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## A TRANSIT ASSIGNMENT MODEL WITH CAPACITY CONSTRAINTS: A LARGESCALE IMPLEMENTATION

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# A TRANSIT ASSIGNMENT MODEL WITH CAPACITY CONSTRAINTS: A LARGE-SCALE IMPLEMENTATION

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## ABSTRACT

The CapTA model is developed to capture the capacity phenomena in passenger traffic assignment to a transit network. These pertain to the interaction of passenger traffic and vehicle traffic: vehicle seat capacity drives the internal comfort, vehicle total capacity determines internal comfort and also platform waiting, passenger flows at vehicle egress and access interplay with dwell time, dwell time drives track occupancy and in turn the period frequency of any service that passes the station along the line of operations, and then service frequency influences service capacity and platform waiting.
The Greater Paris Region is an ideal field for applying a transit assignment model with capacity constraints. The transit network involves about 1 500 bus routes together with 260 train routes that include 14 metro lines and 4 tramway lines. Traffic assignment at the morning peak hour is characterized by heavy passenger loads along the central parts of railway lines. Increased train dwelling, due to boarding and alighting flows, and reduction in the service frequency impact the route and line capacity. The generalized time of a transit trip is impacted mainly through its in-vehicle discomfort component.

*Keywords: Transit network, traffic assignment, capacity constraints*

## INTRODUCTION

In the transit network of large urban areas, it frequently occurs that the transit system is submitted to heavy congestion at the peak hours on working days, especially so at the morning peak in the central part of the urban area. Under that circumstance, not only may the passengers experience the discomfort of crowding, delay and unreliability, but also the operation of services may be disrupted by increased dwelling times, vehicle bunching and delays, leading to reductions in service frequency. Thus, traffic is inconvenienced and disrupted at both levels of mobile units, passenger and vehicle.
Although these issues are addressed in the design phase, and described at length in the Transit Capacity and Quality of Service Manual (TRB, 2003), little attention has been given by the transportation modellers to the detailed description of the transit service operations within a passenger flow assignment model.

The CapTA model (for Capacitated Transit Assignment) is purported to bridge the gap by offering a model of traffic assignment to a transit network that it sensitive to the interplay between passenger and vehicle traffic at the line level. Furthermore, we provide a novel modelling framework that is both systemic and modular. In addition to the capacity effects modelled - in-vehicle comfort, vehicle capacity and track capacity - other effects may be included, as long as the general architecture remains unchanged.
The scope of the paper is to offer a brief description of the CapTA model and demonstrate its efficiency in simulating a large-scale transit network, that of the Greater Paris Region. The application is not purported to act as a diagnostic of the state of the network, but rather to serve as a showcase of the capabilities and the behavior of the models.
The Greater Paris Region covers an area of 12 072 km2 and accommodates a population of 11,7 million. With 35 million trips daily by all motorized and non-motorized transport modes, the adequacy of the transportation system is crucial. The public transportation acts as a structural network with a modal share of 29% of motorized trips – although with a significant spatial diversity from the central core to the outer suburbs.
The rest of the paper is structured in seven parts and one conclusion. In the first section we make a general description of the CapTA model, and essentially the Line Model. Then, we focus on the simulation of the Grand Paris network. First, we present the transit demand on the morning peak hour and the transit supply, as well as the network used for the simulation. We identify the model variants and some simulation characteristics. Then we present the results, starting with the passenger flows on the network and the flow-to-capacity distribution of the arcs. Section six focuses on the impact of passenger flows on the operation of the transit services. In the final two sections we relate the impact of the capacity effects on the passengers' travel time and generalized time and further discuss the effects of total vehicle capacity and in-vehicle comfort. The conclusion points various perspectives of application and development.

# THE CAPTA MODEL AND THE LINE SYSTEM

On a transit network, passengers and service vehicles interact in a number of ways. Vehicle traffic determines the in-vehicle travel times and also the waiting time on platform. Passenger traffic influences the dwelling time, hence also track occupancy and maybe even service frequency. Furthermore, the interplay of passenger flows and vehicle capacity determines the in-vehicle comfort and the residual capacity for access at a station. The CapTA model, introduced in Leurent et al. (2011) addresses these effects by line and deals in a specific manner with the local interactions of vehicles and passengers.
The CapTA model, developed in Leurent et al. (2012) introduced a novel framework for modeling capacity effects, based on a bi-layer representation of the transit network. The lower layer deals with service operations by line and the local interactions of vehicles and passengers, whereas the upper layer pertains to passenger path choice and network flows on links, either pedestrians or line links.
On the lower layer of the network each transit line is modeled as a specific sub-network corresponding to the infrastructure network, with vehicle links either of passage in station or of line section between two adjacent stations, and pedestrian links for service boarding and

alighting. A line model is developed to treat the physical effects that take place and evaluate the attributes of a passenger trip.

On the upper layer, intra line bundling takes place between access-egress pairs of station along the line, meaning that passengers are willing to board any vehicle with available capacity that services their own station of egress. The service network is composed of line legs, introduced in Leurent et al. (2011) and representing a transit trip between two access – egress station on the transit line, and pedestrian links, for access-egress trips and transfers.

There is a two-fold relationship between the two layers by line $\ell$: tip down, a vector of passenger flows $\mathbf{x}_\ell = [x_a : a \in A_\ell]$ by leg $a$ along the line is assigned to the line sub-model, yielding the local passenger flows; bottom-up the line sub-model yields the vector $\mathbf{g}_\ell$ of the average generalized cost, $\mathbf{w}_\ell$ of waiting time and $\boldsymbol{\varphi}_\ell$ of effective operative frequency. In other words, the line sub-model amounts to an elaborate cost-flow relationship in vector form on the upper layer of the network – the passenger network.

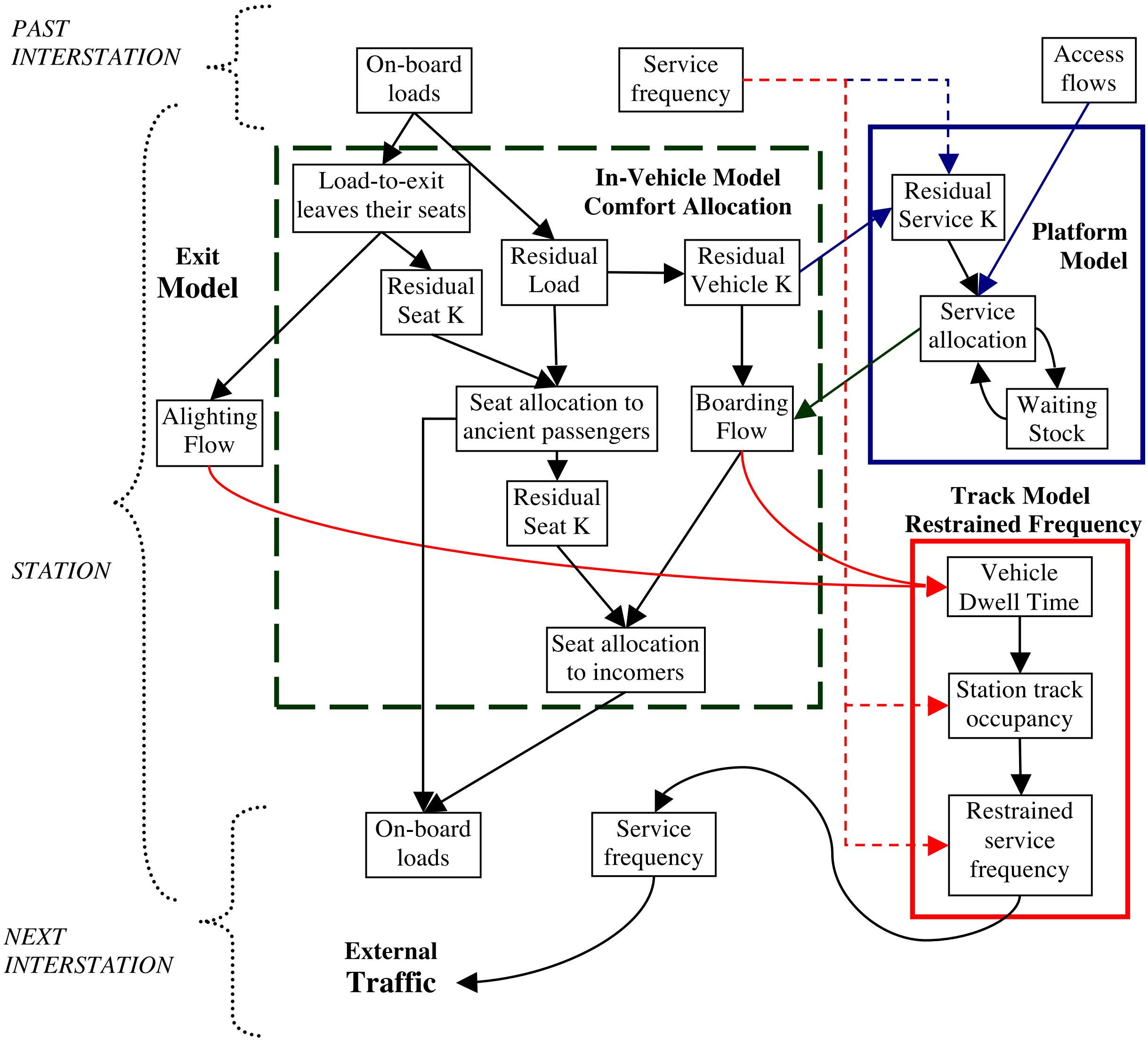


Figure 1 – Overview of the line system (K for capacity)

A line of operations, $\ell \in L$, is defined as a connected, arborescent, acyclic network in a single direction of traffic. The link set – corresponding to the lower layer – includes track links either of interstation run or station sojourn, together with pedestrian links for boarding and alighting at stations. The line and service topology of links and nodes is useful to model not only the topology of service and line legs, but also the chronological order of traffic operations. Figure 1 depicts the process of operations: in fact there are five parallel and related processes of: (1) passenger traffic within the vehicle, (2) passenger alighting, (3) passenger waiting on station platform and boarding vehicles with available capacity and servicing their egress station, (4) dwell time and track occupancy that determine vehicle operations hence in turn service operations and their frequency during the period of reference, (5) interaction with external traffic on interstation links.

In CapTA we address each line system as a particular subsystem in the transit network, on the basis of specific models. There are two main models at the level of the line: a physical model of flow loading in vehicles and of service traffic – the line flow loading model -, and an economic model of cost evaluation in the setting of the individual passenger that would use the line on a given leg – the line leg costing model.

The line flow loading model is used for estimation the physical interactions of the passenger flow on the elements of the transit line and the effect of the capacity constraints. For that, the flow loading algorithm proceeds in the direction of traffic along the line, by handling the track links or equivalently the stations on the line in forward topological order. The treatment of each station involves a number of successive steps, following the chronological order of traffic operation suggested previously. A local model is developed for each operation and the local capacity phenomena are modeled through the following local constraints models.

At the local level, at each station the model aims to capture the capacity phenomena related with the vehicle seat capacity, the total capacity and the interplay of passenger flows at access and egress with the dwell time and the service frequency. These phenomena are dealt with by line of operations on the basis of a set of local models yielding specific flows or costs. The local model of in-vehicle comfort (seat capacity) is adapted from Leurent (2012a), where the vector of passenger flows $[y_{zs}]_{s \in N_z, s>i}$ along a service leg is faced with the available seat capacity $k_{zi}^r$ at every stage along the route; seated alighting passengers that exit at a given station yield residual capacity, while a two level competition (with a priority for on-board standing passengers) takes places where the standing passengers among the same priority level have equal probability to get a seat $p_{za}^r = \min\{1, k/y\}$. Thereafter, the in-vehicle comfort is dealt at the vehicle level.

The transit bottleneck model introduced in Leurent (2011a) for treating the total passenger capacity of the transit services is based on the explicit representation of the passengers waiting to board a vehicle of an attractive service, constituting a passenger stock by given egress station, $\sigma_{ij}$. The passenger stock by service $n_{zi}$, faced with the vehicle's available capacity at boarding $k_{zi}$, yields the probability of immediate boarding $\pi_{zi}$. The average waiting time on platform $w_{ij}$ for a particular egress station $j$ is similar to that of the traffic bottleneck. An interplay is established in Leurent et al (2011) between the passenger flows and the line operation at the station. Indeed, the boarding and alighting flows influence the dwell time of the vehicles of the transit services at the station. Prolonged platform occupancy of the vehicles of a transit service may lead to the accommodation time of the services at that section to exceed the reference period, $H$. Hence the frequency, $\varphi_z$ of all the services, $z : i \in N_z$ is restrained at departure and propagated downstream.

Once a line is treated and the effect of local capacity effects on the passenger flows and transit operations is established, the line cost model yields the cost vectors by line legs as evaluated by a passenger on an individual basis. The line cost algorithm advances in a reverse topological order, treating each station $s$ as a destination. Given the outputs of the line flow loading model, the service leg cost $g_{z(i,s)}$ is obtained by backward accumulation according to Leurent (2012a) and the line leg cost, $g_{\ell(i,s)}$ stems from the weighted average of the service legs, proportional to the leg passenger allocation.

On the upper layer network, a stationary user equilibrium of passenger traffic is defined as the conjunction of (1) passenger choice of minimum cost hyperpath, (2) passenger assignment to upper layer links according to hyperpath bundling (3) flow conservation in the upper layer nodes and (4) the dependency of leg generalized time, wait time and frequency on the vector of upper layer link flows. The mathematical formulation is a fixed point problem with respect to the vector of flows by upper layer link and by destination node, which is the main state variable. Traffic equilibrium is computed by a Method of Successive Averages (MSA) adapted from Leurent (2012a), by replacing the line model of seat capacity with the more comprehensive CapTA line model.

# TRANSIT SUPPLY AND DEMAND IN THE GREATER PARIS

The transit supply and transit demand data used in the current simulation originate from DRIEA (the Regional Directorate for Infrastructure and Development) and the data correspond to the 2008 situation.

## The Transport Demand in the Greater Paris

The simulation in the Greater Paris Region is constrained to the public transportation network and the corresponding demand. The input data is distributed in 1305 emission and reception zones with equal number of centroids. The 1305*1305 origin – destination matrix involves 1,23 million trips during the morning peak hour at 2008.

Even though the input OD matrix corresponds to the most loaded period of the transit network, we wish to show the behavior of the model under heavy demand. In that case we apply a peak hour factor of 1,3 to consider the hyper peak within the morning peak period. The new trip demand elevates to 1,6 million trips.

## The Transit Supply in the Greater Paris

The Greater Paris Region has a highly developed urban public transportation system with great diversity of transit modes and services provided. In order of increasing capacity we find buses, tramlines, metro lines and commuter lines with various operational characteristics (vehicle capacity, frequency and commercial speed). There are approximately 1370 bus routes operated by various public (RATP) and private operators (Optile consortium). Four tramlines have been added with additional four being in the planning and building process. The rail network consists of the Paris Metro, serving the central core and the dense suburbs with 14 lines which run mainly underground, and higher capacity commuter rail, consisting of the 5 RER lines passing through the city centre and the 8 Transilien lines which run from the 6 terminals in the centre to the outer suburbs.

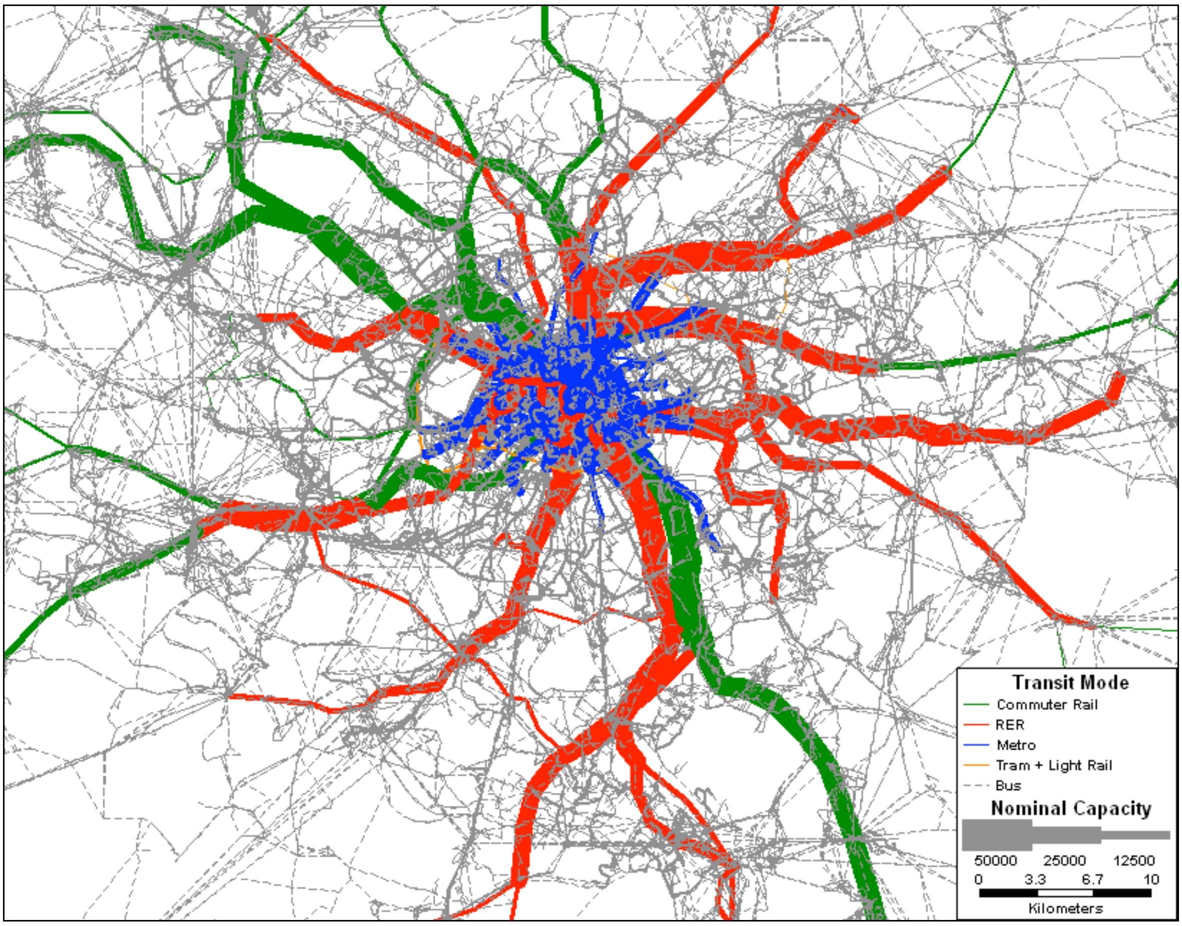


Figure 2 – The total capacity of the transit lines, by transport mode

The transit supply used in the CapTA model is based on the initial data, with some necessary transformations, such as the transformation of a schedule-based service to a frequency-based one and the addition of the vehicle capacity and the operational characteristics. Figure 2 illustrates the line capacity per transit mode. In blue, the metro lines indicate the centre of the agglomeration.

The service network is transformed for use in the transit assignment model. That includes 95 directional railway lines, almost 1900 station platforms for 4 700 transit routes (of which only 259 correspond to rail and the rest to buses). The computation graph, once modified for the calculation, contains 307 000 arcs (of which 30 700 line legs) and 160 000 nodes. The use of the line legs at the upper layer for network assignment contributes only to a marginal increase (3,8%) on the network elements, in comparison to a standard representation with services arcs. In other words, some 19560 service arcs (boarding, in-vehicle sojourn and interstation and alighting arcs) are replaced by 30 729 line legs (+57%) that connect the station couples within each transit line. The number of line legs is sensible to the number of station on transit line, whereas the number of the arcs also depend on the number of alternative transit routes within the line.

# SIMULATION CHARACTERISTICS AND MODEL VARIANTS

The Greater Paris transit network was simulated by 4 variants of the CapTA model. The purpose is to investigate how the various effects contribute in the passengers' path choice and the traffic state of the transit network. These model variants are defined as follows:

- **UC:** It corresponds to the unbounded model, where no capacity constraints apply. The passenger flow under these free-flow conditions selects the best strategies, independent of congestion;
- **CNC:** This variant includes the total capacity and platform occupancy constraints, modelled with the transit bottleneck and the restrained frequency models, as described in Leurent et al (2011). Simple applications, such as in Leurent et al (2012) suggest there is a trade-off between waiting time on the platform (due to insufficient vehicle capacity) and in-vehicle comfort;
- **CWCF:** It includes all the capacity constraints included in CapTA, namely, the total capacity and restrained frequency for guided transit (rail, metro, tramway) and the in-vehicle comfort for all the transit modes (guided transit and buses). In-vehicle comfort only depend on whether the passenger is seated or standing and the comfort multiplier is fixed;
- **CWCV:** Equivalent to the previous variant, except that the in-vehicle comfort factor is variable, depending linearly in the density of standing passengers in the vehicles (which cannot exceed the maximum passenger density). It is the most comprehensive simulation. If not stated otherwise, the results of the bounded model correspond to the CWCV model variant.

The main global parameters in a CapTA simulation are the penalty factors to be considered in the generalized cost function. Indeed, the generalized cost of a path is the sum of the actual travel times for each arc in the path weighted by a penalty factor which depends on the importance of that element to the user's trip. In the simulation we distinguish four types of cost components: access – egress, transfer, waiting and in-vehicle. Each one has a different penalty factor, according to table I:

Table I – Penalty factors

| **Penalty factors of cost components** | |
|---|---|
| Access and Egress | 2 |
| Transfers | 2 |
| Waiting in platform | 2 |
| In-vehicle comfort | Fixed 1,8 or<br>Variable 1,2-2 |

The in-vehicle comfort model is able to include a variety of penalty structures: a constant penalty for standing; a fixed or variable multiplier of the physical travel time; or a combination of those. In addition, the generalized cost for seating passengers can also made to be dependent on the density of standing passengers. That has not been applied in current simulation. The fixed comfort multiplier is assumed to be equal to 1,8 of the in-vehicle seating time, as suggested in Leurent and Liu (2009). However, some researches (TRB, 2003, Debrincat et al, 2007) suggest a linear relation between the in-vehicle comfort coefficient and the standing passenger density or the vehicle load. That is the reason why CWCV is the main variant of the model. A linear function of the standing penalty factor $\chi_{za}^{r}(d_a)$ is considered, where $d_a$ is the density of standing passengers for a certain trip segment $a$. The CWCV variant adopts linear standing multiplier varying from 1,2 (for $d_a = 0$) to a maximum of 2,0 (for $d_a = 4p/m^2$).

The model was coded in C++ using an object oriented approach. The simulation runs on a 2,66 GHz Intel PC with 4 GB of RAM. The average run time per iteration amounts to 8 minutes for the unbounded model (UC). Each iteration in the capacitated model (CWCF and CWCV) – extending the in-vehicle comfort also to the bus services – requires about 23 minutes. Within an iteration, the in-vehicle comfort for the buses takes additional 6 minutes and for the guided transport, 7 minutes, for a total computing time of 13 minutes (of the 23 minutes of an iteration) for treating in-vehicle comfort.

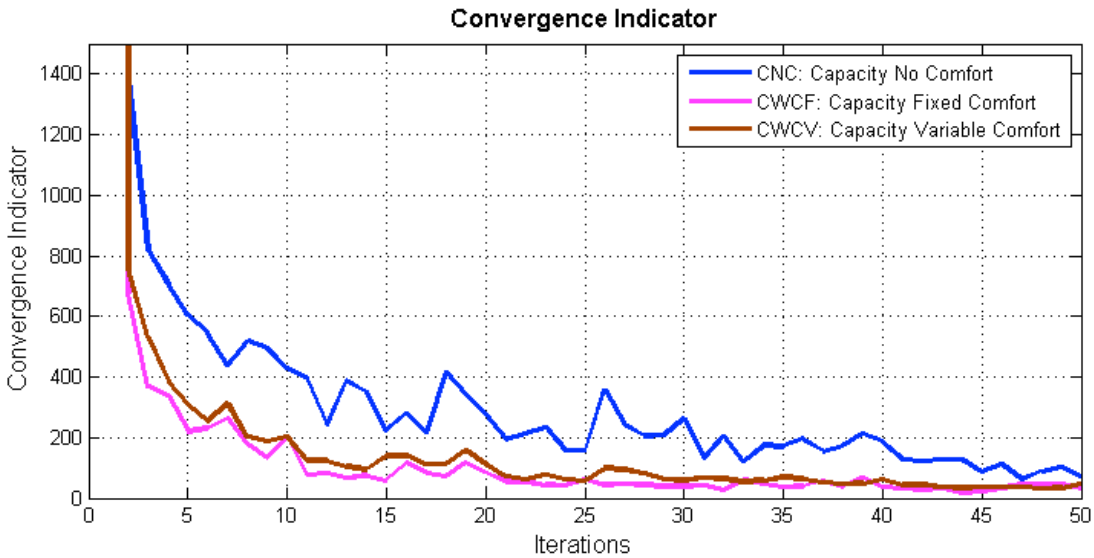


Figure 3 – Convergence Indicator of the bounded model variants

The convergence is calculated by the average gap of the passenger flows on each arc. Figure 3 illustrates the convergence of the model variants, CNC, CWCF and CWCV. An acceptable level was reached after 50 iterations with a gap reduced to 1‰ of the initial value. We observe that the inclusion of comfort leads to a quicker convergence. That can be attributed to the inclusion of a travel penalty from lower flows which leads to a diffusion of the passenger flows to other lines.

# PASSENGER FLOWS ON THE TRANSIT NETWORK

The passenger flow is the main output of the transit assignment model. The unbounded variant (UC) corresponds to the itineraries, without congestion, under free-flow conditions. Some structural lines, such as the main commuter lines, RER A (east-west) and RER B (north-south) are particularly loaded, with flow to capacity ratios that can reach the 1,7 (or 100 000 passengers per direction per hour for a capacity of 58 000) for the central section of the RER A. That corresponds to an excess of 42 000 passengers at the most loaded hour compared to nominal capacity: this, together with the fat that the passengers of the RER A often do not have satisfying alternatives, explains why the RER A suffers from considerable congestion.

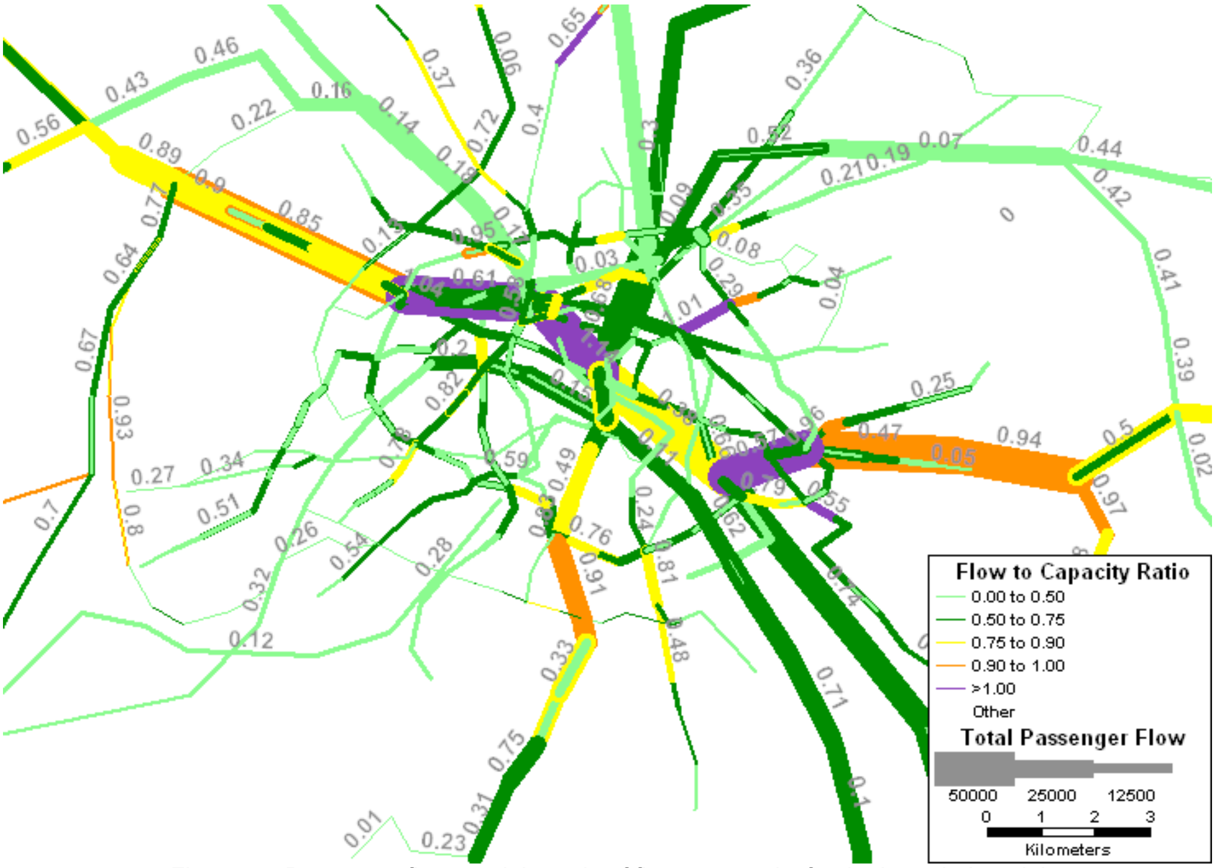


Figure 4 – Passenger flows and the ratio of flow to capacity for the bounded model

For the bounded variants (CNC, CWCF, CWCV), the route choice takes into consideration the effect of the passenger flows on the generalized cost and the path choice due to the local capacity constraints: the vehicle and route total capacity, the seat occupation and the vehicle capacity of the station track.
Figure 4 illustrates the passenger flows on the network (line width) and the flow to capacity ratio (colour) on the guided mode lines for the CWCV variant. The line segments with a flow up to 75% of total capacity are in light and dark green. The yellow (resp. orange) arcs designate a flow to capacity ratio comprised between 75% and 90% (resp. 90% and 100%) of the line's capacity respectively. In purple we illustrate the links where the hourly passenger flow exceeds the hourly capacity. It should be noted that for the CWCV variant these

segments are limited (9 out of 1750) and the highest flow exceeds line capacity by only 3,75%. It is apparent that the capacity constraints induce the passengers faced with increased waiting time to choose to transfer to alternative paths with lower perceived costs.
Figure 5 illustrates the distribution of the volume-to-capacity rations of the rail arcs (light rail, metro and commuter rail) for the four model variants. We observe that the relaxation of the capacity constraints at the flow assignment on the upper layer network for the bounded models (CNC, CWCF and CWCV) results in some arcs being loaded with a passenger flow exceeding their operative capacity. For the CNC model the distribution of the volume-to-capacity ratios is quasi-identical to the unbounded variants up to 80% flow-to-capacity ratio and a significant number of arcs exceed operated capacity (48 out of 1750 with the most loaded arc exceeding capacity by 8%) For the unbounded model (UC) there are more oversaturated arcs (58) and their volume-to-capacity ratios are more severe, with a maximum of 1,78 of the operative capacity. The models with in-vehicle comfort show fewer arcs that exceed line capacity (18 and 9 for the CWCF and CWCV respectively), demonstrating that comfort plays an important role in spreading passengers to alternative routes.

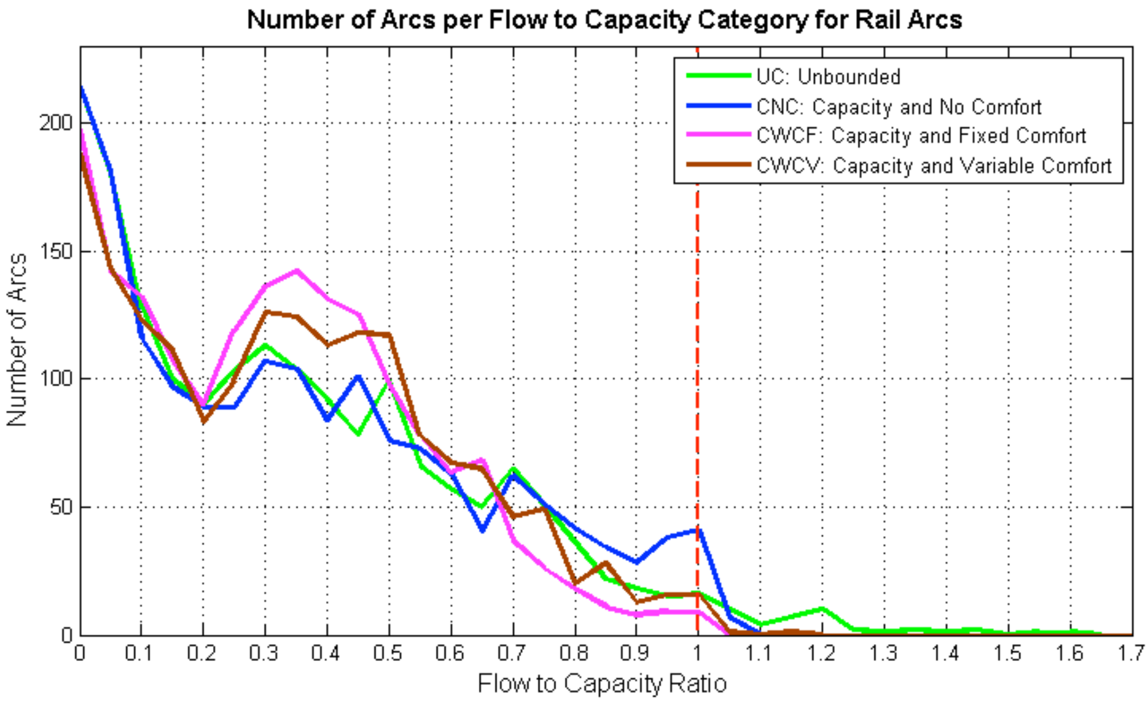


Figure 5 – Number of Arcs in relation to flow/capacity ratio

The CNC model unveils the impact of the transit bottleneck model (addressing vehicle capacity) by reducing the flow of oversaturated arcs, just below their nominal capacity. Indeed, at the CNC model variant, a large number of arcs – compared to all other variants – lies between 80% and 100% of the nominal capacity. As long as the comfort variants (CWCF and CWCV) are concerned, the distribution of the arcs reaches a peak around 35% of the capacity. That reflects the vehicles' seat capacity, which roughly corresponds to 40-60% of total vehicle's capacity for rail, 20% for metro and 30% for tramway. Comparing the two comfort variants, we observe a higher concentration of arcs close to the seat capacity for the CWCF, combined with a lower concentration at high flow-to-capacity ratio. That steams from the fixed penalty discomfort of the CWCF variant, penalizing the standing position uniformly, whereas the standing density is taken into account in CWCV.

# THE OPERATION OF TRANSIT ROUTES UNDER CAPACITY CONSTRAINTS

The track occupancy and restrained frequency model (Leurent et al., 2011) evaluates the impact of passenger flows on the vehicle flowing and route performance. According to the model, the operative frequency, $\varphi_z$, of a transit route at a station depends on the dwell time (and therefore the boarding and alighting flows) and the safe separation time between two following vehicles and that for all vehicles of the transit routes sharing the track infrastructure. The simulation of the Greater Paris transit network allows investigating the behaviour of the bounded variants. We can make two observations with concordance to the theoretic model:

- The effects change significantly, whether the model is applied to an unbounded model (UC) or a bounded one (CWCV). Indeed, taking into account the capacity effects disperses the passenger flows from the most loaded lines, modifying the structure of network flows. Therefore, the critical points of the variants (UC, CWCV) are not located at the same stations and the network externalities influence the localization and the magnitude of their effects;
- The restrained frequency effect is not triggered at the most loaded sections, but rather at the stations where the passenger exchange exceeds the exchange capacity. Thus, the restrained frequency can occur upstream of the loaded sections, reducing the line capacity where it needed the most.

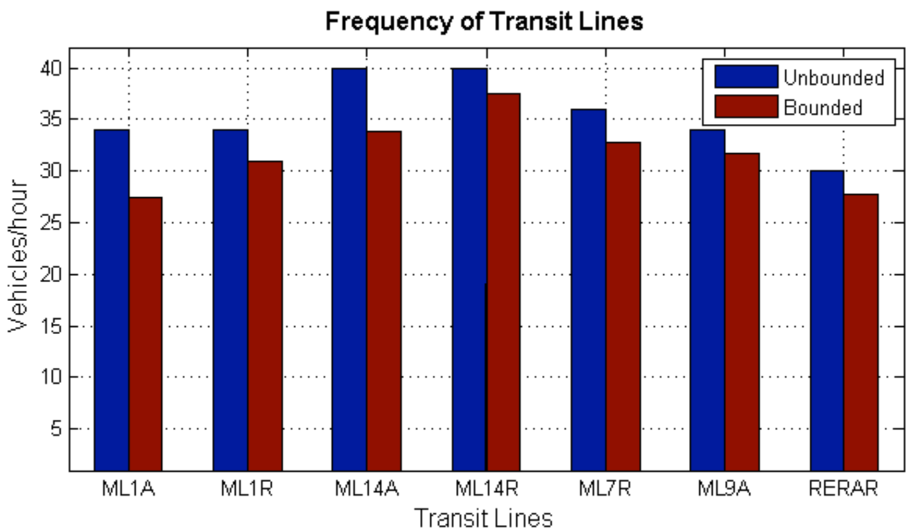


Figure 6 – The initial and restrained frequencies at the terminal for some rail lines in the Greater Paris transit network.

The simulation on the Greater Paris transit network demonstrates that a heavy-duty network with massive passenger flows sees frequencies drop along some of its transit routes. Figure 6 illustrates the drop of the hourly frequency (compared to the nominal frequency) on some structural lines on the bounded CWCV variant. Line M1 (east-west) of the Paris Metro shows a reduction of its hourly frequency from 34 veh/hour to 27,4 veh/hour for the eastbound and

31 veh/hour for the westbound service, while line M14 (automatic, east-west) faces a reduction by 6-15%, from a nominal frequency of 40 veh/hour to 33,9 veh/h for the westbound and 37,4 veh/h for the eastbound service.

Figure 7 demonstrates the relative frequency drop in the central sector of the Greater Paris transit network. While the great majority of the structural transit lines are not affected, a reduction up to 5% of their initial frequency can be observed in lines such as Line M6, M7 and M9 (depending on direction) and the RER C. However, the most sensible lines to restrained frequency, with a reduction over 5% from scheduled frequency are mainly the metro lines.

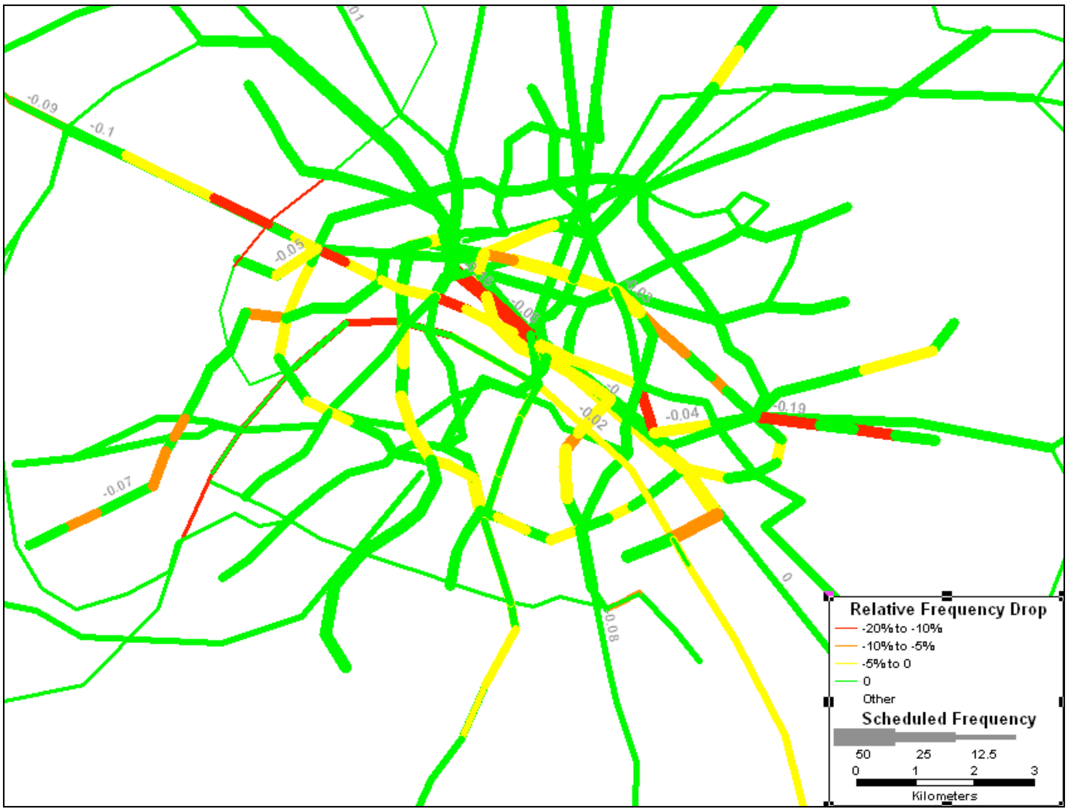

Figure 7 – The relative frequency drop due to the restrained frequency in the central sector of the Greater Paris

The RER A eastbound service faces a reduction of its nominal frequency by 9,3% from 30 veh/h to 27,2 veh/h. Consequently, the service capacity of the RER A westbound service is reduced by 9,3% west of Etoile station, or equivalently by 5 360 passengers and 1 620 seats per hour. That corresponds to the capacity of 2,1 duplex high-capacity trainsets.

## IMPACTS ON USERS

The average generalized cost on the transit network consists of the waiting, the in-vehicle time and the walking time needed for a transfer and the access-egress time. Table II summarizes the average generalized time for the model variants as well as the details of its components. The composition of the average optimal generalized time (GT) for the CWCV model variant is analyzed. The waiting time component consists of both the initial waiting time and any further waiting time due to potential transfer. Waiting time amounts to 29,1% of the total GT. The most important element is the in-vehicle travel time with 41,5% of total GT, while the transfer is only 5,6% and the access – egress time forms the 23,8% of the total GT.

Table II – Average generalized time (in minutes) on the Greater Paris transit network

| Model | Optimal GT | Actual TT | Perceived WT | Perceived IVTT | Perceived Transfer T | Perceived Access-Egress | Nb of Transfers |
|---|---|---|---|---|---|---|---|
| **UC** | 61,56 | 40,63 | 18,79 | 23,10 | 3,96 | 15,71 | 1,42 |
| **CNC** | 62,73 | 41,40 | 19,44 | 23,65 | 3,98 | 15,67 | 1,44 |
| **CWCF** | 69,96 | 41,77 | 20,02 | 29,02 | 3,97 | 16,95 | 1,35 |
| **CWCV** | 68,45 | 41,70 | 19,90 | 28,40 | 3,88 | 16,27 | 1,35 |
| **%diff CWCV-UC** | 11,2% | 2,63% | 5,9% | 23% | -2,04% | 3,6% | -5,13% |

We observe that in the CWCV variant the average generalized time for a journey on the network increases by 11,2% in comparison to the unbounded model (UC). Most of this change results from the increase of the average in-vehicle travel time (26% and 23% for the CWCF and CWCV variants) compared to the UC (and the CNC) variant, due to the inclusion of in-vehicle discomfort penalties. After all, 3/4 of the increase of the generalized travel time is attributed to the in-vehicle comfort. On the other hand, the increase in the waiting time is relatively modest, (it amounts to approximately 14 800 additional waiting hours during a morning peak hour). The combination of the moderate increase in the waiting time and the presence of few arcs whose flow exceed line capacity imply that the overall capacity of the network is sufficient. Note that the average costs discussed here also include the buses where no capacity effects are being applied (except in-vehicle comfort).

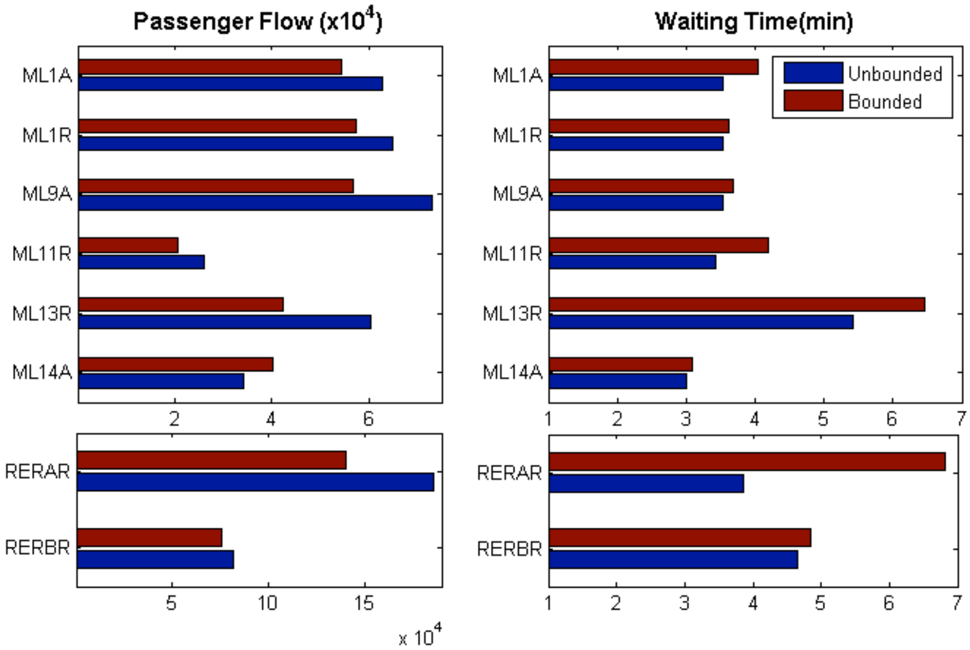


Figure 8 – Passenger Flows and Average Perceived Waiting Time on selected lines for the unbounded (UC) and bounded (CWCV) model

The increased waiting time in some lines makes other transit lines attractive to certain passengers and disperses the passenger flows. Congestion is concentrated on a number of structural lines, inducing a considerable increase in the waiting time of the passengers. The average waiting time of the metro line M1 eastbound service increases by 14% (mainly due to the reduced capacity from the restrained frequency), while for the southbound line M11 increases by 22% and for both directions of line M14 there is an increase around 3%. These effects are considerable, as they correspond to an additional waiting time of 230h for the users of eastbound line M1 and 130h for the users of southbound line M11, during the morning peak hour.

Applying the capacity constraints to a simulation modifies significantly the distribution of the passenger flows on the transit lines. Figure 8 (left hand side) illustrates the total number of passengers travelling on each line during the simulation period for the unbounded (UC, in blue) and the bounded model (CWCV, in brown). We observe a reduction of the passenger flows on the second case. At the right hand side, the effect of the waiting time under strict capacity constrains is illustrated. The increase in the average waiting time is moderate (up to 5%), except for the eastbound RER A (+76%), the southbound M13 (+19%), the M11 (+22%) and the eastbound M1 service (+14%). That suggests that a transit assignment model with capacity constraints, such as CapTA, is successful in both representing passengers choosing alternative routes to avoid the effects of congestion and the impact of public transport level of service of the passengers who do not change their itinerary.

# THE IMPACT OF IN-VEHICLE COMFORT ON THE USERS

In the previous section, we observed that the in-vehicle travel time is the most significant component of the total travel time. In addition, the increase of the generalized time between the UC and the CWCV variants is attributes by 3/4 to the increase of the in-vehicle travel time. The in-vehicle comfort model, which impact all the transit modes (including buses) allocates the passengers to the seats available and evaluates the cost of a trip, with respect to the sitting probabilities and the standing densities.

The analysis focuses on two elements, the in-vehicle cost and the average standing time. Standing passengers can be found in the buses, the tramlines, the metro, the RER and the commuter rail (CR) lines. However, due to the linear discomfort function adopted in CWCV, the additional cost depends on the density of the standing passengers. The additional cost of an average trip (sitting and standing passengers combined) on the metro lines varies from 27% of the average actual travel time for line M10 to 68% for the heavy-loaded line M14.

The average standing time is the ratio of the total standing time and the total number of passengers who have been standing during a trip. It expresses the average time a passenger will stand, if he does not find a seat at boarding. Figure 9 illustrates the average sitting time and standing time for the UC and CWCV model variants. In the case of the M14, the average standing time is evaluated at 2,5 and 4,5 minutes according to the direction. Nevertheless, the impact of standing is more notable on longer lines, such as M8. There, a passenger who fails to seat at boarding will stand for an average of 7,5 minutes (CWCV model) before sitting or alighting. If we compare the two model variants, we observe that the average sitting time increases significantly (from 10,5 to 12,5 min for M8).

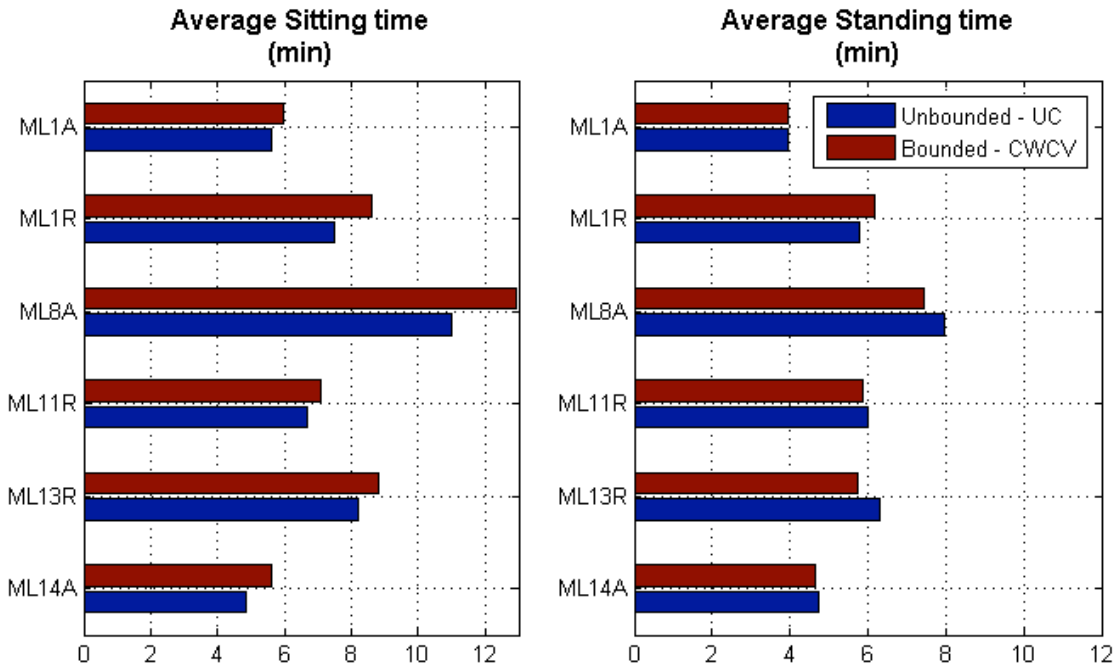


Figure 9 – Average Sitting and Standing time on selected lines for the unbounded (UC) and the bounded model (CWCV)

Two observations are highlighted following the analysis, with relevance to the in-vehicle comfort:

- The intensity and the length of standing are not always correlated and should not be confused with each other. Although discomfort leads to an increase of the cost of the trip up to 68% for M14, the average standing time amounts only to 4,5 min. On the other hand in M8 a passenger stands longer (7,5 min) but in better conditions;
- The in-vehicle comfort significantly alters the structure of passenger flows. The comparison of the UC and CWCV variants (Figure 9) reveals an increase of the average sitting time and a decrease of the average standing time of CWCV compared to UC (except for line M1). That, combined with the reduction of the number of transfers (-5%), implies that indeed, if seated, the passengers prefer longer tips rather than frequent transfers (which are associated with the risk of standing afterwards).

# CONCLUSION

The paper offers a description of the CapTA transit assignment models for capacitated networks together with its application to the Greater Paris Region. It is based on the line model as a framework to represent a variety of features and phenomena in a transit system, both of physical and microscopic nature. The bi-layer network representation allows focusing on a quasi-microscopic level when considering the flow loading and line costing process at a line level, while maintaining the macroscopic level for the passenger flow assignment to the transit network. The framework is essentially systemic and modular: some parts of it may be replaced by mode appropriate sub-models, for instance about track occupancy, or the interaction of access and egress flows in station dwelling.

The transit network of the Grand Paris Region with 4 tramlines, 14 metro lines and 13 commuter rail lines and a central core with line redundancies offers an ideal field for applying a transit assignment model with capacity constraints. Massive passenger flows are concentrated on main north-south lines, the RER B and metro line M13 and east-west axes such as the RER A and metro line M1 and M14. A number of scenarios were tested (UC, CNC, CWCF, CWCV) in order to detect the behaviour of each one faced to high passenger flows. The main comparisons between the unbounded model variant (UC) and the bounded one (CWCV) reveal the adequacy of the CapTA model for simulating such network.

The high passenger flow impacts the operation of the transit routes and the frequency is modulated in most of the metro lines of the Paris network. The frequency is reduced up to 15 and 19% for the metro lines M14 and M1 respectively, inducing secondary effects along the lines due to the reduced downstream capacity and the increased passenger stock for each vehicle. On the passenger side, these effects contribute to the increase of the average waiting time up to 14% and 22% for the line M1 and M11 respectively. Although, the increase seems moderate, it corresponds, only for the eastbound direction of line M1 to additional 230 actual hours waiting during the morning peak hour. In addition to longer waiting times, the passengers face in-vehicle discomfort when they travel standing. The average travel time a passenger stands depends on the topology and the congestion of the line and therefore lines without excessive passenger flows may have the longest standing time, such as line M8 where it takes values from 5,5 to 7,5 minutes according to the direction.

The demand scenario is fictive and we cannot make extensive analysis of the state of the transit network of the Greater Paris Region. However, the model accomplishes its main objectives:

- It addresses a variety of capacity constraints whose effects can be clearly distinguished and prioritized. It this network, the most significant effect is the in-vehicle comfort, since the overall network capacity is sufficient;
- Although a relaxation of capacity effects intervene on the network assignment, the line model achieved to disperse the flows when the exceed line capacity. On the CWCV variant, the maximum flow-to-capacity ratio exceeds operative capacity by 3,7%;
- The calculation time of an iteration amounts to 23 minutes, mostly for the steps of cost formation and of optimal strategy search.

The computation time can be reduced if we treat in parallel order the multiple independent processes treated sequentially. Other than the computation efficiency, the model, being modular, can be further developed. A more detailed interaction may be considered between the boarding and alighting flows, the in-vehicle passenger load and passenger stock at the platform as well the vehicle's and platform's architecture and how these components influence the dwell time. Further microscopic phenomena can be added, such as a willingness to board an overcrowded vehicle, if the available capacity is insufficient and the passenger stock is too important, thus affecting the in-vehicle discomfort of on-board passengers. Finally, additional models may be added, first, within the line model, by considering the effect of general traffic conditions to the vehicle's journey time and second, by developing a station model to capture the effect of passenger flows on the quality and travel time of transfers and access-egress trips.

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