violate safety regulations, voluntarily or not; and since anyway various control systems are installed in order to avoid safety violations (speed control, automatic stop after passing a red signal ...). However, regularity and timetable compliance are subject to many variations, e.g. due to the speed applied in manual driving, to dwell times in stations that are lengthened or shortened depending on the driver's appreciation, but also to drivers' availability (delays, absences) which is the main cause of production loss for the metro lines.

Nevertheless, if one compares transportation to any other type of industrial product, it is normal to expect equipment failures or technical accidents, but also strikes or other hazards associated with operating personnel, which will have an impact on consumption. In the industrial world, when a product is defective or improperly used by its consumers, the impact for producers or for other users is null. When demand increases, it is easy to tailor activities to meet them. An additional difficulty occurs in the transportation industry: the product "transport" is consumed directly at the time of its production by the passenger, who is physically present within the production chain. The consumer becomes the worst enemy of the engineer who must always think in terms of passenger behaviour, and somehow expect the unexpected. Thus, for example, the timetables are computed in terms of passenger load - they are however adjusted by the driver. If it is therefore possible to some extent to integrate the mass behaviour of users, it is completely impossible to prevent individual actions, whether they are malicious (trespass on the tracks, blocking the doors) or not (sick passenger), which are a major cause of delay in the Paris metro.

Part I – Project background

Part II – Metro Traffic Regulation

Chapter 4 – A state of the art of metro traffic regulation

Chapter 5 – Regulation principles at RATP

Chapter 6 – Regulation in the modernised traffic control system

Chapter 7 – Comparison and validation of the new system

Part III – Performance analysis

Part IV – Conclusion

As it was previously mentioned, metro lines are the subject of several constraints of different orders – technical, institutional, human – and of operational hazards which gravity can differ from a few seconds of disruptions to several hours. Nevertheless, operations must keep running at the best level of quality possible, which means that an efficient traffic regulation strategy needs to be implemented in metro systems both to prevent major disruptions from delayed trains, but also to try and recover from such incidents. Chapter 4 serves here as an introduction to the notion of regulation, as it presents a state of the art of metro traffic regulation around the world and throughout history based on the literature review that was performed at the beginning of this project. Chapter 5 presents the regulation policies that have been implemented at RATP for the last 40 years. Chapter 6 explains how the new system for traffic control handles regulation. Finally chapter 7 presents an evaluation of whether or not this new system seems to be in line with what was asked of it along with the challenges it is facing, which are to be addressed in the next parts of this report.

Chapter 4 – A state of the art of metro traffic regulation

Before getting into the subject of metro traffic regulation at RATP, it was considered interesting to research this subject in general. The output of this preliminary literature review is the object of this chapter. First, the reasons why regulation methods are necessary are explained in the first part. Then a brief description of the research and documents that were found on the subject is given. Out of this literature review, two sources provided some very helpful intelligence on the subject. They are presented in more details in this chapter: the first one is a comparison of strategies and constraints across metro systems, the other one is related to the history of RATP and of regulation methods at RATP.

4.1. Importance of traffic regulation in a metro network

Operations of a metro line are specified by numerous technical, functional and regulatory documents. The metro system is anyway designed as a system marked by “repetition and periodicity” (Chatzis, 1995). However, as it was explained in the previous chapter, it is also subject to numerous operating hazards, particularly related to human-based operations, to the presence of passengers in the system, and to natural variations from the program of operations since dwell times at stations are not constant, as opposed to what is given in the reference documents and therefore to the input filled into the system. Running times are also subject to variations. Incidents can occur, delaying the departure of a train from a station or blocking a train on the line or at terminals. Each of these events, even if they only cause a few seconds of delay on a train, has an impact on the whole line: in Paris, the headway between trains is as low as 95s, and the difference between the incompressible technical headway and the produced minimum headway is between 5 and 20s at peak hour on most lines. On line 13, for example, a stop extended by only 5s necessarily blocks the next train for safety reasons since 5s is the available timetable margin at peak hours. Thus, in metro systems that are used to their extreme capacity, such as the one in Paris, the smallest incident on a line can lead to great perturbation. As stated by many researchers of the field, “the traffic [of a metro line] is intrinsically unstable” (Goodman & Murata, 2001) and the theoretical timetable is in practice never achieved, especially at peak hours when the important passenger loads and high train frequencies cause even more incidents and delays.

Yet, theoretical timetables are only there as a reference, and being close to the reference program is not a goal in itself. The real goal is to offer a transport service that can accommodate the right amount of passengers at the right time, and in the case of RATP, to produce a service that meets all of the STIF requirements. Nevertheless, if the drift between the theoretical program and operations is too important, the transport supply will not meet real-time needs, mostly because the headway between trains will be too long. Ensuring that the right headway is applied at the right time is the main goal of regulation in metro networks, and the various methods for doing so are explained later on. However, this is not done only to make sure that the reference service as described by contractual agreements is offered.

Indeed, on a line where trains follow each other at short intervals and are barely sufficient to meet the traffic demand, it is essential to equalize the passenger load of successive trains. The main reason for this lies in the principle that the more delayed a train is, the more delay it will accumulate due to passenger loads. This is simply explained in Figure 13.

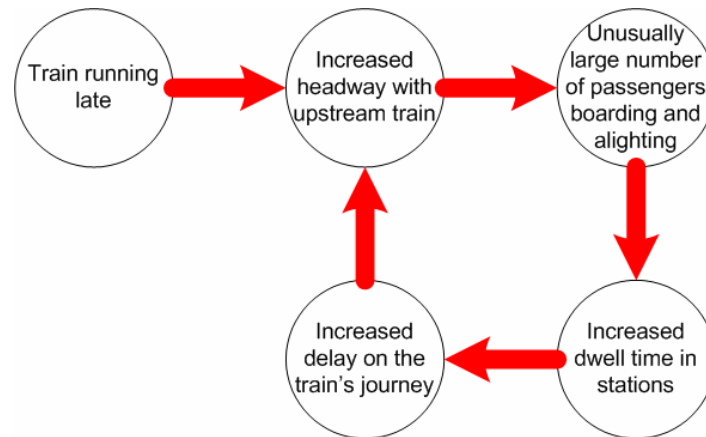


Figure 13 - The irregularity vicious circle

This phenomenon is a vicious circle, because if nothing is being done to stop it the situation will go from bad to worse with very irregular traffic, and uneven saturation of trains. If a train is running late on its schedule to reach a station, more people will be waiting at the station and the train will therefore have to stop for a longer time in the station to accommodate every passenger. Leaving late from the station will increase its delay even more, which, in turn, will lead to even more passengers waiting at the next stations, along with more passengers alighting trains at each stations and so on.

To achieve this regular headway and reduce the drift between theory and practice, it is important to ensure that trains depart regularly from the terminal and that their running mode on the line are similar, which is exactly the aim of traffic regulation. The core principle of traffic regulation in a metro system such as the one of Paris is that a line must be considered as a whole: the running of one train is linked to all the others, every action must be thought of and performed according to operations on the entire line.

4.2. Literature review

Literature on the subject of metro traffic regulation is not abundant. If theoretical studies on railway operations are being performed, it is not always the case for a metro system. A first explanation for this might be that metro system as complex as the one in Paris, such as London or New York, are not so numerous. Furthermore, all those networks have very different characteristics, from station spacing to the way it is being used, from age to infrastructure... making it almost impossible to develop general theories on the subject. However, interesting features were found in the work of some academic researchers, especially those of Goodman & Murata (1998, 2001) who worked on the problem of metro traffic regulation from the passenger perspective, and of Lombart & Favre (1995) who developed a method to assess regularity in a metro network. Those works were used to develop the method for the performance analysis, and to form a good understanding of the relationship between traffic regularity and quality of passenger service, as well as of the importance of metro traffic regulation as presented in the previous part of this chapter.

Furthermore, technical and non-technical literature within RATP is abundant, and an important part of this work was actually to perform a literature review within the institutional and technical documents of the group. Since some people at RATP are dedicated to the support of metro lines, they often provide some very helpful explanations on operations, performance and efficiency which were used along with the technical documents defining the PCC systems.

All the sources that were consulted and used for this project can be found in the bibliography at the end of this report, as well as additional material that can be regarded as interesting information to go further on the subject of metro traffic management. As previously mentioned, some of them were particularly helpful in getting a general knowledge of metro traffic regulation, which is why they are further presented in this chapter.

4.2.1. Existing methods around the world

Schmocker et al. studied the different constraints applied to metro systems across the world and the strategies used for delay recovery (“Metro Service Delay Recovery: Comparison of Strategies and Constraints Across Systems” - 2005). They insist on the importance of ensuring regularity in order to improve passenger service, much like it was explained in the first part of this chapter. They also point out the fact that whereas in other types of railway networks, it is train punctuality that is taken as an indicator for reliability, for metro systems, and especially from the passenger’s point of view, it is rather regularity that is important. Further on, they present the method of Lombart and Favre as a mean to assess regularity on a metro line. This method was used in this project and is to be presented in chapter 9. A drawback to the interest of this paper is that what is looked at is actually the ability to recover from major incidents. The fact that metro lines are unstable and that delay will always occur even in the absence of important incidents is not much being considered.

Nevertheless, the observations that were made in this study by means of a comparison between six metro systems are still interesting to mention. First of all, it is stressed out that line characteristics and the number of incidents that occur on each metro system included in the study are to be carefully taken into account in any conclusion. Indeed, these can influence a great deal both the type of strategies chosen by operators, and their reactivity towards incidents and delays. Therefore, the types of constraints affecting service recovery possibilities are listed, and each metro was ranked depending on the influence of those constraints. The categories are:

- network constraints;
- technological and operational constraints;
- staff constraints;
- passenger constraints.

For this particular graduation project, it is interesting to learn of such classification, and to keep them in mind, especially when the performance analysis of the regulation system was performed.

The various recovery strategies that were observed in the six metro systems are

- stacking (do nothing);
- stacking (de-train – removing passengers from the affected train);
- freezing the line until incident is resolved;
- holding some trains;
- removing trains;
- adding a gap train;
- turning short;
- station skipping;
- diverting (having trains bypass the defective one);
- shuttle service (run the line separately in two or more sections);

Advantages and disadvantages of each method are also expanded on. The interesting point here in this project is to compare those strategies with the ones being used at RATP, and later on try and understand why the choice for one or the other were made. The author also

mentions the fact that choosing one strategy or the other depends on the type and duration of the delay.

4.2.2. A brief history of regulation at RATP

The other source that is worth expanding on for the interest of this project is the paper of Chatzis (1995) which provides a brief history of RATP and the choices that were made along time regarding regulation in the Paris metro. Aside from the facts regarding RATP's history in general, this paper provides some very interesting first-hand notions on regulation principles at RATP. It is in this paper that the idea that the passenger is the engineer's worst enemy was the most insisted on. Indeed, by studying the history of RATP, Chatzis found it obvious that most choices that were made on policies and strategies were made in order to minimize the influence of the human being on the system, either driver or passenger, stating that "the fear of the crowd that haunted the subway from the very beginning will continue to assert itself throughout its history". Not only were stations and corridors designed in order to ensure security and make sure evacuation was possible and easy anywhere at any time, they were also thought of in order not to crowd the metro platforms. In some stations, corridors have several turns that make them longer than they could be, just so that transferring time is extended and the crowd coming from one train cannot all reach the connecting train at the same time. This was actually the first way of regulating service, not through train traffic regulation, but through passenger flows regulation.

This fear of the crowd getting in the way of transport service was materialized by the implementation of automatic gates at the entrance of all the platforms ever since 1920. Those doors were automatically closed by the entrance of a train in the station, thus preventing a continuous arrival of passengers while the train was stopped at the station, which would create a risk for a longer stay in the station. Once the train would leave the station, the gates would re-open. In order to ensure regularity of trains, it is passengers' flow that was regulated.

For around fifty years, those automatic gates were the only real means for regulation in the Paris metro. Drivers were instructed to respect the modal-type for train driving, and terminal managers to simply keep an eye on the clock to enforce the right departure time. When an incident occurred, station managers and train drivers would keep each other informed by phone. If the delay was less than ten minutes, trains around the defective one would be kept in stations in order to make sure that the train loads would remain balanced (thus the automatic gates were manually opened). If the delay was more than ten minutes, some trains would be turned before terminals (short turns) at points of the line where it was possible.

With this method, the key point of traffic regulation was the good communication between trains and between stations. With the low traffic that was that of the years before 1970, this was still possible. However, in the 70's, transport demand and thus traffic on the lines increased greatly, and it was not possible anymore to enforce this point-to-point regulation method. Furthermore, it is in the 70's that automatic driving was implemented on most of the lines, thus changing the functions of the drivers, and leading the way to less human responsibility and more relying on automatic systems. It is in this context that the operational control centre was implemented. From then on, traffic on the line was overseen by the traffic controller from the Bourdon operational control centre, as described in the next chapter. The way operations are controlled has not changed ever since, and the modernisation plan for the implementation of decentralised operational control centre is the first important evolution for operations organisation since the 70's.

After the implementation of the operational control centre, headways at peak hours were reduced by up to 20%, and the time needed to go back to normal service after an incident was divided by ten. The implementation of this new technology also came along with technical

failures that cannot really be prevented, like RATP was used to for equipment that can be maintained. Therefore, this new method of operations also required changes in other departments such as maintenance and engineering.

This article was written in 1995, which means that the latest evolutions in regulation methods and at RATP in general were not presented at all. Some interesting information was found in the work of Foot (1996) about the developments to be implemented afterwards. Especially, in the 1990's, a new policy was implemented to “put the passenger at the centre of attention”. At the core of this new policy was the decision to take the metro line as a basis unit for decentralisation. Each metro line was to be reinstated as a centre for managements and objectives, and thus the centralisation of all the operational control centres in the same place was not needed anymore. Furthermore, it was decided that operational management of a line and general management of a line should be grouped together, and that traffic control should be performed closer from the lines themselves. In this regard, it was decided that the operational control centre of line 14 which was just under development would not be located in the same place as the others. It is also still in that perspective that the modernised operational control centre of line 4 was detached from the others in 2001, and that the PCC project was worked out.

Chapter 5 – Regulation principles at RATP

As explained in the previous chapter, applying the correct methods for regulating the metro traffic is critical for the smooth running of operations. Even more so at RATP since it is not possible to ask a driver to leave a terminal with more than 30 minutes delay from his theoretical planning when reaching the end of his service. If the driver does not depart, that is a lap lost in the daily production. The line managers therefore have multiple financial motivations to make sure that the general delay on the line never exceeds half an hour and that the required headway between trains is applied. In short, relating to the various methods that were presented in chapter 4, the ones being used at RATP in the metro network are usually as follows:

- Strategies not in use
 - **station skipping**: never used for it would increase the delay of passenger that needed to board or alight at the skipped stations;
 - **stacking** (de-train): not in use, since the defective train would still affect the rest of the line.
 - **diverting**: it is not possible for trains to bypass others or use a different route.

- Traffic regulation actions on the line
 - **stacking**: used in case of very small delay on the line (before any action is judged necessary);
 - **holding** some trains: most frequent regulation policy on the line.
 - **turning short**: frequently used in case of events that prevent trains from running parts of the line, or when a train cannot be moved from where it is stationed on the line. This is because it is not possible in the RATP network to have trains overtake others since there is only a single track on each direction.
 - **shuttle service** (run the line separately in two or more sections): considered the same thing as turning short at RATP. In this situation, the lines are indeed operated as two separate entities until traffic can start again in the disrupted section. Bus service in replacement is not very often implemented as the Paris metro network offers many possibilities for alternate routes.
 - **freezing**: operators prefer not to use this as long as an incident is not too important. However, used in case of major events such as bomb alert or serious passenger accident before the turning short actions can be implemented.

- Traffic regulation actions in terminals
 - **removing**: only done at terminals, that is to say that some departures are cancelled to smoothen traffic (schedule compensation);
 - **adding** a gap train: also done in terminals (additional laps);

Thus, the most used methods at RATP are holding trains on the line to equalize headway and enforce regularity, remove or add trains at terminal departures depending on the deviation to the program of operations and turning short in case of major incidents on the line. This chapter presents how those actions are actually being implemented in a metro line in Paris through line traffic control and terminal management.

5.1. Regulation methods

In regulating the traffic on the line, there is a choice than needs to be made between trying to catch up with the theoretical timetable and trying to apply the reference headway corresponding to the actual time.

This leads to three types of regulation in use in the RATP network.

- **Schedule regulation** is applied individually to each train with the aim to try and enforce its theoretical schedule. The idea is to act on the train departure times and driving modes in order to return it to its theoretical time without considering the impacts on the rest of the line. Schedule regulation is effective only in the case of very small delays that do not have an impact on other trains and can lead to highly irregular traffic.

- **Schedule and headway regulation** is applied to multiple consecutive trains together in order to make them operate with a headway close to the reference one while still trying to recover from delays and catch up with the theoretical schedule. The idea is to apply schedule regulation to the extent of complying with a regular-enough traffic.

- **Constant headway** is a drastic method to be used in much deteriorated situations. With this method, only the headway is looked at without any care for the theoretical schedule.

If and when delay occurs on the line, the goal of the operator is to try and recover from it by applying one of those regulation methods and different sets of actions that are to be described in this paragraph. When it is not possible anymore to recover with those “soft methods”, the solution to catch up with the timetable is to cancel laps, which is to be seen as the last resort, since this means loss in production.

The various actions that can be conducted are recalculation and changes of

- departure times from terminals;
- dwell times in stations;
- running mode on the line (normal or accelerated).

5.1.1. Regulation on the line

When schedule regulation is to be applied, either by the control operator or by an automatic system, it is possible in theory to

- extend the stay in a station if the train is running early by means of a “DSO” (Départ sur Ordre” – Departure under order of the controller);
- shorten the stay in a station in case of a delay;
- switch to accelerated mode.

However, in practice, those last two actions are basically impossible to conduct, especially at peak hours, when they would be even more needed. First of all, when a train is driven manually it is not possible to order any kind of speed to the driver, and in automatic mode, all the lines already run in accelerated mode anyway either to catch up with the delay or because they want to prevent any possible future delay by running a little ahead of schedule. Furthermore, except in the case of incidents, delays on the line usually occur every day during peak hour. At those times, the theoretical stay in the station is equal or sometimes even inferior to what is needed in order to accommodate all flows of passengers, and it is not possible at all to reduce it. Therefore, during peak hours, schedule regulation is out of the question. During off-peak hours, it is assumed that there is enough buffer time in terminals to catch up with the delay on the next journey, and therefore that it is of no use either to apply schedule regulation on the line.

If a train leaves a terminal late, it is therefore assumed that the delay cannot be recovered on the line. However, what can be done on the line is to ensure a regular headway between trains by implementing the headway regulation.

When a train is unusually delayed in comparison to other trains upstream and downstream, the headway between trains becomes irregular as represented in Figure 14.

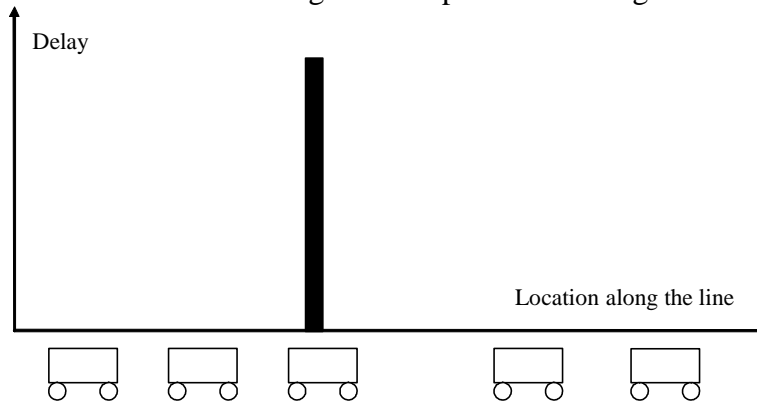


Figure 14 - Situation on the line before any regulation action

The delayed train, referred to as the disruptive train, has an impact on a number of neighbouring trains that depends on the importance of the delay (the more delayed the disruptive train is, the more trains it will affect) and on the reference headway (the shorter the theoretical headway, the more trains it will affect). In order to improve the general regularity of the line, headway regulation acts according to the following principles:

- schedule regulation is to be applied to the disruptive train,
- extension of the stay in stations for both upstream and downstream impacted trains, according to the “Chinese hat principle” – *holding some trains*.

This is represented in the following figure.

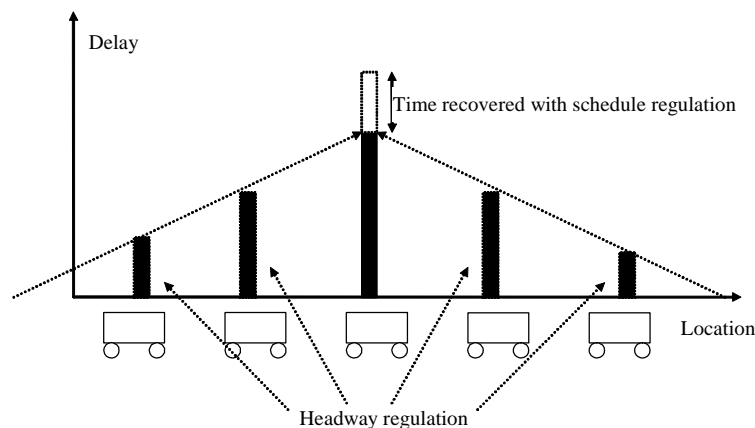


Figure 15 - Situation on the line after regulation actions

Finally, in case of a major incident on the line, it can happen that trains cannot run on the track of one of the interstations. “Temporary service” equipment in some points of the line can be used in order to have train change tracks and directions (*turning short*) to ensure a service on all parts of the line. In those cases, regularity is usually, and most comprehensively, the least of the operator’s problems. Only after the temporary service is finished and the line back to full operation the operator takes actions to try and recover from the delay and disruptions on regularity.

5.1.2. Regulation in a terminal

For each train scheduled to leave the terminal, the following data is defined:

- **HDT**: theoretical departure time (in French *Heure de Départ Théorique*), which is the one indicated in the timetable;
- **HDP**: earliest possible departure time (in French *Heure de Départ au Plus tôt*), which is calculated as explained later in this paragraph;
- **HDC**: calculated departure time (in French *Heure de Départ Calculée*), which is calculated based on HDT and taking into account the delays and the regulation method to be applied;
- **HDR**: real departure time (in French *Heure de Départ Réelle*), which is the time the train actually left the terminal;

For each terminal, the minimum stay is also defined, based on the time needed for manoeuvres, the minimum stay at arrival quay and at departure quay... This allows calculation of the buffer time in each terminal, and later on the calculation of departure time as presented below.

Lap time and buffer time

There are various reference time that are used to calculate the theoretical lap time for a train, that is to say how long it will take to go from one point to the same one having a performed a full lap on the line:

- running time on both directions CV1 and CV2 (CVi stands for *Course sur Voie i*, French for *Journey on Direction i*);
- minimum stay in each terminal SMA and SMb (SMx stands for *Séjour Minimum x*, French for *Minimum Stay*), which is made of the turn-around time and the time needed to be spent at arrival and departure quay to accommodate passengers and make sure all signalling and equipment is in order (approximately 30s each).

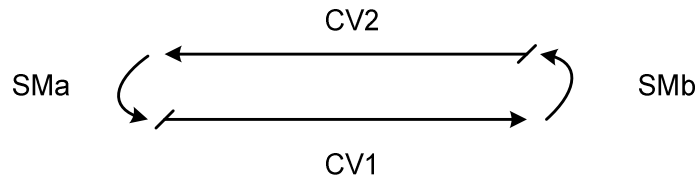


Figure 16 - Schematic of the characteristic times of a line

For a train, the theoretical duration of a lap (*durée théorique d'un tour – DTT*) is therefore as follows :

$$DTT = CV(1, A \rightarrow B) + CV(2, B \rightarrow A) + SM(A) + SM(B) \quad (1)$$

with the minimum stay SM at terminals being calculated as follows:

$$SM(T) = T_{arrival}(T) + DUR_{man.ret} + T_{departure}(T) \quad (2)$$

CV(I,x→y)

- with
- $T_{arrival}(T)$: time to be spent at the arrival quay of terminal T;
 - $T_{departure}(T)$: time to be spent at the departure quay of terminal T;
 - $DUR_{man.ret}$: time needed for the turning manoeuvre in the terminal.

The lap buffer time is defined as the difference between the planned duration of a lap and the minimum duration of a lap. Therefore in this context, buffer time is additional to turn-around time and stay at arrival and departure quay, and to be seen as additional and therefore non-necessary time being spent by a train in the terminal. It is spread more or less equally between the two terminals, leading to a theoretical terminal buffer time.

The terminal buffer time is a very important piece of data to calculate for it is the only thing that allows for delay recovery. Indeed, in practice, it is an additional stay in the terminal which is not needed and can be reduced or even eliminated. The longer the terminal buffer time, the more it can be reduced, and therefore the more delay on the line can be recovered. However, in peak hours, the terminal buffer time is usually close to zero since the headway between trains is very short, and recovering from a delay by means of reducing it is not really possible.

Based on the timetables, the terminal buffer time for train n departing from terminal B on direction 2 is calculated as follows:

$$BTT(n, Term.B) = HDT(n, B, 2) - HDT(n, A, 1) - SM(B) - CV(1, A \rightarrow B) \quad (3)$$

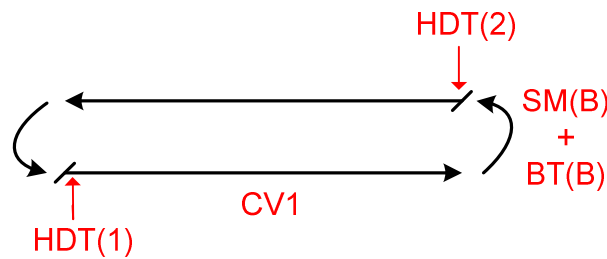


Figure 17 - Schematic for the calculation of terminal buffer time

BTT stands for “*Battement au tour théorique*”, French for “*theoretical lap buffer time*”.

Earliest possible departure time – HDP

For each train of the line, the earliest possible departure time from terminals is calculated in real time as follows (example given for the departure of train n from terminal B on track 2):

- if the train is running on track 1 and located in station i

$$HDP(n, B, 2) = HDC(n, i, 1) + CV(1, i \rightarrow B) + SM(B) \quad (4.1)$$

where $HDC(n, i, 1)$ is the calculated departure time of train n from station i on direction 1;

$CV(1, i \rightarrow B)$ is the running time from station i to terminal B on direction 1.

- if the train has not left terminal A

$$HDP(n, B, 2) = HDC(n, A, 1) + CV(1, A \rightarrow B) + SM(B) \quad (4.2)$$

where $HDC(n, A, 1)$ is the calculated departure time of train n from terminal A on direction 1.

HDP is the earliest time when a train will be available to leave the corresponding terminal. It takes into account the delay on this train since it is based on real-time data and removes the terminal buffer time. It does not take into account the theoretical timetable either. HDP is not a departure time to be applied but rather an indication for terminal operators.

Regulation actions in terminals

As long as for all the trains, HDP remains greater than HDT, it means either that there is no delay on the line, or that the buffer time is sufficient to recover from it. In this case, no action is to be taken in the terminals and the trains can leave according to HDT.

However, as soon as one of the trains' HDP exceeds its HDT, regulation becomes necessary. For each regulation mode, there is a way of calculating the departure time of the train (HDC).

- When applying **schedule regulation**, the goal is to get as close as possible to HDT. Either the train can leave at its theoretical departure time, or it is delayed and will leave as soon as it can without any concern for other trains on the line.

HDC = max (HDT, HDP):

- When applying **headway and schedule regulation**, the calculation is more complex since the goal is to find an optimal compromise between timetable and regularity. This method differs between the former control system and the modernised one and it is therefore explained in the next two chapters for both configurations.
- When applying **constant headway**, the departure time does not take into account HDT and trains simply leave the terminal with a constant headway between them:

HDC(n) = HDC (n-1) + IC

5.2. Organisation of regulation before modernisation

Before 1970, there was no traffic control system per se. Traffic regulation was performed directly by drivers and station managers who were more or less keeping each other aware of the location of trains and the problems on the line by phone. However, with the growing transport demand, it became obvious that there was a need for global control of the line as a whole. Therefore, the first PCC (Poste de Contrôle et de Commande– Operational Control Centre) was installed. The organisation of traffic control and the system and equipments that were implemented are still being used on lines 2, 5, 6, 7 & 7bis, 8, 9, 10, 11 and 12. Traffic control is performed for line regulation at the PCC Bourdon, and for terminal management directly in the terminals.

5.2.1. The Bourdon Operational Control Centre (PCC)

All the lines operated under the former organisation are managed for traffic control on the line from the same place, the Bourdon Operational Control Centre. In this room, all the lines are represented on a separate button control panel which gives information on where all trains are located along the line. There is no command over the track interlocking system which is completely autonomous for safety reasons. Indeed, except for the control over energy distribution on the line, the Operational Control Centre does not have any responsibility related to safety. The PCC has direct communication with all trains on the line via radio transmission and telephone, and with both terminals.

The person in charge of regulation on the line is the CREG (short for “chef de regulation” – head of regulation). When there is no incident on the line, his main role is to make sure that everything goes smoothly and that the headway is more or less the same between all trains running. By means of the buttons on his table of control, he can switch the “departure upon order” signal on or off. This will appear both in the control panel and on the line in front of the driver who then knows that he has to wait until the signal is off to leave the station. If at

some point the controller notices irregularities, he will apply manually the “Chinese hat principle” that was presented in the previous paragraph. If such imbalance occurs without any incident, it is usually because of the tendency of some drivers to adopt too fast or too slow a mode of conduct and the irregularity is not very important. The actions taken by the controller usually is to ask the trains upstream and downstream to wait a little longer at one station until regularity is back.

The main difficulty for the controller is to be able to handle incidents. In such cases, he has the responsibility if necessary to interrupt energy distribution on the line by sub-sections and to put it back when needed, to inform all the drivers, stations and terminals of the disruption, to fix the problem by calling for the right persons, to activate the temporary service that will enable the line to be operated by sub-parts if necessary... After the incident is resolved, he will have to make sure that the traffic goes back to being regular as soon as possible.

5.2.2. Terminal management

Two actors are in charge of the train management in a terminal:

- the manoeuvring chief (in French, “chef de manœuvre”), whose role is to have the trains moved from arrival quays and parking tracks to the departure quays or parking tracks depending on what is indicated in the program of operations;
- the departure chief (in French, “chef de départ”), whose role is to give the order of departure to trains on the departure quay and to give instructions to the manoeuvring as to the changes to the program of operations.

In an ideal situation, the departure chief would strictly follow the theoretical timetable for the trains’ departure times (HDT). However, since the ideal situation does not exist, his main goals are to have train leave as close as possible to their theoretical departure time, mostly because of social reasons regarding the drivers, and to ensure a regular headway between departures. The departure chief is assisted by a departure machine that, in the absence of any action from the departure chief, displays the earliest possible departure time of each train appearing on the program of operations (HDP). The departure machine displays the calculated departure time so that both the departure chief and the driver can be aware of the time the train is set to leave. The departure chief also has a hard copy of the theoretical timetable (called the “garde-temps”) in order to compare it with the display on the departure machine. If he notices a possible conflict between HDP and HDT, this means that there is a delay on the line important enough to have repercussions on the other direction, and that regulation actions need to be taken. An example of this situation is given in Table 8.

Train	HDT	HDP	HDC	Headway
1	10:00:00	10:00:00	10:00:00	
2	10:05:00	10:05:00	10:05:00	00:05:00
3	10:10:00	10:10:00	10:10:00	00:05:00
4	10:15:00	10:14:00	10:15:00	00:05:00
5	10:20:00	10:19:00	10:20:00	00:05:00
6	10:25:00	10:28:00	10:28:00	00:08:00
7	10:30:00	10:30:00	10:30:00	00:02:00

In this example, train number 6 is the disruptive train.

Table 8 - Example for the calculation of departure time

If the departure chief chooses to follow the schedule regulation principle only, the calculated departure time is Max (HDT, HDP) as presented in the table. However, this leads to unwanted irregularities in the traffic. In the case of headway and schedule regulation, the idea is to build up from no delay until the disruptive train, and then back to normal situation. Indeed, in order

to ensure a regular headway between trains, the delay has to be distributed between all the trains scheduled before the disruptive train and that have not left the terminal yet, disruptive train included. The disruptive train will still leave late, but the other trains will be delayed as well in order to build up regularly from 0 min delay on the line to the amount of delay of the disruptive train. This process is performed for the example in the table below.

Train	HDT	HDP	Delay	Additional delay (correction)	HDC	Headway
1	10:00:00	10:00:00	00:00:00	00:00:30	10:00:30	
2	10:05:00	10:05:00	00:00:00	00:01:00	10:06:00	00:05:30
3	10:10:00	10:10:00	00:00:00	00:01:30	10:11:30	00:05:30
4	10:15:00	10:14:00	00:00:00	00:02:00	10:17:00	00:05:30
5	10:20:00	10:19:00	00:00:00	00:02:30	10:22:30	00:05:30
6	10:25:00	10:28:00	00:03:00	00:00:00	10:28:00	00:05:30
7	10:30:00	10:30:00	00:00:00	00:03:00	10:33:00	00:05:00

As we can see, the headway is slightly higher than its reference value but it is regular.

Table 9 - Example for the calculation of departing time in headway and schedule regulation

The role of the departure chief in this process is to

- calculate the delay and input it to the departure machine

Delay = HDP (disruptive train) – HDT (disruptive train) = 3 min in the example

- select the trains upon which the delay must be distributed

Finally, in a much deteriorated situation, the departure chief can choose to apply constant headway methods. On the departure machine, he can switch to this mode and input the headway (IC) he wants to have between trains. The machine then calculates the departure time $HDC(n) = HDC(n-1) + IC$.

However, those methods only lead to regularity, and do not allow catching up with the theoretical timetable and eliminating the delay. In order to do so, the first type of measure is to reduce the terminal buffer time of the trains. However, once again, it is not advisable to solely apply schedule regulation and eliminate the whole buffer time of a train without looking at the others. In order to make sure that the departures are still regular, the departure chief can apply exactly the same recovery method as the one presented for schedule and headway regulation, except that instead of inputting a positive value for the delay, he will input a negative delay that corresponds to the time that he wants to recover from.

With this method, it is possible to recover from minor general delays (up to more or less 15 minutes). If the general delay is more important, the departure chief can proceed to two kinds of actions:

- he can change the order of departure of trains. Let's say train 1 is on the line and expected to arrive late, therefore to leave late, whereas train 2, set to leave after train 1, is parked in the terminal. The departure chief can exchange the two trains, thus reducing the delay caused by the late arrival of train 1;
- he can make sure that drivers start their service at the theoretical time by cancelling trains. Let's say that driver X is set to begin his service with train 11 at 12:30, but the HDP of train 11 is 13:00. On the other hand, train 1, who was set to leave at 11:30, can only leave at 12:00. Instead of having driver X wait 30 minutes, the departure chief cancels all trains from train 2 to train 11, and "turns" train 1 into train 11, asking driver X to leave on time. In this example, 10 trains have been cancelled for "schedule compensation".

Trains being cancelled because of schedule compensation are the last resort for the departure chief, however it is a method that they have to apply almost every day especially because of the delay accumulated on the lines at peak hours (**Removing**). Therefore, a redefined goal of a good regulation method is to reduce the number of trains cancelled for schedule compensation, as it will be expanded on in the performance evaluation chapters. Furthermore, another action that can be taken is to add a train to the program of operations when there is too important a gap at terminal departure that could be filled in by this additional train, however only if both a driver and a train are available in the terminal at that time (**Adding**). Nevertheless, if there is a gap between trains, that means that at some point, there would also be trains running too close to each other, and this would usually lead to removing one of them.

5.3. Conclusion

The organisation of regulation as described in this chapter has not changed since it was first implemented in the 70's. Of course, failing equipments have been replaced, calculations, representations and models have been updated according to changes in the network, but all in all, it remains the same old button-control panel based system for line traffic regulation, and a separate human-based system for terminal regulation.

The first key aspect is that the equipment is too old to be still used and maintained, and obsolete as opposed to what could be implemented, what is being used in other metro systems, and even what is done in the highly-modernised lines of the RATP network (lines 1 and 14). The Paris metro is known all over the world for its efficiency and its modern features but those modern features are based on flagship projects such as METEOR (fully automated line 14) and the automation of line 1. Nevertheless, other lines in the Paris network have a real need for an upgrade in their operations.

Moreover, it is obvious that the way regulation is being managed is highly compartmentalized. Indeed, the two terminals and the line itself are completely separate from each other, while actions being taken in one of them always have repercussions on the other two. Of course, the terminal managers and the traffic controller can keep each other informed by phone, but in case of a highly disturbed traffic, it is not always easy to find the time to take actions, inform drivers and contact the other regulating parties. Thus, it often happens that they are presented with the situation without notice and have to deal with the consequences in their turn. This is a very important disadvantage of separating the regulation actors: the line is not really managed as a whole but rather separately in the critical points.

Furthermore, it was mentioned at the end of chapter 4 that there was a policy to be enforced to reinstate the line at the centre of all attention, and to bring regulation operators and other actors of the line closer together.

For all these reasons, if this regulation system was efficient enough when it was implemented back in the 70's, the question was asked in the year 2000 whether or not it still answered the needs of line operators. Moreover, other modernisation projects were already decided on for train driving (CBTC system) and terminal signalling (computer-based manoeuvre posts), which could not be supported by the old control system, all the more reason to decide to implement a new system for operational control.

Chapter 6 – Regulation in the modernised traffic control system

If the main goal of the modernisation plan is to renew the equipment, it is also taken as an opportunity for the evolution of methods and re-organization of operations.

Within the regulation system, this led to the grouping of all the functions related to traffic control in the same place, the modernised operational control centre (PCC), in a building close to the line itself that also houses the rest of the line operational unit. This was done in order to have a unified mode of operations in the line, integrating traffic control on line and in terminals and bringing them closer together for a better communication between those strategic actors. Indeed, with a robust information system such as the one developed in this project, the terminal manager (formerly departure chief) does not really need to be present in the terminal, especially since manoeuvres are now managed automatically. On the other hand, he does need to maintain continuous communication with the other terminal manager and the traffic controller, thus the choice to bring them together in the same place. An evaluation of those choices, as opposed to the former organisation, is the object of a chapter later on in this report. This chapter presents the new organisation and the tools, methods and algorithm that were introduced in the operations of the line.

The picture below is taken in the modernised operational control centre of line 13.



Figure 18 – Inside the modernised operational control centre (PCC) of line 13

All the operators' work stations (terminal managers, traffic control, maintenance, station coordination) are equipped with computer screen displaying the information they need in order to perform their tasks. They all face a wall with an optical control panel that displays the whole line with its real-time situation.

New tools and methods are made available for the traffic controllers and terminal managers, among which automatic regulation on the line, and several computer-based terminal management tools with a new algorithm for automatic calculation of train departures with or without the need for human intervention.

It has to be stressed out that the idea was to develop a generic system to be implemented with very few adaptations on all the lines. For organisational reasons, the lines were gathered in groups of three for the project, the first group being composed of line 13, 3 and 5. Those three lines are to be equipped with exactly the same version of the operational control centre, especially for the algorithm. As for the second group, composed of line 12, 9 and 10, even though the development is based on the same specifications, they will benefit from some improvements in the system based on the experience of line 13 and 3. The organisation will, however, remain the same in all cases; only the calculation algorithm might differ.

6.1. Traffic control on the line: automatic regulation and the controller's role

An automatic traffic regulation system has been developed for the new operational control centres. Based on the real departure time from a station and on the reference modal type, the system calculates the expected arrival time of all trains at all stations:

(calculation of the arrival time of train n in station i when running on direction x with modal type m)

$$HAC(n, i, x) = HDR(n, j, x) + CV(x, j \rightarrow i, m) \quad (5)$$

with $HDR(n, j, x)$ the real departure time of train n from the last station it stopped at, j being the identification of this station (or from the terminal if the train has not reached the first station yet) on direction x

$CV(x, j \rightarrow i, m)$ is the theoretical running time from station j to station i in driving mode m on direction x .

This calculation is done every second, and the result compared to real times. If a train is detected ahead from the expected arrival time, it is held in the station by means of the “departure upon order” signal commanded automatically.

If on the other hand, a train is detected late, with a delay of more than a threshold value (usually set to 15s), automatic regulation is activated following the headway and schedule regulation that was presented in the previous chapter.

When this function was first implemented on line 4, it led to a major increase in the general delay of the line, and it was therefore rapidly turned off. The main reason for this might be that this calculation is based solely on the reference running times, and does not really take into account the human factors and the possible hazards that operators and drivers have learned to include in their assessment of the situation. Indeed, if the total running time on the line is more or less constant from one train to the other, and close to the modal type, this is not true of the running time between stations, since trains run in accelerated mode, and of the waiting times, which, depending on the stations, are sometimes very different from the reference (for some stations, there is up to 10s difference which, for a dwell time of 25s is substantial enough to be noticed). In general, trains therefore spend less time driving than expected but more time in stations at peak hours. Added up, those differences eliminate each other, but they do appear in the calculation of the expected arrival times.

For example, with the experience, drivers and operators have learnt that it is sometimes advisable to run a little ahead of schedule in order to prevent additional delay to come at overcrowded stations. However, the automatic train regulation system does not allow for this

to happen, applying the double punishment: the train is retained by the system in some stations because it is ahead of schedule and in other stations because it has to wait for all passengers to be accommodated.

Another problem that occurs with this method is that sometimes, a delay could actually be reversed naturally. If a train is late, automatic regulation would be activated, thus creating delay on other trains in the line. However, sometimes, this delay could be reversed by the driver himself by spending less time on following stations when it is possible. The drivers usually know how long they had to stay in each station depending on the time of day, and this is not accounted for at all in the automatic regulation method.

The problem, here, is that there still needs to be a reference for the calculation. Improving the modal types of the lines is a very complicated process, since it implies conducting several studies and negotiations with the operators, and changing all the systems that use those values in their calculations. For now, a study is being done as to how to implement evolutionary modal type, instead of fixed ones that sometimes feat the profile of the line and sometimes not. This is however not the object of this study, especially since the operators have now all chosen not to use the automatic traffic regulation system on the line and to have this function turned off from the very beginning.

Since automatic regulation is not being used, the role of the traffic controller has not changed much between the old and the modernised organisation. The main difference for him here is that he is working in a different place, along with the other actors of the same line instead of with the same actors of other lines (this aspect is expanded on in the chapter on operator's assessment) and that he is now using computers and modern communication technologies instead of the button control panels. The functions and methods remain the same as before.

For technical reasons, the operational control centres are commissioned in two stages. In the first stage, only the traffic controller is moved to the operational control centre, terminal management remaining in the terminals. At the second stage, usually 6 to 18 months afterwards, terminal management is implemented into the system and moved to the operational control centre as well.

6.2. Terminal management

In the new organisation, there is no one left to manage the manoeuvres and departures in the terminal. Indeed, manoeuvres from and to parking spaces are all registered in the program of operation and controlled with the same means as for the train departing on the line. The one and only person responsible for traffic control in the terminal is now called the terminal manager (in French, Gestionnaire de Terminus – GT) and works from the operational control centre.

Every second, the system calculates the earliest possible departure time like the old system did, but now it is also capable of applying schedule and headway regulation by itself, without need for the terminal manager to input any information. Indeed, the system is now capable of calculating the delay and the number of trains to be impacted, which was the former responsibility of the departure chief. The terminal manager is however responsible for assessing the type of regulation needed between:

- no regulation (actually, this corresponds to schedule regulation);
- regulation with recovery (this corresponds to an improved version of headway and schedule regulation);
- regulation with constant headway.

Based on the type of regulation indicated by the terminal manager, who can change it at all times depending on the situation, the system calculates the HDC (calculated departure time)

and a screen for the use of the terminal manager displays what is called the list with three modules for each train as presented in the following screen capture.

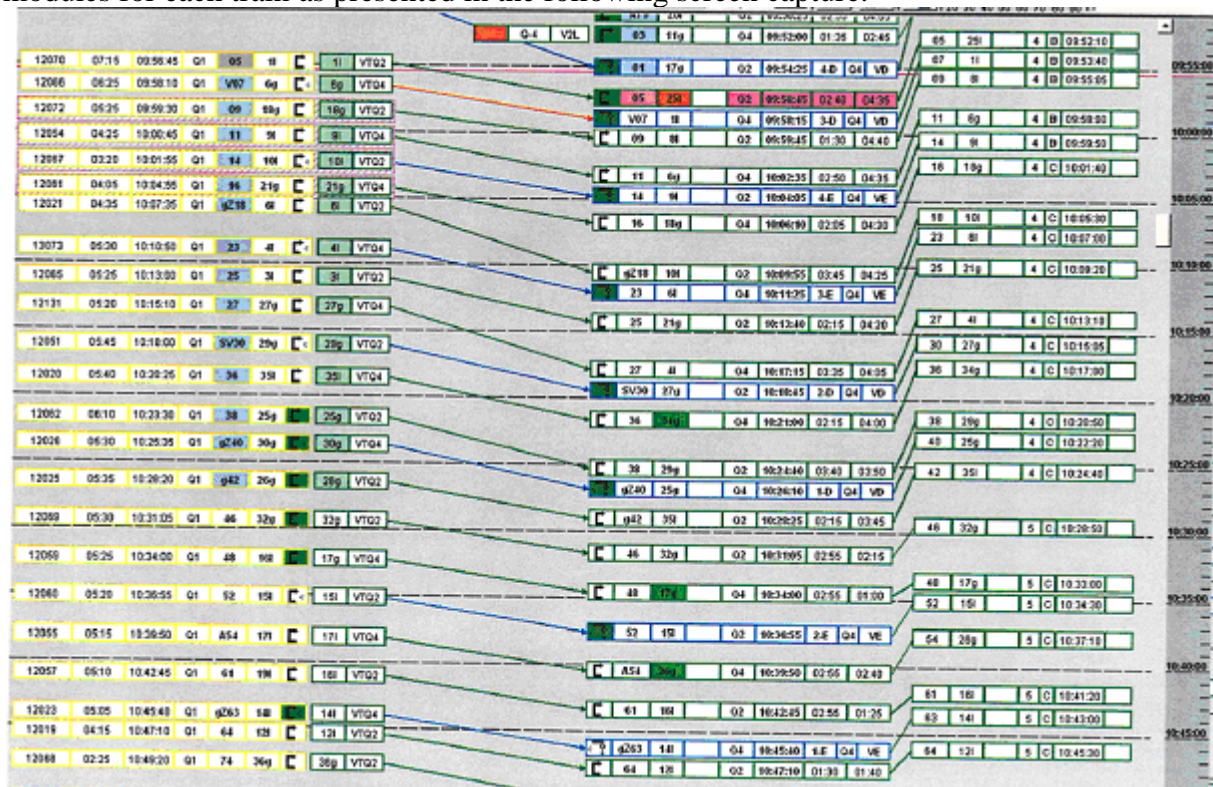


Figure 19 - Circulation lists at terminal Levallois on line 3

The left column represents either the arrival time of the train in the terminal or its earliest possible departure time (depending on a choice from the terminal manager). The middle column shows the calculated departure time. The third column shows the theoretical departure time. Modules corresponding to the same train are linked. Blue links are for trains that do not leave to go on the line but leave to be parked in the terminal. Red links indicate the trains that have a very short turn-over time (if the planned turn-over time is shorter than what is needed, the module appears in red). The red line on the background indicates the time, and the pink module is the next one to leave the terminal.

If he chooses to apply constant headway regulation, the terminal manager also has to indicate the headway he wants to have between trains.

Within its regulation functions, the system can only apply the “soft methods”, that is to say changing the departure time, as long as it keeps the list of departures in order. When more important actions need to be taken, only the terminal manager can intervene. In the list, the terminal manager can choose to cancel modules, thus cancelling the trains like he did in the old system, or to exchange the departure times of trains, by either moving a module in the middle column or exchanging links between modules. Finally, the terminal manager can also indicate a departure time manually.

6.3. Calculation of the departure times

Much as it was done in the old system, departure times from the terminal are calculated based on the theoretical time given in the program of operations, and then re-calculated depending on the real-time situation of the train. Those calculations are performed and updated every second. First, the earliest possible departure time from the terminal is calculated. Then depending on the regulation mode the desired departure time is calculated with as few

interventions from the terminal manager as possible. In this paragraph, the calculation for lines 13, 3 and 5 are presented. The last part gives an overview of the evolution that will be implemented for lines 12, 9 and 10.

6.3.1. Earliest possible departure time

For every station of the line, including the terminal, the expected arrival time is calculated as presented in paragraph 4.1. Therefore, every second, the system calculates the expected arrival time in the terminal much like for every other stations as presented in Equation (5).

The system also calculates the earliest possible departure time (HDP) of each train as follows:

- if the train is parked in the terminal and the driver available, the earliest possible departure time is the theoretical departure time as listed in the program of operations;

$$HDP = HDT$$

- if the train is parked in the terminal but the driver not available, the earliest possible departure time is the expected arrival time of the driver plus the minimum mandatory resting time for drivers (BT_{driver})

$$HDP = H_{\text{driver's arrival}} + BT_{\text{driver}}$$

This usually happens if the driver is driving at the time, and therefore his arrival time is that of the train he is driving. The information that the driver is not available sometimes has to be filled in by the terminal manager manually.

- if the train is running the line, the calculation is based on the calculated arrival time, taking into account the minimum time the train has to wait both at arrival quay and departure quay (mainly to make sure that all passengers are able to alight or board the train) and the manoeuvring time.

$$HDP(n, T, x) = HAC(n, T, y) + SM(T) \quad (6)$$

with $HDP(n, T, x)$: earliest possible departure time of train n from terminal T in direction x (Heure de Départ au Plus tôt) ;

$HAC(n, T, y)$: calculated arrival time of train n in terminal T on the other direction - y ;

$SM(T)$: minimum stay in terminal T as calculated in equation (2) .

6.3.2. Calculated departure time in recovery mode

The recovery mode was designed in order to apply headway and schedule regulation without any intervention of the terminal manager. It is important to mention that all times calculated with this algorithm are then rounded up to the closest 5s.

Headway correction induced by a delay

The first step in this process is to calculate the delay caused by a specific train, or rather the additional delay said train could cause. For each train, the absolute delay is the difference between its earliest possible departure time HDP and its theoretical departure time HDT as listed in the program of operations. However, the interesting figure is not the absolute delay of each train, but rather the contribution of each train to the general delay on the line, that is to say how much worse or better the delay is because of this train. The next train to leave the terminal at any given time being identified with the letter p , and the train being studied with the letter n , the contribution to the general delay of train n is the difference between his absolute delay and that of train p :

$$Ret(n) = [HDP(n, T, x) - HDT(n, T, x)] - [HDP(p, T, x) - HDT(p, T, x)] \quad (7)$$

- with
- Ret(n): contribution of train n to the general delay (standing for the French “retard”, delay);
 - HDP(...,T,x): earliest possible departure time of train ... from terminal T in direction x;
 - HDT(...,T,x): theoretical departure time of train ... from terminal T in direction x.

The idea is to share this additional delay between trains in order to reach as regular a headway as possible between the next train to leave the terminal and the disruptive train n. This is done by calculating an automatic correction induced by train n on any train l between p and n:

$$Cor(n/l) = Ret(n) \times \frac{M - L}{M} + [HDP(p, T, x) - HDT(p, T, x)] \quad (8.1)$$

- with
- Cor(n/l): correction induced by train n on train l;
 - Ret(n): contribution of train n to the general delay;
 - M: number of trains among which to share the delay, i.e. the number of trains between p and n;
 - L: rank of the considered train l with the disruptive train as a reference to the numbering. For the disruptive train, L=0, and for train p, L=M.

Since multiple trains can induce corrections on each other, the maximum one has to be applied, leading to the following correction on train l, which will be added to its theoretical departure time in order to get to a regular headway between trains:

$$Cor(l) = \max_n [Cor(n/l)] \quad (8.2)$$

Headway reduction

If only the headway correction was to be applied, it would never be possible to recover from delay. Indeed, the correction keeps adding delay to each train in order to ensure regularity between the departures. Therefore, this measure has to be limited by what is called a headway reduction. This method works out the possibility to reduce the terminal buffer time, yet spreading this reduction between the scheduled trains in order to keep the regularity aspect of the overall method.

For each train n, the theoretical buffer time can be calculated with the formula presented in equation (3). This buffer time can be reduced, as long as it does not get lower than the mandatory buffer time allocated to drivers' break (BTF – parameter that is usually set to 0 if the driver shifting method is applied, but has to be strictly positive if drivers are set to depart with the same train they arrived in). However, in order to ensure regularity, this reduction is spread between the trains that are part of the same group in the theoretical program of operations (usually, the train with id number 1 is set as the reference to differentiate the groups. Any trains between two theoretical departures of train 1 are part of the same group). This leads to the following possible headway reduction to be applied to train n:

$$MI(n) = \frac{BTT(n) - BTF}{N(n)} \quad (9.1)$$

- with
- MI(n): possible headway reduction for train n (MI stands for Minoration d'Intervalle);
 - BTT (n): terminal buffer time of train n as calculated in equation (3);
 - BTF: minimum buffer time that cannot be spared for the sake of driver's working conditions (BTF stands for Battement au Tour Forfaitaire);
 - N(n): theoretical number of trains running the line with train n according to its theoretical buffer time and headway

$$N(n) = \frac{DTT + BTT(n, A) + BTT(n, B)}{I_{th}(n)} \quad (9.2)$$

- with
- DTT: minimum duration of a lap as calculated in equation (1);
 - I_{th}(n): theoretical headway before train n.

Calculation of the departure time

The trains are set to leave in a specific order, and are sent to the departure quay depending on this order and on their calculated departure time. Once a train is present at the departure quay with driver on board, the calculated departure time is frozen, meaning it cannot be changed anymore, and becomes the programmed departure time. If this was not done, the departure time would be susceptible to changes at the last moment, which would be quite inconvenient for both the driver and the terminal manager.

The synthesis of the two methods of headway correction and reduction leads to the following calculation for the departure time:

$$HDC = HDT + COR - MI \quad (10.1)$$

At first hand, one could say that it does not really make sense to add a correction and reduce the headway at the same time. However, it needs to be explained that situations when the correction is non-negative occur almost always during peak hours, when the terminal buffer time, and therefore the possible reduction Mi, are null. On the other hand, when the terminal buffer time is non-null, it is important to try and recover from the delay rather than keep adding it. Therefore, both terms in this calculation are important, and even if they do have opposite actions, they are necessary to ensure schedule recovery and headway regularity at the same time.

Since the train is still bound to obey technical constraint such as the earliest possible departure time or the minimum technical headway, the actual calculation is as follows:

$$HDC_{recovery}(n, T, x) = \max \left\{ \begin{array}{l} HDT(n, T, x) + Cor(n) - MI(n) \quad (1) \\ HDP(n, T, x) \quad (2) \\ HDC(n-1, T, x) + I_{th}(n) - MI(n) \quad (3) \\ HDC(n-1, T, x) + I_{min} \quad (4) \\ H + T_{departure} + T_{el} \quad (5) \\ HDT(n, T, x) \quad (6) \end{array} \right. \quad (10.2)$$

- with (1) basic formula of the delay recovery method;

- $HDC_{recovery}(n,T,x)$: calculated departure time in recovery mode of train n from terminal T in direction x;
- $HDT(n,T,x)$: theoretical departure time;
- $Cor(n)$: headway correction induced on train n by disruptive trains;
- $MI(n)$: possible headway reduction on train n;

(2) departure cannot be set before the train's earliest possible departure time HDP;

(3) even in recovery mode, the applied headway (except for further reduction) should not be lower than the reference headway as listed in the theoretical program of operations

- $HDC(n-1,T,x)$: calculated departure time of the train just before the one being studied (n);

- I_{th} : theoretical headway between trains n and (n-1)

$$I_{th}(n) = HDT(n,T,x) - HDT(n-1,T,x);$$

(4) trains cannot leave with a headway lower than the incompressible technical headway I_{min}

(5) this term in the calculation is here for when the studied train is the next one to leave and should already have left, having exceeded all the previously calculated trains, but has not reached the departure quay yet. In this case, the departure time is supposed to be as soon as possible

- H: real time;
- $T_{departure}$: minimum time to spend at departure quay;
- T_{el} : quay constant that includes the time to enter the quay and the time for the departure signal to open.

(6) The trains can never leave the terminal before their theoretical departure time.

For a better understanding of this formula, Figure 20 gives a graphical representation of equation (11.2) based on a particular example.

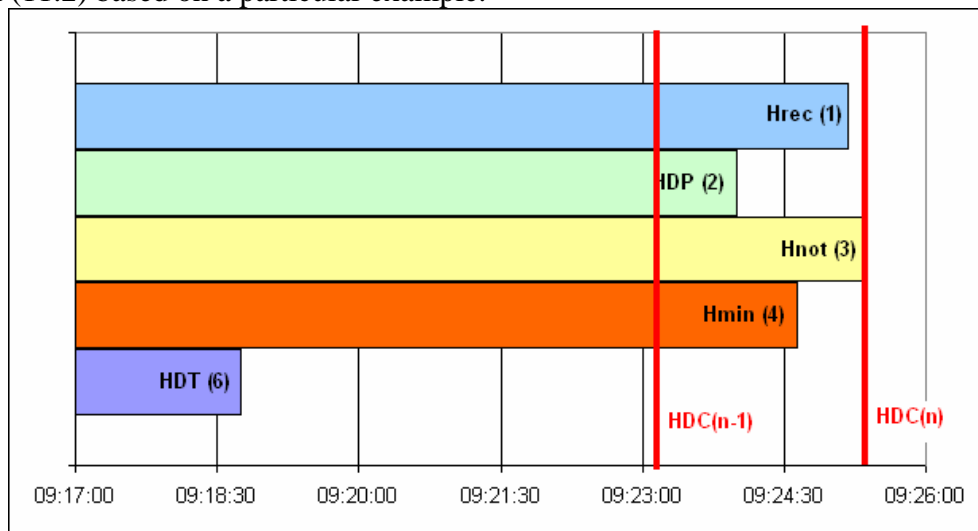


Figure 20 - Graphical representation of equation (11.2)

6.3.3. Calculated departure time in other modes

If the terminal manager does not want to apply the recovery mode, he can either choose to be in a no-regulation mode or in a constant headway mode.

In the no-regulation mode, the system simply tries to apply the theoretical departure time:

$$HDC = \max(HDT, HDP) \quad (11)$$

In the constant headway mode, the terminal manager indicates the headway he wants to have between trains, IC, and the system calculates the departure time based on this:

$$HDC_{IC}(n, T, x) = \max \begin{cases} HDC(n-1, T, x) + IC \\ HDC(n-1, T, x) + I_{\min} \\ H + T_{\text{departure}} + T_{el} \end{cases} \quad (12)$$

As we can see the technical features of respecting the minimum headway and of departure as soon as possible in case the train has exceeded its departure time are still present, however, no mention is made either to the theoretical departure time HDT or to the earliest possible departure time HDP. The absence of HDT means that with this mode, as opposed to with the recovery mode, the system can set departure times ahead of schedule. The absence of the earliest possible time leads to a possibly non-realistic calculation of departure times. In this case, the modules on the list would appear in red and the terminal manager knows that he has to change either the applied headway or even the regulation mode in order to make sure that trains can leave on the programmed time. The system developers and commissioners were well aware of the fact that this method of calculation could lead to unrealistic times. However, they chose not to include HDP in order not to change the core principle of the method, which was to apply constant headway. Furthermore, the constant headway mode is designed to be used very carefully, and only in case of highly deteriorated situations. The possibility of not having realistic times makes it sure that the operator will at some point have to switch back to a less drastic regulation method.

Finally, the terminal manager can indicate the departure time manually, in which case this manual departure time always has priority on the others, as long as it is set later than the earliest possible departure. When the terminal manager changes the order of departure, cancels a train or adds a new train to the list, he either indicates the departure time manually, or he recreates links between the modules, therefore changing the calculation by changing the reference theoretical values and order between trains.

6.3.4. Evolutions in the latest version

In the new version of the algorithm, to be applied on line 12, 9 and 10, and possibly to serve as an update of the version on line 13, 3 and 5, depending on its performance, changes have been made to the calculation of the earliest departure time and to the different regulation modes.

In the calculation of the earliest possible departure time, there is a possibility to take into account the minimum time to be allocated to drivers in terminals, referred to as BT_{driver} . If this option is switched off, the calculation is the same as in the other version. Otherwise, it becomes the following:

$$HDR(n, Tx) = HAC(n, Tx) + SM(T) + BT_{driver} \quad (13)$$

As for the regulation modes, there are now 4 different modes:

- schedule regulation mode;
- headway regulation mode;
- headway and schedule regulation mode;
- constant headway mode with or without possibility to be ahead of schedule.

In **schedule regulation mode**, the calculation is as follows:

$$HDC_{schedule}(n, T, x) = \max \begin{cases} HDT(n, T, x) \\ HDR(n, T, x) \\ HDC(n-1, T, x) + I_{\min} \\ H + T_{departure} + T_{el}(1) \end{cases} \quad (14)$$

The only objective is to be as close as possible to the theoretical program of operations (HDT) as long as it complies with the technical constraints presented before in the description of the former version.

In **headway regulation mode**, the system first calculates the correction induced by all disruptive trains exactly like it did in the former version. The subsequent calculation is:

$$HDC_{headway}(n, T, x) = \max \begin{cases} HDT(n, T, x) + Cor(n) \\ HDR(n, T, x) \\ HDC(n-1, T, x) + I_{th}(n) \\ HDC(n-1, T, x) + I_{\min} \\ H + T_{departure} + T_{el}(1) \end{cases} \quad (15)$$

The calculation is therefore almost the same as in the recovery mode of the former version, although it does not include the headway reduction term. Indeed, the only objective of this mode is to ensure a smooth headway between trains, without caring for theoretical schedule or delay recovery. It does, however, take the reference headway into account.

The **headway and schedule regulation mode** is a combination of both objectives (smooth headway and delay recovery) and is almost the same as the recovery mode of the former version.

$$HDC_{h\&s}(n, T, x) = \max \begin{cases} HDT(n, T, x) + Cor(n) - coef_{Mi} \times MI(n) \\ HDR(n, T, x) \\ HDC(n-1, T, x) + I_{th}(n) - coef_{Mi} \times MI(n) \\ HDC(n-1, T, x) + I_{\min} \\ H + T_{departure} + T_{el}(1) \end{cases} \quad (16)$$

The headway reduction M_i is calculated exactly as before, the difference is that it is applied with a coefficient coef_{M_i} . If he is applying this regulation mode, the terminal manager has to set this coefficient (between 0 and 200%) based on the trade-off between delay recovery and driver's convenience. Indeed, if the buffer time is being reduced, this leads to less break time for the drivers. The terminal manager's role is to assess how much reduction he can apply without inconveniencing the drivers too much. It should be noticed here that when the coefficient is set to 0, this leads to applying the headway regulation mode, therefore with the introduction of such coefficient, there was not really a need for introducing the headway regulation mode as well.

Finally, in the constant headway mode, the terminal manager can choose between having the possibility to get ahead of schedule or not. If he chooses to be able to do so, the calculation is the same as in the former version. If he chooses to respect the theoretical schedule, the HDT is introduced into the calculation:

$$HDC_{IC}(n, T, x) = \max \begin{cases} HDT(n, T, x) \\ HDC(n-1, T, x) + IC \\ HDC(n-1, T, x) + I_{\min} \\ H + T_{\text{departure}} + T_{el}(1) \end{cases} \quad (17)$$

6.4. Conclusion

This new organisation of things for operational control of the lines presents three key aspects:

- renewal of equipment;
- re-organisation of operations;
- changes in the calculation techniques.

The first two aspects were indeed the goals of this modernisation project. However, implementing a fully computer-based system meant that everything had to be defined, modelled and calculated, thus leading to the development of the third aspect. Logically, it is not supposed to be a change in the calculation of times, but rather a formalisation of the algorithm. Indeed, the calculation techniques that were developed are supposed to be the exact reflect of what was being done before, as it is explained in the next chapter. However, in terminals, those calculations were being performed but were not really formalised, especially since they relied on the experience of terminal managers. What was being done by a human being with the help and control of a machine is now to be done by the computer, with the help and control of the human. This is a major inversion of responsibility that is expanded on in chapter 8 which presents the reaction and assessment of the operators regarding this new system.

Chapter 7 – Comparison and validation of the new system

The main objective of the modernisation plan was to renew the equipment used for the operations on the metro lines, an objective that was indeed met in the two lines where the system is now in operation. However, the methods and organisation were also modernised, and before going into a performance analysis of this new system, it is important to make sure that it does, indeed, comply with the requirements that were set and is susceptible to offer an improvement compared to the former system. First a comparison of the functionalities of the two systems and with the requirements is performed in order to make sure that none were left out in the development of the new system and that it complies with the regulation methods of RATP. Then, the main challenges that the system is to face are presented.

7.1. Requirement check

Only the regulation methods directly related to the calculation algorithm are discussed here. Indeed, the new system came along with a new organisation and new tools for the operators. However, those cannot really be assessed on paper and their evaluation is closely related to the impression of operators in their day-to-day tasks, which is the object of chapter 8 in the next part of this report. As for the regulation algorithm, it was supposed to meet a set of detailed requirement issued by RATP, which can be summed up as being able to handle the same tasks as the previous system with fewer intervention of the operator. Some of those requirements are expanded on here in order to justify the validation of the system that was developed. The differences with the old system are also mentioned, as well as a quick assessment in theory of the new methods.

7.1.1. Automatic regulation on the line

According to the requirements of RATP, terminal regulation is always to be accompanied by headway regulation on the line. The algorithm that was developed for the latter on lines 13 and 3 is based on the modal types declared for the line, much like the one that is implemented on line 4 which was equipped with the first modernised operational control centre. However, this system on line 4 quickly proved to be inefficient, causing more and more delays on the line as it was being used. Therefore, as a feedback from this experience, line 13 and line 3, where the generic modernised regulation system has been implemented, decided never to even try using this feature of the regulation system, and to keep relying on the traffic controller. Since this feature was a new functionality, there was not much complaint about its complete uselessness.

All in all, the algorithm that was developed here follows the specifications of RATP. The problem lies within the fact that the specifications of RATP themselves are not really consistent with the realities of network operations (inadequate modal types, use of the accelerated mode at all times, driver's experience). Therefore, the parameters that are provided to the system are somewhat false and it is not really possible to test and use this algorithm correctly. However, since those parameters are bound to disappear with the development of a new process for the calculation of timetables and for the driver's assistance or autopilot system, it would not be wise to pursue further study on this for now.

Furthermore, the operations on the line are highly dependent on human factors, namely the passenger's flow and behaviour which is totally random, and the driver's assessment of the situation. This kind of factors is very difficult, even sometimes impossible, to take into account in a computer-based system, whereas a human traffic controller can better assess a random situation and allow for small deviations when he knows they can be recovered from

easily. With an automatic system, it is not so easy to take into account the operator's experience and knowledge. The drift tolerance because of human behaviour and human decisions and knowledge would have to be modelled in order to be implemented into the system, which could prove very long and complex, especially compared to the low benefits it could deliver.

The other problem of regulation on the line is that it relies on the possibility to drive in accelerated modes. However, an accelerated driving leads to higher energy consumption, and faster wearing of the rolling stock. Since nowadays, there is a growing consciousness about energy-efficient driving, the accelerated driving mode is at the opposite of the policies that RATP is trying to implement regarding eco-friendly behaviours and sparing of material.

7.1.2. Terminal regulation

Whereas on the line, the train is limited by human constraints, actions on terminal obey specific rules that can easier be modelled and represented in an algorithm. Therefore, this part of the algorithm is bound to be more reliable.

Constant headway

The requirement for this regulation mode was mostly that it provided the same method as in the old organisation, which is the case. The only downside here, and that was already the case with the old system, is that this calculation can lead to the programming of unrealistic departure times since it does not take into account the earliest possible departure time. Therefore, when applying this mode, the terminal manager must always keep an eye on the lists to check for unfeasible departure times. The list visualisation tool was however built in order to make it easy to spot such conflicts. Furthermore, since the constant headway mode is only to be used in highly deteriorated situations, this feature forces the terminal manager to try and apply the recovery mode as soon as possible, and therefore only use the constant headway mode in extreme situations.

Recovery mode

According to the requirements of RATP, the definition of this mode is that it tends to recover from a drift with the schedule, partly or in totality, on several trains. It is always to be applied along with schedule regulation and can be accompanied with headway regulation. The recovery mode acts through a reduction of the buffer time spread between all trains of the same group.

The calculations of the reduction and of the correction were mentioned in the requirement, and are the same as the one used in the algorithm. As for the headway reduction, it should be explained that this method leads to an increasing reduction along the trains of the same group, until the last train of the group whose buffer time is entirely suppressed with this method. Indeed, the additional step in the reduction is the buffer time (which is the same for all trains of the same group) divided by the number of trains in the group. The last train in the group receives a reduction of its entire buffer time, if the recovery mode is still active and necessary. The algorithm for the recovery mode is consistent with the requirements, in that it takes into account the theoretical departure time (schedule regulation) at all times, and includes the feature on theoretical headway. Furthermore, it only recovers from delay while ensuring regularity between departures, which follows the requirements on regularity having the priority over production.

The main difference between this and the former method is that it is not the terminal manager but the system that chooses the number of trains upon which the delay recovery must be spread. Thus, if the parameters for the calculations are correct, the operator could easily let

the algorithm run its course without lifting one finger, and this is what was asked of the system in the RATP requirements.

In this method, regularity between train departures has the priority over production. With the calculation in the recovery mode algorithm, the headway reduction is minor compared to the correction, and it is always the latter which has the most important effect, thus leading to a longer time necessary to catch up with the schedule, but to smoother headways. When the requirements were written and the system developed, it was indeed the main objective of the operator to ensure regularity before production, since back then, the production was assessed for the metro network as a whole whereas regularity was already differentiated between lines. However, this is not the case anymore. First of all the production is now assessed separately for all the lines, and secondly the criterion of production during peak hour has been introduced. Therefore, operators would like to be able to take less time to get back on schedule, even if this means lacking in regularity. This is already one of the reasons for the evolutions in the regulation algorithm for the second group of lines to be modernised.

Evolutions in the new version of the algorithm

The first aspect that should be mentioned is that in the new version of the algorithm as developed for lines 12, 10 and 9, the comfort and needs of train drivers seem to be taken much more into account. First of all the mandatory rest time can be accounted for in the calculation of earliest possible departure. However, this means that said mandatory rest time has to be pre-defined, which has yet to be done.

Secondly, in the headway reduction, there is a possibility to choose the rate at which to reduce the buffer time, which, depending on the policies applied in the line and by the terminal manager, can ensure an additional rest time for the drivers.

Nevertheless, there would be an additional rest time only if the coefficient is chosen lower than 100%, which means that the time needed to recover from delays would be longer. This coefficient seems highly interesting for schedule recovery in that it can actually exceed 100% up to 200%, which means that the delay recovery process can be speeded up by two compared to the former version of the algorithm. This reduction is however still applied to the buffer time allocated to the whole group and shared between trains, that is to say to the buffer time divided by the number of trains, which is actually a very small amount. This is illustrated in the following example.

Example:

The theoretical duration of a round trip is 3600s.

During a 1h time slot, a headway of 240s is to be ensured, leading to a need for 15 trains.

If 16 trains operate the line, this leads to an additional buffer time for all trains of 240s.

In the headway reduction feature of the algorithm, the allocated time that can be regained for

each train is therefore $M_i = \frac{240s}{16} = 15s$.

However, as we progress along the group, the possible reduction increases and, if the reduction coefficient is set to 100%, at the end of the group, the whole buffer time would be reduce. In the example, this means that after the 16th train, 240s can have been recovered from if necessary. This, however, means that after the group, there is a risk to have a gap of 240s until the next group. Now, if the coefficient is set to 200%, the 240s will have been recovered from after the 8th train.

Even though the idea was indeed to speed up the process of delay recovery, it is still important to ensure regularity, which may be the reason why the headway reduction was kept this way. Furthermore, if the coefficient is set higher than 100%, at some point in the group,

the trains will not be able to leave at the calculated time, leading to a need for a parked train to replace another one, or to operate with a gap between departures.

Therefore, this new version of the algorithm not only takes into account the driver's need more than the previous one did, it primarily puts the emphasis back to transport production rather than regularity, which might be a good thing from the operator's point of view, but needs to be used cautiously for the sake of a regular traffic and a correct level of passenger service.

7.2. Challenges for the new system

7.2.1. Important parameters

As it was understood, the reason why any attempt at automatic regulation on the line keeps failing is that the parameters fed to the system are not, and cannot be, a good representation of reality. Therefore, in order to avoid the same problems for terminal management, a special attention needs to be given to the various parameters involved in the calculation of departure times.

The main goal here is to make sure that the calculations regarding the time spent in terminals, and the minimum time needed to be spent are close to reality. Indeed, every delay recovery strategy in terminals, whether it is done through applying constant headways or simple buffer time reduction, relies on the possibility to reduce terminal buffer time as much as possible. In order to get a clear view of what amount of time can be gained in terminals, one needs to know the minimum amount of time that needs to be spent in the terminal. In the general situation, the train is turned around between its stay at arriving and departing quays. Possibly it is parked between arriving and departing, but since the aim here is to understand the minimum time needed in terminals, this option is not being considered in this particular analysis. The usual extreme situation is therefore as presented in Figure 21.

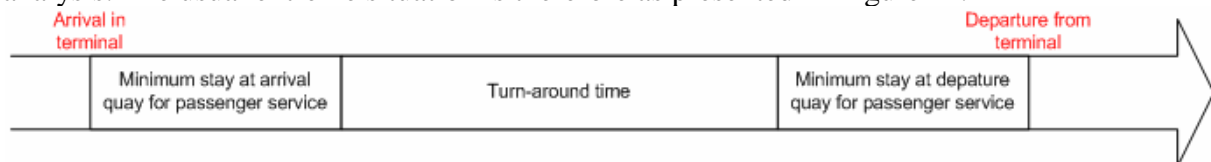


Figure 21 - Minimum stay in terminals

Before getting into the problem of turn-around time, it should be mentioned that minimum stays at arrival and departure quays are the same and do not differ from one line to the other or between peak and off-peak hours, staying equal to 30s no matter what the conditions are, because they are highly related to social issues caused by the driver's working conditions. It is therefore important for drivers, who like operators are subject to frequent change of lines, to apply the same waiting policy at terminals. The question could actually be raised as to if this is coherent with the real needs of passengers and of operators.

Another difficulty appeared with the minimum stay at departure quay. Indeed, for security reasons, before a train leaves a terminal a warning signal needs to be emitted and last for 5s. After this, there is a security time of 15s before the signal at the beginning of the quay can become green. This means that there are already 20s during which the train needs to stay at departing quay. However, when the system was first implemented on line 3, the signal was emitted at the calculated departing time, thus leading to an inevitable delay of 20s at every departure. This was soon fixed, but raised the problem of applying a good calibration of parameters, especially since this problem had not been foreseen, even during the on-site try outs of the system.

As for turn-around times, their calculation depends on the characteristics of the terminal and on the number of people performing the manoeuvre. The two possible arrangements for the

track are either a U-turn, and thus only one driver is necessary for the manoeuvre, or a single track. With a single track, the manoeuvre is performed either by two persons: the first driver leaves the arrival quay and enters the turning track in one direction. The other driver who waited either at the end of the arrival quay or at the beginning of the turning track lets himself into the driving cabin at the other end of the train and immediately takes control to enter the departing quay. When only one driver is available for this manoeuvre, this means that he needs to walk all the way from one end of the train to the other, leading to an additional time of around 20s. Nevertheless, this amounts to various turn-around times (at least 2, or even 3 depending on the terminal) that need to be rightly calibrated, and would still be a function of human behaviour, which is difficult to model.

All those parameters are important to determine rightly for the sake of algorithm reliability. One could think that since the problem is of merely a few seconds, it is secondary. However as it was explained, in the metro lines, even a few seconds are critical to ensure regularity, and thus it is important not only to have a clear definition of those times, but also to apply the right ones to the right trains depending on its program in the terminal.

7.2.2. Expectations

It makes sense that when having this system implemented on a metro line, its operator expects it to perform at least as efficiently as the former one. It was, anyway, what was asked of this project. However, the investment put on this operational modernisation was such that it was actually hoped that this system would help improve the situation on the lines, especially in the case of line 13 who is not only suffering from passenger saturation, but also has a very difficult profile of operations being a branched line, but more importantly having a very short headway between trains at peak hours.

Indeed, the margin between minimum technical headway and programmed headway is a very critical aspect for operations. The shorter the headway between trains, the less time they have to recover from delays, but also the more damage one defected train can cause on the overall situation. Thus, the margin is very small (getting as low as 5s on some lines at peak hours), the line becomes even more unstable, and at risks of having a much degraded situation very frequently, leading to a loss in production and a poor quality of service. As it turns out, the lines that are considered a priority for modernisation projects are the ones with the shortest margins, which makes sense because for this reason, they are also the ones with the more problems regarding transport production and quality of passenger service, as presented in Figure 22.

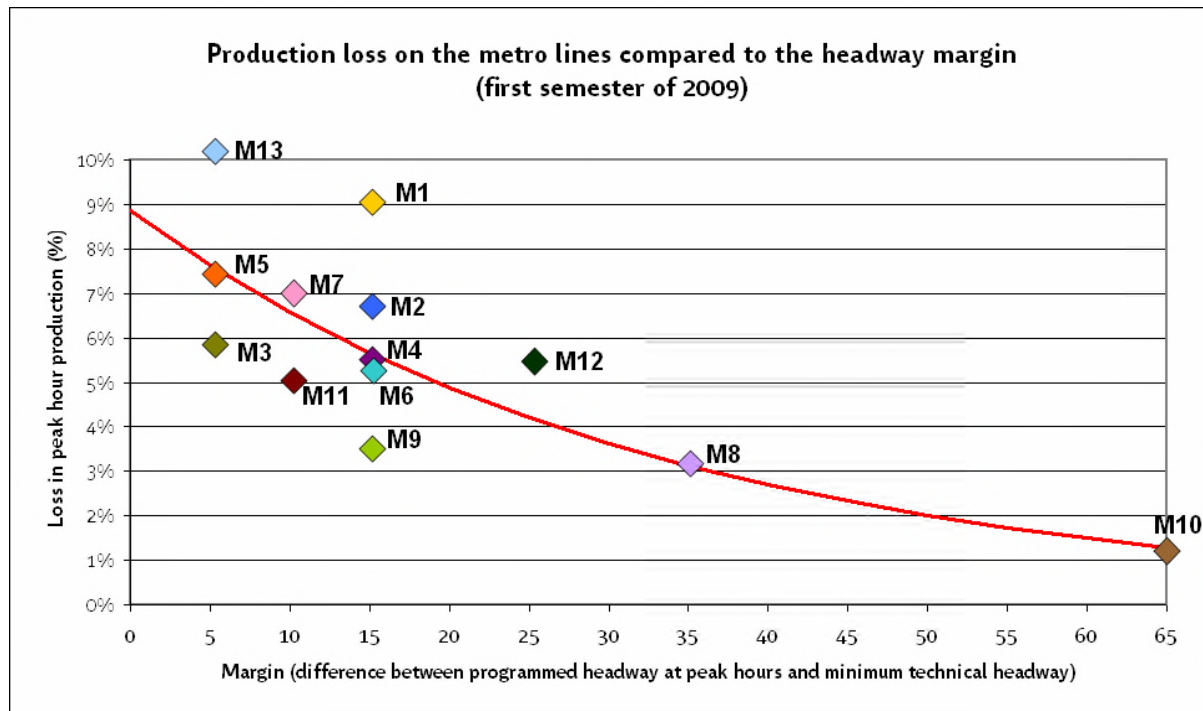


Figure 22 - Correlation between margin and production loss (RATP, 2009)

It was thus expected that the modernisation plan would help operations on the line, and would allow for a more efficient use of infrastructure and an improvement in passenger service by increasing the capacity of the line. Regarding the PCC project itself, it was expected that the use of the new system would first of all reduce the time needed for a degraded situation to get back to normal operations, and that it would reduce thus reduce the impact on production of incidents, thus leading to a reduction in the number of lost laps for schedule compensation. Whereas the first aspect is very difficult to assess, the second one is at the core of the analysis that is presented in the next part of this report.

Finally, one of the main challenges of this new system was its acceptance by people who were to use it, both operators and maintenance. This issue is addressed in chapter 8 regarding operator and the new system. It was however planned all the way through to implement a drastic change in the organisation of operations, which was indeed the case, the problem now is to understand how this was felt by the people whose working conditions were so greatly modified, and how it actually changed their working habits to have this new organisation, but also those new tools.

7.3. Conclusion

On paper, this new system seems to answer the requirements of RATP, both on the technical level of developing tools according to the regulation methods that have been in use for more than 40 years, but also on the institutional level. Indeed, with this new system, not only have operators changed their organisation by moving to other places of work, grouping regulation actors together, being separate from the other lines but closer to their own fields of operations, their responsibility have also changed. This is especially the case for the terminal manager, who has seen an inversion between his and the computer's functionalities.

The questions to be asked now regarding this system are how it actually affected operators, and what are their impressions and feelings towards it, but also on a more objective level, how it actually affected operations on the line, which can to some extent be answered with a data analysis. Those questions are the object of the next part of this report.

Part I – Project background

Part II – Metro Traffic Regulation

Part III – Performance analysis

Chapter 8 – The operator and the new system

Chapter 9 – Framework for the data analysis

Chapter 10 – Data analysis observations

Chapter 11 – Improvements and drawbacks of the new system

Chapter 12 – Study of the system's behaviour

Part IV – Conclusion

If on paper, everything seems to be in line with requirements, the general impression is not completely in favour of the new system. This part of the report attempts to underline the causes for this. The objectives of the PCC project did not mention much about performance regarding regulation and quality of passenger service. Nevertheless, it was obvious that the performance of the new system should be at least as good as the one of the former. As the results in this regard did not completely satisfy the operator, it was deemed interesting to conduct the performance analysis presented in this part of the report. Indeed, with the modernised PCC, three main aspects have changed: the organisation of operations, the tools being used, and the methods implemented for regulating the traffic. The effect that this had on operations are assessed here, first from the operator's subjective point of view, and then through an analysis of the operational data made available by the metro department. Finally, in the last chapter, an attempt was made at studying the system's behaviour in order to try and see if already some improvements could be made to the algorithm or its parameters.

Chapter 8 – The operator and the new system

With the implementation of the modernised operational control centre, the operators' work was greatly modified in their day-to-day operations, but also in the general methods. The object of this chapter is to understand how so, and to describe the impression, assessment and feelings of operators about this. Those changes are classified in three categories that correspond to the three major types of changes that were experienced for the line operators. First, the actual tools that operators are using (computers, means of communication, visualisation tools...) and the environment in which they work were reformed, which is the object of the first part of this chapter. Secondly, operations on the line were reorganised with the gathering of all operators in the same place nearby the actual field of operations and the separation from other line for line traffic control as described previously. The second part of this chapter explains how this actually affected the operators work and habits. Finally, the regulation system itself did evolve through the development of the algorithm and the assessment of the operator over this particular function of the operational control centre is given in the third part of this chapter.

8.1. Advantages and difficulties of the new tools and environment

It would not really make sense to try and compare the equipments of the Bourdon PCC to those of the modernised PCC, since more than 30 years of technology separate them. Nevertheless, one can assess whether or not the new tools and environment are considered satisfactory by the operator. Overall, the answer to this question is that both the terminal managers and the traffic controller are happy with the tools that were developed for their functions, and that operators are all quite satisfied with their new working environment.

8.1.1. New tools are appreciated but difficult to adapt to

In the case of the traffic controller, there were not much new functionalities in their specific tools, and the main evolution for them is that instead of having a button-control panel, they are now using computers, which are, to their opinion, clearer and more easy to use. Furthermore, they have dedicated screens displaying the situation on the line on their desk additionally to the optical control panel at the end of the room, which in their opinion facilitates their work a great deal.

As for the terminal managers, it is them who were really given tools very different from the ones they were used to. The first one of those is the circulation list that displays the departures as presented in Figure 19 (6.2). With this new visualisation tool, they have a more complete overview of the situation in their terminal and can anticipate further in the future. In the former system, they could only have an idea of departure time for the next few trains to depart, and were thus obliged to work and take actions in the moment and as things came, whereas now, they can foresee the times for the whole day and have a more global approach of things. Furthermore with the lists, they immediately have a visualisation of the effect of their actions on other trains. Nevertheless, it was observed that most of the terminal managers still considerate their computer to be the same as the old departure machines, but with a little more visibility on the future, which is not the way it was thought of and developed. Thus there are some complaints from the terminal managers that they cannot really apply there old ways for terminal recovery and delay distribution, but on the other hand, they do not use some other functionalities of the system. This is further expanded on in the third part of this chapter, as it relates more to the regulation methods applied in the news system than in the tools being

used to do so. Other than the list, there are new functionalities that are quite valued by the terminal managers, and especially one that allows for a visualisation of all the drivers of the line and their program of operations. All in all, the new tools for terminal management are much appreciated by their users. However, there is, in their opinion, a problem regarding the people who have to switch from this modernised system to the old ones. Indeed, it is very frequent at RATP to have agents asking for mobility and changing lines in which they operate. The problem here is that if a terminal manager is now trained first in the new system, he will have great difficulties to switch back to the old one if he changes from a modernised line to a classical one, as long as all the lines are not modernised. Furthermore, when a new terminal manager arrives from a non-modernised line, it does take him some time to get acquainted with the new tools and be confident enough to use it on his own. Much is done in this regard, and special training equipment for each line has been developed to help people discover and get used to the new system. Nowadays, only five lines are equipped with a modernised PCC (lines 1, 3, 4, 13 and 14), it therefore still makes sense to first train people on the old system – as operators are trained before knowing on which line they will be working – but when the next two PCCs will be implemented on lines 5 and 12, that would make up for half the lines, and the question will have to be asked whether there should be changes in the training methods. This problem is further addressed in the last part of this report as a ground for improvement regarding training and technical accompanying of operators.

8.1.2. Importance of the new environment

Other than the tools being used, the working environment has also changed for operators. Without speaking of the reorganisation of operations, which is addressed in the next part of this chapter, it is interesting to reflect on the ergonomics of the operational control centre room itself. Now that all the lines are to be equipped with a decentralised PCC, they also have different places and rooms. Indeed, if it was possible to have the same generic system on the lines, having the same physical room was quite impossible. Since the project management team was aware of the importance of this aspect, the room layout, the furniture, the lights, etc... were also the object of very specific requirements that were described in very official documents. The furniture to be used was designed specifically for the needs of the operators, leading to the choice of curved desks that would all face the optical control panel in two ranks. Even the chairs to be used by each operator, and the additional ones were specified in the requirements. This might not seem important at first, however, the operators who are to work in this environment are supposed to spend seven hours straight with their attention focused on their screens to detect the slightest problem and keep an eye on every thing at all time. It is therefore very important to make sure that they will have to do so in the best possible conditions. It is interesting here to mention the differences between the two PCCs that are already in service. The one of line 13 merely has a window that does not provide much light from the outside, whereas the one of line 3 is much more enlightened by the numerous windows and the natural light coming from them. Thus, it is actually much more agreeable to be working in the PCC of line 3 than in the one of line 13. However, in times of a very bright weather, it is also more difficult to distinguish the optical control panel in the room of line 3. Those particular problems were not really thought of beforehand, however, they are now being taken into account in the development of the next PCCs. All in all, it is considered more agreeable to work in the PCC of line 3 than in that of line 13. If the reason for this is the problem of light and the ergonomics of the room, or if it is also related to the general working environment of the line and the operational profile (line 13 is a more busy one, thus there is more work to be done) is a rather difficult question to answer and relates more to human psychology.

8.2. Reorganisation of operations

The major change in the modernised PCC is the fact that it completely reorganises the way operations are being conducted. The operational control centre is now called a « decentralised PCC » for it is decentralised from the rest of the network, with the detachment from the Bourdon PCC. However, it is also a centralised organisation, which now revolves around the line as a whole since all operators have been gathered in the same place close to the field of operations. The main aspects of this evolution discussed here from the operator's point of view (the external point of view on the choice for this new organisation of the writer of this thesis is presented in chapter 15) are

- for the traffic controller, the separation from the other lines, but the newly felt proximity to the line;
- for the terminal manager, the separation from their terminals;
- for every one, the gathering in one place.

8.2.1. Traffic controller separated from the Bourdon PCC

Before modernisation, the traffic controller used to be located at the Bourdon PCC, along with his peers from other lines which allowed for several advantages. First of all, there was a true sharing of knowledge and experience between traffic controller that was very valuable. Indeed, when one of them is presented with a problem on his line, the other ones can give him much needed advice if they are familiar with his line, or if they have themselves faced the same kinds of problems. Furthermore, in case of a major incident on the line, the traffic controller alone is not sufficient to solve the crisis. Indeed, between taking actions, communicating with the drivers and the terminal managers, relaying the information to stations and passengers, calling the maintenance team and sometimes the safety officers, filling in the obligatory forms and the reporting tool in the computer, one person alone is not at all sufficient to solve the problem in a timely manner. When such a situation occurs, the traffic controller is often helped by his binomial operator (lines are grouped by pairs because of material organisation, thus leading to a pairing in operations as well) or even by others if needed. This sharing of experience and support from other traffic controller is not possible anymore in the new organisation for PCCs that were detached from the Bourdon PCC, and it is greatly missed by them. Even more so, at night, when there is no traffic on the line, there still needs to be a traffic controller in the operational control centre to oversee security, especially when work of construction or maintenance is being conducted on the line or the stations. In Bourdon, that means there is one traffic controller for two lines, thus leading to at least 4 people in the room, whereas in the decentralised PCC, the controller now has to spend the seven hours of the night alone, which is a much more difficult task to accomplish, both for agreeability but also for responsibility and security reasons. Finally, the last aspect that traffic controller seem to regret from the former organisation is that they are now completely detached from the rest of the network. Although there is a new sense of unity within the line, as it is described later on in this part of the chapter, the controllers feel that they do not know at all what is happening on other lines, other than by the institutional information, and that the other lines do not know what is happening on theirs either. This is to be related with the problem of knowledge and experience sharing, however it is also a problem regarding operators mobility, since now, if they want to change lines where they work, they have less ways of knowing which like they would prefer to be affected to, or if they are presented with the option of changing to another line, they do not know its general situation and would need to learn from scratch. This is also a problem on a psychological level, as traffic controller of modernised PCCS are more and more losing what the French call “*esprit de corps*”, that is to say the idea of belonging to a group within society, here the traffic controller group. Even if

that is not of so much importance for operational issues, it is a bit resented by controllers who do not have contact with their peers anymore as they did before.

However, being detached from the PCC Bourdon led, among other things, to being closer to the line itself. This is important psychologically speaking, for them being physically closer to the line is felt by drivers as if they were also operationally closer to them, even if the communication methods have not changed a bit between them. Indeed, the Bourdon PCC is a very important symbol in the metro operations at RATP. It is a place that somehow inspires respect to those who visit it. When one first gets into the room, he is led into a corridor above the room itself with windows that allows overseeing operations from the above. When it was first implemented in the 70s, people working there were instructed to wear white lab coats, which are still being used by some to those days. The lights in the room, the large number of control panels, the general atmosphere add up to all those features to create some kind of sanctuary to the eyes of the metro department, and of RATP in general. The function of traffic controller in the Bourdon PCC is thus somewhat sacred, which provides the advantages of being sure that drivers will respect the instructions, but this is actually ensured anyway by their training and the security procedures, but it also has the inconvenient that the drivers feel that this person who gives him order from above is very far away and not aware of the reality of things on the field of operations. With the decentralisation, this perception of sacralization is decreasing. Controllers are perceived as being closer to operations, which is felt by a great advantage from their point of view but also from that of drivers.

8.2.2. Terminal manager separated from the terminals

While traffic controllers feel that they have been brought closer to the line, the exact opposite was observed for terminal managers. Indeed, they used to work directly from their terminals, which meant that they had a good knowledge of the physical layout of the terminal, of the critical points, of the possible technical failure... Being separated from the terminals means that they do not have this direct relationship with the terminal environment, and thus have a risk of losing sense of the field's reality. This is not so much a problem now, as the terminal managers who operate on the modernised lines are all from the "old generation", meaning that they were already operating under the former organisation, and thus are quite acquainted with their terminals. However, when new terminal managers will arrive on the line, current terminal managers are afraid they will not be acquainted enough with the terminals to apply the right methods in their work. The other aspect that terminal manager have lost in this relocation is the proximity and direct relationship with drivers. Indeed, when they were in the terminals, they used to work directly from the departing quay, and thus, they had a direct contact with drivers. With the new organisation, they do speak to each other, but they do not actually see each other, which is greatly felt by both drivers and managers. Terminal managers do have cameras that allows for them to see every thing that is happening in the terminal, so this is not so much a problem regarding operations. This is once again a psychological problem, especially from the driver's point of view, which feel very much alone nowadays on the line, as the day passes and they do not see any one from the operating team else than the other drivers. Furthermore, once again when new terminal managers will arrive on the line, they will not be acquainted at all with the drivers. The same goes for new drivers who would have to take orders from people they very seldom see.

8.2.3. Gathering of all operators in the same place

Nevertheless, if this new organisation came along with regrets and some resentment from operators, it also brought back a sense of unity within the line units, still a psychological

aspect, but also to a better communication and integration of every one within the same system, which led to several new advantages in day-to-day operations.

Before this re-organisation, the terminal managers were in their terminals and the controller at the PCC, while the director of operations and his staff, the other teams of the line unit (infrastructure, rolling stock, stations, accounting, human resources, etc...) would be in another one. Thus, while operations are the most important and critical feature of the line's unit, they very much separated from the rest of the line's staff. This is not the case anymore, having every one work in the same building, and furthermore, the director of the line is now much closer to the operators, and much more aware of the reality of the problems encountered in day-to-day operations.

Not only were operators brought closer to the rest of the line's unit, they were brought together. All actors for regulation and operation on the line now work from the same place, which has the great advantage of facilitating communication. In the former organisation, the two terminal managers and the traffic controller had to keep each other informed of the situation in their field of operations and of their action at all times, and thus by phone. However, communicating with the other two was never a priority, and it would happen often that one would forget to do so, and thus the other two would be presented facts and problems without warnings. Now that they are all in the same room, this is not a problem anymore. Indeed, terminal managers and traffic controllers have quickly developed a habit of speaking while taking actions in order to inform every one else in the room in real time. When an incident occurs on the line, the first person to be warned is the traffic controller, who would usually then have to warn the other ones. Being in the same room, this is not necessary anymore: any information that is given to either the traffic controller or the terminal managers is heard by every one, as it is always communicated either by radio or phone with speakers on. All information is thus transmitted to every one much more rapidly. It is worth mentioning that in the PCC, there is a person in charge of station information. Whenever this person hears of a situation that might slow down traffic on the line and bother passengers, his role is to warn all the stations of the line so that they can inform passengers waiting there, and all the connecting lines station information person so that they can be kept aware of the possibility that an unusual number of passenger will try and take a diverting route. This aspect tackles with the problem of network awareness that was mentioned earlier in this part of the chapter and goes along with the great improvement that were noticed regarding communication on the line.

Furthermore, they all have the visibility of the situation on the line through the optical control panel, which was not the case beforehand. They also have access to the other one's tools (line control, terminal circulation lists, driver's management, energy...) if they want to take a look and be informed without having to bother the others. Therefore, operators are a more complete vision of the situation on the line, and the communication between them is completely fluid. Furthermore, they all have a clearer idea of how the other ones work, making the understanding and the communication between them even easier. This is especially the case for terminal managers. Indeed, they used to be dedicated to one terminal only, without really knowing the other one, or being aware of its particular specificities and difficulties. In the new organisation, the management of both terminals is done the same way, and they can thus exchange roles if they want – and this is actually asked of them in both lines 3 and 13 to make sure that they are able to operate both terminals at all times.

8.3. Operator's assessment of the regulation system

Before looking into the actual performance of the system regarding regulation, which is the object of the next two chapters, it is important to describe and try to understand the opinion of the operator towards it.

First, of all, regarding automatic regulation on the line, it was already mentioned that this feature is neither working, nor wanted by the operator. First of all, it is based on parameters that are too difficult to model to be reliable, and indeed, when it is being used, it actually adds up even more delay than without it. Furthermore, when there are no incidents, the work of the traffic controller is only to keep an eye on the situation on the line and make sure that headways between trains are more or less equal. If not, he can himself ask the drivers to wait for a while, which does not take that much time or effort. Furthermore, the traffic controller actually knows how to do this from both his training and his experience, and it does not really make sense to take this function away from him, as otherwise this would mean leaving him to do nothing, at risks of having his attention decrease too much. Thus, the working methods of the controller regarding regulation have not changed much, aside from the advantages of a better integration and communication with other actors.

On the contrary, the work of the terminal manager has been greatly modified regarding regulation. As the system was thought and developed, the responsibilities of both are supposed to have been exchanged between regulatory actions (formerly the terminal manager, now the automatic system) and control (formerly the system, now the terminal manager). However, the terminal managers are not satisfied with the recovery mode that was developed for the calculation of departure times. The recovery mode was supposed to be the main one, to be used at all times without the terminal manager having to interfere. However, operators feel that the recovery capacities are not used at their best with this mode, and thus at peak hours, they do not use it and prefer to operate under constant headway mode, choosing the headway to apply themselves. Nevertheless, it is not possible for them to apply the constant headway they would like to at all time, since otherwise, there would be a gap at some point between departures. Thus, as they describe it themselves, the work of the terminal manager is to apply a short constant headway, until it cannot be done anymore because it would lead to a departure time earlier than the earliest possible departure. They then switch back to the recovery mode, in order to put back some delay on the terminal, and then again to constant headway, and so on... In this sentence lies a key problem of the recovery mode: it adds delay to the general delay of the line. This is not a malfunction of the system or an error in the development. Indeed, the recovery mode is conceived to have the general delay shared between trains to ensure regularity. The real problem is that terminal managers do not care so much about regularity, and they prefer to have train leave the terminal as soon as possible, especially at peak hours since they need to ensure the transport production. As it was mentioned before in this report, ensuring the transport production and regularity are two goals that are sometimes contradictory. Indeed, when one wished to have a smooth equal headway between trains, he has to delay some of them and retain them longer than necessary in the terminal. On the other hand, when the terminal manager is running behind on the program of operations, his goal would rather be to make sure that as many trains as possible leave the terminal as soon as possible, leaving problems of regularity to be handled by the line traffic controller. This is especially important since it might happen that if trains are being detained in the terminal, there would not be space anymore for the next trains to arrive without having to change the parking spaces of some trains, thus taking some time, and leading to an increased delay on the line while trains wait to enter the terminal.

A solution to this problem, as proposed by operators would be to add modes to the existing ones, such as an “earliest possible departure mode”, or some kind of semi-manual recovery mode in which the terminal managers would be able to choose the number of trains on which to share delay, like they used to do in the former system. The problem here is that this would mean reversing to a mode of operations where the terminal manager takes charge over the

machine, which was not the objective of this new system. This is further discussed in the fourth part of this report.

The last problem that was observed regarding the way terminal managers use the regulation system is that they do not understand how it works very much. Whereas they do know how to use it, and the general principles behind it, they are not especially aware of how those calculations are being made, or to what they correspond, thus leading to misinterpretations on their parts, and complaints that are not always founded.

8.4. Conclusion

All in all, this reorganisation of operations brought both inconvenience and advantages. However, one could argue that the inconvenience it brought are mostly psychology-related issues that are not of great importance to the well-being of operations, especially since psychology, opinions and habits are bound to evolve at some point. People do not like things to change, that is a well-established fact, once again witnessed in this project. However, since this change also brought some consistent advantages, all cannot be taken as bad.

The main advantages that come out from this are the availability of the new and improved tools for operators, in an agreeable environment. The decentralised PCCs are places that people like working in, and their tools are much valued by users. Furthermore, the new organisation as led to a better communication, and possibly thanks to that an increased level of reactivity to incident solving. While traffic controllers were brought closer to the line, terminal managers were retrieved from it, to get to a common location in the middle, where they can have the same visibility. Finally, if this decentralisation has made people lose the sense of unity that existed in the overall metro network, it has greatly helped create a sense of unity within the lines unit, and after all, since operations from one line to the other are completely segregated, one can wonder whether it is more important to have a united network that lacks of independent units, or to consider each line as a whole, independent and fully-functioning body.

If operators are overall satisfied with the system, they do mention however that its performance regarding delay recovery and regularity are not as good as they expected, and they even complain that situation was better before. Assessing if this is indeed the case is the object of the rest of this part of the report through an extensive data analysis that was performed using operational data of lines 13 and 3.

Other than this problem of performance, it should be mentioned that the general opinion of operators, reflected in the words of the current director of line 3, is that this system does not take human beings into account as much as it should, especially for the calibration of some parameters. This was done without always thinking about the differences that can be caused by human apprehension, especially since all drivers do not have the same way of driving or performing the same manoeuvre. The larger problem here is how to implement automatism in a system that is operated by humans. Indeed, human behaviour, whether it be that of the passengers, of the drivers or of the control operators, is very difficult to manage and take into account in automatic system. All in all, the metro operators and manager feel that it might have been more appropriate to develop an assisting system rather than a deciding one, and leave the responsibility of taking actions to the terminal managers and traffic controller, with the help of the system to make the calculation and model the actions in real time.

Chapter 9 – Framework for the data analysis

Using the operation data provided by RATP, and especially by what is called the IGT and the OSIRIS database, it is possible to some extent to assess the performance of the regulation system in place. However, before doing so, it is important to have a good understanding of the data available and a clear idea of the evaluation and comparison methods to apply. This is the object of this chapter, in which first the IGT and the OSIRIS database is presented, then the data relevant to this study is expanded on with the method for the data mining and analysis is presented. The last part of this chapter gives on the one hand the criteria for the data analysis, and the results that were expected to be found beforehand.

9.1. Operation reporting and database: IGT and OSIRIS tools

9.1.1. The IGT: automatic reporting of train movements

IGT stands for Indicateur Graphique du Transport – Graphical indicator for transport. It is a tool where all circulations are automatically recorded and therefore give a detailed report of every train movements of all the lines of a chosen day. To that end, all train movements are recorded through the information collected directly on the tracks, that is to say for all trains, the exact time when it entered and left any station, along with basic information regarding the id number of the train, the id number of the driver, the modal type that was being applied at the time... This information is crossed with both the theoretical planning and the calculated time, and the difference between them is calculated for all characteristic times.

In the IGT, it is possible to display for any of the fourteen lines the time-distance diagram, as displayed as an example in Figure 23.

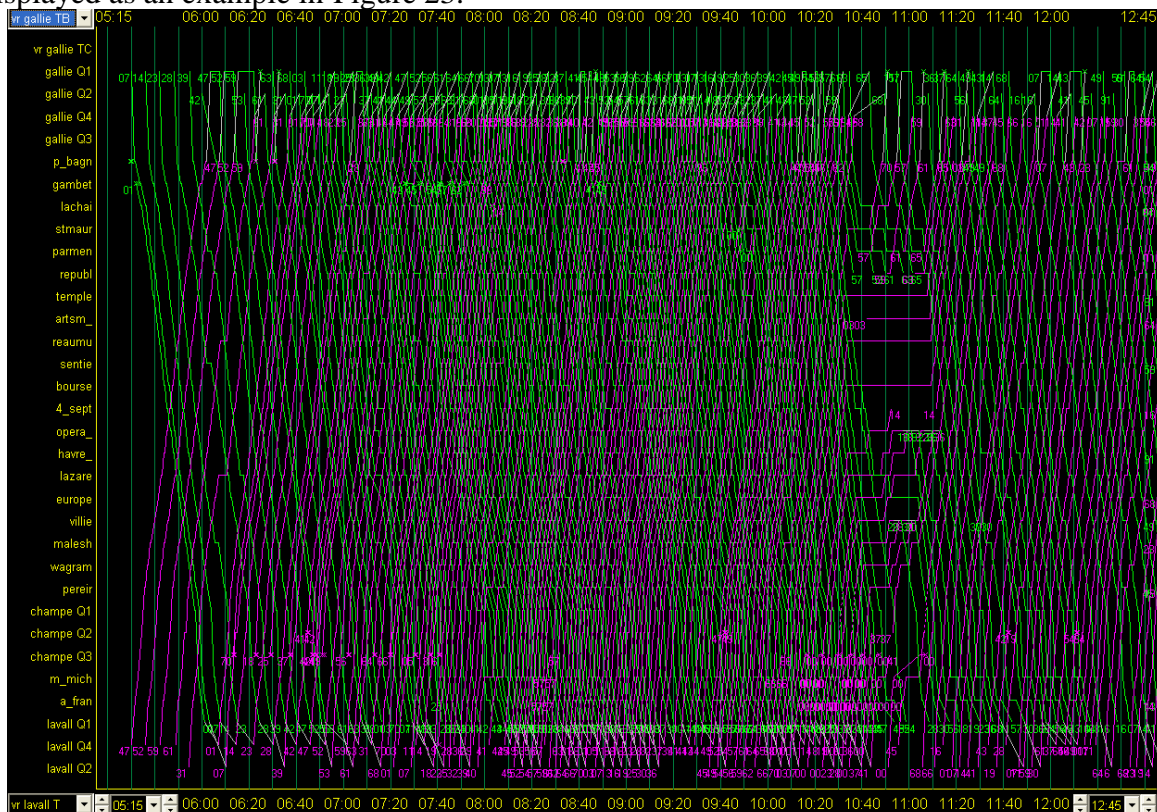


Figure 23 - Time-distance diagram of line 3 on a 26/05/2011 (morning)

The trains in direction 1 are represented in green, the ones in direction 2 in pink. Vertically, the names of the stations are displayed, while horizontally is the time. The theoretical circulations can also be displayed, separately or in the same graph. In the day represented in Figure 23, we can see that there was an incident that led to the use of the short-turns located in stations République and Opéra because train movements between the two were suspended between 10:30 and 11h15.

All the information needed in the establishment of the time-distance diagram can also be displayed in tables, and especially:

- journey listing – list of all the train departures in one direction or the other that actually happened during the course of day with id number of the train, time of departure, calculated time of departure, difference between them, headway that was planned, headway that was realised...
- station listing – for all stations, list of the trains that passed through the station with the times of arrival and departure in both directions;
- train listing: for each journey performed by a train, the times it went through each station of the line (arrival and departure).

Those tables can display either the theoretical data or the realised production data.

Since the IGT also calculates delays and headways, it is possible to display graphs and tables that present the evolution of those data, either for a train, or for a station. For example, Figure 24 displays all the intervals between trains at station Havre-Caumartin on the day displayed in Figure 23. The white lines mark the theoretical interval.

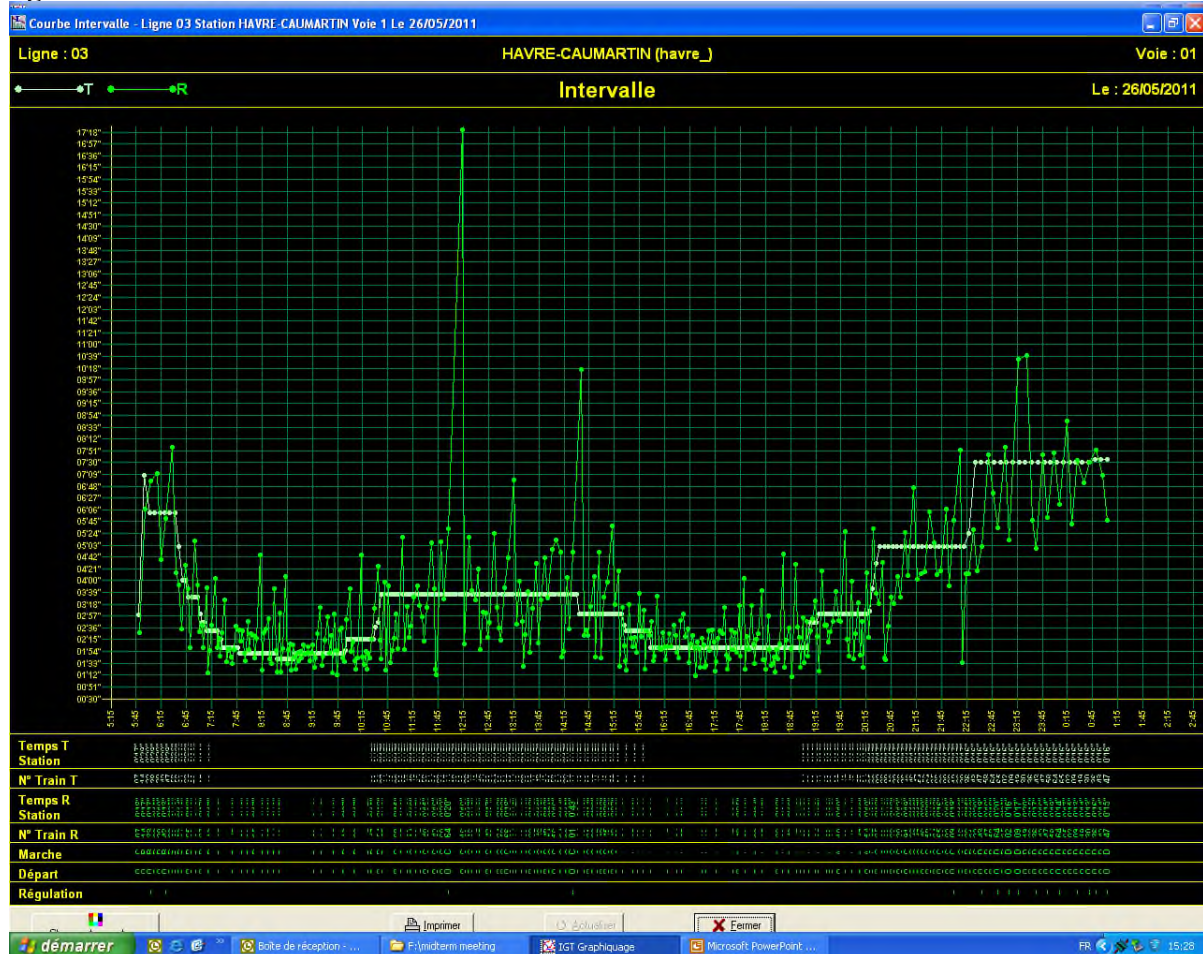


Figure 24 - Evolution of the headway at station Havre-Caumartin during the course of a day in direction 1

The IGT can also display the time spent at stations by each one of the trains, as presented in Figure 25 for station Havre-Caumartin.

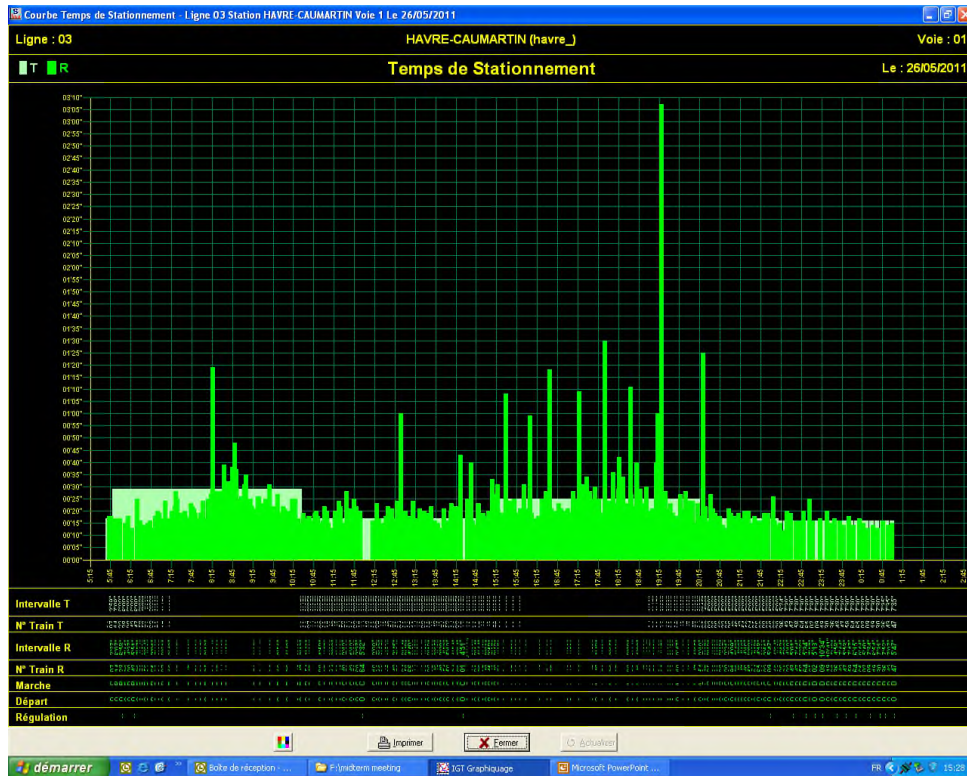


Figure 25 - Time spent at station Havre-Caumartin by trains on a working day in direction 1

Finally, the IGT can also display the general delay during the course of a day, as presented in Figure 26. The delay is taken as an average for each hour of the day between all stations of the line here (however, it can also be displayed for only one station at a time).

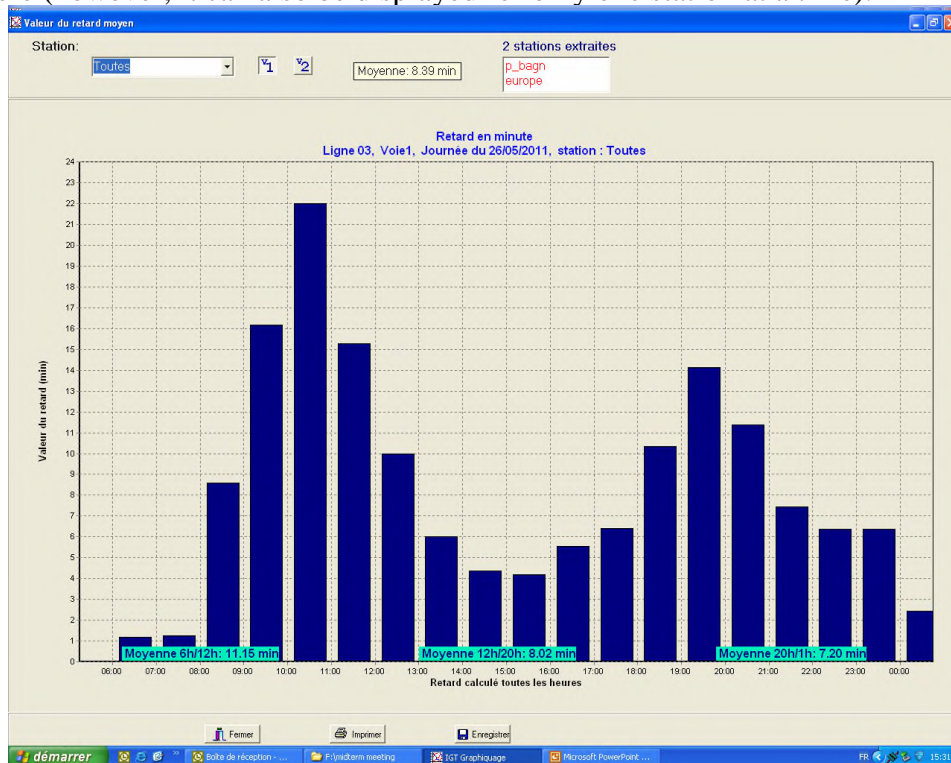


Figure 26 - Delay on direction 1 of line 3 on the 26/05/2011

Figure 26 is one of the diagrams directly provided by the IGT. It can be regarded as a representation of the general delay on the line during the course of one day. For each hour of the day, all delays of all trains at all stations are taken into account in calculating an average for the general delay which is represented here. So-called “delay” is the difference between the theoretical times course of a train and its real times (arrival and departure from stations). The peak hour is easily recognizable here with a maximum morning delay being reached between 10 and 11 and a maximum evening delay between 19 and 20, which is the direct result of the delay accumulated because of passengers and high traffic frequency during the peak hours.

Finally, the IGT also displays the regularity indicator that is to be used crossed with the quay occupation matrices that were mentioned in chapter 2. This regularity indicator is shown in Figure 27.

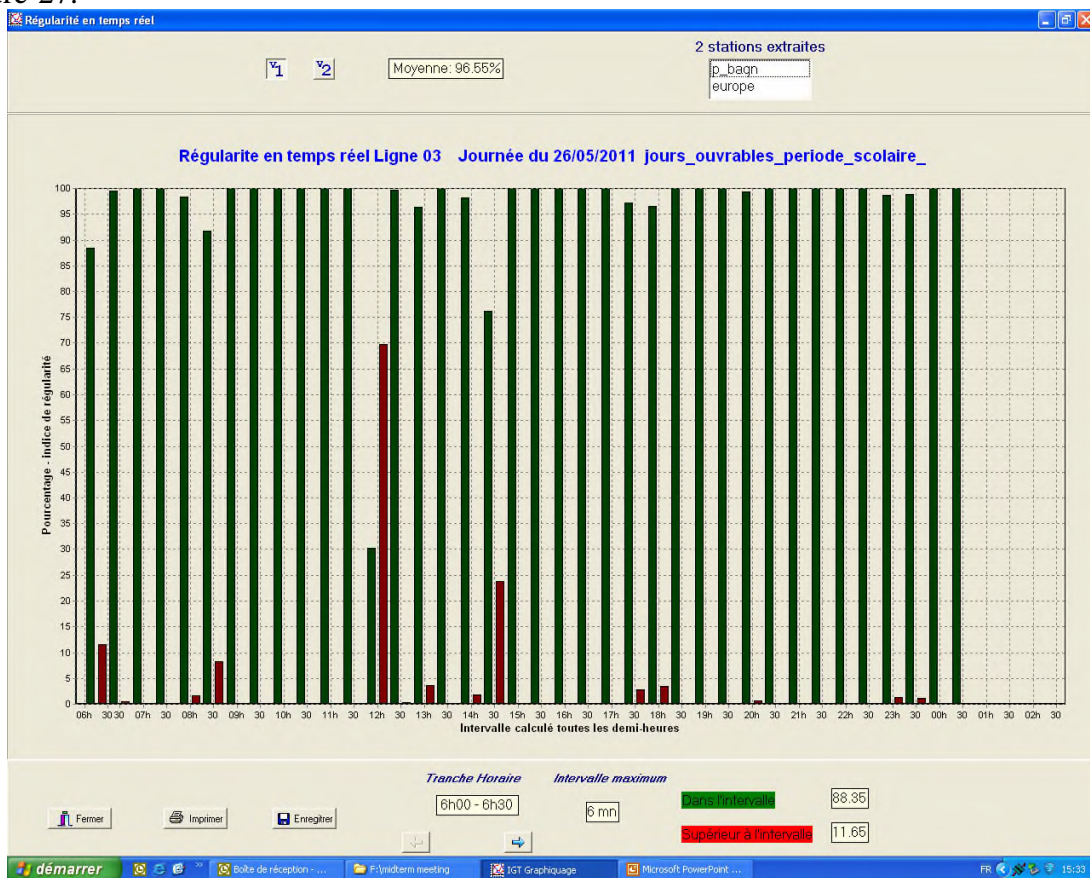


Figure 27 - Regularity indicator on 26/05/2011 for line 3

For each half hour of the day, the average theoretical headway is calculated. The share of trains running with this headway or less in that half hour is presented in green. The complementary number, i.e. the trains running with more intervals than the theoretical one, are presented in red.

The IGT thus gives a very detailed overview of operations on the lines, and a very objective one, as all data in there are recorded without any human intervention. This information is available in real time in the PCCs, both modernised and Bourdon, and greatly used by traffic controller who have thus access to the theoretical program of operations, but also to the actual data. They are made available as archives on the following day to other people at RATP who might need them for the sake of line operations study. However, since this data is very

extensive and memory-consuming, it is only available online for the last six months. All data retrieved by someone is however kept on his personal disk, so one can make his own backup.

9.1.2. The OSIRIS database: reporting of incidents

OSIRIS stands for the French « information system tool for computerized reports and statistics » (Outil du Système d'Information pour Rapports Informatisés et Statistiques). It is a data management software developed specifically for the metro department of RATP in order to help keep track of all the incidents on the network, as well as to keep a record of all the operational data for each line of the network. This paragraph gives a presentation of the aspects of OSIRIS related to traffic control. Indeed, this tool can also provide information on drivers, energy supply, signalisation... that are not useful to this particular study.

The information on OSIRIS is filled in two stages:

- in real time operation by the traffic controller of each line;
- in feedback mode by the head of transport of each line and via automatic database management.

All the data can then be consulted for example for statistical studies or in the case of an investigation on an incident. It is also used as a help when establishing the yearly operating balance between STIF and RATP.

OSIRIS was first implemented in 2002 and has been evolving for improvement ever since. At the beginning of the year 2010, major changes occurred both in the information filling methods and in the data management that changed the user's habit as it is presented in this paragraph.

Filling-up of information in real-time

Whenever an incident occurs on the line, the traffic controller is not only in charge of handling it, he also has to keep track of every single event related to the incident from simple observations to actions that were taken by the operators and total delay that was caused by said incident. For each type of observation or action, there is a pre-entered frame in which the traffic controller has to fill in all the information he can get. For example, the following picture is taken from an operational day on line 3.

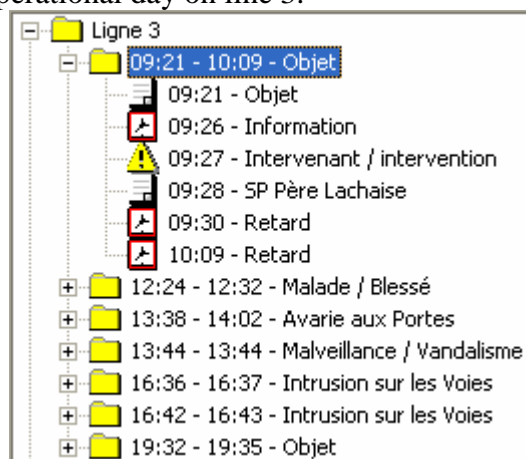


Figure 28 - Screenshot of the reporting on line 3 through OSIRIS

At 9:21, an object was noticed in one of the trains and prevented the doors from closing. Since no one claimed the object at first, the train had to wait for intervention and the traffic controller opened a chain of event with the notice of the object.

At 9:26, information was given to the passengers.

At 9:27, intervention took place, in this particular place leading to the owner of the bag claiming it.

At 9:28, due to the disruption on the line, a train had to change direction (SP) in order to ensure a regular traffic in the direction that was blocked by the train where intervention had taken place.

At 9:30, the train was able to leave the station with a delay that had to be mentioned.

At 10:09, the disruptive train arrived in the terminal with a final delay replacing the former one in the general data of the day.

Those procedures allow for an accurate description of all the events on each line, and as far as this regulation study is concerned, this means that the delay caused by each incident can be found. However, this delay corresponds to the maximum delay on the most delayed train (usually the disruptive train), not to the total delay on the line. Furthermore, until 2009, operators were instructed to fill in only important events (referred to as “incidents”) which could have impacts on operations and security. Thus, the so-called “micro-incidents” that could lead to delays of a few seconds up to 5 minutes were usually omitted from the reporting. However, since the beginning of 2010, it was decided that all events could be relevant to assess the production of the line, and therefore that everything had to be listed. Therefore, whereas the data since January 2010 is a very accurate description of all events, the data before that only shows part of the reality. Figure 29 shows the number of events that were listed on OSIRIS for line 13 between 2003 and 2010.

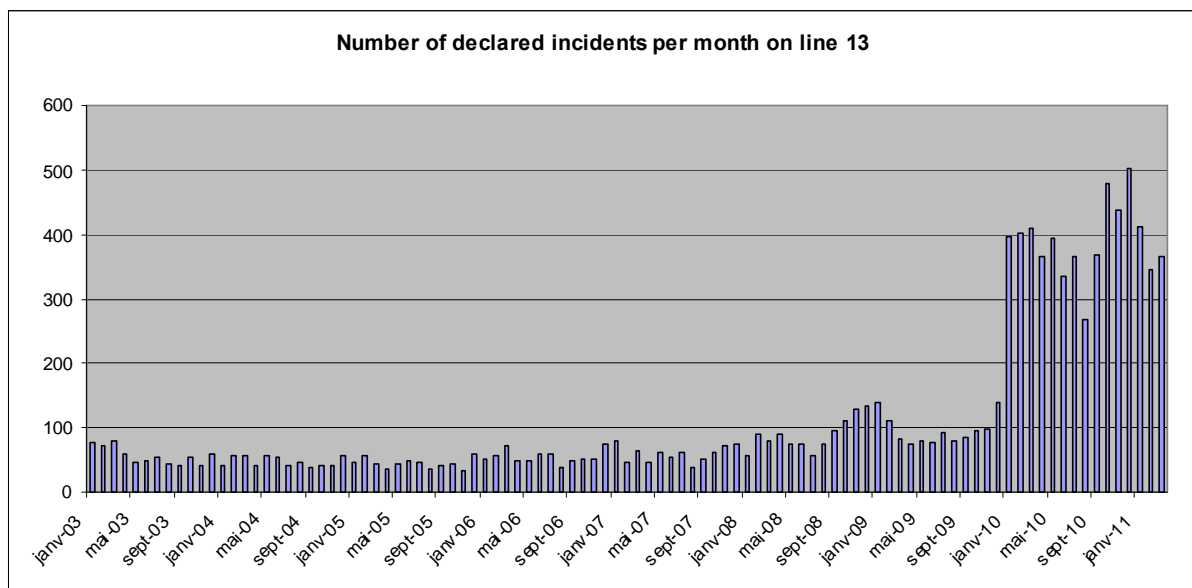


Figure 29 - Number of incidents declared on line 13 in OSIRIS

At first hand, one could say that there has been way more incident ever since the beginning of January 2010. However, such a difference cannot be explained like this, but rather by the changes in the rule of reporting. Figure 30 shows the number of events causing less than 10 minutes that were listed on OSIRIS for line 13 between 2003 and 2010, this time classified by the duration of the delay they caused.

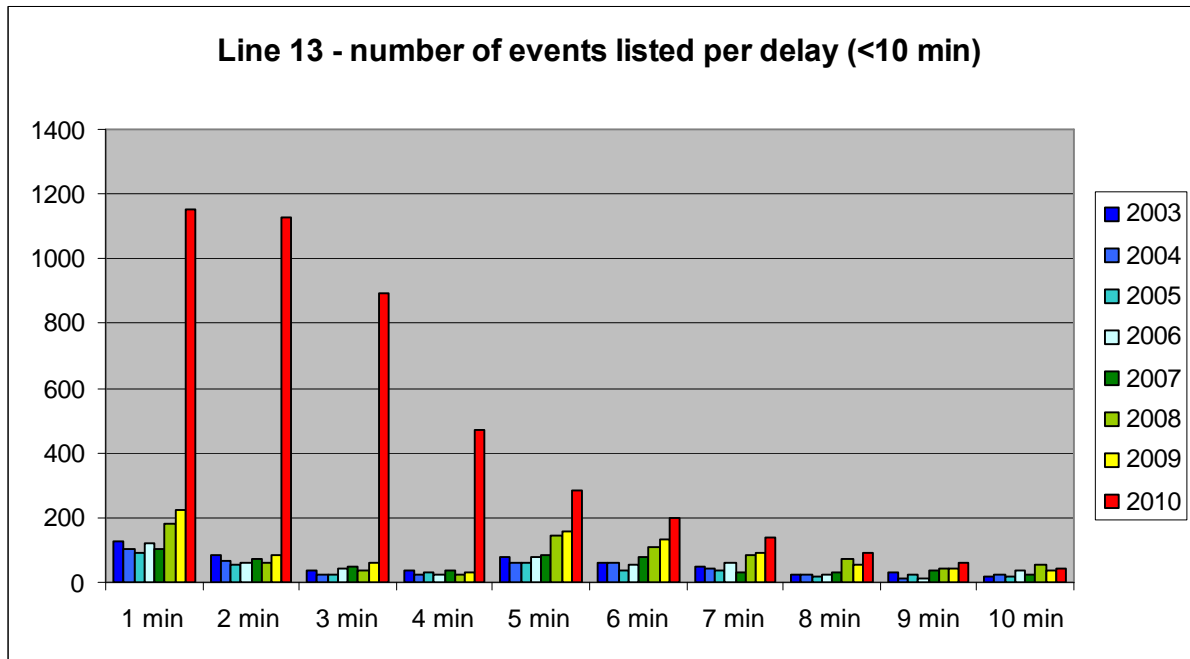


Figure 30 - Number of events of less than 10 minutes in the OSIRIS reporting listed per delay

As we can see, in 2010, there are much more incidents causing 1 to 5 minutes and this is not to be explained by the fact that there were indeed more incidents, but by the fact that the rule on reporting small incident has changed. This evolution in the reporting of event causes a difficulty in trying to compare data from before and after 2010.

Other than this, the traffic controller also fills in the information on the trains that were not able to depart from terminals due to material reasons (not to be confused with trains that are cancelled for regulation). Those are referenced as gross lap loss.

Feedback information

For each line, the head of transport operations is in charge of filling in the feedback data. Indeed, the role of OSIRIS is not only to give a description of operations, but also to provide some analysis on the events, which can only be performed after the operational day is over.

For every operational day, the head of transport operation fills in the total number of trains that did not leave a terminal for their laps, which will be referenced as lap loss, and includes both gross loss (for material reasons or lack of driver for example) and laps that were cancelled for schedule compensation. This number is simply the difference between the theoretical number of laps and the actual number of laps produced.

Furthermore, for each event that took place (incidents on the line and trains not departing a terminal), the head of transport inputs the maximum delay that it caused on the most delayed train, usually based on the reports from the traffic controller, and more importantly for organisational reasons within RATP, designated an entity to be held responsible for the incident (any of the departments of RATP, passengers, weather conditions, fire, or external parties). The responsibility can be shared between several actors.

Finally, the head of transport fills in the “delay after peak”: at fixed times depending on the line and corresponding to the end of both peak hours, the delay on the whole line is listed

(that is to say the difference in time between the program of operations and the actual situation).

After the head of transport is done filling in the feedback information, an automatic feature of OSIRIS provides additional information on the sharing of production loss between actors and between events. Indeed, all the production that is lost during a day is lost because of the events that took place. Therefore, the production loss can be spread between the events of the day by a simple cross-multiplication method based on the delay caused by the incidents. Table 10 gives a simple example of how this works.

Event	Responsible party	Delay after sharing (min.)	Gross lap loss	Lap loss for SC	Total lap loss
Total		39	5	6	11
Lack of equipment	Rolling stock dep.	0	2	0	2
Malicious act	Passenger	5	0	0.77	0.77
Absent driver	Metro dep.	0	1	0	1
Defective equipment	Rolling stock dep. (shared)	2	1	0.31	1.31
	Metro dep. (shared)	2	0	0.31	0.31
System failure	Engineering dep.	5	0	0.77	0.77
Trespassing on the tracks	Passenger	15	0	2.31	2.31
Malicious act	Passenger	5	0	0.77	0.77
Absent driver	Metro dep.	5	1	0.77	1.77

Table 10 - Example for the calculation of lost lap for schedule compensation

Thus, an event that causes delay on the line necessarily causes some production loss for schedule compensation.

9.2. Methods for a performance assessment through data mining

For study purposes, it is possible to consult the IGT and the OSIRIS database via the same software as the one used to fill-in the information. Special access granted by the Metro department is needed to do so. Furthermore, this means that the computer be linked to the Metro information network, which can be quite busy at some time. All the operating profiles of the OSIRIS software having priority on the consultation version, it can sometime take a while to get the wanted information, and it is therefore advised to limit a request to the specific data they want and not extend it too much. For example, it is very difficult to get the list of all the events of a line within a period of more than 6 month without crashing the connexion, and depending on what needs to be done with this information, one can either split the request between smaller periods (one month of data takes approximately 3 minutes to be delivered) or change the nature of the request to a more general table of data (for example a table providing the total number of events and minutes of delay per month can sometimes be sufficient for the purpose of the study).

For those technical reasons, it is important to have a good understanding of the information available and of their organization before going into further study of the data. While the IGT data were only used to assess and understand typical behaviours on the lines, the OSIRIS data was much used to assess the performance of the system, which method is presented in this part of the chapter.

9.2.1. Using the IGT to assess typical behaviour and irregularity

The data available in the IGT presents the inconvenient of dating back from only 6 month, which means that it is not possible to use it to compare before/after situations on line 13. On line 3, the PCC was fully implemented on the 25 of October 2011. For the sake of this study, data was retrieved from the 1st of October on, leaving a few weeks to represent the “before situation”, which was not much, especially since the month of October is never a good representation of things, as it is the months of strikes at RATP (and it so happens that in 2010, the October strikes were of great extent.

Nevertheless, the IGT data could be used to assess at least the typical behaviour of the lines, in order to get a good impression of how operations go, that is to say especially to try and assess the typical delay and headway profile of different days. It was also used to assess the correctness of the modal type, or rather to understand why it was considered not reliable and not close enough to reality.

Finally, an attempt was made to assess irregularity on the lines using the method of Lombart & Favre (1995). This method relies on the fact that it is not so much delay and deviation to the theoretical program that is important in assessing metro operations, but rather deviation from the theoretical headway and irregularity on the line. They use the following formula for the calculation of average deviation:

$$d = \frac{1}{N} \sum_{i=1}^N |I_{real_i} - I_{th}(i)| \quad (18.1)$$

- with d : average deviation from theoretical headway ;
 N : number of trains during the studied period of time ;
 I_{real_i} : realised headway between trains i and $i-1$;
 $I_{th}(i)$: theoretical headway between trains i and $i-1$

The absolute value in this formula attests the fact that from an operator’s point of view, but also to some extent from a passenger’s point of view, having too short a headway is as hindering as one that is too long. Furthermore, a very short headway between two trains does not make up for the very long one between two others. The irregularity coefficient is then defined as follows:

$$b = \frac{d}{I_{th_av}} \quad (18.2)$$

- with b : the irregularity coefficient in % ;
 d : average deviation from theoretical headway ;
 I_{th_av} : average theoretical headway during studied period of time.

b can be interpreted as the share of the service that was not in line with the theoretical requirements.

This method uses the data retrieved from the IGT at chosen stations. It was deemed interesting to study this in three key points of a line: one station at the beginning of the line, which could help assess regularity at departures, one station in the middle and one station at the end, which would help see how the running on the line changes the regularity profile. An attempt was also made at comparing data from before and after the modernised PCC was implemented. Finally, it was also attempted to try and compare the results of different lines, but one could argue that lines having very different profiles of operations, this would not be very appropriate.

In order to perform this analysis, it was important to find suitable periods of times, and thus days similar to each other during which there was no major incident that disrupted the traffic. The study was performed for the 6 different times of days (morning off-peak, morning peak, day off-peak, evening peak, evening off-peak and night) and on average on the whole day. The difficulty of this analysis lied on the definition of the average value for the theoretical headway, as even in the theoretical planning; it sometimes still varies a lot along short periods of times. However, once this was done, the calculation could be applied to any days since they always have the same program of operations, as long as they are of the same type.

9.2.2. Relevant data in OSIRIS

This part of the chapter gives an overview of the OSIRIS data that was considered relevant to the performance analysis of traffic regulation. The idea is to find a way to assess the ability of operators and of the system to apply efficient policies for traffic regulation, particularly for terminal regulation and schedule catching-up. This data is therefore presented from a regulation perspective, and distinguished on whether they are imposed on the system and the operators (exogenous data) or resulting from their actions (endogenous data).

List of incidents and events

Incidents (for the period between 2003 and 2009) and events (2010-2011) are the main reason why there is a need for regulation. Without them, operations on the line could be performed without any traffic control system.

From the perspective of regulatory systems, events are external inputs. They are random and unpredictable, both in occurrence and importance. It is the very ability of the regulatory system to handle them that must be evaluated.

Incidents and events are all listed and available in the OSIRIS database along with the delay and production loss they caused, the party responsible for it, their type... Crossed requests can be performed by type of incident, by responsibility, by line and/or by period of time.

Delay in minutes

For any event, the delay listed is the maximum delay of the most delayed train. It is therefore not a cumulative delay on the whole line, which is not available on any of the control tools of RATP, but rather the time difference with the theoretical schedule due to this specific event. It can also be seen as the maximum delay experienced by any passenger due to this event.

OSIRIS provides this data both in the list of event, and in a database that lists the cumulated delay for each day, along with the number of incident, and that can be requested gathered in periods of time along with the sharing between responsible parties.

Moreover, as it was previously mentioned, “peak delays” are also available. This data is however difficult to use because they correspond to a state of the network that is not necessarily indicative of the overall situation of the day, unlike the delays related to events.

Production loss

As it was mentioned before, the production loss is listed in number of laps that were not produced (lost laps) which are of two types:

- gross lost laps: those are the trains that were not able to leave the terminal for material reasons such as absent driver or defective equipment.
- lost laps for schedule compensation: those are the laps that were cancelled in order to catch up with the theoretical timetable. As it was presented before, they are automatically dispatched between the events that caused delay on the line after their total number has been assessed (difference between total production loss and gross lost laps).

Ever since 2010, for each event, both the gross lost laps and the total lost laps are listed (therefore the lost laps for schedule compensation can easily be found). Before that, for each day, the lost laps for schedule compensation and the total number of lost laps were listed. The list of incidents only displayed the total number of lost laps (therefore including both types), therefore, additional work is necessary before being able to deduce the production loss for schedule compensation related to each incident. However, with the previous reporting rule, incidents that caused both gross loss and loss for schedule compensation were listed in two parts, thus the production loss that was reported was always either one or the other. Therefore, the rule to be applied is that incidents listed with a delay of zero minutes only cause gross loss, whereas incidents listed with a strictly positive delay only cause loss for schedule compensation.

The gross lost laps are independent from the regulation systems actions. They are a given upon which the operator cannot do much. On the contrary, the lost laps for schedule compensation are a direct result of the regulation actions. Indeed, those laps are lost because there was delay on the line that the regulation system was not capable of handling. The more lost laps for schedule compensation there are, the less the system was able to recover from the delay through normal regulation methods. Thus, this feature might be a very interesting indicator to assess the performance of the regulation system in place.

9.2.3. Indicators for performance evaluation with OSIRIS data

Thus, there is a distinction between exogenous data, which the operators and the regulation system must cope with, and endogenous data arising from regulatory actions, methods applied, decisions taken by the operator...

From the perspective of regulation systems, the number of incidents or events is clearly an exogenous data, and so is the number of gross lost laps. However, to some extent, the number of minutes of delay could be considered as an endogenous variable, since it could describe the reactivity of the traffic controller confronted to an incident. Nevertheless, in reality, it is observed that the average delay per incident varies little in time. The following graph show respectively the number of events, the cumulative delay caused by those events and the average delay per event for each month between 2003 and march 2011. Those were extracted from the database that cumulates those numbers per day.

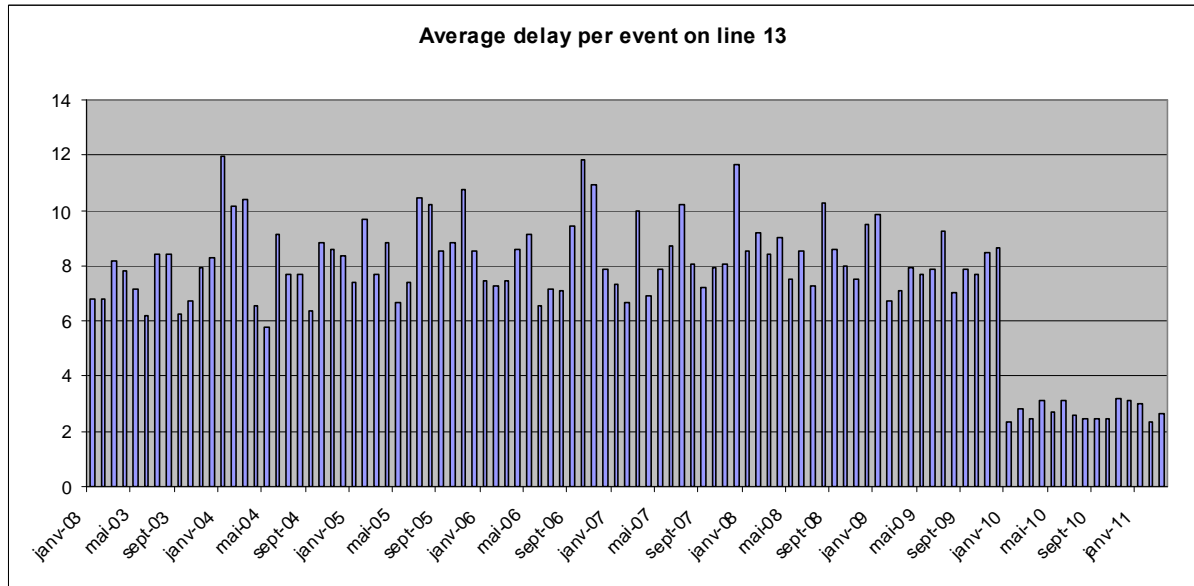


Figure 31 - Average delay per event on line 13

First of all, the difference in the two periods with different reporting rules is very clear. There are much more incidents reported since January 2010, but the additional events are more or less all small incidents that cause less than 5 minutes delay, thus reducing the average delay per minute. Furthermore, as it was announced, the average delay per incident varies little, and not significant trend can be deduced from it, remaining between 6 and 9 minutes before 2010, except on some occasions that could be explained with further analysis of the list of incidents), and between 2 and 3 minutes after 2010. This would therefore lead to consider the cumulative delay on the line as an exogenous variable as well, separately between the two periods.

On the contrary, as it was previously mentioned, the amount of lost laps for schedule compensation (further referred as SCs) is the very variable that can best evaluate the effectiveness of the regulation system. Indeed, for the same daily cumulative delay, a smaller number of SCs indicates a greater ability of the system in place to catch up with the theoretical program of operations by means of delay recovery, mainly in terminals, such as reduction of the buffer time and control of the headway between train departures. In contrast, a high number of SCs indicates that those “soft” methods of delay recovery were not sufficient to catch up with the theoretical schedule, and that more drastic methods consisting in cancelling laps had to be taken to ensure regularity on the line.

SCs are therefore function of the system and operators’ actions; however, they also depend on the number of incidents and delay on the line. It is therefore more relevant to study the number of SCs as opposed to the number of incidents or to the cumulative delay on the line. Indeed, when there are fewer SCs, the first reason is usually that there were less incidents that caused delay on the line. Therefore, the indicators that are studied are the following:

- number of minutes per event: low number corresponds to a good reactivity, whereas high numbers correspond to a bad handling of the situation.
- number of SCs per event and/or number SCs per minute of delay: a low number means a better management of the recovery methods in terminals, whereas a high number means that the delay was too big to be handled by smooth methods.

Those are assessed for different periods of time, type of incidents, lines... They are also to be split between workdays and week-ends.

One of the difficulties of this study is to be able to assess the performance of the regulation system and to discriminate its consequences from other measures that can be taken on the lines where it is implemented (for example on line 13, glass doors are being installed, automatic train driving is being reformed...). Whereas those other projects may have impact on the number of events or on their duration, they do not contribute in the number of SCs, which are the sole doing of the regulation actors. Therefore, this choice of indicator seems to be the most relevant to assess the evolution of the situation due to the changes in the regulation system.

9.2.4. Evaluation and comparison methods

The main goal of this study is to assess the performance of a new regulation system. Since all lines in the metro network have very specific characteristics, it is not considered relevant to compare the situation on two different lines. For example line 11 is a relatively small line (6.3 km) equipped with rubber-tire trains, whereas line 13 is a branched line of 18.3 km equipped with steel wheels trains. Even though those two lines operating under the two different versions of the system could make it interesting to compare their performance indicator, the differences in operations make it impossible to do so. Therefore, it is decided that each line has to be evaluated separately and any comparison between them should be either avoided or conducted very carefully.

The two lines that are the object of this study are line 13 and line 3. Indeed, those are the two that are now equipped with the modernised operational control centre. Line 1, 4 and 14 also have their own regulation system, but it has been developed separately from the generic project that is due to be installed in all the other lines of the network. Furthermore, the implementation of their equipment dates back from before the development of OSIRIS, making it impossible to access the data before modernisation. Line 13 was equipped with the operational control centre stage 1 (traffic controller only) on the 18th of December 2006, and stage 2 (terminal management as well) on the 27th of July 2008. Line 3 was equipped with stage 1 OCC on the 23rd of November 2009 and with stage 2 on the 25th of October 2010. As it is almost not possible to compare data from before and after January 2010, two different methods are applied for those lines

- for line 13, the data between 2003 and 2009 is used, which covers a period of time long enough before implementation of the system in late 2006 and of a year and a half after the implementation of stage 2;
- for line 3, the data of 2010-2011 are used, which allows to assess the performance of the system in stage 1 as opposed to stage 2. However, since the main focus is the regulation actions related to terminal management, since on-line automatic regulation is not being used at all, this should already provided relevant analysis.

Initially, the adopted method was to group data by month. However, the comparison from one month to the other is not always wise (typically the summer months and fall months have too different operating profiles to make comparisons between them interesting). It is therefore necessary to find suitable references for an objective comparison of the indicators.

Different approaches were tested in order to try and compare the SCs per incident or per minute of delay for the studied period:

- comparison of the gross value of the indicator;

- indicator normalized with the global average on the studied period in order to get an idea of the value of the month as opposed to what can be considered as the “average situation”;
(→ $\text{value}(\text{month})/\text{global average in \%}$)
- for line 13, indicator normalized with the monthly average on the studied period, that is to say that first the average of each month throughout the years is calculated, and then each monthly indicator is divided by the corresponding average. This allows for a better and smoother comparison of the months that follow each other, comparing them to the “average situation of this month”
(→ $\text{value}(\text{month})/\text{monthly average in \%}$)
- for line 13, indicator normalized with the (global or monthly) average from 2003 to 2005. This method means considering that the 2003-2005 period is representative of the “before modernisation” situation, and therefore can be taken as a reference in the evaluation of the new system
(→ $\text{value}(\text{month})/2003\text{-}2005 \text{ (global or monthly) average in \%}$)
- for line 13, indicator normalized with the value of one particular year that is taken as a reference (for example the year before stage 1, or 2003 as the year way before modernisation);
(→ $\text{value}(\text{month})/\text{value}(\text{same month in the reference year})$)

After this general assessment was performed, another form of evaluation is to try and compare the fallouts of incidents per delay they occasioned. That is to say for example for all incidents causing 10 minutes of delay, comparing the number of laps lost because of this. However, since before 2009, the difference between gross loss and SC loss was not made separately for each incident but globally for each day, this part of the analysis is to be performed even more cautiously.

Observations and analysis made through these different methods are presented in the next chapter.

Chapter 10 – Data analysis observations

This chapter presents the results of the data analysis that was performed according to the methods presented in chapter 9. Those are merely the observations that were made, as the comments, reflections and conclusions over them are mostly gathered in chapter 11. First, the study performed with the IGT data, both observations of recurrent behaviour and calculation of irregularity coefficients, is presented. A more extended analysis of the OSIRIS data is presented, as it gives an interesting assessment of the performance of terminal management and of the difficulties encountered by the operator facing this new system.

10.1. Recurrent behaviour

With the help of IGT consultation, it was interesting to observe the usual behaviour of traffic on the lines for the eight main types of days, that is to say normal working day, Friday, Saturday and Sunday in non-vacation and vacation times. The delay for each half hour of the day as recorded in the IGT for four typical days (non-vacation) are presented in Figure 32 (scales are not the same).

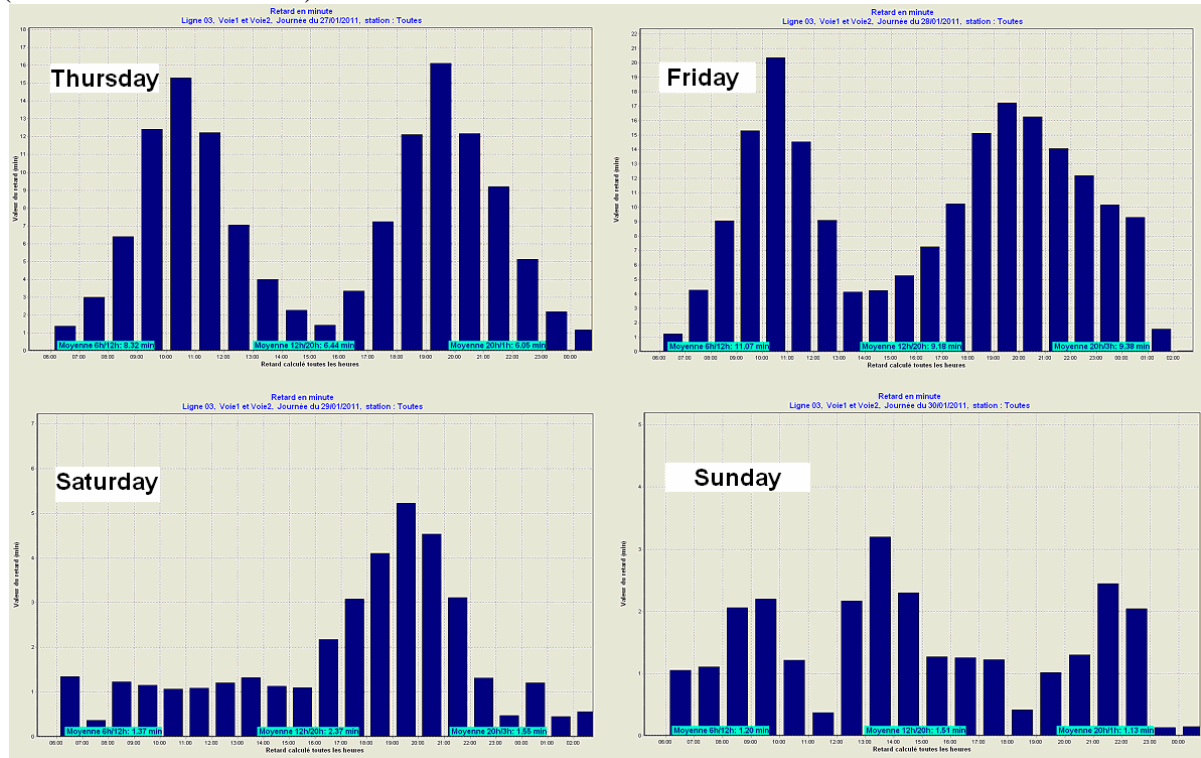


Figure 32 - Delay on line 3 for typical operational days

The same profile of operations was noticed throughout normal days, that is to say days without major incidents on the line. On vacation days, the profiles are more or less the same, but they reach lower levels of delay. Operators are aware of those numbers and they plan their actions according to them, assessing that those are incompressible delays that they have to handle. The interesting fact here is to notice that the delay has the same profile as the passenger demand, that is to say that when there are more passengers, there are more delays, which is explained by the fact that there are more trains to handle and that they run closer to each other. When there are less passengers, there is less delay, for that is the time during which the line can recover from degraded situations.

The other typical behaviour that was observed is the ability of the drivers to follow the modal type of the line. Those modal types are made of both running times and dwell times at stations. In theory, all driver-based lines are equipped with semi-automatic driving, with which the only task of the driver is to command the departure of the train from stations. When the automatic driving program is available, the driver can choose between manual (with speed control) and automatic driving. In the marche-type, the running times are based on the time performed by automatic driving and is therefore only a reference value that is seldom subject to be respected. Indeed, on the one hand, manual driving leads to variable running times for the same interstation depending on the driver, the load of the train, the time of day... and on the other hand, even in automatic driving, the speed can be switched to accelerated mode. Furthermore, the reference dwell times that are given by the marche-type are also subject to variations. Of course, there needs to be such a reference as the marche-type when computing a timetable, however it should be kept in mind that theoretical numbers as those ones can never be performed exactly in real operations.

The data of the IGT allowed comparing the marche-type of the lines with the actual data of operations. Although no general trend could be found, with some stations or interstations needing more time than the reference time, some less, and some depending on the time of day, it did underline the fact that at least in driver-based lines such as lines 3 and 13, it is very difficult to try and provide theoretical numbers such as those provided in the modal types. As it was mentioned in chapter 6, this is one of the main reasons why it is so difficult to implement automatic regulation on the line. The detailed data on this particular analysis can be found in Annex 3.

10.2. Regularity on the line

Regularity on the line can be displayed with the IGT using the representation of headways, as presented for example in Figure 24. This however does not lead to systematic observations as the method of the coefficient of irregularity presented in chapter 9 could.

The first step of this study was to assess irregularity on line 3 in three different stations: Père Lachaise (beginning of direction 1, fourth station), quatre septembre (middle of the line, thirteenth station) and Pereire (end of direction 1, twenty-first station). Study of average on several working days led to the following numbers for the irregularity coefficient:

	Père Lachaise	Quatre Septembre	Pereire
Daily average	16,40%	27,35%	26,10%
Morning off-peak	17,72%	22,02%	25,77%
Morning peak	18,64%	26,18%	27,16%
Day off-peak	18,64%	26,56%	28,66%
Evening peak	18,69%	23,80%	25,65%
Evening off-peak	17,20%	33,24%	29,97%
Night	10,00%	30,61%	20,13%

Table 11 - Irregularity coefficient on line three (average over 10 working days in 2011)

Those numbers do not particularly give interesting information. Irregularity does seem to increase in the beginning of the line, but also seems to decrease a bit afterwards. Also, there is no particular difference between the times of day regarding irregularity. It might have been interesting to try and compare those numbers before and after the implementation of the PCC, unfortunately, data dating back from then is either not available or not usable.

It was then decided to try and compare regularity between the different lines of the network. Even lines were included in this comparative study to try and have some elements of comparison. Their main characteristics are presented in

	Number of stations	Average theoretical headway	Average realised headway	Minimum theoretical headway	Minimum technical headway	Margin	PCC
line 3	25	181	182	100	100	0	Modernised
line 4	26	167	168	115	95	20	Modernised
line 5	22	180	184	110	110	0	Old
ligne 7	33/34	178	181	105	100	5	Old
line 10	20	272	271	180	120	60	Old
line 12	28	205	204	130	110	20	Old
ligne 13	26/24	153	154	100	95	5	Modernised

NB : lines 7 and 13 are branched lines

Table 12 - Characteristics of the studied lines

The study was performed in the first half of May 2011. The results of this analysis are presented in Figure 33.

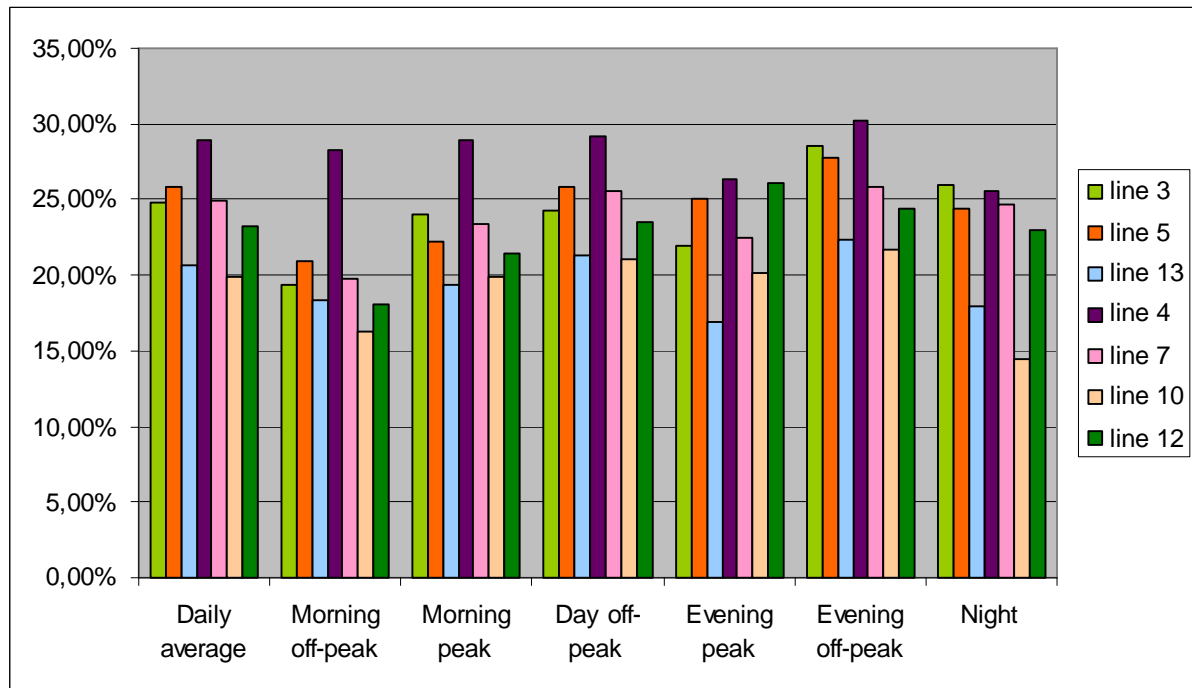


Figure 33 - Irregularity coefficient on the first half of May 2011, average value on working days

Although it seems that line 13 is performing slightly better than the other ones, it is very difficult to try and make any conclusion on this, especially regarding the performance of the regulation system. Indeed, if regularity is indeed the objective of the regulation system, many other functions, strategies and policies influence it such as management methods, implementation of glass doors, passenger affluence, construction work, modernisation work... If there had been a clear difference between modernised lines and the others here, one could have drawn some conclusions over this, however, this is not the case, and it is therefore not possible to use the irregularity coefficient to try and assess the performance of the regulation system.

10.3. Reactivity of the traffic controller

The methods and tools of the traffic controller have not changed much, however, his environment and integration in the operating team have and it might be possible to try and assess his reactivity through the evaluation of the number of minutes of delay per event. Indeed, assuming that there is the same type of incidents coming back on same types of days over the years, if on average, there is less time dedicated to each event, that might mean that the traffic controller's work is indeed easier to perform, or at least faster. Figure 34 presents a comparison of this number over the months for line 3 in 2003, 2005 and 2009, the PCC having been implemented in 2006 (stage 1) and 2008 (stage 2).

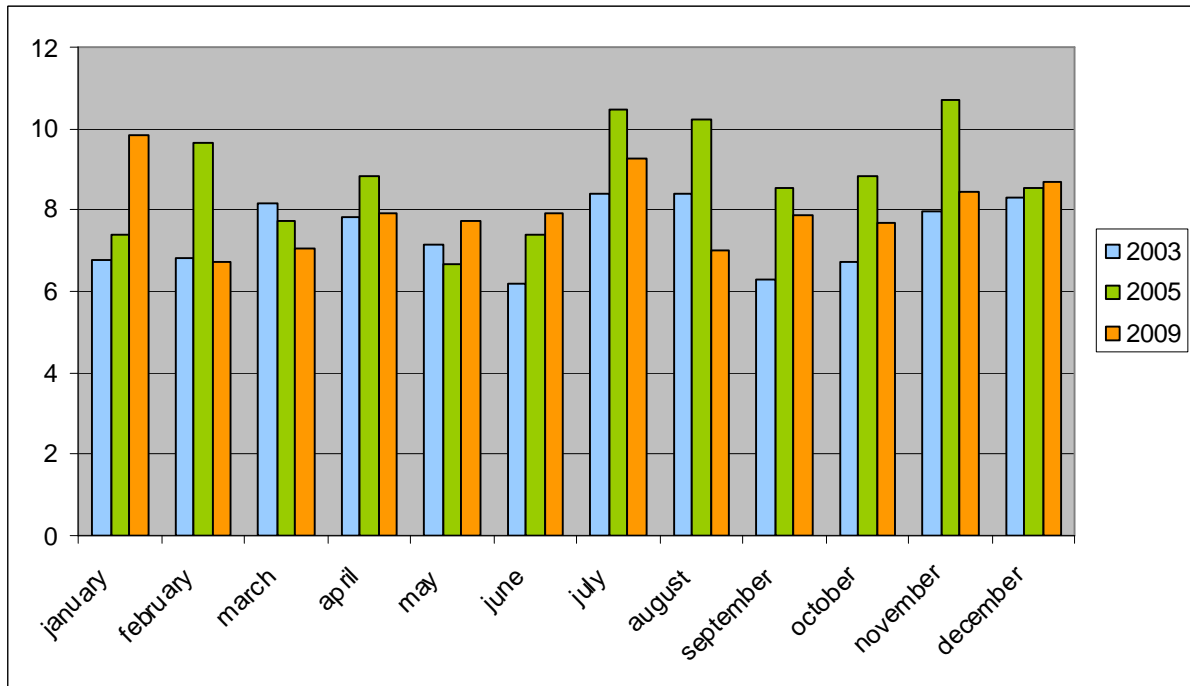


Figure 34 - Average time per incident on line 13

If it does appear that the situation is slightly better in 2009 than in 2005, that is not the case compared to 2003. This is either that the situation was especially difficult in 2005, which is somehow true for 2005 was a year during which there were lots of construction and modernisation work going on in line 13, or it could be that thanks to the modernisation in the PCC, situation is indeed better, and 2003 cannot really be taken into this comparison as it is too far away from the present situations. Indeed, in 2003, the situation has evolved greatly ever since 2003. Furthermore, the more incidents there are on the line, the harder it is for traffic controller to handle, especially if incidents occur at the same time. Thus, the relationship between incidents and amount of delay is not completely linear. Figure 35 shows that ever since 2003, there has been an increase in the number of incidents on line 13, which might explain why reactivity of traffic controller has not improved as much as it was hoped.

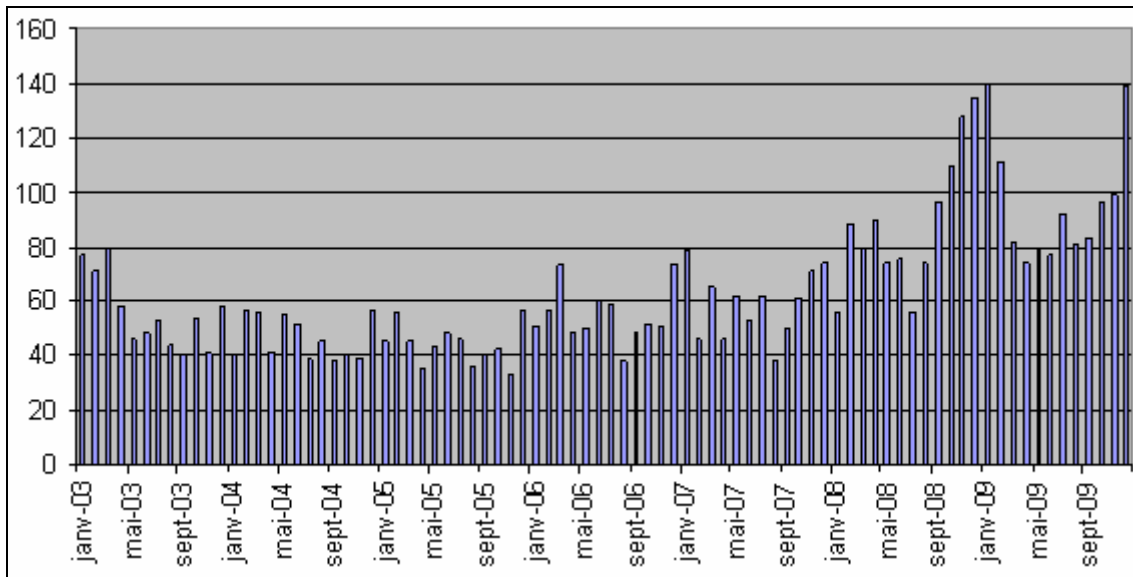


Figure 35 - Number of incidents per working days on line 13

10.4. Terminal management

As it was explained in chapter 9, the best way to evaluate the performance of strategies applied in terminal management is to assess the number of laps lost for schedule compensation. However, those are also highly related to the number of incidents on the line, or rather to the amount of delay to be recovered from. Therefore, it was decided to rather study the average number of lost laps for schedule compensation compared to the amount of delay on the line. In Figure 36 the unit is compared to ten minutes of delay, that is to say that reading this diagram is for example done as follows: on line 13, in February 2006, if there were 10 minutes of delay caused by incidents on the line, this would lead to the cancellations of 2.1 laps for schedule compensation on average.

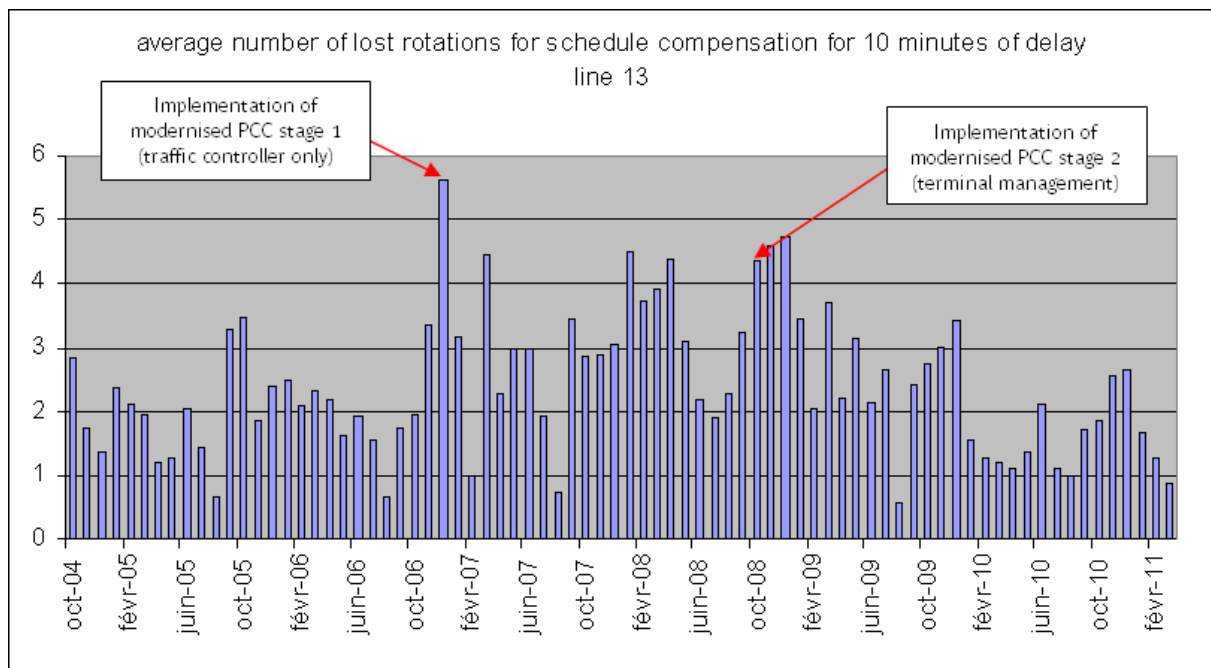


Figure 36 - Average number of lost laps for schedule compensation over the years on line 13

The profile of the diagram limited to working days is more or less the same as it can be seen in Figure 37.

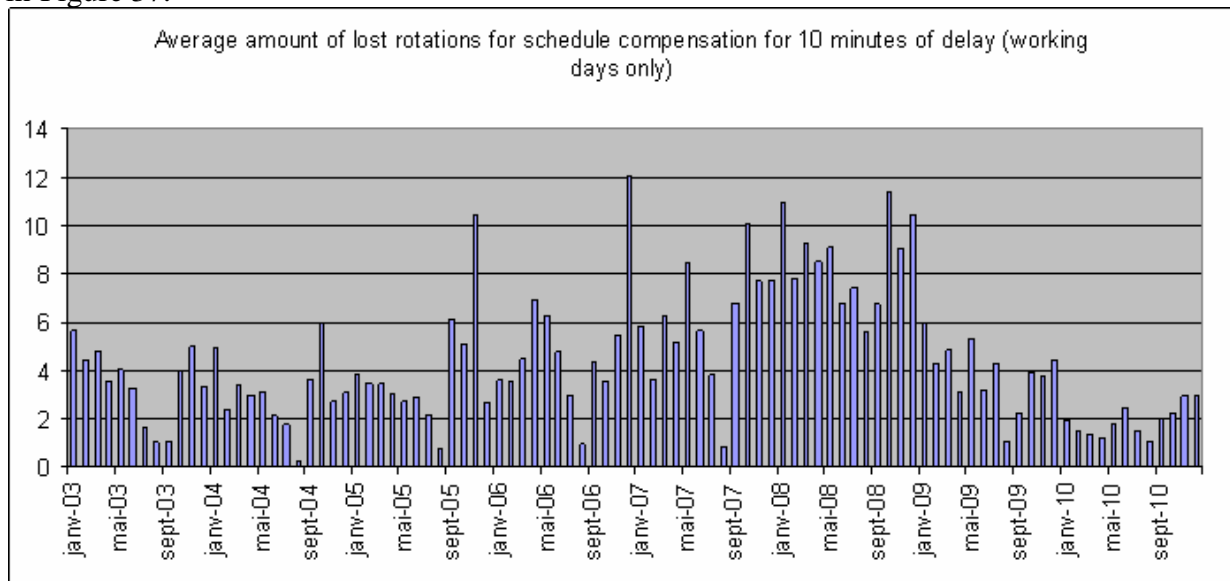


Figure 37 - Average number of lost laps for schedule compensation in working days on line 13

In those diagrams, it is obvious that following the implementation of stage 1 of the PCC (in December 2006), there was a degradation of the situation on the line. This is even more felt right after the implementation of stage 2 in July 2008 which is followed by unusual amounts of cancelled laps. However, after this, the situation in 2009 gets back to normal, being more or less the same as the one between 2003 and 2004, or even better. (The situation in 2010 cannot really be taken in the comparison as there have been changes in the reporting of data that render it incomparable).

It also appears that the situation is very different depending on the month, with very low numbers in the summer months and higher ones at the beginning of the year. Figure 38 presents the same data but with comparison month by month that make the differences between stages of the PCC clearer.

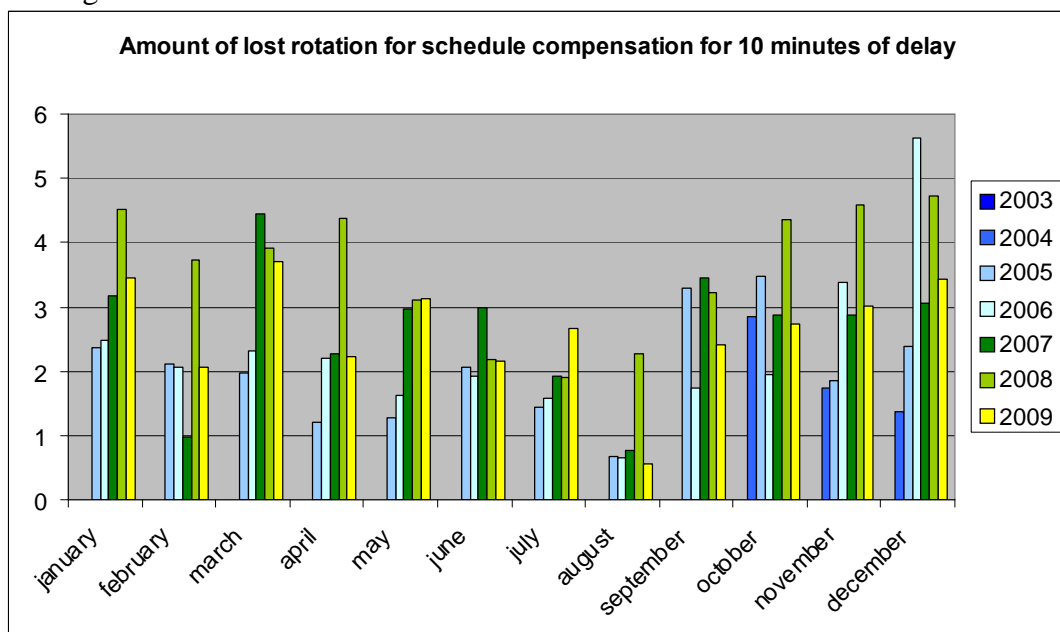


Figure 38 - Average number of lost rotations on line 13 - comparison by month

Indeed, we can see that august 2008, following the implementation of stage 2 of the PCC was badly felt by operators. Furthermore, the situation in 2007 and 2008 is indeed worst than the one before, but it gets more or less back to normal in 2009.

Conclusions on these observations are drawn in chapter 11, but already one perceives that the transitional period between two stages of the PCC is a very difficult one for the operator.

This was also felt on line 3 as it can be seen in Figure 39.

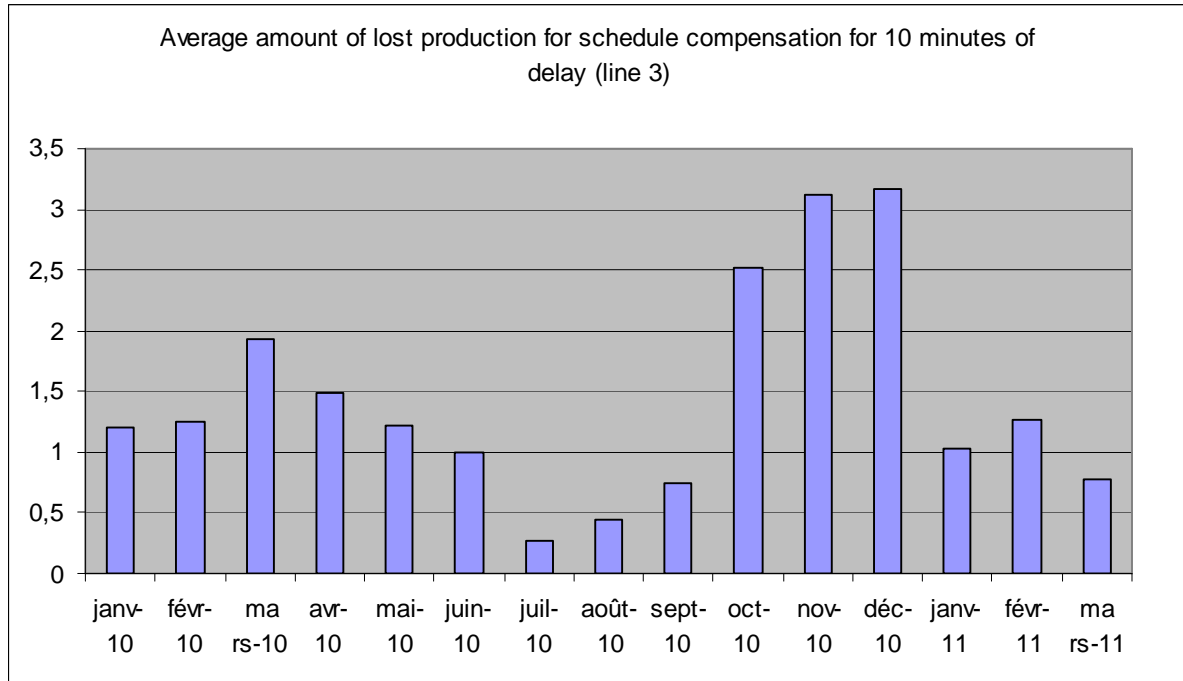


Figure 39 - Average amount of lost laps on line 3

Stage 2 of the modernised PCC was implemented in October 2010, which, as we can see, was followed by an increase in the number of lost laps for schedule compensation, typical of the transitional period noticed on line 13 for the terminal managers. However, those problems were of greater importance than the ones noticed on line 13, and thus an investigation was performed, leading to the re-calibration of some parameters. The implementation of those changes happened in January 2011, which can indeed be observed in Figure 39.

Those results give a general overview of the situation continuously. However, it is also interesting to try and compare the three different stages of the PCC separately. This was done by choosing three representative periods for the PCC of line 13:

- Bourdon organisation represented by the year 2006 (except for December, replaced by December 2005);
- Stage 1 represented by the year 2007;
- Stage 2 represented by the year 2009.

Indeed, in those periods, it is hoped that the problems of the transitional periods are not existent anymore. The days of each period were grouped by their amount of delay and an average was calculated for each amount. Figure 40 is the discreet representation of this work.

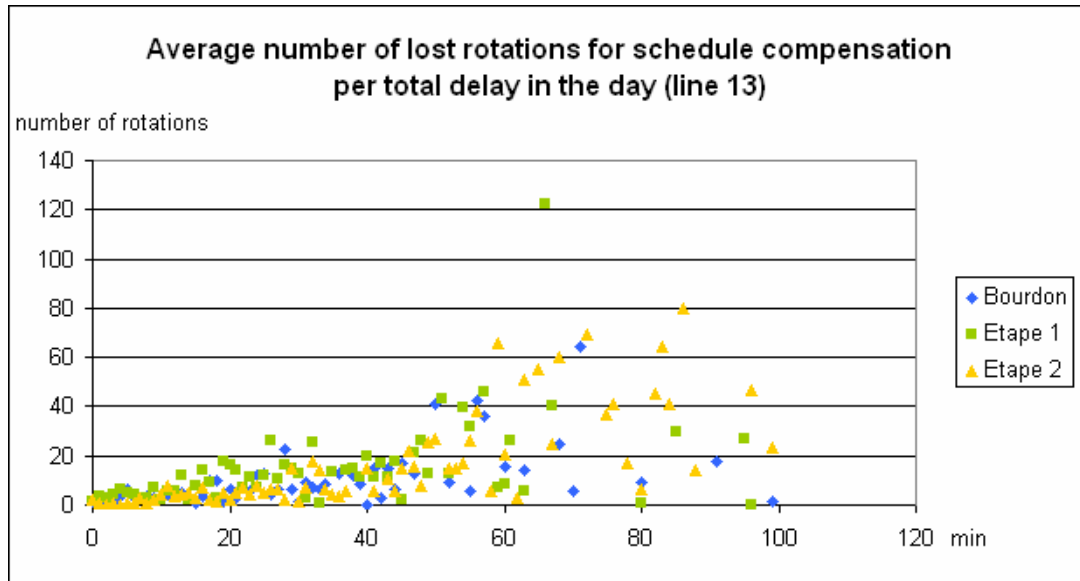


Figure 40 - Average number of lost rotations for schedule compensation in the three different stages of the PCC

It is not easy to try and observe a trend in the representation of Figure 40. Therefore, days were gathered by groups according to the total amount of delay caused by incidents. Then for each group, the average number of lost laps was calculated, leading to the representation in Figure 41.

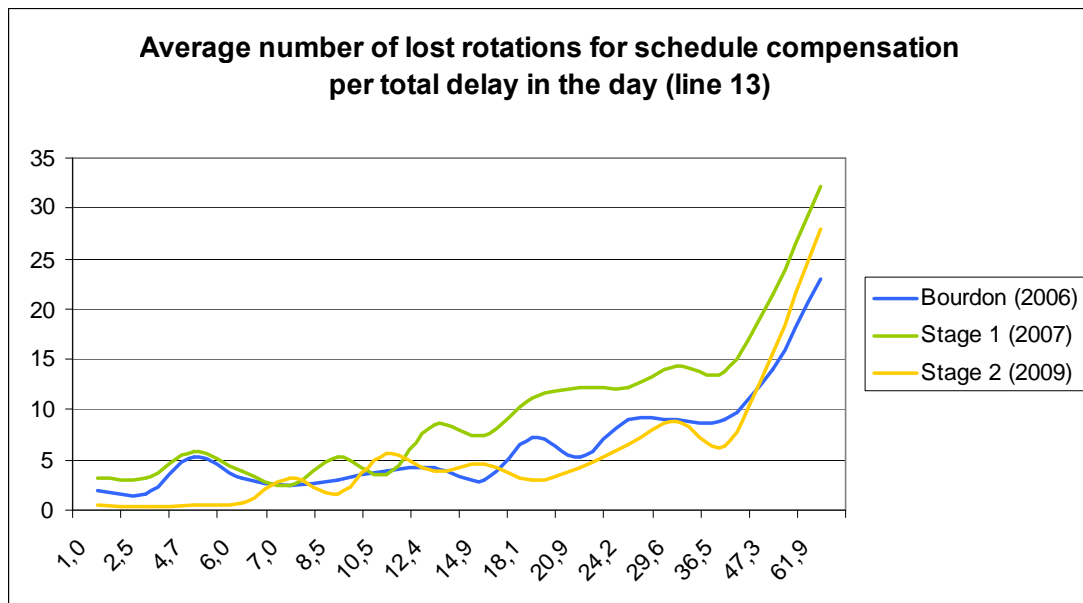


Figure 41 - Comparison of the three stages of the PCC of line 13

As we can see, it seems that for small delays (less than 10 minutes), the modernised PCC fully implemented performs better than the Bourdon PCC. Afterwards, they have more or less the same results. It can also be noticed that the threshold of 30 minutes, which corresponds to the limit above which drivers are allowed to refuse to leave on their last lap, is very much visible here. Indeed, up until 30 minutes of delay, terminal managers seem to be able to handle the situation without having to cancel too many trains, but the situation gets out of their control in more important delays. This might also be due to the fact that days with a delay of more than 30 minutes actually have a much greater delay and correspond to very serious incidents.

Chapter 11 – Improvements and drawbacks of the new system

In chapter 8, it was described that overall, even if some aspects of the former organisation are missed by operators, they are also quite pleased with the new tool. They are, however, doubtful regarding the efficiency of the regulation system. The objective of the rest of this performance analysis was to see if facts did indeed corroborate with their impressions. The conclusions on this are the object of this chapter that first gives an overview of the conclusions that can be driven from the data analysis, both as rough analysis and taking into account the evolving conditions, before confronting it with the operators impression in the conclusion of this chapter.

11.1. First-hand observations

On the performance of line traffic control, there is not much that can be said on first hand observations. The situation does not seem to be better than before, but it is not worst. It is regarding terminal management that more can be said.

Indeed, first of all, a very critical point was noticed concerning the periods of time following the implementation of the modernised PCC. Those dates are followed by months during which the terminal managers seem to have great difficulties handling the situation properly, thus leading to more cancellation of trains for schedule compensation because the recovery methods are not efficient enough. However, it is difficult to say whether this is due to the automatic system itself, or rather with problems that cannot be prevented such as technical failures or difficulties to adapt to the new tools, environment and system.

However, on a more long-term basis, it seems that the performances of the modernised PCC are completely acceptable. It does not seem to be performing worse than before, even if it does not prove more efficient, as it was hoped. It is therefore a bit difficult to understand the reservation of the operators regarding the calculation of departure times.

Another important observation that was made is the problem of parameterization. First of all, this is a great difficulty regarding line traffic control, especially if one wants to be able some day to implement automatic regulation on the line. It was observed that the modal-types parameters are not completely coherent with reality, but also that it is very difficult to make them coherent, as the real times spent at or between stations can vary greatly from one driver to the other, from one day to the other, etc... This problem of calibration of parameters is actually also present in the terminal management system. Indeed, it was noticed that on line 3, the situation was very much degraded after the implementation of stage 1 of the modernised PCC, leading to unusual delays at the end of the day, according to the operator. This was fixed by a re-calibration of parameters, which led to improvements in the operational results that were observed in the data analysis, thus insisting once more on the importance of rightly calibrating all parameters.

However, having a regular traffic is not a goal in its own, as much as it has to be seen as a way to ensure a good level of service to passengers. The measures taken as part of the regulation strategies implemented first need to ensure that the delay occasioned by an incident is not too important, in order not to hinder passenger's travel. Traffic controller of the lines equipped with a modernised PCC have a personal opinion that with the new system, that have a better vision of the situation, and more importantly better communication with other actors of the line, thus leading to an increased level of reactivity and ability to handle incidents. This

is very positive regarding passenger service, however it was not particularly observed in the data analysis. However, it is quite difficult to assess objectively the average delay occasioned by an incident, as they are of very various types and natures. Some of them are bound to cause more delay than others whatever the reactivity of the controller might be. The analysis performed in the previous chapter showed that there was clearly a transitional period after each stage implementation. Thus, the analysis regarding traffic controller reactivity was re-evaluated, taking only the three representative periods as described before. The average delay per incident was of 8,4 minutes with Bourdon (data of 2006) against 8,1 with the modernised PCC (data of 2009), which is not a very important difference, especially from a passenger's point of view. Indeed, if in the metro operation's perspective, a few seconds are important to the well being of the whole line, passengers do not really feel such difference in time. Therefore, the first hand observation in this is that the work of the traffic controller may have been made easier with the modernised PCC, but it has not brought any major change for passengers.

Regarding terminal management, the aim here is to ensure regular departure while still producing the right amount of traffic. It was seen that assessing regularity in itself is not really possible. Furthermore, even in a regular traffic is the only way to ensure a good level of service, from a passenger's point of view, it is not deeply felt, unless irregularity exceeds a few minutes, but this only happens in case of an incident, in which case passengers are kept informed, and although they do experience some inconvenience, it is not of a different kind. What passengers do experience greatly is the saturation of the network, and in particular in the very train they are travelling in, it being overcrowded or not. It was seen that terminal management's performance could be assessed through the number of cancelled rotations per delay. This is also a way to assess the discomfort of passengers. Indeed, if a large number of trains are cancelled, this means that less train were used to accommodate the flow of passengers, thus leading to more crowded trains. As the number of cancelled rotations on a whole day does not usually exceed four, this is not felt very deeply by passengers. Nevertheless, having a cancelled rotation for schedule compensation means that terminal managers and traffic controller on the line were not able to handle a delay with smooth methods, and is thus the only way of assessing the working performance of the operators regarding traffic regulation. In this regard, it was observed that the modernised PCC seems to perform slightly better than the former organisation, contrary to what the operator seemed to think. However, it was seen that since they do not trust the recovery mode implemented in the system, terminal managers prefer using the constant headway mode with their own judgement of the situation to choose the headway to be applied. As it is not possible to know which regulation mode was being used at which moment, the observation made here is more a performance analysis of the overall organisation, and not especially of the regulation methods and algorithms. This is why a further study of the algorithms is presented in the next part of this report.

11.2. The problem of a changing operating environment

First-hand conclusions, coming both from the operator's opinion and the data analysis, are that the system is doing OK. Situation is not worst than before, but it has not substantially improved. However, this is considered acceptable, as it was never a direct objective of this modernisation project to improve the situation regarding traffic regularity or quality of passenger service. Indeed, the PCC project was mainly technology-driven for the real problem was the equipment's obsolescence. Nevertheless, any project in the transportation fields, or in any other fields for that matter, should also have measurable objectives regarding its impacts on passengers, or users in a larger sense. It was therefore a mistake from RATP's part not to

set those objectives prior to conducting the project. It is of course difficult to have direct cost-efficiency proof of such system's usefulness, however, when taken into perspectives, the results conclusions that were drawn from the performance analysis can lead to different conclusions that show the benefits of the new system for the passengers, especially if compared to the changes in the operational environment.

Indeed, the comparisons that have been made here completely forget the fact that the situation on line 13 is very different nowadays from what it was in 2003, and it is actually a much more difficult environment to operate it now than it was 6 years ago, before the implementation of the modernised PCC. The number of passengers keeps increasing in the whole network, even more so on line 13. It is not really possible to assess the exact numbers, for there is no way of counting the affluence on each line separately, however, the assessment of RATP and STIF is that there was a need for an increase in the transport supply on line 13. Thus on working days, the number of trains running the line, which was of 430 up until 2006, was raised to 470 in 2007, and 475 in 2009. First of all, this means that the headway between trains was reduced, thus leading to a headway even closer to the minimal one at peak hours (minimum theoretical headway is now of 90seconds which is the minimal technical headway, and is therefore considered as not achievable). Furthermore, there are now more trains to handle, and thus more incidents, more delay on the line when one train is defective... This was indeed observed in the data analysis, as the total number of incidents on line 13 keeps increasing. It was explained that the relationship between the number of incidents and the total delay of the line is not completely linear. When several incidents occur in the same day, it becomes more and more difficult for the operator to handle, thus leading to a decreased level of reactivity. The operating environment of line 13 is thus a much more difficult one to operate today than it was before implementation of the modernised PCC. However, this system was observed to offer the same performance as the previous ones. The conclusion to be drawn here becomes obvious: a system that is able to perform as good as another one but in more difficult conditions is inevitably to be considered more efficient. An interesting experience would be to try and switch back to the Bourdon organisation those days, to see how well it performs with this new environment, which is unfortunately not possible, as the equipment for line 13 has now been gotten rid of. However, it seems that the conclusions would be that the new system is unquestionably better than the former one. Operators would not, anyway, like to switch back to the old system as they have experienced a great increase in their working habits and environment, but it seems that even for the well-being of the line, and of passengers, this new system is indeed more efficient than the old one.

Another aspect that has changed since 2003, when the requirements for the modernised PCC were issued, was explained in the previous part of this report. Up until 2008, pure regularity and its effects on passengers was the only way to evaluate the operational performance on a line. Indeed, even if the overall transport production is the first money-making aspect, it is a very easy goal to attain, and in the metro network, the transport production never falls lower than the acceptable threshold of 3,5%. Thus regularity was indeed very important, as it was the next objective to attain. However, in 2008, it was decided to change the way to assess regularity and to complete it with an evaluation of the transport supply at peak hours, which was apparently very poor compared to what is asked of the metro lines. It has therefore become the priority of line operators to have as many trains as possible running the line at critical times of the day. Thus, regularity is not so much an objective anymore, or at least it is not the priority. However, the requirements for the modernised PCC were written with regularity in mind rather than transport production. It is therefore a question to be asked whether this should be revised in order to be more in line with today's needs.

11.3. Conclusion

The operators are happy with their new tools and environment, this is an unquestionable fact. Although they do experience some regret regarding the changes that were made to their working habits – proximity to the other lines for traffic controller, and proximity to the drivers for terminal managers – they do recognize the advantages of this new organisation that ensures a better communication between all the operators of the line, and a real sense of unity in operations, and in the line unit as a whole. However, their opinion on the regulation methods applied by the system was not as good.

The data analysis, however, did not really corroborate with this opinion, as it showed that the system is actually performing better than the previous one, even more so when taken into perspective the changing environment of line 13. However, it is not known which type of regulation is being used by operators, and this data analysis is not sufficient to assess the performance of the algorithm itself.

This data analysis also showed that the implementation of the modernised PCC was inevitably followed by a very difficult transitional period for the operational situation on the line. This could be imputed to the difficulties of the operators to adapt to the new system, or to the system itself. First of all, such a complex new system always brings new types of technical failures and problems that are at first not very easy to handle. Thus, there have been more incidents following the implementation of both stages on line 13 because of this new system. Furthermore, even with all the work that is being conducted before implementation, it is always very difficult to try and take every single characteristic details of the line into account in the definition of the algorithms and its parameters. Therefore, only after it has been implemented and used on the line can the system be validated or re-evaluated. This was observed on line 3, as the system was obviously during the first three month of being used adding delay to the normal delay experienced on the line, which can explain the very bad opinion that line 3 had of the system when it was first implemented and still when this graduation project began. This problem was quickly corrected by a re-calibration of parameters, but it also put the emphasis on the importance of performing an extended study of line characteristics before jumping to conclusions and implementing the wrong parameters.

Chapter 12 – Study of system’s behaviour

The analysis conducted in the previous chapters led to the conclusion that the system was performing well enough regarding terminal management. However, first of all, this is not the impression of the operator, and more importantly it is impossible to know which regulation strategy was being used. As it is not an option to experiment directly on the line and enforce one policy or the other to compare their results, it was considered that the best way to assess the algorithm’s efficiency to recover from delay was to try and make up a simple model of the calculation of departure time. How this work was performed is presented in part one of this chapter. This allowed for some interesting observations regarding the results and performance of the calculations that are presented in part 2 of this chapter. Finally, some proposals for an evolution of the algorithm on lines 13, 3 and 5 are presented, one of them being the one currently proposed by RATP, the other one being a proposal based on the observations made through the model.

12.1. Building and using a simple model

In order to build this model, it was important to be able to get all the information possible, and to try and keep it simple enough to still be usable, while staying coherent with reality. It was decided to develop a model of the calculations of departure times at one of the terminals of line 3 as it is the one with the most recent modernised PCC, still under improvement works, but also the one that was best known through the course of this study.

12.1.1. Calculations to be modelled

The aim is to run calculations according to the formula presented in equation (11).

Line (1) of this calculation requires the gathering of the theoretical timetable, as well as the calculation of the correction *Cor* as presented in equations (8) and (9) and of the headway reduction as presented in equation (10). This part of the calculation is the one that requires the most time and effort, as well as the largest number of data. Indeed, in order to run this, a particular time slot needs to be chosen to define the terminal buffer time, the number of trains in the group, the number of trains that interact with each other...

Line (2) requires the calculation or the recording of earliest departure time, which is however needed for the calculation of line (1).

Line (3) requires the theoretical timetable, in order to have access to the theoretical headway, and the headway reduction as calculated for line (1).

Line (4) only requires the minimum technical headway.

Finally, line (5) is not to be modelled, as it only exists here in order to handle last-minute difficulties that are not to be accounted for in this study.

12.1.2. Recording of data

First, the technical parameters of the line were gathered. Those are presented in Table 13 and Table 14 according to the data given by the metro technical unit. Table 13 presents the total running time on the line for each direction and each modal type, while Table 14 gives the minimum stay in each terminals for each two types of manoeuvre (minimum stay at arrival and departure quay + manoeuvring time depending on whether there are one or two drivers involved).

Total running time		
Mode	Direction 1	Direction 2
A	0:31:35	0:33:00
B	0:32:45	0:32:00
C	0:30:35	0:31:15
D	0:29:45	0:30:35

Table 13 - Running times on line 3 (CV)

Maneuver	1	2
Gallieni	00:03:45	00:02:40
Levallois	00:03:50	00:02:45

Table 14 - Minimum stay in terminals of line 3 (sej.min.)

Suitable days were chosen for this modelling work, that is to say working days that did not present major incidents. For those days, the theoretical timetable and the realised one were available on the IGT. However, direct retrieving from the PCC data allowed for more detailed information, including calculated arrival times, earliest possible departure time, calculated departure times, and real departure times. Most of the data presented here, and used in the model, are retrieved from the PCC on Tuesday June 9th 2011, as presented in Table 15 for a group of trains between 09:16 and 09:40 which are to be used for this model (the model was also run on other groups, at other times of day, leading to results that will be presented in the conclusions of this chapter as well).

Train ID	HDP	Real departure time	HDT
1	09:16:00	09:16:35	09:10:00
3	09:18:05	09:18:40	09:12:00
5	09:19:45	09:21:15	09:14:15
7	09:21:35	09:23:25	09:16:30
9	09:24:00	09:25:25	09:18:45
11	09:26:10	09:27:50	09:21:00
14	09:30:00	09:29:55	09:23:15
16	09:31:50	09:32:05	09:25:30
18	09:33:25	09:34:15	09:27:45
20	09:36:10	09:36:30	09:30:00
23	09:38:25	09:38:55	09:32:15
25	09:40:05	09:41:50	09:34:30

Table 15 - Data retrieved at terminal Gallieni on 09/06/2011

In the real departure time, the data presented in red correspond to the trains that left with a difference of more than 15s with their indicated calculated departure time (earlier or later). Train n°3 is to be regarded as the “next train to leave the terminal” in this study.

For each period of time to be studied, and especially for each group of trains, several parameters had to be calculated. For the calculation corresponding to the data of Table 15, they are as follows:

Theoretical lap duration	
$DTT = CV(1) + CV(2) + sej.min.(1) + sej.min.(2)$	01:10:10
Minimum Headway I_min	00:01:30
Theoretical headway I_th	00:02:15
Theoretical buffer time at terminal BTT	
$BTT = (HDT(1,n) - HDT(1,n-1) - DTT) / 2$	00:00:30
Number of trains in the group	
$N = (DTT + 2 * BTT) / I_notice$	31,6
Headway reduction	
$Mi = BTT / N$	00:00:01

12.1.3. Calculations

After all this data is retrieved and calculated, the implementation of the formula can be conducted. All trains interacting with each other, the calculation of the correction should require a square matrix of the size of the number of trains in the day. However, it is assumed that only a few number of trains close to the next departing one can actually influence the departure times at a given moment. Thus, this calculation was limited to ten to twenty trains, depending on the group of trains being studied. Furthermore, it is the situation at a given moment that is interesting, and thus, it is of no need in this study to try and model the behaviour of the line in a whole day, which would lead to very extended but unnecessary data, and to a very complex work.

The various data that was calculated for each group in this order are:

- contribution of each train to the general delay;
- for each train *i* with a positive contribution to the general delay, delay correction to be applied to each train between 0 and *i*;
- correction to be applied to each train, i.e. the maximum correction;

When this was done for the whole group, it was possible to calculate the 4 different departure times to be taken into account in the final calculation:

- $H_{rec} = HDT + Cor - M_i$ - line (1) of the calculation (rec stands for “récupération”, French for recovery, for line 1 is the core principle of the recovery mode);
- HDP - line (2) of the calculation (either calculated using the arrival time + minimum stay in terminal, or directly retrieved from the PCC software);
- $H_{not} = HDC(n-1) + I_{notice} - M_i$ - line (3) of the calculation (not stands for “notice” which is the name given to the theoretical headway for this line is included to make sure the trains more or less respect this theoretical feature);
- $H_{tech} = HDC(n-1) + I_{min}$ - line (4) of the calculation (tech stands for “technique”, French for technical for this line is included to make sure trains do not depart closer than the minimum technical headway).

For the group of train of Table 15, the correction table was as follows:

Train ID	Absolute delay	Impact train 1		Impact train 2		Impact train 3		Impact train 4		Impact train 5		Impact train 6		Impact train 7		Impact train 8		Impact train 9		Impact train 10	
		Ret	0	Ret	0	Ret	0	Ret	0	Ret	40	Ret	15	Ret	0	Ret	5	Ret	5	Ret	0
		M	1	M	2	M	3	M	4	M	5	M	6	M	7	M	8	M	9	M	10
		L	Cor	L	Cor	L	Cor	L	Cor	L	Cor	L	Cor	L	Cor	L	Cor	L	Cor	L	Cor
3	00:06:05	1	365	2	365	3	365	4	365	5	365	6	365	7	365	8	365,0	9	365	10	365
5	00:05:30	0	0	1	365	2	365	3	365	4	373	5	367,5	6	365	7	365,6	8	365,6	9	365
7	00:05:05	0		0	365	1	365	2	365	3	381	4	370	5	365	6	366,3	7	366,1	8	365
9	00:05:15	0				0	365	1	365	2	389	3	372,5	4	365	5	366,9	6	366,7	7	365
11	00:05:10	0						0	365	1	397	2	375	3	365	4	367,5	5	367,2	6	365
14	00:06:45	40								0	405	1	377,5	2	365	3	368,1	4	367,8	5	365
16	00:06:20	15										0	380	1	365	2	368,8	3	368,3	4	365
18	00:05:40	0												0	365	1	369,4	2	368,9	3	365
23	00:06:10	5														0	370,0	1	369,4	2	365
25	00:06:10	5																0	370	1	365
27	00:05:35	0																		0	365

Table 16 - Calculation of the corrections

This led to the following results for the calculation of the departing time:

Train ID	HDP	HDT	Hrec	Hnot	Htech	HDC	HDR
3	09:18:05	09:12:00				09:18:40	09:18:40
5	09:19:45	09:14:15	09:20:27	09:20:54	09:20:15	09:20:54	09:21:15
7	09:21:35	09:16:30	09:22:50	09:23:08	09:22:29	09:23:08	09:23:25
9	09:24:00	09:18:45	09:25:13	09:25:22	09:24:43	09:25:22	09:25:25
11	09:26:10	09:21:00	09:27:36	09:27:36	09:26:57	09:27:36	09:27:50
14	09:30:00	09:23:15	09:29:59	09:29:50	09:29:11	09:30:00	09:29:55
16	09:31:50	09:25:30	09:31:49	09:32:14	09:31:35	09:32:14	09:32:05
18	09:33:25	09:27:45	09:33:53	09:34:28	09:33:49	09:34:28	09:34:15
23	09:36:10	09:30:00	09:36:09	09:36:42	09:36:03	09:36:42	09:36:30
25	09:38:25	09:32:15	09:38:24	09:38:56	09:38:17	09:38:56	09:38:55
27	09:40:05	09:34:30	09:40:34	09:41:10	09:40:31	09:41:10	09:41:50

Table 17 - Calculated departure times

The departure times calculated here are in line with what was indeed performed by the system in real life, thus validating the calculations. (It should be mentioned that this was not the case at first, and that indeed, comparisons between the model and reality led to the finding of several mistakes in the course of building the model.)

This model was used on different sets of data that led to the observations and conclusions presented in the following part.

12.2. Observations on the algorithm's performance

The study was performed for different moments in the day, peak and off-peak hours, in order to try and observe its ability to recover from delay while ensuring regularity in the departures. In off-peak hours, there was not much to be observed, as there is anyway not a lot of delay to be recovered from.

However, in off-peak hours, an interesting fact was observed in that the calculated departure time was almost always equal to the departure time calculated with the theoretical headway formula ($HDC = HDT + I_{th} - Mi$). Most of the times, the disruptive train is calculated to depart on its earliest possible departure time, as the other calculation lead to results that are not feasible. However, the other trains to depart do not get a calculated departure time according to the delay distribution method, but according to the theoretical headway with interval reduction. This phenomenon can be witnessed in Table 17 for the data presented in the previous part of this report.

Observation of this fact led to wondering if this could have been foreseen by theoretical analysis. The calculation is a max between several formulas, including Hnot and Hrec. Indeed, originally, the departure time should have been Hrec, however, the other formulas are included to make sure that the calculated departure times respect the operational constraints of the line, including the theoretical headway. The most pessimistic between all of the calculation is thus, and the question here is thus in which case is Hnot more or less pessimistic than Hrec.

It is reminded that $Hnot(n) = HDC(n-1) + I_{th} - Min$
thus $I_{th} - Min = Hnot(n) - HDC(n-1)$

and $Hrec(n) = HDT(n) + Cor(n) - Min$

$$\text{with } HDT(n) = HDT(n-1) + I_{th}$$

$$\begin{aligned} \text{thus } Hrec(n) &= HDT(n-1) + I_{th} + Cor(n) - Min \\ &= HDT(n-1) + Cor(n) + Hnot(n) - HDC(n-1) \\ &= Hnot(n) + Cor(n) - (HDC(n-1) - HDT(n-1)) \\ &= Hnot(n) + Cor(n) - Absolute_delay(n-1) \end{aligned}$$

Therefore, $Hrec > Hnot$ if and only if $Cor(n) > Absolute_Delay(n-1)$

That is to say, except in the cases where the earliest possible time or the technical time intervene, $HDC = Hrec$ if $Cor(n) > Absolute_Delay(n-1)$ (situation 1)
 $Hnot$ if $Cor(n) < Absolute_delay(n-1)$ (situation 2)

In situation 1, the correction to apply to a train is larger than the delay of the previous train, which means that the delay distribution method has the specific delay of each train increase from one to the next. This is the case at the beginning of the peak hour, or when the traffic is in a normal situation with suddenly one train suffering from an important delay.

Thus, the algorithm for the calculation of departure time in recovery mode only applies the correction method in cases when the absolute delay on the line is not important, and more importantly when delay recovery is not possible. Outside of these exceptions, the applied method of calculation is the theoretical headway with headway reduction. That is to say that indeed, the role of $Hrec$ is to add delay to the trains in order to ensure regular departures from the terminals, and when the cause of the original delay has disappeared, $Hnot$ is there to ensure delay recovery with headway reduction methods. However, as explained in the next part of this chapter, $Hrec$ could very well itself take on the task of recovering from delays.

The first problem one can see in those observations is that the formula of $Hrec$ is the one that was specified to be the one applied in general, and which is a reflection of the method that was applied by terminal managers in the former system. However, this formula was completed by several constrain-oriented others, which render its effect void, as apparently it is most of the time the constraints that prevail. Furthermore, it is a method that requires a lot of computer power, as this calculation is being performed every second for all the trains that have not yet left the terminal in the day. The object of the next part is thus to give some proposals for possible evolutions of the algorithm in order to increase its efficiency.

12.3. Proposals for an evolution in the algorithm

There obviously seems to be a lack of efficiency on the results of this algorithm, which is in line with the impression of the operator. Their feeling is that the system increases the delay on the line, and indeed, as it turns out, the recovery method that they used to apply manually and that was developed for the automatic calculation, is never being used because it gives a more optimistic result than that of the constraints of the theoretical headway. This means that trains that could leave the terminal, and that would have left the terminal already if the terminal manager was still in charge of deciding this as he was in the former system, are kept there in order to ensure regularity. In the eyes of the operator who wants to have train leave the terminal as quickly as possible in peak hours, this is equivalent to increasing the delay on the line.

12.3.1. Evolution without the theoretical headway constraint

As the problem seems to be caused by the theoretical headway constraints, it could be interesting to try and see what the results would be if it is left out of the calculation. The results of the calculation with and without the theoretical headway are presented in Table 18.

Train ID	HDP	HDT	HDC according to the algorithm			HDC in recovery mode without the theoretical headway constraint				
			HDC	Absolute delay at departure	Headway at departure	HDC - HDP	HDC	Absolute delay at departure	HDC - HDP	HDC - HDP
3	09:18:05	09:12:00	09:18:40	00:06:40	00:02:14	00:00:35	09:18:40	00:06:40	00:02:23	00:00:35
5	09:19:45	09:14:15	09:20:54	00:06:39	00:02:14	00:01:09	09:20:27	00:06:12	00:01:47	00:00:42
7	09:21:35	09:16:30	09:23:08	00:06:38	00:02:14	00:01:33	09:22:50	00:06:20	00:02:23	00:01:15
9	09:24:00	09:18:45	09:25:22	00:06:37	00:02:14	00:01:22	09:25:13	00:06:28	00:02:23	00:01:13
11	09:26:10	09:21:00	09:27:36	00:06:36	00:02:14	00:01:26	09:27:36	00:06:36	00:02:23	00:01:26
14	09:30:00	09:23:15	09:30:00	00:06:45	00:02:24	00:00:00	09:30:00	00:06:45	00:02:24	00:00:00
16	09:31:50	09:25:30	09:32:14	00:06:44	00:02:14	00:00:24	09:31:50	00:06:20	00:01:50	00:00:00
18	09:33:25	09:27:45	09:34:28	00:06:43	00:02:14	00:01:03	09:33:53	00:06:08	00:02:03	00:00:28
23	09:36:10	09:30:00	09:36:42	00:06:42	00:02:14	00:00:32	09:36:10	00:06:10	00:02:17	00:00:00
25	09:38:25	09:32:15	09:38:56	00:06:41	00:02:14	00:00:31	09:38:25	00:06:10	00:02:15	00:00:00
27	09:40:05	09:34:30	09:41:10	00:06:40	00:02:14	00:01:05	09:40:34	00:06:04	00:02:09	00:00:29

Table 18 - Calculation with and without the theoretical headway constraint

The three ways of assessing each method are:

- the absolute delay at departure, as the goal of regulation here is to recover from the delay, a better method would have this delay decrease more rapidly;
- the headway between trains at departure, as regularity still needs to be ensured;
- the difference between the earliest possible time HDP and the calculated departure time HDC, seen by the terminal manager as an unnecessary additional time spent in the terminals.

Indeed, at peak hours, their objective is mostly to have trains leave as soon as possible in order to make sure that the terminal will not get crowded, while still ensuring some regularity. The compared representation of those three criteria for the set of data presented in Table 18 can be seen in Figure 42, Figure 43 and Figure 44.

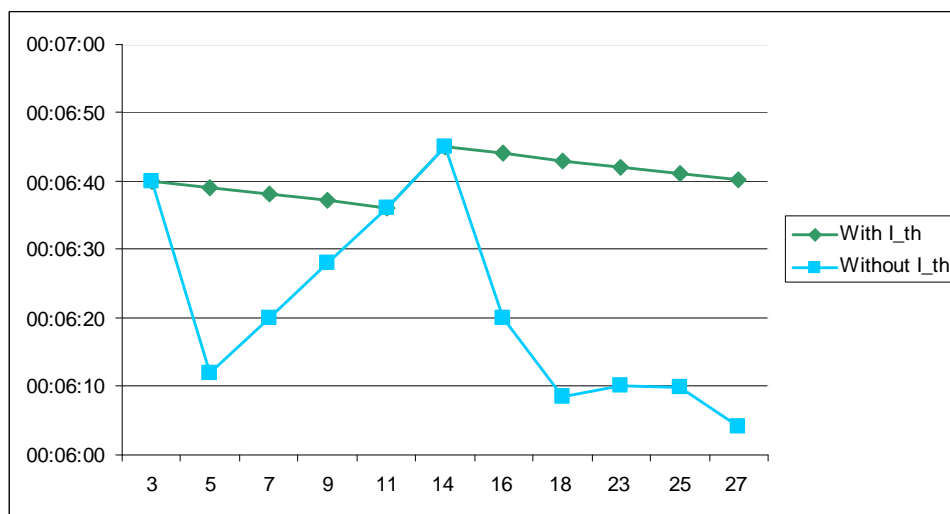


Figure 42 - Absolute delay at departure

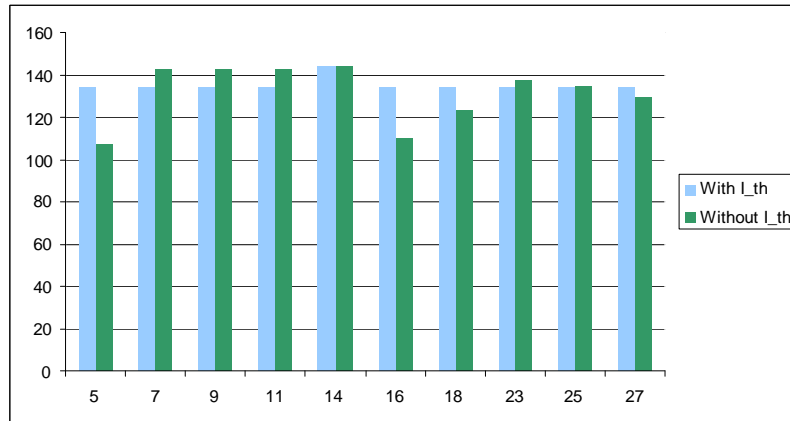


Figure 43 – Headway to previous train at departure in seconds

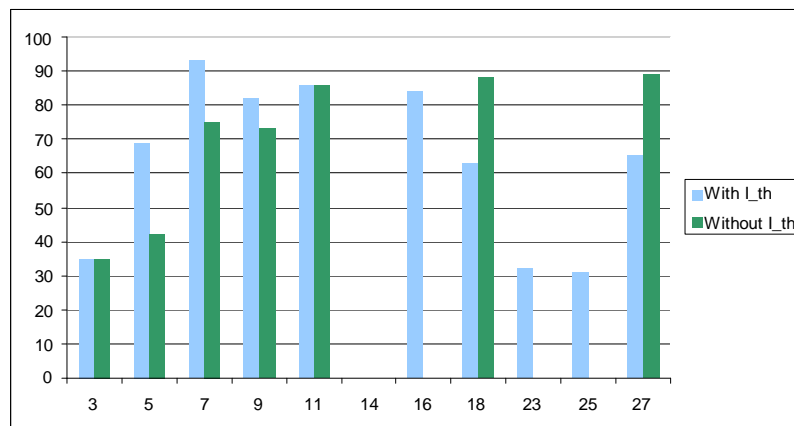


Figure 44 – Unnecessary time spent at the terminal for regulation (HDC-HDP) in seconds

If the theoretical headway constraint was to be abandoned, it seems that delay would be recovered from faster, mostly because trains would more often leave the terminal at their earliest possible departure time, but also because when they do not, their departure time is more optimistic. However, departure times would lose in regularity as it can be seen in Figure 43.

Getting rid of the theoretical headway constraint is thus a possible evolution for the algorithm. However, this could be at the cost of regularity, thus an idea would be to leave operators with the option to respect the theoretical headway or not when they choose to operate under the recovery mode. Furthermore, in reality, the reason why the algorithm without the theoretical headway constraint is performing better is that it actually applies earliest possible departure much more often. This is not a very intelligent method to apply, since it is being done at the cost of regularity, and does not use any of the strategies developed and applied by RATP. It might, however, solve the problems encountered by the operator at peak hours, although it is at risk of getting closer to the “no regulation” mode.

12.3.2. Evolution with a different headway reduction method

As it was already mentioned, in the eyes of most people at the metro department, the problem is that the trains spend too much unnecessary time in terminals when they would be able to leave on the line already. Rather than getting completely rid of the theoretical headway, another evolution would be to change the way it is being reduced by the system through the headway reduction, as recently proposed by the person in charge of the functional developments of the PCC at RATP.

Indeed, in the current version of the algorithm, the headway reduction is based on the terminal buffer time divided by the number of trains in the group. This is done for the sake of regularity, in order not to create too important a gap between train departures. However, this means that the headway reduction is actually a very small one (around 1s at peak hours). Another way to calculate the unnecessary theoretical time spent at a terminal by trains is thus simply to take the difference between the minimum technical headway and the theoretical headway:

$$TBC = I_{th} - I_{min} \quad (19)$$

(TBC stands for “temps de battement conducteur” as it is regarded here as an additional resting time for the train driver. It is however a misnomer as train drivers almost never leave with the same train they arrived in.)

The new calculation as proposed in this evolution is then as follows:

$$HDC_{recovery} = \max \left\{ \begin{array}{l} HDT + Cor - Mi \quad (1) \\ HDP \quad (2) \\ \min[HDC(n-1) + I_{th}(n) - Mi; HDC(n-1) + I_{th}(n) - \tau \times TBC] \quad (3) \\ HDC_{n-1} + I_{min} \quad (4) \\ H + T_{departure} + T_{el}(1) \quad (5) \\ HDT \quad (6) \end{array} \right. \quad (20)$$

In equation (21), only the third line (theoretical headway constraint) has changed. It is equivalent to having the system choose the best option (the one that will provide a greater recovery) between the usual headway reduction Mi , and the new buffer time reduction multiplied by a coefficient to be chosen by the terminal managers between 0 and 1. However, since Mi is always a very small value (maximum 15s), it is to be anticipated that the second option will always prevail.

The first advantage of this method is that it gives some control back to the operator, following their wishes, in that the terminal manager is now in charge of choosing the recovery rate to be applied to the theoretical headway. However, it was seen that the third line of this calculation is more or less equivalent to implementing constant headway in reverse. It is not the headway itself that is chosen by the terminal manager, but how much lower than the theoretical headway it should be, with a range varying from equal to the technical minimum headway to the theoretical headway itself. It is thus a new way to implement constant headway.

However, there is also a chance that with high values of the coefficient, the theoretical headway constraint will become less optimistic than the delay distribution method in most situations at peak hours. This evolution of the algorithm is thus a way to have the system perform what the terminal manager is currently doing manually, that is to say constantly switching from constant headway to recovery mode in order to have trains leave the terminal as close to their earliest possible time as possible. It is therefore not directly answering to their request for a better way at recovering from delay, rather than it is a way at improving the already existing, but not always used recovery method. Furthermore, the specific request of the operators was not only to improve the ability of the system at recovering from delay, but also to give them more decision power on the recovery method. Although the choice of the coefficient might give them the impression that they are responsible for the choice of how much time the system recovers, it is only an impression as the system would still be the one choosing between delay distribution and theoretical headway.

Part I – Project background

Part II – Metro Traffic Regulation

Part III – Performance analysis

Part IV – Conclusion

Chapter 13 – Findings and recommendations

Chapter 14 – Discussions

The overall conclusion of this research project is that the new PCC system is not only in line with RATP's requirements, it is also performing as good as was expected of it. However, the operator himself does not feel like this, which might be either because he had higher hopes for its performance, or because his needs have evolved since the requirements were set. Furthermore, it is not really known how well they use the system, and if indeed they use the recovery methods during peak hours, or if they still apply regulation strategies manually using the constant headway mode. All in all, this means that there are still grounds for improvement in the system, which is the object of chapter 13. Finally, some discussions on the PCC modernisation project were raised through the course of this research project and they are the object of chapter 14.

Chapter 13 – Findings and recommendations

Although it was observed that the new PCC system is in line with the requirements and is performing acceptably enough, several ways of improving it have been highlighted in this report. Before those recommendations are expanded on in this chapter, an overall conclusion on the main observations of this study is drawn. As for the possible improvements, some of them are fairly technical, as they consist in calibrating the algorithm in a more fitting way, as presented in the previous chapter and in part 2 of this chapter, or in taking better into account the physical and operational characteristics of the lines, as described in part 3. However, there also are other ways that do not relate directly to the technical features of this project, but rather to project management, and more especially to how the evolving needs of the lines are being taken into account, and how the operators are being trained and accompanied when they first come to use the system.

13.1. Conclusions on the performance of the new PCC

The main question that was asked by RATP was whether or not the regulation system that had been developed for the modernised PCC was in line with the requirements that were set, and if it led to an improvement in operations. To the first part of this question, the answer is that indeed, the system complies with the requirements. However, as it turns out, those requirements themselves are not completely in line with the metro operator's needs. They insist more on ensuring regularity than in transport production, which is not the way the operator would prefer things to be.

Regarding the second part of this question, there is no definite answer. The new system has not led to spectacular improvements, as it could have been hoped for, regarding delay recovery methods or regularity on the line. However, it does allow for operations to be as efficient as they were eight years ago while the operational environment has changed and become more difficult to handle. In this regard, the system may thus be more efficient than the previous organisation. Furthermore, it is very probable that such an automatic system will still be able to handle the growing traffic and the increasingly complex operational environment, whereas the former organisation, based on human skills might not have been. Nevertheless, from the operator's point of view, things are not as satisfying as they could be. First of all, the delay recovery method that is implemented for terminal management is not as efficient as it could be. This causes sometimes even more delay on the line, and furthermore, it forces the operator to choose for different methods and constantly stay alert to any problems during peak hours. Improvements on this problem have been proposed, but they would probably still go against the operator's will, as what they are asking for is to have human controller get the power back on the decision-making calculations regarding delay recovery in terminals. Thus, while from an outside point of view, the system seem to be efficient enough, from the operators' point of view, it does not really answer their needs, and it provides them with a solution integrating high level of automation which they did not ask for.

However, as much as the operator might be dissatisfied with the new system, and especially with the fact that the functions of the human controllers have been reduced, the main object of attention should be the impact that those changes had on the quality of passenger service. Indeed, on a wider scope, recovering from delay or ensuring regularity on the lines are not goals in themselves. The real objective is to comply with passenger's demands regarding quantity and quality of service.

All in all, passengers do not care so much about regularity or overall transport production. What they do care about is their own travel time: they want it to be as short as possible, with not too crowded trains, and more importantly here, they want to be able to assess their travel time in a reliable way. Since all those aspects are actually directly related to regularity of traffic, it makes sense to say that the proper regulation strategy will ensure the proper level of quality of service to passengers. However, those regulation strategies have not changed much, other than having been partly automated, and had their process and organisation changed. Passengers do not especially feel a difference between before and after the modernised PCC, which might be regretted from the point of view of the project management team, but it should be stressed out that it was never a direct objective of this modernisation project.

The new PCC system therefore does not seem to offer obvious advantages compared to the previous one. However, those are still very new systems. Time only can tell if indeed, they seem to be more efficient than before or especially if they are able to handle the growing traffic. Furthermore, they were not implemented alone, and are coming along with modernisation in other systems such as the communication-based train control system, or the computer-based manoeuvring system in terminals, and for the next PCCs extension of the lines. Those evolutions could probably also not have been handled by the former system, as there is a high level of integration between them. The question is therefore not whether or not implementing the modernised PCCs was a good idea, as it was not possible to do otherwise. The real problem is that now that they are implemented, or under implementation, how can they best be used by operators to improve the regularity on their lines and thus the quality of passenger service.

13.2. A better calibration of the algorithm

A first proposal that was made was to re-evaluate the calculation methods and have them better adapted to the operator's needs, either by improving the precision of the parameters involved, or by changing the methods of calculation. However, those are very important evolution that should not be taken lightly, as they would require a lot of time and money. Furthermore, unless a detailed model of the line is built to predict the impact that those changes would have on operations, it is unsure whether or not it is possible to apply a new method that would be more in line with the operator's needs and requests. Finally, in this regard, it also needs to be asked whether the operator's requests are in the best interest of the line and of the passengers, or if they only come from habit and their natural aversion to changes in their working methods and organisation.

It should be stressed out here once again that, as concluded in part II of this report, this algorithm is in line with the requirements that were set. The reason why it could be improved is not that it does not perform well-enough regarding its objectives of regularity, it is because the needs and wants of the operators are different than the ones described in the specifications, either because they have evolved or because they were already not well taken into account in the specifications.

Indeed, it was observed that the algorithm calculated departure times that are more pessimistic than they could be, mostly because it is taking into account the theoretical headway. One could say that this theoretical headway was calculated in order to answer the needs of the line, and that this method should therefore be sufficient to answer the needs for a regular traffic. Applying this method ensures that the headway between trains are always the same in a group. However, first of all, when there is already a general delay on the line, there is a chance that the theoretical headway is not the one that should be applied at that moment. For

example on line 3, it is of 1min50s between 7:45 and 8:30. If there is a general delay of 15 minutes, this means that between 8:30 and 8:45, trains would still run with a headway of 1min50s, whereas at that time, the theoretical headway is of 1min40s. It is therefore not in line with what was developed for the traffic's needs. Furthermore, at peak hours, it is not so much a regular interval that operators want to have. Their main objective then is to have trains leave the terminal as soon as possible, regardless of the regularity for two main reasons: first of all, if they do not do so, the terminals could get crowded, leading to trains waiting too long to enter it, and thus increasing the general delay on the line; and secondly since 2008, they have financial motivation to have the correct number of trains running the lines at peak hours. Furthermore, it is assumed that at peak hours, the headway between trains is so short that even if they do not leave the terminal regularly, regularity will be naturally forced back on the line, either for signalling reasons or through the work of the traffic controller.

A possible improvement for this problem would be to lower the impact of the theoretical headway constraint. However, this has to be done in a way that it does not hinder the performance of the algorithm at off-peak periods as well. Simply getting rid of it might not be an option, but when the terminal manager chooses for the recovery method, he could be presented with the possibility or not to respect the theoretical headway constraint. Another way of doing so is the second one developed in the previous chapter, that is to say a change in the headway reduction strategy. However, this could lead to important gaps between groups. Furthermore, it gives the impression to operators that they have control over the regulation strategies, whereas they actually do not. If this solution is implemented, it is very possible that they will feel that their needs were only partially listened to, and that they were given a tool to make them believe they have control, whereas they do not, thus increasing their level of dissatisfaction regarding the regulation function.

Whether it is through one of those methods or yet another one, the calculation part of the regulation system needs to be improved. Indeed, the operators are not satisfied with it, and the modelling work that was performed proved them right. However, what operators really want is to get the control back on making the calculation, and in short, have their old way of doing things implemented on the new system. This, however, goes against the idea of having a system that can run without any human intervention. The question whether this choice for a completely automated regulation system is the good one is discussed in next chapter. Nevertheless, if one wants to stick with it, the experiences of line 13 and 3 already prove that the calculation methods could be improved with an evolution, or first with a better evaluation of the parameters involved.

13.3. Line characterization

The modernised PCC system was designed to be a generic one that could be implemented on any lines of the network. In this regard, it is not only interesting to try and understand why this choice was made, but also to point out the different aspects that need to be taken into account, both to keep the system generic, and to have it be fit to the lines where it is installed. Indeed, as it will be discussed in the next chapter, some might wonder about the appropriateness of trying to develop a generic system for lines that have very different operational and physical profiles. Nevertheless, as this choice was the one made by RATP, the system has to do with it, and to stay flexible to the differences between the lines where it is to be installed. It is advisable that those characteristics be taken into account with maybe more attention than they are right now.

When the modernised PCC of line 13 was implemented, it was the first one of the kind. Thus, it was considered normal that they'd be some misfits afterwards regarding calibration of parameters. However, those same problems happened after the implementation of line 3's modernised PCC, thus, one might wonder whether enough time is being spent on studying the line's characteristics, and it is to be hoped that the next modernised PCCs to be implemented will not suffer from the same calibration problems.

Adapting the system to the characteristics of the line should not be too difficult a process, however, this means having a perfect knowledge of such characteristics. This does not only mean physical aspects, such as whether it is a branched line or not, how the terminal facilities are organised, where the short-turns are available... First and foremost, it means having a clear definition of the parameters to be used. Those parameters are to be calculated both through empirical methods and with scientific calculations, in order to compare those numbers, and come up with the ones most close to the general case. Indeed, the problem here is that for most of those parameters, there is no definite absolute value. For example, the manoeuvring time in the terminals highly depends on the driver that is performing it and can vary a lot from one to the other. This is also true of the total running time on the line, as they intervene in the calculation of earliest possible departure, and thus of calculated departure time, but depend on the situation of the line, and especially of passengers' affluence.

On both lines where the system is being used, parameterization works have been performed both before and after implementation of the system, to try and stick the closest to reality. However, first of all this work should have been done before implementation of the system, and it is advisable to do so for the next PCCs. Furthermore, the terminal managers of line 3 feel that even after this, the calculation for earliest possible departure time is still too pessimistic compared to what is could actually be. They are speaking from experience, of course, but it should be stressed out that after several years of working a terminal, an operator is bound to know how it works better than every one else, and especially better than the engineers that are developing the system. Thus, some attention should be paid to those problems, for each line separately, and on a larger scale, to a general method to assess all those characteristics in the most objective way possible.

13.4. Taking into account evolving needs and structures

Several times in this study, the idea of an evolving environment came into light. The main two changes were the way line's efficiency is being evaluated and rewarded, and the changes in the operational profiles of the line.

The first important change is the increase in passenger traffic, which had repercussions on the number of incidents which as grown a lot since 2003, but also on operations, as it was decided to reinforce the transport supply and thus reduce the theoretical headway between trains. On line 13, the operational environment has thus changed and is now more difficult to handle, and it is believed that the system which was being used in 2003 might not have been sufficient to accommodate this increase in traffic.

Furthermore, it was seen that when the requirements for this system were written, the one and only priority of the lines was to ensure a regular traffic at all time, to make sure that they do indeed get the bonus that corresponds. This policy has now changed, and the operator's objective is now to have as many trains as possible run the line during peak hours. They are now willing to do so even if it means having a very irregular traffic at some point, since such irregular traffic will anyway fall under the criteria of the STIF, which allow for intervals between trains way larger than the ones being applied.

Changes are bound to happen, and engineers, operators, project managers, programmers and other actors involved in the PCC project, or in any project for that matter, should be able to not only accept it, but also to include it in their work. Of course, it is annoying to develop a system and when it is finally ready, to have people tell you of evolutions that should be made to it in order to better answer their needs. However, it should be remembered that it is those needs that should come first at all times, as they supposedly go along with the needs of passengers, which are to be at the centre of attention. Needs are evolving, and thus, so should system, even if it costs time, energy and money. Right now, for the PCC system, this means that indeed, the regulation strategies should be looked at as they were in chapter 12, in order to try and control if it is still answering to those needs, or if some changes need to be done. This should be done not only by the project team, but also with the operator, who is best aware of the needs of his lines. However, this proposal is valid only if the operator already has a good enough understanding of how the system works, which question is the object of the next part of this chapter.

13.5. Training and support of the operator

Through discussions with the operators of line 3, and more especially with the terminal managers, it became obvious that there is a serious lack of understanding in their part. Indeed, most of the complaints of questions that they have seem to be quite easy to solve with a little basic explanation of the methods of calculation.

Before the system is first implemented, all the terminal managers of the line receive a training course using simulators specifically designed for each of the line (which, along with the PCC, are equipped with a dedicated training room with a model of their line and of the PCC system to). In this course, they learn of how to use the tools, of the differences with the former organisation, of the actions they can take regarding regulation, but also drivers management, equipment, etc... However, they do not receive any theoretical explanation on how the system works. This is not to say that they should have a complete explanation to the smallest details, as this would take way too much time, effort and money to achieve. Furthermore, it would be quite unnecessary, as terminal managers do not really have the skills or inclination to know about these highly technical features. However, it might be interesting to give a brief introduction to how the system works, how it calculates departure times in the different modes, the effect that it has on line operations and terminal situation. First of all, the terminal managers, and in general operators could feel more involved in the system, more integrated, that their role is not just that of overseeing things, as they would have more insight in how it works. Furthermore, this might prevent lots of questions that they might have, and do not always dare to ask, which often leads to misuse of the system.

Lots of systems are designed to be useable without an understanding of the principles behind, which is the case of the PCC systems, however having such an understanding may lead to a better even use by operators. Operators keep asking for an evolution in the algorithm without really giving their reasons, and thus, people from the project management team feel that it is only because they are not comfortable with the fact that things have changed, and that their responsibilities are not the same any more, some might say that they are less important. However, if operators had a better understanding of the system, they might explain better their complaints, or even make proposals themselves for the improvement of the system.

Chapter 14 – Discussions

In the previous chapter, some proposals have been made to try and improve the existing modernised PCCs, or at least to improve the implementation for the next ones to be installed. However, those conclusions, as well as the rest of this report, raised some questions regarding the choices that had been made in the PCC project, or in the way traffic regulation is being conducted at RATP. A few of those questions are discussed here. They relate to four main issues: the choice that was made to develop a generic system, the way this project is being managed, the reorganisation of operations and the use of automation in a human-based system.

14.1. On the choice for a generic system

It can never be stressed out enough that a lot regarding operations and in particular metro traffic regulation is dependant on the line characteristics. Nevertheless, the choice of RATP was to have a generic system installed for his network. In the field of computer programming and algorithmic, generic systems are those which are written in terms of *to-be-specified-later* types provided as parameters. Applied to the PCC system, this meant that it was to be developed regardless of the line were it was to be implemented so that it could be installed in any line with differences only in the parameters and no changes whatsoever in the methods and functionalities. Indeed, even if the reorganisation of operations goes against the unification of the network, there is a will to try and ensure the same methods of operations on all the lines. The first reason for this is that operators are bound at some point to change from one line to another. Thus, this possible mobility should be made easy and the tools being used need to be if not exactly the same, at least similar in their use and principles. Furthermore, maintenance of all the equipment is performed by a one and only department, separate that that of metro operations. Thus, a multiplication of system types would make their work more difficult, and would probably cost more men, more money, more energy... Finally, it is probably less expensive to develop a system once and make a few adaptations for each of its implementation, than to start back from scratch every time.

Yet, there are difficulties that rise because of this choice for a generic system. Indeed, first of all, the requirements for it had to be written as a whole, and thus had to take into account all the particularities of all the lines. This is particularly a problem as the operational profiles of the lines differ greatly from one to the other. The amounts of passengers using it are very different, and thus so are the number of trains having to run the line, and the theoretical headway to be applied. Peak hour times are not the same either. In short, their needs and recurrent problems can be very different. Their physical and technical characteristics also differ, and it was already mentioned that a way to improve the system was to spend more time in the calibration of those parameters.

However, there, one can wonder until which point a system can be characterized as generic. Indeed, in the PCC project, each line unit keeps adding its particular situations, special cases, problems... and asking for changes in the system, whether it be related to regulation or to other issues. At some point, those demand might be considered too specific and are not only related to parameterization, thus leading to systems that are not generic anymore. More importantly, those changes can be found unnecessary for they would be too costly as opposed to the advantages they would bring to the lines. Furthermore, answering to all the demands of the operators would actually bring the PCCs of the lines further away from each other, and thus would probably contribute in losing the advantages of a generic system.

Another interesting aspect of this discussion is that it was not only asked to have a generic system, it was also asked that the system be developed specifically for RATP. Indeed, the industrial group that is developing this system (THALES) is actually the developer of other similar traffic control systems over the world, such as that of Singapore. THALES regards those PCC as products that they develop and sell to be implemented in any types of network. A cheaper, easier and probably faster solution for RATP would thus have been to buy this product and have it installed on its network. RATP would therefore have had to accept the product without really taking part in the conception of the traffic control methods, which was out of the question for them. Indeed, it may be easy to install a completely new system on a new network that does not have much experience or history but this is not the case of RATP. The implementation of a new system was already difficult enough as operators were quite reluctant to the change, even if they did know that it was much needed. However, it was still accepted, especially due to the fact that the system was developed for RATP, taking their methods into account, and with the RATP engineering department being integrated into the development process of the algorithm. Choosing for a system specific for RATP might make the relationship with the industrial group more complicated, but it ensures that the system will indeed comply with all their very specific needs.

It might not be feasible to implement in the RATP network an already-developed system that would not have taken into account the experience and knowledge of more than a hundred years of operations. However, developing a generic system would actually be more cost-efficient if it did stay generic and thus if the project manager were stricter on the demands of the lines, making it clear that even if their needs are being heard, they should not differ that much from one line to the other, and that the actual functionalities of the system cannot be modified according to one line or the other. When it is important to have the system customized according to the parameters, it is on the other hand not advisable to comply to each of the operator's demand separately and thus develop very different systems.

14.2. On the project management

As it was explained, modernisation projects are being managed by the engineering department of RATP, and are separated from the operating department. Yet another department, MOT, is the project owner, and thus provides the financial means, and decides on the needs and requirements of the projects. The way it goes is thus that the operator asks MOT for a project. According to this demand, MOT decides on a budget, and writes the requirements, being, however assisted by the metro department. The engineering department is then in charge of realising said project along with the industrial group that they choose after a regular tendering. This means that in between the people that are developing a system, and the ones that are actually using them, there are a lot of different stages, and thus several possibilities for information to be misunderstood, forgotten or misinterpreted. Of course, each of them has to stick to what they know how to do, and the operator could in no way do the work of the others. However, in this chain of information, there is a real risk of shift between the needs and the product, and it should always be kept in the mind of every one involved in the project.

Regarding the PCC project itself, this is especially true, as the operators often seem to think that their demands are not answered. There really is a lack of understanding between all those parties, in both directions, as the operators do not always seem to understand the various issues at stake in project management either. RATP calls itself an integrated company, but it seems however to be very compartmentalized with every one staying in its function and not really trying to understand the point of view of other departments. The idea here is not to

suggest that project management methods be revised, as this is an entirely different subject. However, it is interesting to point out the effects that they have on the actual realisation in the metro network. This is especially a problem nowadays, although it was not so important before. Indeed, when the line 13 modernisation project was launched, the problem owner was the metro operating department, and they were much more involved in the project than they are today. A few years later, it was decided to create a new department specific to project management and separated from the metro department, thus leading to less involvement of the operators in the project. Therefore, there is a risk that the needs of the following lines are now less taken into account and less studied than what was the case for line 13, which could explain the difference in the operators' satisfaction between line 13 and line 3: line 13 was an actor of its own modernisation whereas line 3 is undergoing it without a direct say in the matter.

This problem regarding the chain of information illustrates well the fact that at some point, people at every stage sometimes need to forget about all the processes, rules, paperwork and other time-consuming project management-related issues, and remember what they are doing, what system they are implementing, for who to use, and more importantly to really take the passenger into account.

14.3. On the operations reorganisation

One of the main aspects of the PCC project was to have all the operational control centres relocated in separate places dedicated to each line. This led to several changes in the operator's habits and working environment which were presented in chapter 8, among which for the advantages:

- the traffic controller is now closer to the field of operations;
- the terminal managers have a more direct relationship;
- there is a better communication between all the actors involved in regulation and traffic control;
- terminal managers and traffic controller have direct access to all the information that the other ones have.

All in all, the advantages all relate to a better integrated system, with better communication between the actors. However, there were drawbacks to this relocation:

- traffic controller being separated from the Bourdon central PCC have lost the sharing of experience and the help of their peers when needed;
- terminal managers are separated from their terminals, thus losing the direct relationship with drivers, and also with a chance of losing grip on the realities of the field at some point.

The former organisation of things was performing ok, and had been so for the last forty years. One can therefore wonder why there was this decision of changing it so radically. With the multiplication of incidents on the lines, due to the growing complexity of the systems and the increasing number of passengers, and thus of trains, it became however more and more obvious that incident solving was not efficient enough with the lack of communication between the regulation actors. This might be one of the reasons for this decision.

However, the main one is that a more general policy is being implemented at RATP taking the passenger as the centre of attention. This policy led to a decentralisation of the metro department, with more power and importance being given to the line operational units. The line being then at the centre of management and operational objectives, it was only normal that the traffic control functions be relocated as well under its responsibility.

This reorganisation of operations thus was done according to the general policy of the company, and brought several advantages for the operational management of the lines. Nevertheless, the inconvenience of losing the direct relationship that existed between the lines is deeply felt by traffic controllers, and indeed, this might lead to a very segregated operational profile for the overall network, with not much in common between the different lines as time goes by. Each line is now to be completely separated from the others, and time will tell if this brings problems or not. However, this also prepares the ground for the opening of the market to competition that is to happen by 2030.

14.4. On the use of automation

Aside from the reorganisation of operations, an important change in the new system was that it relied much more on computers, introducing much more complex automated function. It was observed that the automated function for traffic regulation on the line was very far from answering the real needs of operators, and was thus never used. Regarding terminal management, the main complaints of the operators are actually related to this introduction of automation. On the one hand, they claim that it is not performing well enough, which was already discussed previously. However, the main proposal that they make is not to improve the algorithm, but to go back to the former way of doing things, in which they were the ones who had the most decision power, being helped and controlled by the machine, and not the other way around as it is the case now. Further than this, it was seen that the operator seems reluctant to the system, claiming that they never asked for an automatic decision tools. What they would like is a guidance tool that would help them make the decisions.

The question being raised here is actually the wider one of introducing automation in a human-based system. Indeed, even if the system is now the one in charge of making the calculation, the human operators still have the responsibility of traffic control, security, regulation... However, with more and more automated features, the human controller's role is highly reduced, and its function is at risks of being depreciated by managers, who would probably get the impression that they are paying someone to do nothing but keep his eyes on a screen to make sure every thing goes smoothly. More importantly, this loss in responsibility might lead to a depreciation of the terminal manager regarding his own function. There is thus a chance that with time, operators who were partly replaced by computers will lose interest in their function, and their level of efficiency would inevitably decrease because of this.

An even greater risk than losing interest in their job is to lose the knowledge and experience that they have acquired by manually operating in the former organisation. RATP is already quite aware of this risk when it comes to security, as it was deeply felt in the Notre Dame de Lorette incident. After the automatic pilot was implemented on all trains of all the lines, drivers almost completely stopped driving manually, for the automatic pilot was considered efficient enough, and more importantly made their work way easier. In August 2000, a train derailed on line 12 while entering the station Notre Dame de Lorette. Thanks to the reactivity of a driver on the other direction, no important collision happened, as it could have been the case had he not paid attention. This accident led to several injuries and material damages. In the investigation, it came into light that the automatic pilot had been out of order in this interstation for a few months then. As the track at this location is a curved slope, it is a critical section for drivers, and they had to be particularly careful regarding their speed when driving manually. The accident was therefore imputed to the fact that because of the use of the automatic pilot, drivers had lost some of their driving abilities. Following this incident, it was decided that drivers would always have to drive at least one complete lap per service manually.

The example described above is thus an extreme situation when the careless use of automation can lead to disastrous consequences. However, the regulation function of the PCC is not a security function, and thus the consequences of its failures or of operators losing their capacities are less important. Nevertheless, with this new system, there is a chance that indeed, the operators would rely too much in the system, and a few years from now, will not be capable of doing this job themselves anymore. There is thus a risk of a permanent loss of skills on their part, and on longer scale, of a disappearance of the operator's functions.

Going back to the former system would be very difficult for technical reasons. Nevertheless, it would be possible to implement a new method for regulation that would be based on the operator's decisions rather than on the system's automatic calculations. However, as much as it can be felt as an inconvenience to have this level of automation, it should be reminded that such an automated system is also more precise, more reliable and more systematic than a human-based method. Indeed, when the human controller is in charge, the performance of the regulation method depends on his personal evaluation of the situation, as well as on his experience and skills. With an automatic system, the method is always the same, ensuring a real continuity throughout the day. Furthermore, terminal managers might claim that they were able to do their job perfectly well before, but with the growing number of incidents and the increasing number of passengers that make the operational environment more and more difficult, would they still be able to make all those calculations today, tomorrow or ten years from now?

Introducing a high level of automation in a human-based system might have disadvantages that should be carefully looked at, but is going with the actual trend, which is a natural evolution of things. When human ticket punchers were replaced by machines, people were also not satisfied with the evolution. However obviously today, humans could never be as fast and as efficient as the machines.

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Annexes

Annex 1 - Map and main characteristics of the Paris metro network



Figure 45 - Map of the Paris metro, RER and tram network (RATP, 2010)

















Line	Length (km)	Above ground (km)	Stations	Yearly traffic (STIF - 2004) (million pass.)	Open in	Latest extension	Wheels	Specificity
	16,4	0,6	25	161,6	1900	1992	Rubber tire	Undergoing transformation project to go from driver-base to driverless operation
	12,3	2,2	25	92,1	1900	1903	Steel wheels	
	11,7	-	25	87,6	1904	1971	Steel wheels	Modernised PCC system fully launched in October 2010. Fully operated under the CBTC system OCTYS since 2011.
	1,3	-	4	1,7	1971		Steel wheels	Formerly part of line 3, detached after the extension but still under the same operating staff. Modernised PCC since 2011.
	10,6	-	26	154,1	1908	1910	Rubber tire	First decentralised PCC (launched in 2001 but not as part of the generic PCC project)
	14,6	2,5	22	86,1	1906	1985	Steel wheels	Next decentralised PCC to be implemented (2012).
	13,6	6,1	28	100,7	1909	1942	Rubber tire	
	19,2	-	38	120,5	1910	1987	Steel wheels	Branched
	3,1	-	8	3,6	1967		Steel wheels	Formerly part of line 7 but detached because of imbalance in the traffic.
	22	2,8	37	89,1	1913	1974	Steel wheels	
	19,5	-	37	116,2	1922	1937	Steel wheels	
	11,6	-	23	41,5	1923	1981	Steel wheels	
	6,3	-	13	45,1	1935	1937	Rubber tire	
	13,9	-	28	72,1	1910	1934	Steel wheels	Decentralised PCC to be launched by 2013.
	18,3	2,4	32	105,1	1911	2008	Steel wheels	Branched - Modernised PCC launched in July 2008 - New CBTC system OURAGAN under development.
	8,6	-	9	64,1	1998	2007	Rubber tire	Fully automated.

Table 19 - Main characteristics of the 16 metro lines in the Paris network (RATP, STIF)

Annex 2 – Estimation of running times, manoeuvring times and minimum headways

In order to come up with the timetables, programs of operation and terminal management, but also with the implementation plan for security signalling, it is necessary to have a very precise knowledge of the running times on the line and of manoeuvring times in the terminals. Coming up with those parameters is the dedicated work of the MATYS unit (Marche-Type et Signalisation, French for modal-types and signalling). Those running times are assessed using speed distance diagrams, much as described by Brünger & Dalhaus (Railway Timetable and traffic – Chapter 4: Running time estimation – 2008). From those, the running times in both normal and accelerated modes are derived. Those diagrams are also the basis for the definition of signal spacing and of manoeuvring times.

Speed/distance and time/distance diagrams

The operation of the metro line is based on the principle that all trains stop at all the stations of the line. Therefore, each interstation has one, and only one possible speed profile, unlike for other types of network with trains that can skip some stops and remain at important speed when passing through a station. For each one of those station, a speed/distance and time/distance diagram is built with a software specially conceived for RATP as presented for one interstation of line 3 in Figure 46.

In order to build this diagram, first the needed characteristics of the rolling stock and of the railway are inputted. For the rolling stock, those are mainly the tractive effort / speed diagram and the acceleration – deceleration data (characteristics and braking distance). Regarding the railway, the data needed are mostly the curves and the slopes, but also of course the distances between stops, and more importantly the speed limits which are worked out depending on the rolling stocks and on the curves and slopes so that trains can stop with a maximum distance of 300m every where. Although the general maximum allowed speed in the network is of 70 km/h (80 on the fully automated lines), this is not a continuous speed limit, and it is often lower than this because of the physical and operational constraints. In Figure 46, the speed limits appear in **green** (the green curve is also called the “speed polynomial”).

As for the train loads, although it is possible to calculate the diagrams with whatever load chosen, the reference running times are always the same whatever the time of day, and thus whatever the average load is at that specific time. They are based on a calculation with 6 passengers / m² (EL6). This load is called the “normal load” and is actually superior to the “comfort load” of 4 passengers / m², corresponding more or less to the load at peak hour. The reason for this is that, although the aim here is to try and define an “average driving behaviour diagram”, it is also important to make sure that drivers can never go slower than the reference speed and time indicated in the modal types. If they go faster, they can always wait longer at stations to balance the difference in time, whereas if they were to go slower, it is not assured that they would be able to wait less because of passenger affluence. Thus, there is a small reserve time already planned in the modal types.

Once those parameters are inputted, the software can draw the speed/distance profile applying the principle of maintaining maximum speed as long as possible. Acceleration is maximal, but braking is not, in order to once again have a small reserve time available. This speed profile appears in **blue** in Figure 46. From this first theoretical speed profile, a time/distance curve is also drawn, appearing in **red** (of the two red curves, this one is below the other). Those curves could be regarded as the optimal situation.

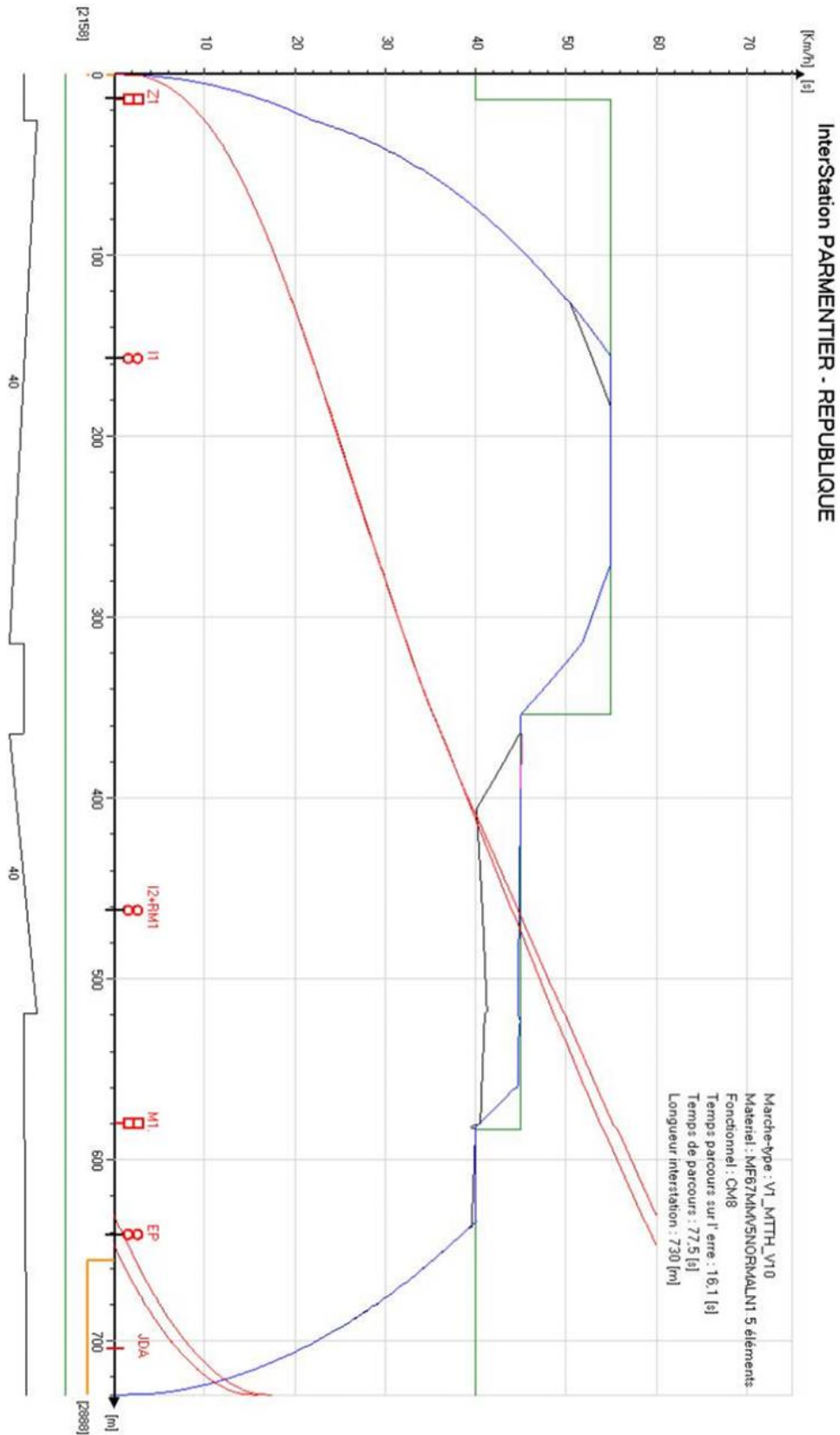


Figure 46 - Speed and time / distance diagram of Interstation Parmentier – République

After the optimal speed profile is drawn by the computer, the person using the software can choose to apply different methods to re-evaluate the curves and try to make them closer to reality, that is to say to get a profile that all drivers could naturally apply. Indeed, it is almost impossible for a driver to know exactly where to stop acceleration and when to start braking with which importance of braking if he wants to apply the optimal profile. The most usual driving behaviours are as follows:

- acceleration is maximal until a certain point lower than the maximum allowed speed (more or less 5 km/h lower) and then reduced until maximum speed is reached;
- maximum speed is not always maintained. Instead, the driver coasts through the section until he needs to start braking. When coasting, if the slope is downward, the maximum speed will be applied naturally anyway. When the slope is upward or straight, the speed will decrease, and when the driver reaches 5km/h lower than the speed limit, he starts accelerating again.

Those behaviours have been modelled and inputted into the software, and this leads to the black curve in Figure 46, corresponding to the second red curve (above the other one) for the time/distance curve. The black curve is considered as the average driving behaviour on the line and leads to the objective running time.

Definition of running times in the modal types

The interstations on the line can be operated either manually by the drivers or using the automatic pilot (most of the train movements are actually performed with the automatic driving when it is available). The running time that is derived from the black curve in the speed-distance diagram is called the “objective running time”, it is considered to be achievable by all drivers at all time (ensured by the reserve time) and is regarded as a “target time” for the automatic pilot. Therefore, one could think that this time (for the example of Figure 46, 77.5 s) is the one inscribed in the modal-type but it is not always the case.

The automatic pilot can have either one or two so-called “paces”: normal or accelerated. When the automatic pilot is developed with two paces, the objective running time corresponds to the time realised when applying the accelerated pace. Depending on the location of the interstation along the line, the running time realised when using the normal pace of the automatic pilot is defined as either the objective running time when no other pace is to be defined, or a reduced version of it as presented in Figure 47.

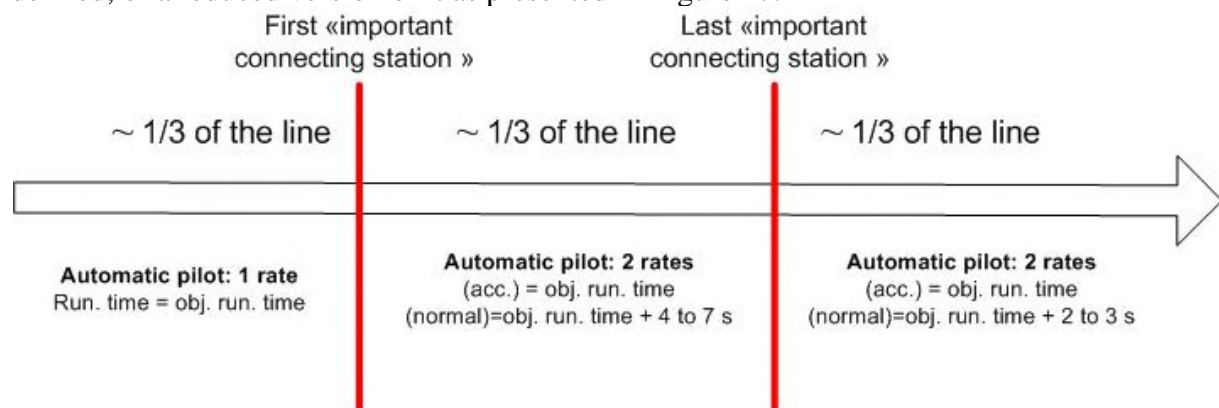


Figure 47 - Definition of the automatic pilot rates

Between the normal and accelerated rate, there is a total difference of up to 70s on some lines, all the more time that can be recovered from in case of delays. This is actually the main reason why the automatic pilot was implemented with two rates. It is considered that in the

first third of the line, trains are not very likely to fall behind too much, thus only one rate is defined. The middle part of the lines being located in the centre of Paris, it is there that the passenger affluence is the most important. The risk of new delay is greater and there is more need for delay recovery, thus the definition of two rates with a time difference up to 7s (the exact choice depends on the interstation, and especially on its length and on the importance of the two stations concerned). Finally on the last third of the line, there still needs to be some possibility to recover from the delay occasioned on the line, but it is not likely that additional delay will occur, much like in the first third. The division between thirds is of course arbitrary, and is not always exactly followed. As presented in Figure 47, it is actually the first and last important connecting stations that would define this separation. On line 3, which is represented in Figure 48, the division is made at stations République and Saint Lazare.



Figure 48 - Line 3 of the Paris metro network

After those times are decided, the speed-distance diagram is updated for the automatic pilot to implement the correct program of driving.

In the modal-types of the lines, it is the normal rates of the automatic pilot that are inscribed. Thus, it is ensured that the actual running times will always be equal or lower than the reference running times, but never greater, in theory.

It should be mentioned here that although the definition of dwell times is a completely different process, stations can be regarded as equivalent to interstation in terms of track occupation. Although there might exist some problems in both the running times and dwell times, and especially since all those calculations are not often updated (on line 3, the last update was performed in 2003) as explained in Annex 3, the modification of the modal types is a very delicate thing to do, for it also might lead to modification in the signalling implementation, in the timetables, etc...

Spacing of the signals and technical minimum headway

Signals are placed along the track to ensure security. The spacing of those signals also depends on the speed-distance diagrams and acceleration/deceleration data and for they are placed so that upon seeing a signal, the driver always has time to stop before the next one. Their exact spacing also depends on the headways that need to be ensured between all trains, for, as explained in the main text of this report, there always has to be an empty signalling section between two trains. Thus, if the sections are too long, the interval between trains can get too important. Signals therefore need to be placed as close as possible, as long as it is possible for the driver to stop before entering the next section.

The minimum technical headway of the line directly depends on the fact that there needs to be an empty signalling section between two trains. Based on the speed-distance and time-distance diagram, the exact time needed for the trains to run each signalling section at normal rate is calculated, those are called “temps de déblocage du signal” (French for “signal release time”). The greatest of those times is taken as the minimum technical headway (“signal pendule”).

Manoeuvring times

In terminals, the signals are actually placed on the track regardless of the speed or time/distance data, as terminals have very complex layout and signals are mainly here to prevent trains running different directions to collide, rather than two trains running in the same direction. With the same method as for the interstations on the lines, a speed-distance and time-distance diagram is built for each signalling section in the terminal using the speed limits of the terminal. Each maneuver being the sequence of a list of signalling sections, the manoeuvring times are calculated as the sum of each signalling section running time. For type 1 manoeuvres, which require the driver to walk from one end of the train to the other, 65s are added to this in case of trains with 5 cars (most lines except for example line 3bis whose trains only have 3 cars).

Annex 3 - Observations made on the modal-type and operational data (IGT) of line 3

On several days, observations were made on single trains of line 3, considered representative of the time of day (one for each period of time) both for dwell times and running times at all the stations. It was noticed that most trains had the same typical behaviour with some interstations taking always either longer or shorter to run than the theoretical time. The same was observed for time spent at the stations. Table 20 and Table 21 present those measurements for the 29th of March 2011. Table 20 indicates in seconds the difference between the realised running times and the theoretical running times between indicated station and the previous one (thus, there is no information in the first line of the table), while Table 21 indicated the difference in seconds between realised stay and theoretical stay at stations (there is no indication for the two terminals as the stay also depends of the departure times set by the system in one direction or the other).

A, B, C and D refer to the different modal types defined and used during the course of operations.

Direction 1	A		B		C		D
	15h	18h	6h	9h	12h	21h	0h
GALLIENI							
PTE DE BAGNOLET	9	22	0	5	9	4	2
GAMBETTA	12	5	7	6	6	7	10
PERE LACHAISE	1	0	6	6	-1	1	1
SAINT MAUR	4	0	0	1	0	0	-1
PARMENTIER	1	2	0	2	0	1	0
REPUBLIQUE	5	3	4	5	3	3	2
TEMPLE	-1	-3	-4	-1	-3	-4	-3
ARTS ET METIERS	2	2	0	2	2	0	2
REAUMUR-SEBASTOPOL	1	1	3	3	1	2	1
SENTIER	-7	-8	-8	-6	-8	-7	-8
BOURSE	2	1	2	3	1	1	0
QUATRE SEPTEMBRE	-2	8	-6	-4	-2	-6	-7
OPERA	-1	-3	-1	-1	0	-4	-5
HAVRE-CAUMARTIN	3	-7	-7	-6	0	-7	-8
SAINT LAZARE	3	-2	-1	0	0	-2	-2
EUROPE	-3	-8	-8	-5	-4	-6	-8
VILLIERS	11	4	10	13	9	5	5
MALESHERBES	-2	-4	-1	25	-2	-2	-4
WAGRAM	1	-1	-2	6	1	-1	-2
PEREIRE	10	6	6	11	7	6	6
PTE DE CHAMPERRET	5	6	2	12	1	0	5
LOUISE MICHEL	4	10	3	2	4	2	2
ANATOLE FRANCE	4	7	3	9	2	0	1
PONT DE LEVALLOIS	5	12	6	31	0	-1	6

Table 20 - Measured difference in seconds between theoretical running time and realised running time on representative train, 29/03/2011

As we can see, most running times appear to be lower than the reference time, except on the first part of the line (which makes sense because the objective running time is the one inscribed in the modal-type). The few occurrence of running times much higher than usual

(such as the 25s) usually correspond to trains that were stopped in front of a red signal because they were running too close to each other (typically at peak hours). However, there is no logical explanation for the fact that some times are always higher than the reference ones, as for Pereire or Porte de Champerret.

Direction 1	A		B		C		D
	15h	18h	6h	9h	12h	21h	0h
GALLIENI							
PTE DE BAGNOLET	19	15	-5	-3	6	6	-3
GAMBETTA	-6	-2	-12	-12	-8	20	-3
PERE LACHAISE	7	4	4	2	4	2	1
SAINT MAUR	0	4	0	6	-1	-1	-2
PARMENTIER	1	-1	2	4	-3	-3	6
REPUBLIQUE	0	-4	-4	0	-2	2	-4
TEMPLE	3	3	2	4	-1	5	2
ARTS ET METIERS	3	-2	-4	0	9	2	4
REAUMUR-SEBASTOPOL	4	0	-5	2	3	2	-1
SENTIER	-1	-2	-2	-2	-1	-1	0
BOURSE	1	-2	0	4	0	1	3
QUATRE SEPTEMBRE	2	4	1	6	1	-2	1
OPERA	4	-2	-6	4	0	14	0
HAVRE-CAUMARTIN	2	-5	-11	-4	-4	5	-4
SAINT LAZARE	3	-3	-8	4	3	6	-1
EUROPE	3	12	-3	12	1	4	3
VILLIERS	0	-6	-5	2	2	0	-3
MALESHERBES	9	0	-7	9	14	2	3
WAGRAM	3	1	12	5	1	-3	1
PEREIRE	8	-1	0	21	8	1	4
PTE DE CHAMPERRET	1	3	-2	6	11	8	2
LOUISE MICHEL	1	3	-2	7	0	6	2
ANATOLE FRANCE	6	0	-3	18	9	-2	-1
PONT DE LEVALLOIS							

Table 21 - Measured difference in seconds between theoretical dwell time and realised dwell time on representative train, 29/03/2011

As we can see, there is no general trend on the course of a whole day that can be detected. At the same station, some trains might need longer timers, whereas others need less. Some drivers drive slowly whereas others apply a higher speed. However, it does appear that during the course of the day, some stations show the same characteristics with running times always larger or smaller than the theoretical one as presented in Figure 49.

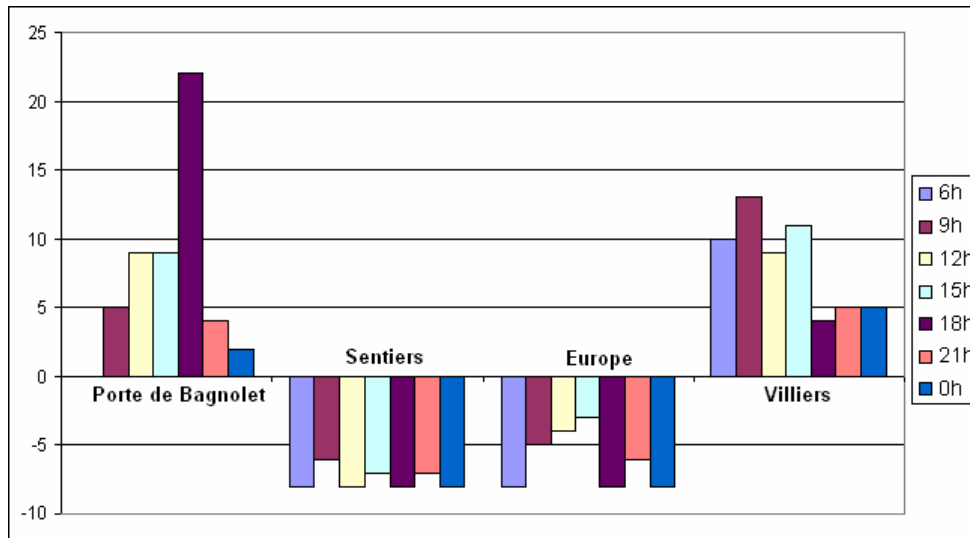


Figure 49 - Difference in running times before stations Porte de Bagnole, Sentiers, Europe and Villiers on line 3 at different times of day

Such observations cannot so easily be made on time spent at stations, although some stations seem to present the same general trends (more or less time needed than the ones defined in the theoretical modal types), as we can see in Figure 50.

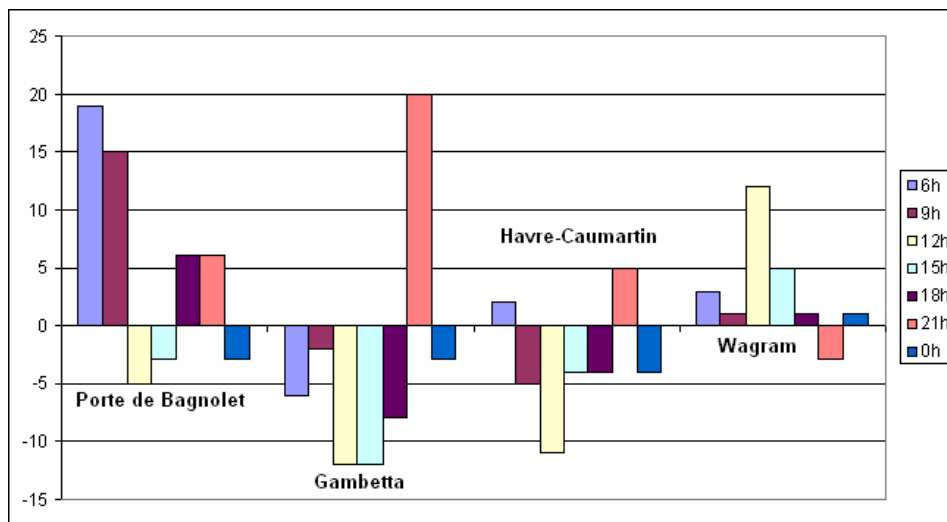


Figure 50 - Difference in dwell times at stations Porte de Bagnole, Gambetta, Havre-Caumartin and Wagram on line 3 at different times of day

Indeed, dwell times depend a lot on passengers flow and behaviour, which is a very difficult thing to predict and model. In any case, this once again shows the difficulty of defining clear general parameters.

For four representative trains (one for each modal type), the difference between the programmed running times – i.e. from the calculated departure hour the times that should have been respected if the train had run according to the modal type - and the realised running times (arrival and departure from stations) is presented in Figure 51.

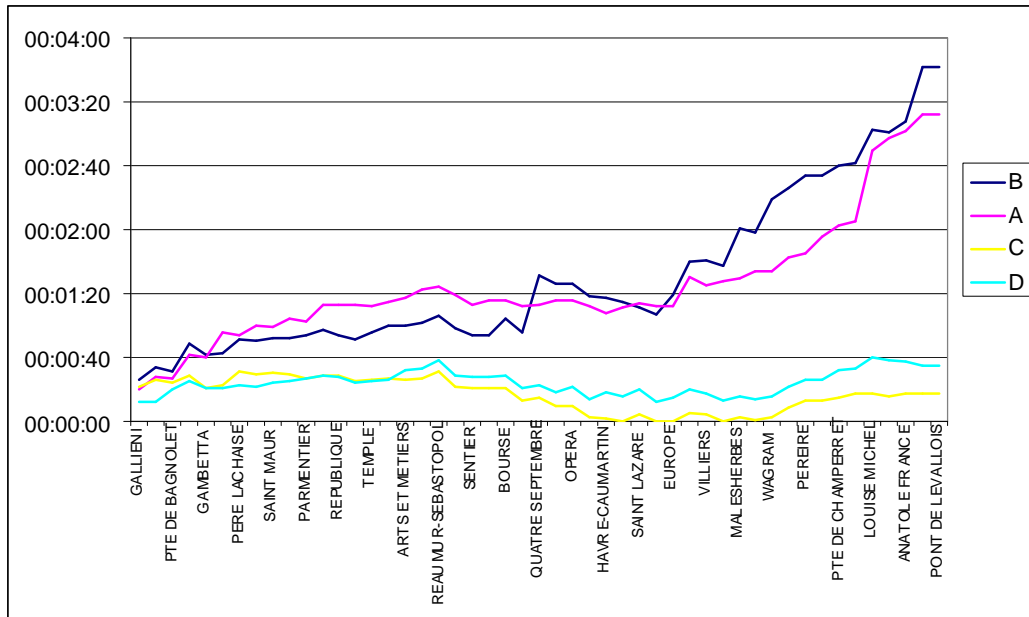


Figure 51 - Difference between programmed running time and realised running time of four representative trains

The blue (B) and pink (A) lines correspond to peak hour trains. As we can see, at those times, it is not possible for drivers to recover from delay along the line, and on the contrary, along with their running the line, their delay increases. On the contrary, during off-peak hours, drivers seem to be able to recover naturally from their delay at departure. This phenomenon is to be linked to the fact that when there are fewer passengers, it is easier to respect the theoretical times. However, this is true for dwell times, and it does not explain the problem of running times which could obviously be improved to be closer to reality.

When one looks at the course of the whole day, it turns out that the dwell time defined at some stations could indeed easily be improved and changed to be closer from reality. And even without changing the whole modal type, it could be interesting to think back on whether or not the right modal type is applied to the right moment of day. For example, modal-type B (designed for the morning peak hour) is applied from the very beginning of the day. However, it would be much more advisable to apply modal-type C for the first hours (for example between 5 and 7) as the demand at that time is not comparable to that of the real peak hour. In Figure 52 and Figure 53, the time spent at stations Gambetta and Havre-Caumartin by trains between 5 and 10 is represented for the 24th of March. In red is the theoretical time as defined in the modal type B applied at that time, and in blue the one of modal type C.

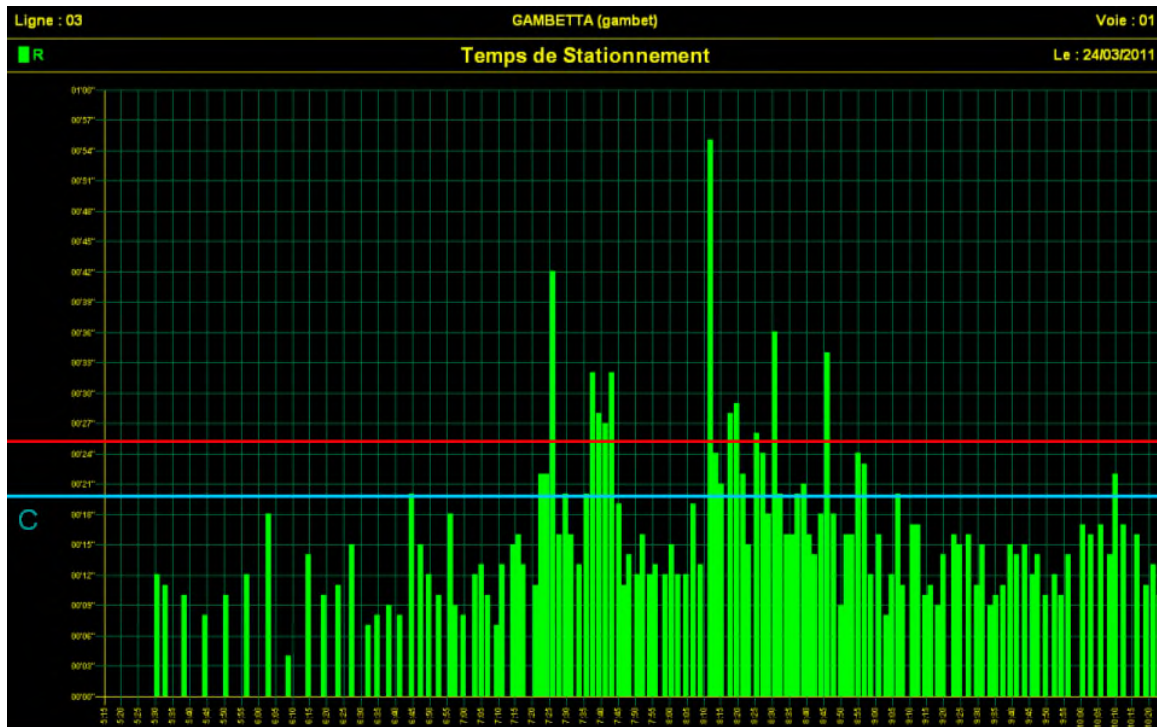


Figure 52 - Dwell time at station Gambetta on 24/03/2011

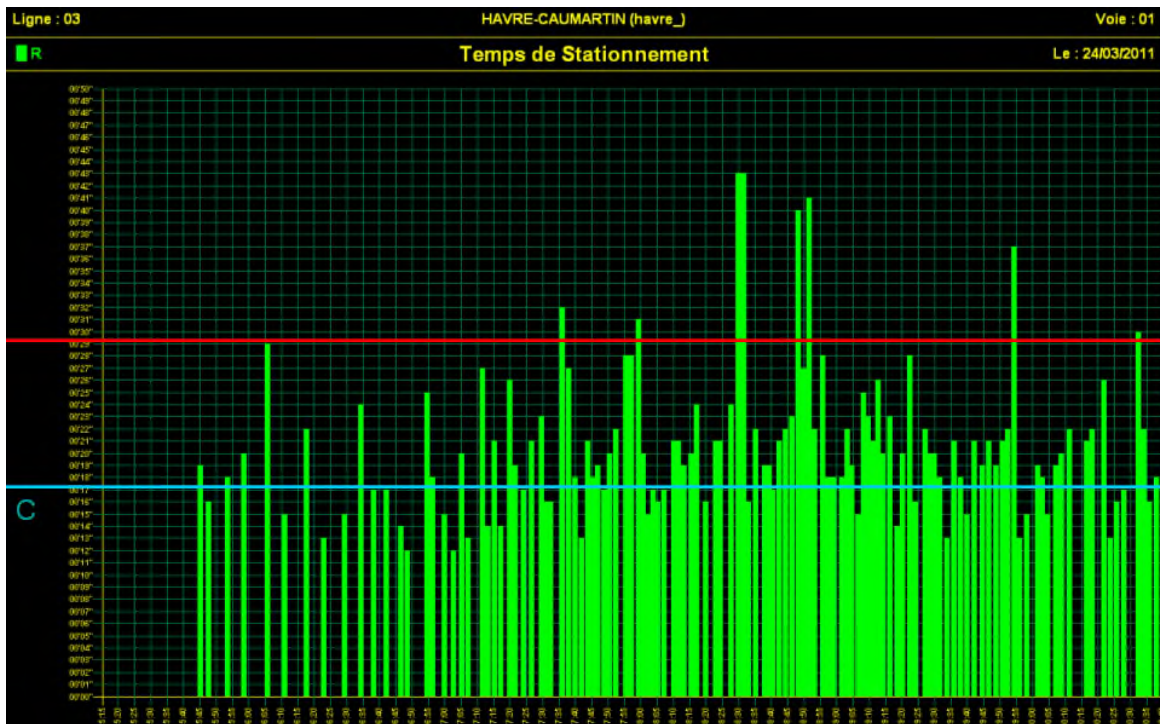


Figure 53 - Dwell time at station Havre-Caumartin on 24/03/2011

Those times are very uneven, and it is indeed difficult to define an average one that would be close enough to all of them. However, already we can see that some easy efforts could be made in this calibration of parameters that could help solving the problem of automatic regulation on the line, but would also lead to a more correct assessment of the running time on the line.

