DENFERT: PROJECTING TRANSPORT PLAN ROBUSTNESS

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BACKGROUND

The rail system is complex, with multiple sub-systems that interact intensively with each other: infrastructure, rolling stock, the transport plan, command and control systems, traffic management, passengers and more.

Hyper-concentration in densely developed areas makes the interdependence of these sub-systems even more critical, according to a strategic audit of the Paris Region's Transilien system carried out in 2015 by Ecole Polytechnique Ferroviaire de Lausanne (EPFL). The reason is simple: the slightest flaw in any of the components will spread and affect the others even more acutely because of the powerful amplifying effects of high density.

The Paris region has one of the most densely woven rail systems in the world, carrying more than 50% of total French rail traffic on only 10% of the nation's network. With public transport so important in these areas, it is all the more crucial to make sure that transport plans are reliable right from the design phase—and, in particular, to ensure that they are robust, so that small disruptions have the smallest possible impact on the network and can be quickly absorbed.

In addition, Ile de France Mobilités and French rail operator SNCF have identified "passenger punctuality" as vital in assessing the quality of their transport offer: this criterion is extremely important to passengers, in particular for the daily commute between home and work. Every line of the Transilien network has punctuality performance targets[1] tied to financial incentives, and actual performance is measured every day.

Once the transport service has been delivered, it is relatively simple to measure passenger punctuality using the actual time trains spend in stations, passenger-counting systems and information on departure and destination stations. But it is much harder to predict how punctuality performance will be affected when changes are made to one or more components of the rail system. How do planners know that they can trust the timetables for a new transport offer?

To meet these complex challenges, SNCF Transilien developed DENFERT[2], a new simulation tool with a model, a method and hands-on practices.

CORE PRINCIPLES BEHIND THE DENFERT PROJECT

The rail system is so complex that it is very hard to gain a nuanced understanding of its functional dynamics using an analytic approach.

[1] Percentage of passengers arriving at their destination less than five minutes late.
[2] DENFERT stands for *Discrétisation d'ElémeNts Ferroviaires pour l'Evaluation de la Robustesse Transilien*

That is why DENFERT was created—to give Transilien a powerful, highly accurate, scalable tool for simulating rail traffic.

Although Transilien created DENFERT primarily for use in the Paris region, we designed it to be usable throughout the French rail network for all types of operations-based research, including studies of capacity, running time, changes in service and robustness.

To meet these goals, DENFERT had to enable users to model and simulate the French system, including:

- Infrastructure, power profiles, traction restrictions and more
- The various signalling systems with the French rail network
- Rolling stock, its acceleration/braking performance, effort-speed curves and more
- Various types and parameters of driving behaviour
- Principles and standards for timetable design, including khi
- Rules for regulating traffic
- Various operating incidents

To ensure that DENFERT met these goals, Transilien made two critical decisions.

First, we wanted to develop a microscopic, dynamic simulation model similar to SISFYE[3]. Developed by SNCF's Innovation & Research Division, the SISFYE prototype was built iteratively over 15 years and is a testament to the added value that this approach creates across many operations-based studies.

To make DENFERT both sustainable and scalable, Transilien made a second critical decision. After calling for tenders in 2013, we chose to use Railsys®, an OTC software package made by RMCon, and adapt the product to our specific needs. Railsys® is an integrated timetable planning and simulation software tool with an excellent reputation on the global market. It allows users to plan timetables in detail and test the quality and robustness of their transport plan at the same time.

In choosing an existing software package, we gained a number of advantages:

- native Railsys® solutions that are already versatile and highly effective
- economies of scale, thanks to new features developed by RMCon for its other clients
- access to the publisher's skills and experience in rail simulation.

CHOOSING A MICROSCOPIC, DYNAMIC MODEL

The Paris Region's rail network is the second-busiest in the world, ranking behind Tokyo and ahead of London and Seoul. It carries five times more traffic than New York's system.

Every day, the Paris region handles 6,200 trains and 3.2 million passengers, with a wide range of traffic—local, long-distance, regional, freight and more—placing heavy demands on an ageing infrastructure. These diverse traffic flows are not always separated, and the slightest delay for one train inevitably carries over to the ones behind it.

[3] See the article "Simulation de Systèmes ferroviaires, SISYFE apporte sa pierre à la modernisation de la SNCF," by Daniel GAUYACQ, *Revue Générale des Chemins de Fer*, April 1999

This made it abundantly clear that a microscopic[4] simulation model was the best choice for the Paris region—as well as for many regional lines and rail junctions.

There are two types of microscopic model for two different needs: planning and simulating.

Planning models have been widely used in the past, but are static. These software programs can be used to plan traffic on the rail network and can detect train path conflicts based on occupation or simultaneous booking of a certain number of block sections. This means that they can map out theoretical itineraries for timetables, but cannot run rail simulations.

By contrast, dynamic models allow users to run rail simulations, in which the movement of each train is influenced by the movements of the trains around it. With these models, users must characterize the behaviours of moving components and rules for regulating traffic, as well driver behaviours in response to signalling. Disruptions—including trains delayed in their station of origin and incidents in the network—can then be introduced into the simulations, allowing users to analyse system performance and robustness under disrupted conditions.

Railsys®/DENFERT is the only microscopic, dynamic simulator on the market that has both a highly accurate timetable design module (incorporating SNCF guidelines) and a highly accurate rail simulation module that can run predetermined incidents ("deterministic simulations") and multiple, randomly generated incidents ("stochastic simulations"). As a result, users can move seamlessly from creating a transport plan to analysing its performance in operation, and to iterating smoothly between design and robustness analysis.

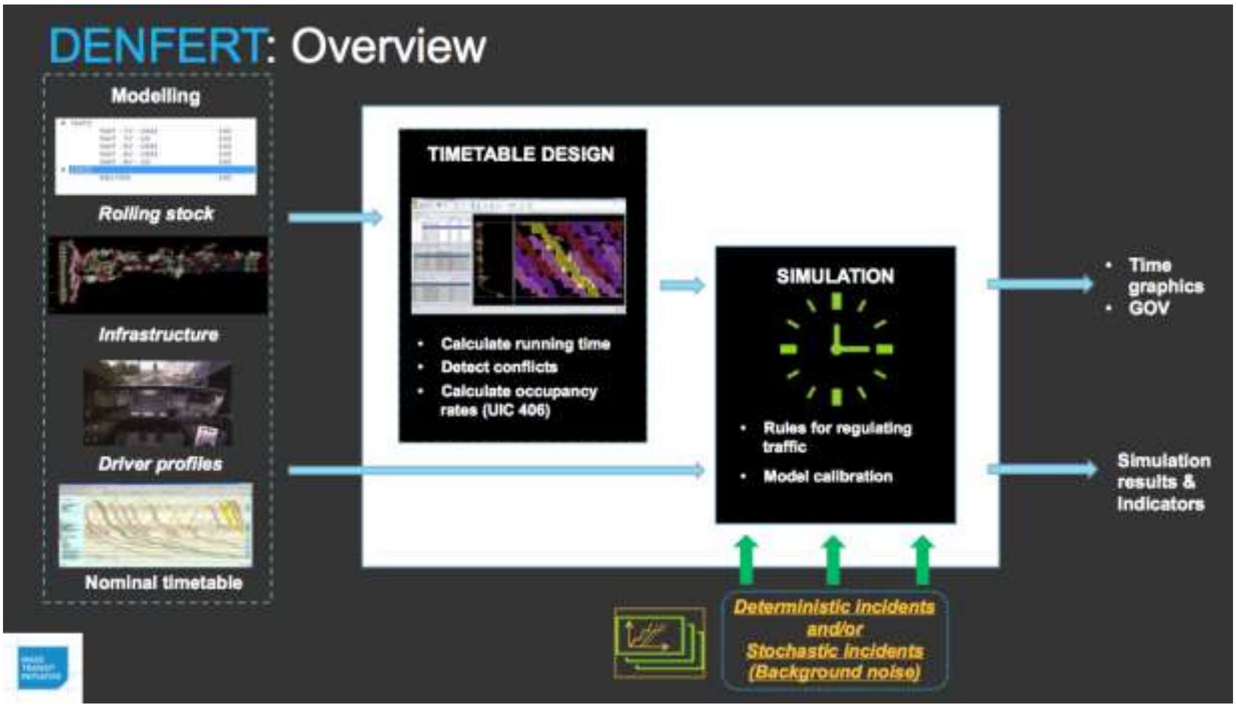

Figure 1: overview of DENFERT's functional architecture

With DENFERT's timetable design module, users can simultaneously generate online graphics together with station track occupation graphics. It includes a highly accurate engine for

[4] By "microscopic model" we mean a model that provides an extremely granular description of rail infrastructures and the performance characteristics of rolling stock. The modelling level for infrastructures is similar to the level for signalling configurations, including signals, switches, itineraries, and more.

calculating running time, detecting traffic conflicts (head-on collisions, rear collisions, convergence, divergence), developing timetables that comply with best practice and construction standards, especially for headway between trains.

Railsys® / DENFERT includes a core simulation module that generates:

- “deterministic” simulations of the nominal timetable, with or without introducing selected operating incidents;
- “multiple stochastic” timetable simulations that introduce random incidents according to the Monte Carlo principle (probabilistic distribution).

As a result, the model is particularly well suited to studying robustness and transport plans. In particular, DENFERT can subject transport plans to simulations of small-scale disruptions caused by factors both inside and outside the rail system—the “background noise”[5] of daily operations.

The impact on the performance and reliability of the transport plan can then be measured and compared (delays, on-time performance of trains, passenger punctuality and more)

HIGHLY ACCURATE MODELLING OF THE FRENCH SIGNALLING SYSTEM

The ability to set parameters and adapt them to the unique characteristics of a national rail network is one of the criteria for assessing the accuracy of dynamic simulation models.

Key actions—distinguishing driver behaviours under KVB vs KVB-P; differentiating between a “reduce speed” sequence that has a warning with a flashing indicator versus one without; registering and understanding the presentation of a flashing semaphore signal; driving at sharply reduced speed—cannot be modelled using the parameter-setting rules of a non-French signalling model.

The DENFERT model includes 16 customizable variables designed specifically for France’s BAL and BAPR signalling systems and their related speed control systems (KVB and KVB-P). Nearly one hundred use cases are described in detail to represent potential signalling indications, the relationships between these indications, and driving behaviour in response to each.

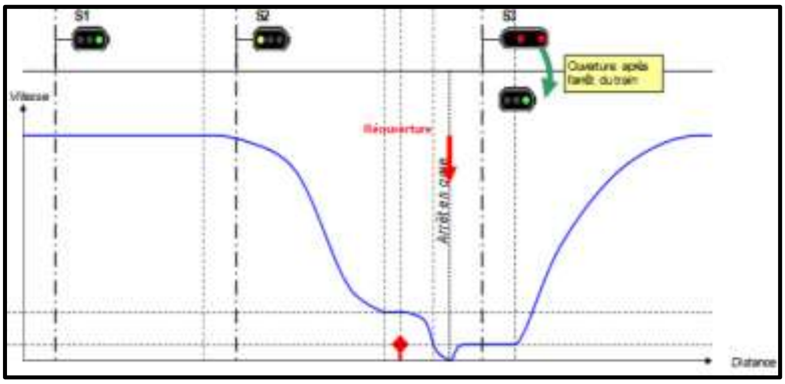

Figure 1 : Sample use case (driver authorized to proceed; special conditions apply)

5 Background noise consists of minor, everyday delays observed for a given timetable over a given year, at stations of origin, between stations, and while trains are stopped at stations along the way.

OTHER ESSENTIAL CHARACTERISTICS FOR NUANCED SIMULATIONS

DENFERT includes other characteristics essential to generating nuanced simulations:

- Rolling stock characteristics, including effort-speed curves and running resistance
- Description of timetables for commercial and utility trains
- Various in-station operations (turnaround times, detaching/assembling carriages, etc.)
- Train connections (such as turnarounds)
- Required connection time between trains (up to a specific lateness threshold)
- Longitudinal profile of the infrastructure under the entire train (other models treat the train as a single moving dot in the centre of the convoy).
- Stopping points based on train type and composition (this is not available in conventional timetabling tools which use a single stopping point regardless of train type and composition).
- Maximum speed profiles for pairings of infrastructure and rolling stock
- "Drop pantograph" and "cut power" areas, power profiles and restrictions on traction, if any
- Switches, including complex units
- Time required to set up and adjust switch configurations -
- Signal visibility points (often difficult to determine but essential for the KVB-P speed control system)
- And more.

A heuristic algorithm that prioritizes trains by lateness thresholds allows us to simulate a realistic approach for human routing supervision.

THE LIMITATIONS OF OUR MODEL

Like any model, Railsys®/DENFERT gives a simplified view of the reality it depicts, and some phenomena—the effects of weather on adhesion, for example—are not reproduced.

The first source of these limitations is the "human factor" in the rail system, which is not only difficult to know with any accuracy but also difficult to reproduce reliably.

This is due primarily to manual driving, which produces a natural dispersion of speed profiles among different drivers. While it is possible to analyse the running of trains in depth with tools such as REX micro and TAIDO[6], which rely on ATESS ("black box") recordings, it is still very challenging for users to accurately characterize the driving profiles they wish to model. Result: we cannot avoid using hypotheses to some degree. In addition, it is hard know whether and to what extent today's practices would continue if timetables or other major system components were significantly changed. So by definition, these are only hypotheses—but expert hypotheses all the same.

The same applies to the process of modelling operational management of a transport plan. While our tool knows how to reproduce a few simple actions to regulate traffic in response to minor incidents that do not require changing the transport plan, it cannot decide to reassign rolling stock, interrupt service for trains in operation, or cancel trains. As a result, the model's actions may not fully correspond to the finely honed decisions of a seasoned traffic controller or transport plan manager.

[6] SNCF software products that can recreate and analyse how trains run in connection with the actions of the driver.

This means that while it does produce indicators of robustness, these cannot be directly compared to official on-time performance or punctuality statistics.

The DENFERT model is designed to reproduce and project large-scale dynamics and trends. Users must be thoroughly familiar not only with the model and its limitations, but with the grey areas in the scenarios they are studying—an essential condition for actual situations and, even more important, for modelled scenarios. In other words, the results generated by DENFERT must be carefully and properly interpreted, analysed, challenged and extrapolated with an eye on the model's known limitations, as well as on unknown and poorly understood factors in both actual and modelled scenarios.

As with any simulation, DENFERT results are particularly useful for comparing a modelled scenario to a baseline—in short, for relative values rather than absolute values.

STUDYING TRANSPORT PLAN ROBUSTNESS

Ordinarily, DENFERT simulations involve comparing a baseline scenario to a model scenario, enabling the user to analyse the impact of one or more changes to system components

The changes can affect:

- infrastructure
- command and control system
- locomotives and carriages
- driving behaviour
- operating rules and traffic regulation methods
- structure of service

CALIBRATING THE MODEL

We begin by calibrating the baseline scenario based on a current or past annual timetable. The process involves three main steps, and the baseline can be more or less finely calibrated to strike the right balance between the time available for the study and the accuracy of the results.

In the first step, we calibrate parameters for driving behaviours under different conditions, working with experts from SNCF Traction. This step can incorporate analysis of ATESS "black box" data using SNCF tools such as Taïdo and RexMicro.

In the second step, we calibrate traffic regulation parameters, applying operating rules such as "first come, first served" or assigning priorities by type of traffic, including semi-direct, omnibus, TER and Intercités. These are based on lateness thresholds that can be refined later, sector by sector, with the requester of the study. We then simulate a number of isolated incidents to confirm that the behaviours adopted for the scenario accurately reflect observations in the field.

In the third step, we choose the disruptions that are most frequent and most representative of the incidents observed in the study area (locations, values, lateness distribution). Complex analysis and filtering are required if the user plans to run lateness distributions at the point of origin, between stations and while trains are stopped in stations. Lastly, we work to match the model output with the on-time performance history of the baseline service by adjusting the various parameters of the simulation model.

THREE COMPLEMENTARY STEPS, INCREASING COMPLEXITY

Transilien's operations unit has divided analysis of rail system robustness into three steps. (See

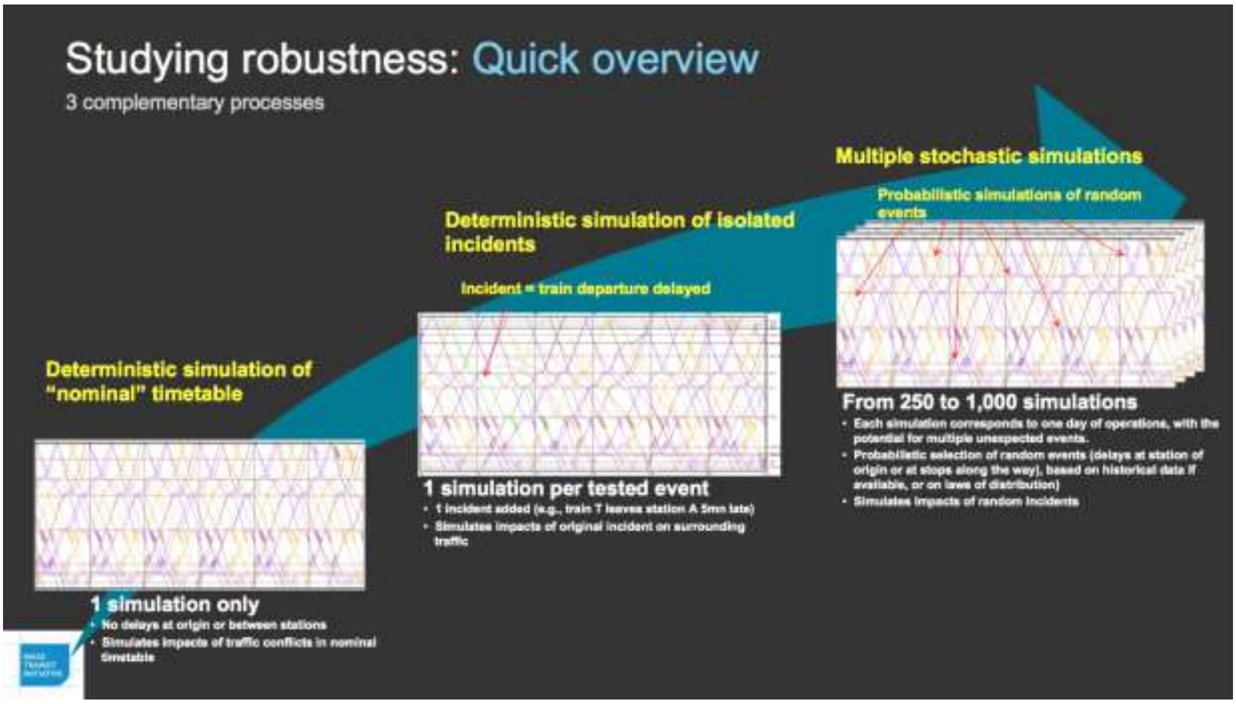

Figure 2)

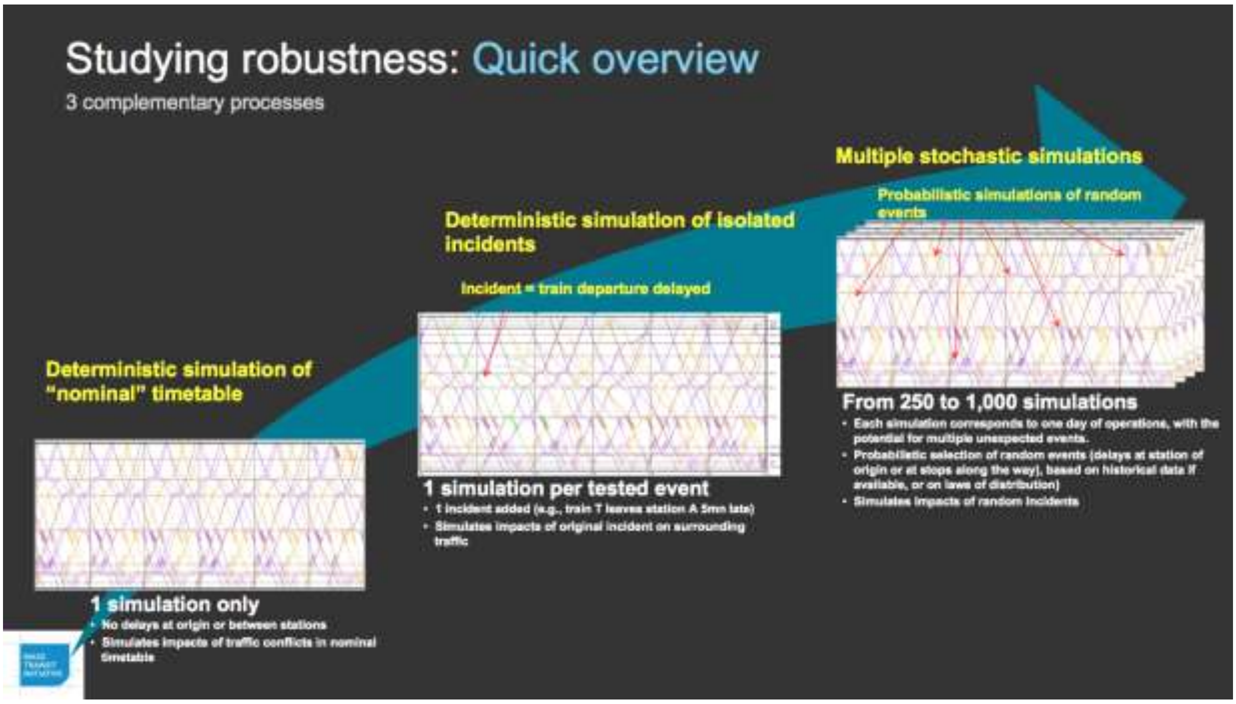

Figure 2: Robustness study methodology

DETERMINISTIC SIMULATION OF “NOMINAL” TIMETABLE (ZERO INCIDENT)

The first analysis is commonly called “zero incident,” which simply means that we observe how the rail system reacts under the nominal timetable, with no added incidents. If the signalling system has changed, we focus in particular on determining the resulting interval between trains. For each timetable, we list the conflicts, and if necessary we work to determine the saturation level (as defined in UIC Leaflet 406) section by section, station by station, and switch area by switch area.

When one of the main components of the system has changed, we work to identify its impact without adding other disruptions (such as a temporary speed restriction for works, with no other operating incidents).

“Zero incident” analysis produces a simple, easy-to-interpret diagnostic.

Key indicators generated by this analysis include:

- Running time for current and future infrastructure and rolling stock
- Minimum time between two successive trains
- Number and location of conflicts
- Saturation levels on lines, in stations and in station approaches
- Average, cumulative and maximum delays in various locations

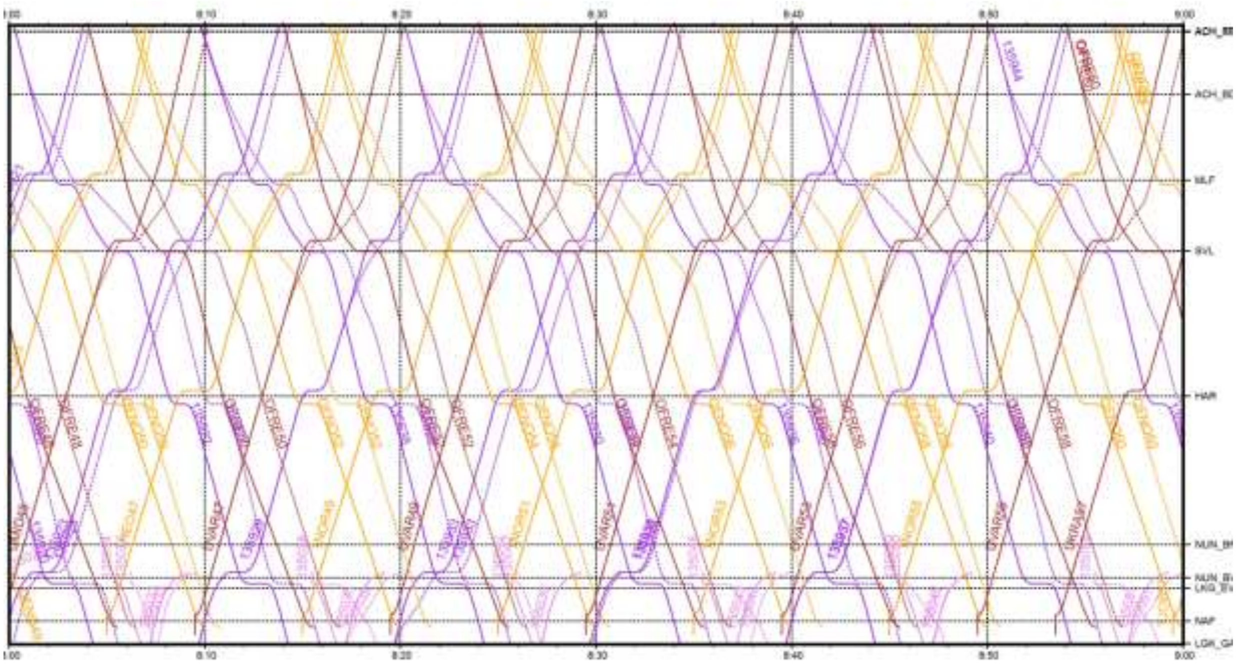

Figure 3: Sample simulation of nominal timetable with traffic conflicts (shown as dotted lines)

DETERMINISTIC SIMULATION OF SPECIFIED INCIDENTS

In this simulation we can identify incidents commonly encountered in everyday operations, such as delays at origin or when stopping in stations along the way.

In general, we simulate one or more isolated incidents over a specific time period and in a specific area.

Key indicators generated by these simulations include:

- Number of affected trains
- Average delay for affected trains
- Maximum delay
- Time to return to normal for the entire area under examination

We can even generate results on the comparative robustness of the modelled system and the baseline system at this stage, provided we carefully choose a few disruptions that are typical of frequently encountered incidents.

In addition, this step allows us to calibrate rules for regulating traffic—an essential point for carrying out stochastic studies in the next step.

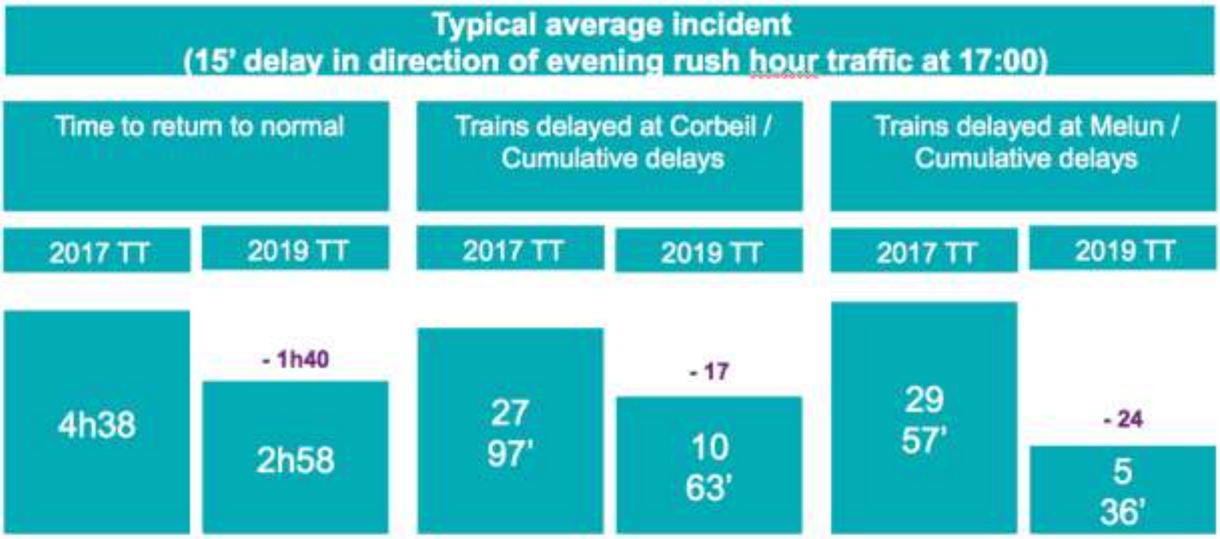

Figure 4: Simulated results of an isolated incident

MULTIPLE STOCHASTIC SIMULATIONS (PROBABILISTIC METHOD)

This method analyses a timetable's robustness against the "background noise" of everyday events. Background noise is characterized by distribution of delays at origin, between stations and during stops, and is generally determined from historical data on the lateness and on-time performance of the baseline service.

Once this distribution has been refined by direction of travel, type of mission (for individual trains if necessary) and time period (morning rush, evening rush, off-peak periods), it can define disruption rules that will be linked to trains in the baseline timetable.

Every time we run a simulation for the time period under study (morning rush, evening rush, 24 hours), we add lateness distribution curves, beginning with the simulation model for the baseline service, using a series of iterations to calibrate the model and seeking convergence between the model's output and the on-time performance of the baseline service.

It is essential to run enough simulations (generally several hundred) to allow the various on-time performance indicators to converge. During each simulation, the previously defined disruption rules are applied to the trains. Each simulation corresponds to one day of operations, with the potential for multiple unexpected events.

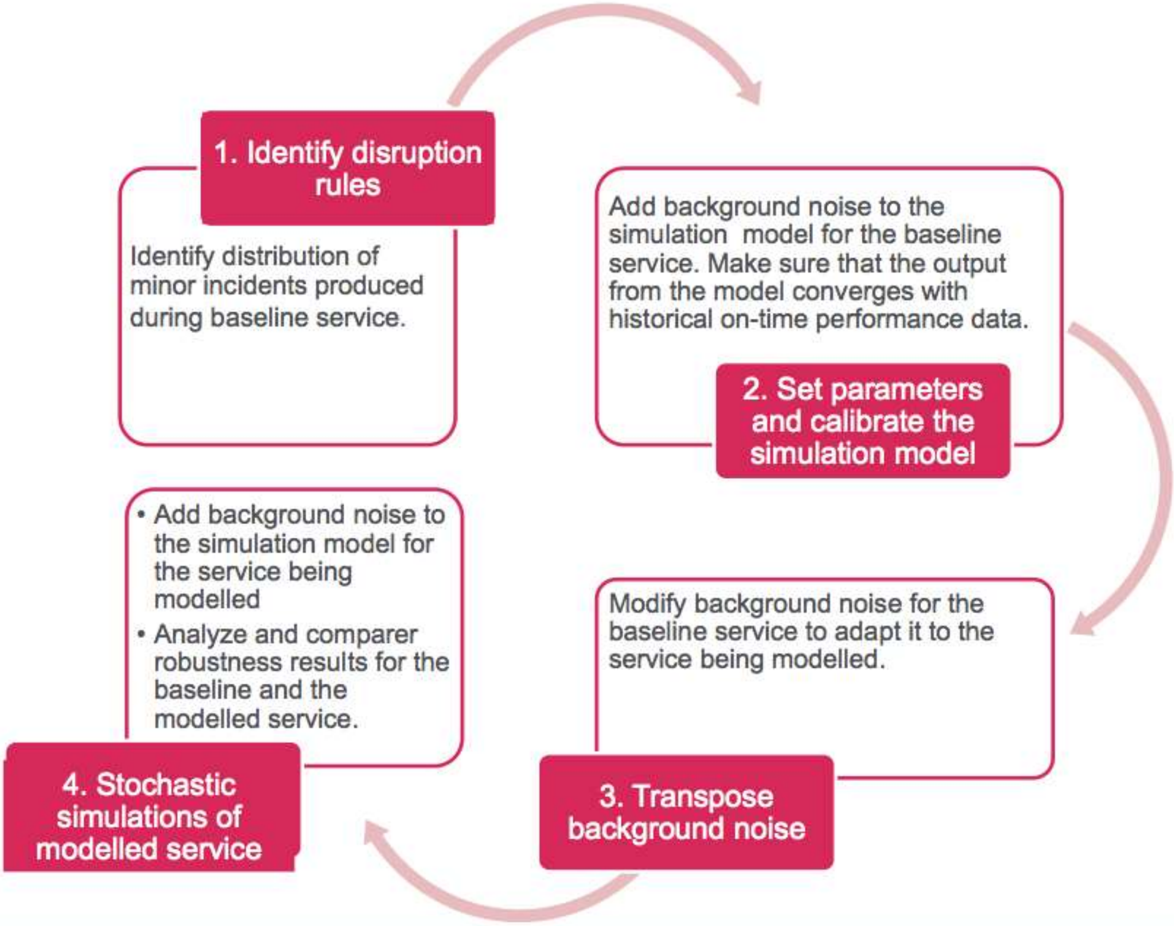

Figure 5: Stochastic simulation methodology

Once the model is calibrated, it may be necessary to transpose the “background noise” to the modelled service, for example if there have been changes in service structure, stopping time or other key variables.

Once transposed, the background noise is run on the modelled timetable. Once again, it is essential to run enough simulations (corresponding to the right number of days with disrupted traffic) for the resulting indicators to converge.

Key indicators generated by these simulations include:

- On-time performance within X minutes at each station by origin/destination
- Passenger punctuality rate
- Average/median delay, maximum delay and cumulative delay, measured in key locations

Figure 6: Sample robustness study comparing annual timetables for 2017 on 2019 RER line D (Paris Region)

STUDIES WITH DENFERT

As illustrated here, DENFERT can be used to study any aspect of operations—running time, capacity, timetable design and robustness.

Studies carried out by the Transilien operations unit focus primarily on the robustness and performance of major updates to the rail offer in the Paris region, including:

- L2 Sud (Paris St Lazare / Saint-Nom la Bretèche – Versailles Rive Droite) for the 2016 timetable**
- RER A and L3 (Paris St Lazare – Cergy le Haut) for the 2018 timetable
- RER line D for the 2019 timetable
- RER line C for the 2020 timetable
- EOLE (RER line E) Mantes extension
- 2020 timetable for Normandy

We generally carry out these studies as the new offer is being developed, testing major variants and selecting the best-performing options. In addition to showing the robustness of new transport offers, most of these studies generated proposals to adjust timetables, configurations for track occupation graphics, and recommendations to modify signalling or other infrastructure components.

For the L2 Sud, A and L3 lines, lessons learned were applied, and the updated offers studied with DENFERT went into effect in December 2015 and December 2017 respectively. And punctuality performance improved significantly, in line with the trends generated by the DENFERT studies (See Figure 7).

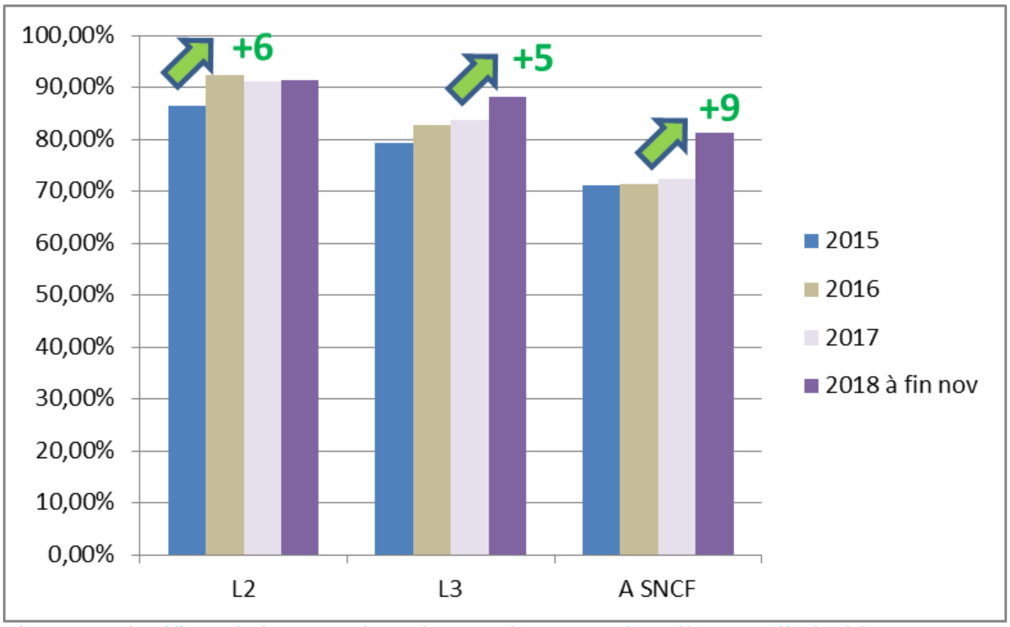

Figure 7: Significantly improved on-time performance for offers studied with DENFERT (L2, L3, and RER line A – SNCF)

The Transilien operations unit has also used the DENFERT simulator to run other types of studies. These include:

- Running saturation diagnostics on the E-P line, for IDF-Mobilités, and the EPT4 line.
- Studying the impact of works requiring temporary speed restrictions on lines U and E. Purpose: determine the feasibility of maintaining the nominal transport plan during the restrictions.
- Studying the impact of infrastructure upgrades linked to the future CDG Express line on the operability of Line B.
- Studying ways to improve signalling-driving behaviour (in combination) on the Chatelet-Gare-du-Nord segment
- Simulating new transport plan management rules to optimize management on the segment shared by lines L2 and U.

In addition, SNCF Transilien makes DENFERT available to other units within SNCF Group. Today nearly 40 in-house users are studying operations with DENFERT, and the number is rising sharply.

CONCLUSION

For SNCF Transilien's in-house clients (generally the heads of Transilien lines), DENFERT is an important building block in the decision-making process, though obviously they have other sources of support. Today DENFERT is an integral part of Transilien's team effort to create a successful transport offer, and it is helping to reframe the conversation with our organizing authority and our passengers.

DENFERT is also a powerful teaching tool. For example, it has been used to produce training videos showing the impact of driving behaviours in densely developed areas, including the importance of departing on time and the influence of certain traffic regulation decisions.

And beyond the tool itself, the DENFERT project is helping to forge a culture of operational excellence at Transilien. It has raised the bar for drafting transport plans and for addressing issues around the operational performance of rail within the mass transit system.

In short, running rail simulations is now a reflex—definitely part and parcel of how we operate in the Paris region—and has become one of the golden rules for operating mass transit systems.

ILE-DE-FRANCE MOBILITÉS AND DENFERT

In response to the dense development and increasing number of works in the Paris region, we are on a relentless quest to make our timetables as robust as they can possibly be. When timetables are updated, SNCF Transilien's DENFERT tool is essential to the decision-making process, both for us at Ile-de-France Mobilités and for the regions concerned.

A DENFERT simulation of the RER A timetable showed that it was impossible to deliver the offer defined in our 2008 contract under nominal conditions—objective proof that the timetable needed to change.

With DENFERT, we can approximate how the modelled timetables will behave in response to ordinary disruptions and make the most of the gains we expect from the measures SNCF has submitted to Île-de-France Mobilités. Knowing how the simulated results for the baseline timetable compare to results for the modelled timetables is a critical factor in choosing the final scenario.

When we upgraded RER line D, boosting performance was a core goal, along with a strong commitment from SNCF to improve on-time performance. The acceptability of the new service, which introduced the idea of connecting shuttle services to public transport services, hinged largely on the increased robustness measured by the DENFERT tool.

Naturally Ile-de-France Mobilités will pay close attention to the performance of the new offer to see how closely the actual outcome reflects the results of the DENFERT simulations.

Pauline Gautier, head of the Rail Offer department at Ile-de-France Mobilités