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Report on travel behaviour modelling for Ile-de-France case study

André de Palma
Mohammad Saifuzzaman

CES, ENS-Cachan, France

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Contents

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André de Palma
CES, ENS-Cachan
61, avenue du Président Wilson
94235 Cachan cedex, France

Teleph.: +33 6 88 71 43 44
andre.depalma@ens-cachan.fr

Mohammad Saifuzzaman
CES, ENS-Cachan
61, avenue du Président Wilson
94235 Cachan cedex, France

Teleph.: +33 6 19 21 58 31
mohammad.saifuzzaman@ens-cachan.fr

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Abstract

This report is about travel behaviour modelling for Ile-de-France. The report includes various studies undertaken to estimate travel behaviour parameters of this region. It also includes various models for traffic analyses that take account these parameters.

Keywords

Travel behaviour ; value of time; schedule delay early; schedule delay late

Preferred citation style

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1 Introduction

Latest advancement in travel behavior modeling lets us analyze various time of the day dependent policies such as flexible or staggered hours, variable traffic restraints or modular road or parking pricing which are proposed to relieve congestion in private or public transportation. The impact of these policies depends on the values of the driver behavioral parameters to be estimated as well as on their distribution.

Numerous surveys and empirical studies have been conducted during the past 35 years in order to understand driver behaviors. Those studies were mainly concerned with commuters and private transportation. Today, dynamic policy evaluation needs more comprehensive analysis of driver behavior, in particular for various groups of users and for different trip purposes. The standard parameter to be estimated is the Value of Time (VOT). Other parameters also play a key role, in particular to explain the peak shift. The reason is that user's change mode, but also departure time when time of the day dependant policies is implemented. Therefore, in dynamic models few more parameters are needed which are: willingness-to-pay to avoid early arrivals, willingness-to-pay to avoid late arrivals, Preferred departure/arrival time distribution, value of time for using public transport, etc.

This paper summarizes the travel behavior analysis and modeling for Paris and its suburb. To acquire a better knowledge of the trip time decisions in this region, several surveys were conducted. The first survey in this respect was conducted in the year 2000. It was a phone survey where 4230 individuals answered the questionnaire. The phone calls have been processed from 5 to 8 PM by the French company SOFRES concerning the morning trips for the same day. In the end of 2011 another survey was conducted to update previous estimation of driver behavior parameters. It was a stated preference survey, where 3497 individuals were questioned about their residential locations, their automobile use, and some of the trips they carried out in last week. The details of these surveys and their estimated results are described later in this report. This report also summarizes some of the travel models used in Ile-de-France and policy analysis results from these models.

The rest of the paper is organized as follows: Section two describes theoretical background of travel behavior modeling; Section three provides some basic characteristics of the study area Ile-de-France; Section four describes the dynamic transport model 'METROPOLIS'; Section five describes the survey and estimation results for travel behavior parameters; finally Section six concludes with brief summary of different policy analysis for Ile-de-France.

2 Background of travel behavior modeling

This section provides a brief overview of the theoretical developments related to travel behavior modeling. We start with a simple static model of congestion and then expand it to a more complex dynamic model considering scheduling preferences in the basic bottleneck model.

2.1 The static model of congestion[1,2]

2.1.1 Static networks

We begin with a simple example. Consider a fixed number $N > 0$ of travellers having two routes available. The travellers split with $n_1 > 0$ on the first route and $n_2 > 0$ on the second route, where $n_1 + n_2 = N$. The cost associated with each route is taken to be a linear function of traffic such that the average cost on route i is $C_i(n_i) = a_i + b_i n_i$. The cost is a so-called generalized cost, combining monetary cost and travel time in a single monetary equivalent. The Nash equilibrium occurs when no traveller wants to change route, which requires that $C_1(n_1) = C_2(n_2)$. Solving this equation leads to the equilibrium solution[3]

$$n_1^e = \frac{a_2 - a_1}{b_1 + b_2} + \frac{b_2}{b_1 + b_2} N, n_2^e = N - n_1^e .$$

The Nash equilibrium has every traveller minimise his/her own cost. We can alternatively consider social optimum where the total cost for all travellers is minimised. In general the social optimum is not a Nash equilibrium. The social optimum minimises the total cost function

$$\min_{n_1, n_2} W(n_1, n_2) = n_1 C_1(n_1) + n_2 C_2(n_2) .$$

[1] de Palma, A., Fosgerau, M. (2011), Dynamic and Static Congestion Models, *Handbook in Transport Economics,Volume 1 & 2*, Edgar Elgard.

[2] For a more detailed analysis of congestion in the static model see the chapter by Santos and Verhoef in Handbook in Transport Economics, Volume 1 & 2 (de Palma, A., R. Lindsey, E. Quinet & R. Vickerman 2011), Edgar Elgard.

[3] We assume the parameters are such that this equation leads to positive flows on each route.

The total cost associated with use of route i is $n_i C_i(n_i)$. The marginal cost of an additional user is

$$\frac{d\left[n_i C_i(n_i)\right]}{dn_i} = C_i(n_i) + b_i n_i .$$

In this expression, $C_i(n_i)$ is the cost paid by the marginal user. The remainder $b_i n_i$ is an externality: it is the part of the increase in the total cost that is not borne by the additional user. The first-order condition for social optimum requires equal marginal costs, or

$$C_1(n_1) + b_1 n_1 = C_2(n_2) + b_2 n_2 . \quad (1)$$

The only difference between this and the first-order condition for the equilibrium is the terms representing the externalities of the two routes. The externalities are zero if $b_i = 0$, i=1,2, *i.e.* if adding an additional user does not lead to increased travel cost. In this case, the social optimum would be the same as the equilibrium.

The social optimum has

$$n_1^o = \frac{a_2 - a_1}{2b_1 + 2b_2} + \frac{2b_2}{2b_1 + 2b_2} N,\ n_2^0 = N - n_1^o . \quad (2)$$

The solution is written in this way to emphasize the similarity to the Nash equilibrium. The only difference between the optimum and the equilibrium outcomes is that the marginal costs, the b_i, have been replaced by $2b_i$ in the expression for the optimum outcome. This indicates that the optimum can be achieved as an equilibrium outcome by setting a toll equal to $n_i b_i$ on each of the two routes. This has the effect of doubling the variable cost from the perspective of users and the expression in (2) then becomes the equilibrium outcome.

2.1.2 Elastic demand

The discussion so far has considered a fixed number of travelers N . We now allow demand to be elastic, limiting attention to just one route. Travelers on this route are identical, except for different willingness to pay to travel. Figure 1 shows a downward-sloping inverse demand curve $D(N)$ to reflect that demand decreases as the cost increases. The curve $C(N)$ is again an average cost curve expressing the cost that each traveler incurs. The curve $MC(N)$ is a marginal cost curve, expressing the marginal change in total cost following a marginal increase in the number of travelers; in other words[4]

$$MC(N) = C(N) + N \cdot C'(N).$$

When the cost curve is increasing, the marginal cost curve will lie above the cost curve.

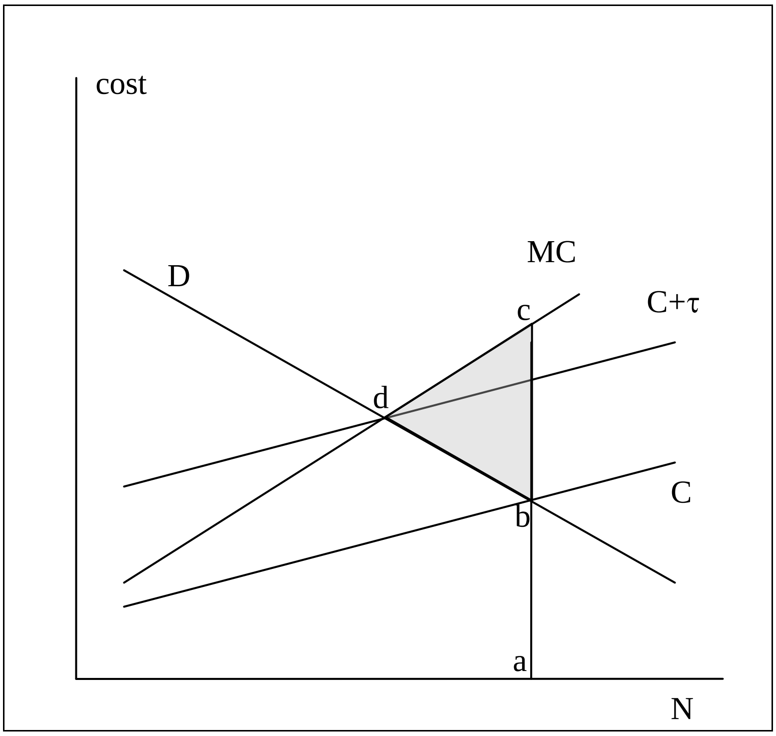


Figure 1 A static model

The equilibrium occurs at the intersection of the demand curve with the average cost curve at the point b. The marginal traveller at this point is indifferent between travelling and not travelling, he faces a cost corresponding to the line segment a-b and a benefit of the same size. For travellers in aggregate, however, the cost of adding the marginal traveller is given by the MC curve. For the marginal traveller at point b, this cost corresponds to the line segment a-c. So the last traveller imposes a net loss corresponding to the line segment b-c on the group of all travellers. If usage was reduced to the point where the MC curve crosses the demand curve, then the corresponding loss is zero for the traveller at the point d. The total loss in market equilibrium is then represented by the shaded triangle b-c-d on the figure.

[4] C' denotes the derivative of C.

The optimal toll, labeled τ in Figure 1, implements the optimum at the point d, where the private benefit is equal to the marginal cost. The toll is required because drivers ignore the costs they impose on other drivers. The toll is just the difference, evaluated at the social optimum, between the marginal cost and the average cost, *i.e.* the externality.

2.2 The basic bottleneck model

We now introduce the basic Vickrey bottleneck model in its simplest form. Consider a continuum of $N > 0$ identical travellers, who all make a trip. They have to pass a bottleneck, which is located d_1 time units from the trip origin and d_2 time units from the destination. Denote the time of arrival at the bottleneck of a traveller by t and the exit time from the bottleneck as a. The situation is illustrated in Figure 2. A traveller departs from the origin at time $t-d_1$ and arrives at the bottleneck at time t. There he/she is delayed until time $a \geq t$ at which time he/she exits from the bottleneck to arrive at the destination at time $a+d_2$.

Each traveler has a scheduling cost expressing his/her preferences concerning the timing of the trip. Travelers are assumed to have a preferred arrival time t^* and they dislike arriving earlier or later at the destination. Travelers also prefer the trip to be as quick as possible. For a trip that starts at time t_1 and ends at time t_2, consider then a cost of the form

$$c(t_1,t_2) = \alpha \cdot (t_2 - t_1) + \beta \cdot \max\left(t^* - t_2, 0\right) + \gamma \cdot \max\left(t_2 - t^*, 0\right), \qquad (3)$$

where $0 < \beta, 0 < \gamma$ and $\beta < \alpha$. In this formulation, α is the marginal cost of travel time, β is the marginal cost of arriving earlier than the preferred arrival time, γ is the marginal cost of arriving later, and these values are constant. The deviation $t_2 - t^*$ between the actual arrival time and the preferred arrival time is called schedule delay and it is possible to speak of schedule delay early and schedule delay late, depending on the sign of the schedule delay.[5]

[5] Small (1982) tested a range of formulations of scheduling preferences, including the $\alpha-\beta-\gamma$ preferences as a special case.

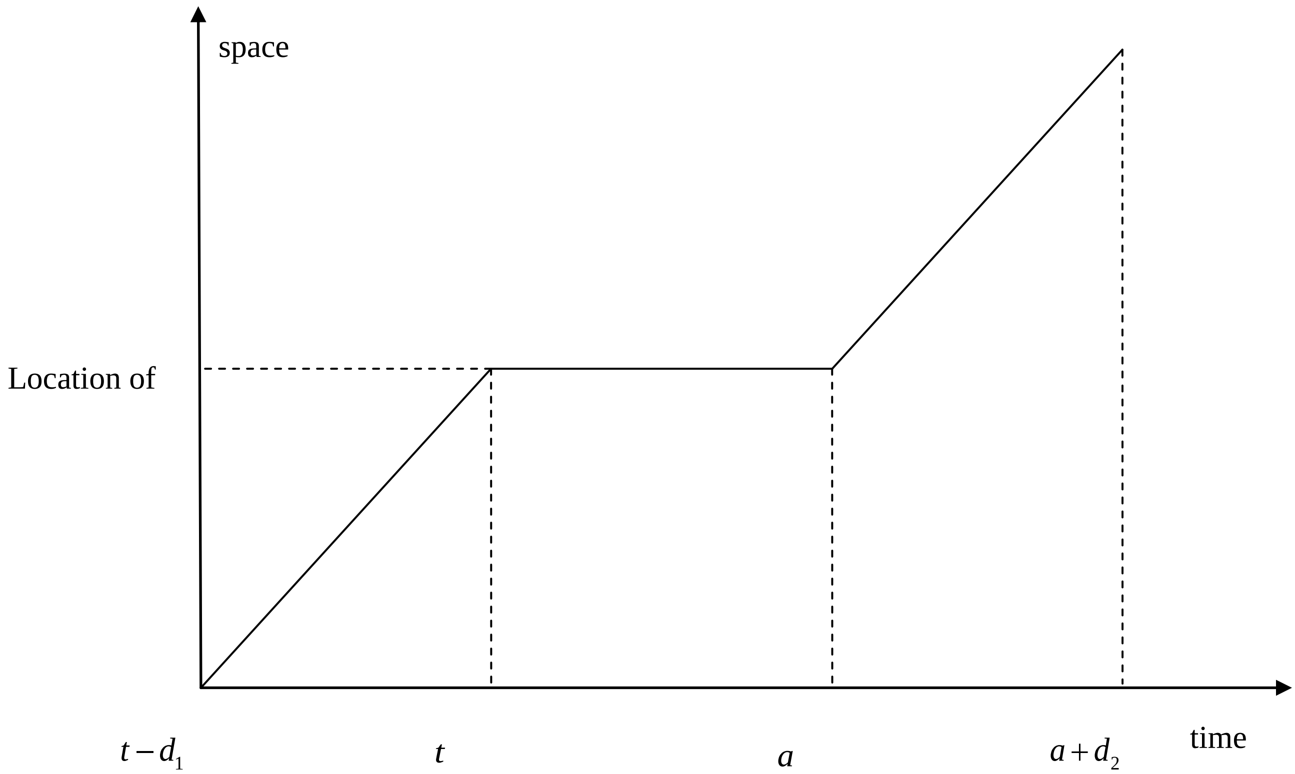


Figure 2 Trip timing

This cost formulation has become colloquially known as $\alpha-\beta-\gamma$ preferences. Later, we shall consider scheduling cost of a general form.

The travel time d_1 between the origin and the bottleneck adds the same constant amount to the scheduling cost of all travellers and so it can be set to zero without affecting the behaviour of travellers in the model. Similarly, the travel time d_2 between the bottleneck and the destination can be set to zero by redefining the preferred arrival time. So without loss of generality we may let $d_1 = d_2 = 0$. This means that the time of departure is the same as the time of arrival at the bottleneck and that the time of exit from the bottleneck is the same as the time of arrival at the destination.

Travelers depart from the origin according to an aggregate schedule, described in terms of the cumulative departure rate R, where $R(a)$ is the number of travellers who have departed before time a. So R is similar to a cumulative distribution function: it is proportional to the probability that a random traveller has departed before time a. R is increasing, since travellers never return. Moreover, $R(-\infty)=0$ and $R(\infty)=N$. The departure rate $\rho(a)=R'(a)$, wherever R is differentiable.

The bottleneck can serve at most s travellers per time unit. Travellers who have not yet been served wait before the bottleneck. The bottleneck serves travellers in the sequence in which they arrived (first-in-first-out or FIFO). The bottleneck capacity is always used if there are travellers waiting before it.

Recall that Nash equilibrium is defined as a situation in which no traveller is able to decrease his cost by choosing a different departure time. Since travellers are identical, this definition reduces to the requirement that all travellers experience the same cost and that the cost would be higher for departure times that are not chosen by any travellers.

Denote the interval of departures and arrivals as $I=[a_0,a_1]$. Let us consider some properties of Nash equilibrium. First, there will be queue from the time the first traveller departs until the last traveller departs, since otherwise there would be a gap in the queue and somebody could move into the gap to decrease cost. Second, the queue will end at the time the last traveller departs, since otherwise he/she could wait until the queue was gone and reduce cost. This shows that the departure interval is just long enough for all travellers to pass the bottleneck. Third, as the cost of the first and the last travellers are equal and since they experience no queue, they must experience the same cost due to schedule delay. These insights are summarised in the following equations.

$$a_1-a_0=N/s, \quad (4)$$

$$\beta\cdot\left(t^*-a_0\right)=\gamma\cdot\left(a_1-t^*\right). \quad (5)$$

Equation (4) ensures that arrivals take place during an interval that is just long enough that all travelers can pass the bottleneck. Equation (5) ensures that no traveler will want to depart at any time outside I.

Solving these two equations leads to

$$a_0=t^*-\frac{\gamma}{\beta+\gamma}\frac{N}{s},$$

$$a_1=t^*+\frac{\beta}{\beta+\gamma}\frac{N}{s}$$

and the equilibrium cost for every traveler is

$$\frac{\beta\gamma}{\beta+\gamma}\frac{N}{s} \equiv \delta\frac{N}{s}.$$

This is linear in the number of travelers and so the simple static model could be viewed as a reduced form of the dynamic model.

Equations (4) and (5) are extremely useful in that they determine the equilibrium cost of travelers as a function of the number of travelers and the bottleneck capacity. The total cost is then $\delta N^2 / s$ with corresponding marginal cost $2\delta N / s$, of which half is internal cost to each traveller and the other half is external. The marginal change in total cost following a change in capacity s is $-\delta N^2 / s^2$. Since there is no toll, price equal travel cost: $p^e = \delta N / s$, that is price is a function of N and s. The function is this a reduced-form supply function, which is very usefull, especially in analytical work, together with a trip demand function.

There is always a queue during the interval I. This means that the bottleneck capacity is fully utilised and hence that sd travellers pass the bottleneck during an interval of length d. At time a, a total of $R(a)$ travellers have entered the bottleneck, taking a total time of $R(a)/s$ to pass. The first traveller enters and exits the bottleneck at time a_0. Hence a traveller arriving at bottleneck at time a exits at time $a_0 + R(a)/s$. Travellers are identical so they incur the same scheduling cost in equilibrium. Normalising $t^* = 0$, it emerges that

$$\delta\frac{N}{s} = \alpha \cdot \frac{R(a)}{s} + \beta \max\left(-a_0 - \frac{R(a)}{s}, 0\right) + \gamma \max\left(a_0 + \frac{R(a)}{s}, 0\right).$$

Differentiating this expression leads to

$$\rho(a) = \begin{cases} s\dfrac{\alpha}{\alpha-\beta}, a_0 + \dfrac{R(a)}{s} \le 0 \\ s\dfrac{\alpha}{\alpha+\gamma}, a_0 + \dfrac{R(a)}{s} > 0 \end{cases}$$

during interval I. A few observations are immediately available. Initially the departure rate is constant and higher than s (since $\beta < \alpha$). It is high until the traveller who arrives exactly on time. Later travellers depart at a constant rate which is lower than s.

Figure 3 shows the resulting departure schedule. The horizontal axis is time and the vertical axis is the number of departures, ranging from 0 to N. The thick kinked curve is the cumulative departure rate R. Departures begin at time a_0 and end at time a_1 with $R(a_1)=N$. The line segment connecting point a_0 to point e represents the number of travellers served by the bottleneck, it has slope s.

The first departures take place at a rate larger than capacity and queue builds up. For example, at time a, the number of travellers who have departed corresponds to the length of the segment $a-c$, while the number of travellers who have been served by the bottleneck corresponds to the length of the segment $a-b$. Thus the queue at that time has length corresponding to the segment $b-c$. The travellers in the queue at time a will all have been served by time d, which is then the time at which the traveller departing at time a is served by the bottleneck. The time spent in the bottleneck equals the length of the queue at the time of departure divided by the capacity.

The traveler departing at time d exits the bottleneck exactly at time a_*. Therefore the departure rate drops below capacity at this time and the queue begins to dissolve. It also follows that the queue reaches its maximum length at time d.

For the top half of the figure, the horizontal time axis refers both to the departure from the origin and to the arrival time at the destination. For the bottom half of the figure, the time axis instead refers to the arrival time at the destination. The shaded areas on the bottom half of Figure 3 show the composition of the scheduling cost throughout the peak. The first traveller arrives early and is not delayed in the bottleneck so his cost is $\beta\cdot(a_*-a_0)$. Later travellers do not arrive as early, but are delayed more in the queue and incur the same trip cost. The traveller who arrives at the preferred arrival time is the most delayed and his trip cost comprises solely travel time cost. Later arrivals are less delayed in the queue, but arrive later at the destination. The last traveller is not delayed in the bottleneck at all, but arrives last at the destination and incurs a cost of $\gamma\cdot(a_1-a_*)$.

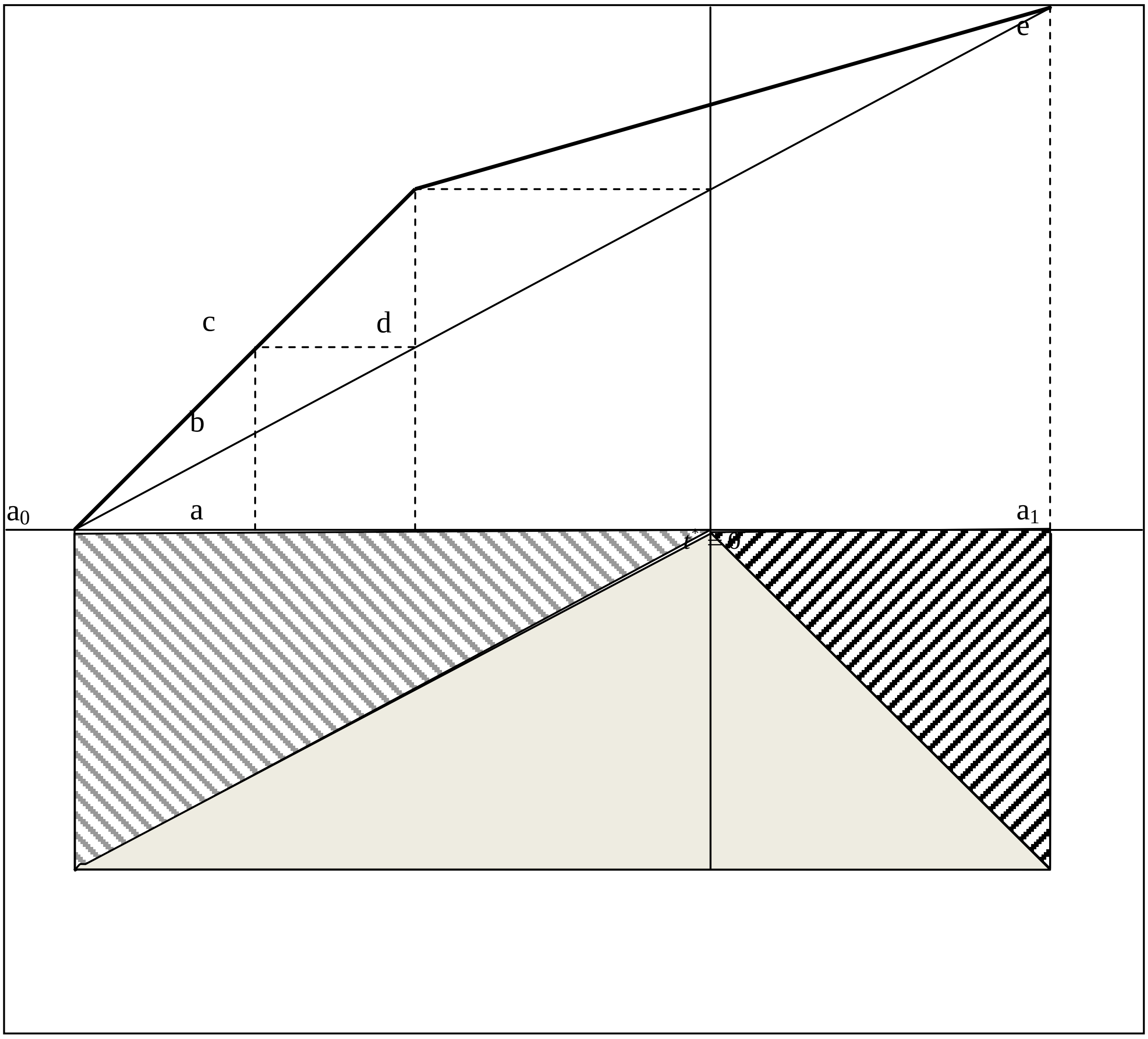


Figure 3 Equilibrium departure schedule under $\alpha - \beta - \gamma$ preferences

2.2.1 Optimal tolling

The queue that arises in equilibrium in the bottleneck model is sheer waste. It generates no benefit at all. If travellers could be induced to depart at the capacity rate s during the equilibrium interval I, then there would be no queue. All travellers (except the very first and the very last) would gain from reduced travel time while arriving at the destination at exactly the same time as in equilibrium. A main insight of the bottleneck model is that it is possible to achieve this outcome through the application of a toll.

So consider a time varying toll $\tau(\cdot)\geq 0$ charged at the time of arrival at the bottleneck. We make the additional behavioural assumption that travellers choose departure time to minimise the sum of the toll and the trip cost. We restrict attention to tolls that have $\tau(a_0)=\tau(a_1)=0$ and are zero outside the departure interval I . This means that (4) and (5) still apply. If the toll is well-behaved, in ways to be explained below, then Nash equilibrium exists and departures still occur in the interval I . Therefore the equilibrium cost is the same as in the no-toll equilibrium discussed above.

Travellers do not lose, but somebody else may gain since revenue from the toll can be used for other purposes. The size of the toll revenue is

$$\int_{a_0}^{a_1}\tau(s)ds, \quad (6)$$

and this represents a net welfare gain.

Since the cost must be constant in equilibrium, we have

$$\tau(a)=\delta\frac{N}{s}-c\left(a,\frac{R(a)}{s}+a_0\right), \qquad (7)$$

where R is now the departure rate that results when the toll is imposed. It is (intuitively) clear that maximal efficiency is attained when the toll revenue is as large as it can be without destroying the equilibrium. Increasing $\tau(a)$ in (7) will reduce $R(a)$.[6] Moreover, the queue cannot be negative and so we must require that $R(a)\geq s(a-a_0)$. Therefore the maximal toll maintains zero queue and the least possible cumulative departure rate, *i.e.* $R(a)=s\cdot(a-a_0)$. This corresponds to a constant departure rate $\rho(a)=s$. The optimal toll is

$$\tau(a)=\delta\frac{N}{s}-c(a,a)=\delta\frac{N}{s}-\beta\cdot\max(-a,0)-\gamma\cdot\max(a,0)$$

for $a\in I$ and zero otherwise. This toll is initially zero at time a_0. Then it increases at the rate β until it reaches a maximum of $\delta N/s$ at time 0. It then decreases at the rate γ until it is again zero at time a_1. The optimal toll corresponds to the grey shaded area in Figure 3. In a

[6] Since $c_2(t_1,t_2)<0$. This follows since $\beta<\alpha$. We use subscripts to denote partial derivatives.

sense, it just replaces the cost of queueing by a toll. The efficiency gain is achieved because queueing is pure waste whereas the toll revenue is just a transfer.

2.2.2 Elastic demand

The discussion of the bottleneck model so far has assumed demand to be inelastic. A natural extension is to assume that the number of travelers deciding to participate in the peak depends on the equilibrium cost (Arnott *et al.*, 1993a). The trip cost

$$p = \tau(a) + c\left(a, a_0 + R(a)/s\right) \qquad (8)$$

is the same for all travelers in equilibrium. This implies that the total toll payment is $N \cdot (p - \bar{c})$, where $\bar{c}$ is the average scheduling cost of travellers. Let $N(\cdot) > 0, N'(\cdot) < 0$ be a downward sloping demand function such that $N(p)$ is the realised demand.

This is a very convenient way to extend the model: conditional on any equilibrium number of travellers, the properties of equilibrium are exactly the same as in the inelastic case. The equilibrium number of travellers is uniquely determined since demand is decreasing as a function of the equilibrium cost of travellers while the equilibrium cost of travellers is increasing as a function of the number of travellers. This simplicity comes, however, at a cost as it requires separability between trip timing on the one hand and participation on the other.

The separability of trip timing and participation implies that the optimal toll with elastic demand is the same as in the case of inelastic demand. To see this, note first that the optimal toll is able to remove queuing, so the average cost of travellers remains equal to $\delta N / s$. Consider the following welfare function

$$W(p) = \int_p^{\infty} N(s)\,ds + N \cdot (p - \bar{c}),$$

i.e. the sum of consumer surplus and the total toll revenue. To find the welfare optimising toll, note that

$$\bar{c} = \frac{s}{N} \int_{a_0}^{a_1} c(a, a)\,da,$$

which can be shown to imply that

$$\frac{\partial \bar{c}}{\partial p} = \frac{N'(p)}{N(p)}\left(\delta N/s - \bar{c}\right).$$

Using this to evaluate the first-order condition for maximum of $W(p)$ leads to $p = \delta N/s$. That is, the optimal price should equal the equilibrium scheduling cost. Using (8) shows that the optimal toll is $\tau(a) = \delta N/s - c(a,a)$, which is the same as in the case of inelastic demand.

2.2.3 Optimal capacity and self-financing

Consider now a situation in which the optimal toll applies while capacity s is supplied at cost $K(s) \geq 0$, with $K' > 0$. We extend the social welfare function with the cost of capacity provision

$$W(p,s) = \int_p^\infty N(r)\,dr + N \cdot (p - \bar{c}) - K(s).$$

For any given capacity s, the optimal value of $\tau(a) = \delta N/s - c(a,a)$ is as shown above. Note that

$$\frac{\partial \bar{c}}{\partial s} = \frac{1}{s}\left(\delta N/s - \bar{c}\right).$$

This can be used to show that capacity is optimal when $sK'(s) = N \cdot (p - \bar{c})$. That is, the revenue from the optimal toll is equal to $sK'(s)$.

This finding leads directly to the self-financing theorem for the bottleneck model. If capacity is produced at constant returns to scale, *i.e.* if $K(s) = sK'(s)$ with $K'(s)$ constant, then the optimal toll exactly finances the optimal capacity $K(s) = N \cdot (p - \bar{c})$. If there are increasing returns to scale, then $K(s) > sK'(s)$, in which case the optimal toll cannot finance the optimal capacity.

The self-financing result is also called the cost recovery theorem. It is an instance of a general self-financing theorem by Mohring & Harwitz (1962), which assumes that travel cost is homogenous of degree zero in capacity and use. A number of results on self-financing are summarized by Verhoef & Mohring (2009).

The optimal capacity can be computed in the three regimes: no toll, coarse step toll and optimal fine toll. It can be shown that the optimal capacity is the lowest for the optimal fine toll, intermediary for the coarse toll and larger for the no toll regime (see Arnott, de Palma and Lindsey, 1993b, for a proof). Note that these proofs are correct with inelastic (and elastic) demand.

2.3 Scheduling preferences

2.3.1 General formulation

The $\alpha-\beta-\gamma$ formulation of scheduling cost used above is a special case of more general scheduling preferences, introduced in this section. Below we revisit the bottleneck model from the perspective of these general scheduling preferences.

In order to describe the traveller choice of trip timing in a more general way, we formulate scheduling preferences for a given trip in the form of scheduling utility $u(t_1,t_2)$, where t_1 is the departure time and t_2 is the arrival time,. We shall make minimal assumptions regarding the specification of u.

It is natural to require that $u_1 = du/dt_1 > 0$, such that it is always preferred to depart later, given t_2.[7] Similarly, requiring $u_2 = du/dt_2 < 0$ ensures that arriving earlier is always preferred, given t_1. A marginal increase in travel time then always leads to a utility loss, since travellers will either have to depart earlier or arrive later. Define the function $v(a) = u(a,a)$ as the scheduling utility that a traveller would receive if travel was instantaneous. Assume that v is quasi-concave and attains maximum at $v(t^*)$. This assures that for any $d > 0$ there is a unique solution to the equation $v(a) = v(a+d)$. It also implies that v is increasing for $a < t^*$ and decreasing for $a > t^*$.

We incorporate monetary cost by considering utility to be $u-\tau$. In some cases it is more convenient to talk about cost, which will then be the negative of utility, *i.e.* $\tau-u$. In either case, it is implied that there is separability between scheduling and monetary cost. That is, a constant cost does not affect the preferences regarding trip timing.

[7] We use subscripts to denote partial derivatives.

In some situations it is necessary to specify scheduling utility further by imposing a certain functional form. For example, the $\alpha-\beta-\gamma$ formulation specifies the scheduling cost completely up to a few parameters. Such restriction can be necessary for reasons of identification in econometric work, but in general it is preferable to specify as little as possible, since restricting the model entails the risk of introducing errors. In theoretical models it is similarly preferable to work with general formulations, since otherwise there is a risk that the results one may obtain depend on the specific formulation.

In some cases it may be considered acceptable to impose a separability condition, just as we have done in the case of monetary cost and trip timing. The timing of the trip is given by a departure time and an arrival time and we work under the assumption that these times are all that matter about trip timing. The travel time is the difference between the departure time and the arrival time. We could equivalently describe trip timing in terms of travel time and arrival time or in terms of travel time and departure time. From the perspective of general scheduling utility $u(t_1,t_2)$, this leads to three possibilities for introducing a separability condition.

$$u(t_1,t_2) = f(t_2-t_2) + g(t_1)$$
$$u(t_1,t_2) = f(t_2-t_1) + g(t_2)$$
$$u(t_1,t_2) = f(t_1) + g(t_2)$$

The first condition would say that scheduling utility is separable in travel time and departure time. The second condition would say instead that scheduling utility is separable in travel time and arrival time. The $\alpha-\beta-\gamma$ scheduling cost is a special case of this second possibility: Changing the travel time does not affect the traveller preferences regarding arrival time and vice versa. The third possible separability condition is used in the Vickrey (1969) formulation of scheduling preferences that we will consider in the next section. Here scheduling utility is separable in departure time and arrival time. That is, changing departure time, does not affect the preferences regarding arrival time and vice versa.

The concept of the preferred arrival time t^* was used to define the $\alpha-\beta-\gamma$ scheduling cost. It makes sense to talk about a preferred arrival time when there is separability in travel time and arrival time, since then the preferred arrival time is not affected by the travel time. Without this separability, there is no single preferred arrival time since the preferred time to arrive depends on the travel time. If instead scheduling utility is separable in departure time and travel time, then we would want to talk about a preferred departure time. In some contexts, for example the PM commute from work to home, this might be a more natural concept. In general, neither the concept of a preferred arrival time nor a preferred departure time may be relevant. We shall now discuss Vickrey (1973) scheduling preferences, which are separable in departure time and arrival time.

2.3.2 Vickrey (1973) scheduling preferences

Consider an individual travelling between two locations indexed by $i=1,2$. He derives utility at the time dependent rate η_i at location i. Let us say he starts the day at time T_1 at location 1 and ends the day at time T_2 at location 2. If he departs from location 1 at time t_1 and arrives (later) at location 2 at time t_2, then he obtains scheduling utility

$$u(t_1,t_2)=\int_{T_1}^{t_1}\eta_1(s)\,ds+\int_{t_2}^{T_2}\eta_2(s)\,ds. \quad (9)$$

The formulation is illustrated in Figure 4.

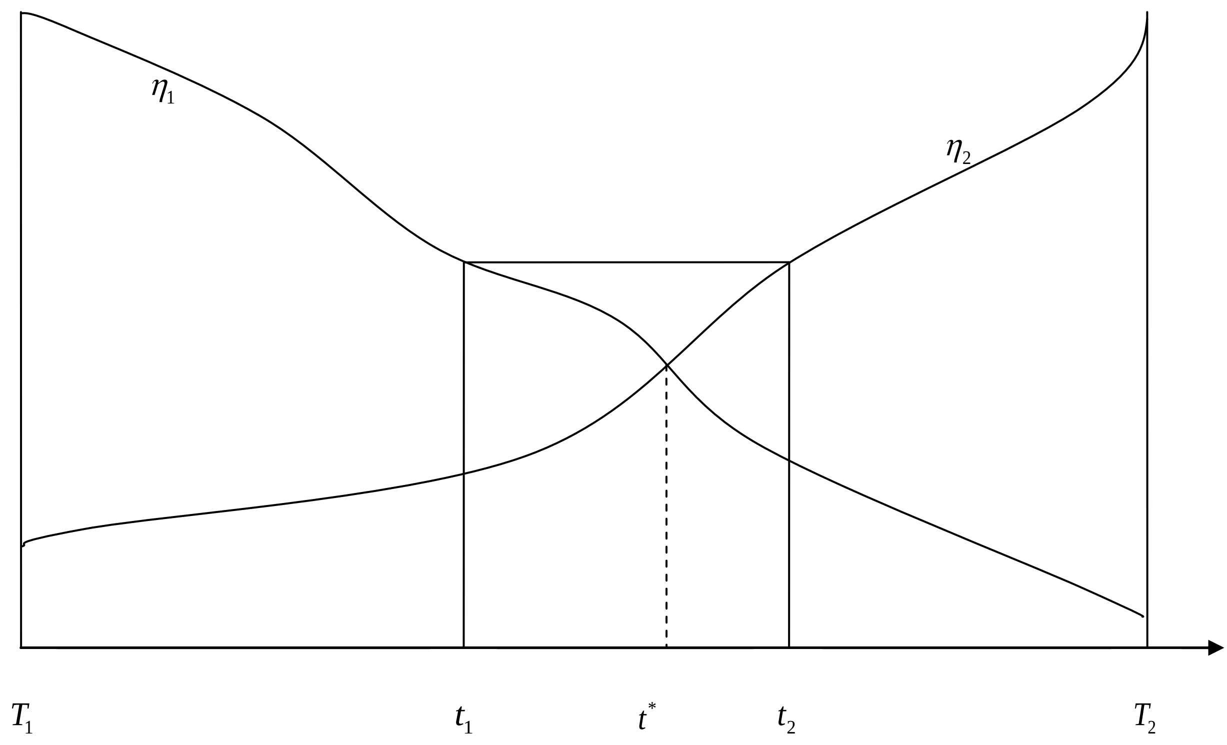


Figure 4 Vickrey (1973) scheduling preferences

Note that when T_1 and T_2 are fixed, these numbers can be replaced by arbitrary numbers in equation (9) without affecting the implied preferences. Assume that $\eta_1 > 0,\ \eta'_1 < 0$, $\eta_2 > 0,\ \eta'_2 < 0$ and that there is a point in time, t^*, where $\eta_1\left(t^*\right) = \eta_2\left(t^*\right)$. Speaking in terms of the morning commute these conditions imply that a traveller prefers to be at home or at work to travelling, that his/her marginal utility of staying later at home is decreasing, that his/her marginal utility of arriving earlier at work is also decreasing, and that there is a time (t^*) when he/she would optimally transfer from home to work if instant travel was possible. Given a travel time of d, he/she would optimally depart at the time $t(d)$ depending on d when $\eta_1\left(t(d)\right) = \eta_2\left(t(d) + d\right)$. It is straightforward to derive that his/her value of time would be

$$-\frac{\partial u\left(t(d), t(d) + d\right)}{\partial d} = \eta_2\left(t(d) + d\right).$$

This is strictly increasing as a function of d. Using survey data on stated choice, Tseng & Verhoef (2008) provide empirical estimates of time varying utility rates corresponding to the Vickrey (1973) model.

2.3.3 The cost of travel time variability

When travel time is random and travellers are risk averse, the random travel time variability leads to additional cost, the cost of travel time variability. Both Vickrey formulations of scheduling preferences are useful for deriving measures of the cost of travel time variability as well as of the scheduling impact of the headway of scheduled services. Such cost measures can be useful to incorporate elements of dynamic congestion in reduced form in static models. Consider a traveller who is about to undertake a given trip. The travel time for the trip is random from the perspective of the traveller. While he/she does not know the travel time outcome before making the trip, the traveller knows the travel time distribution. The travel time distribution is independent of the departure time of the traveller. The latter is a strong assumption but necessary for the results

The traveler is assumed to choose his departure time optimally, so as to maximise his/her expected scheduling utility. That makes the expected scheduling utility a function just of the travel time distribution. Therefore it is possible in principle to evaluate how the expected scheduling utility depends on the travel time distribution. Simple expressions are available for the two Vickrey specifications of scheduling preferences.

In the case of $\alpha-\beta-\gamma$ preferences, Fosgerau & Karlstrom (2010) show that the expected trip cost with optimal departure time is

$$\alpha \cdot \mu + \sigma \cdot (\beta + \gamma) \int_{\gamma/(\beta+\gamma)}^{1} \Phi^{-1}(s)\,ds,$$

which is linear in the mean and in the standard deviation of travel time. This is a practical advantage in applications. The expression depends on the shape of the travel time distribution through the presence of Φ in the integral and so Φ must be taken into account if the marginal value of standard deviation of travel time is to be transferred from one setting to another. In the same vein, Fosgerau (2009) uses $\alpha-\beta-\gamma$ scheduling cost to derive simple expressions for the value of headway for scheduled services. In the case of Vickrey (1973) scheduling preferences with linear utility rates, Fosgerau & Engelson (2010) carry out a parallel exercise. They show that with random travel time and unconstrained choice of departure time, the expected scheduling cost with the optimal choice of departure time is linear in travel time, travel time squared and the variance of travel time. Parallel results are also provided for the value of headway for scheduled services. In contrast to the case of $\alpha-\beta-\gamma$ scheduling cost, it is possible also to derive a simple expression for the expected scheduling cost for the case of a scheduled service with random travel time.

2.3.4 The bottleneck model revisited

The results discussed above for the basic bottleneck model survive in some form with more general scheduling preferences. The setup of the model is as before, the only change is that now travellers are only assumed to have scheduling preferences of the general form discussed above. Without loss of generality we may again consider $d_1 = d_2 = 0$, since the exact form of scheduling preferences is not specified.

It is easy to argue, using the same argument as in the simple case, that Nash equilibrium requires departures in an interval $I = [a_0, a_1]$ satisfying

$$a_1 - a_0 = N / s, \quad (10)$$

$$v(a_0) = v(a_1). \quad (11)$$

This is illustrated in Figure 5. Moreover, the queue has length zero at time a_0 and a_1 but it is strictly positive at any time in the interior of this interval. The second condition (11) has a unique solution since v is quasiconcave and it ensures that no traveler will want to depart at any time outside I .

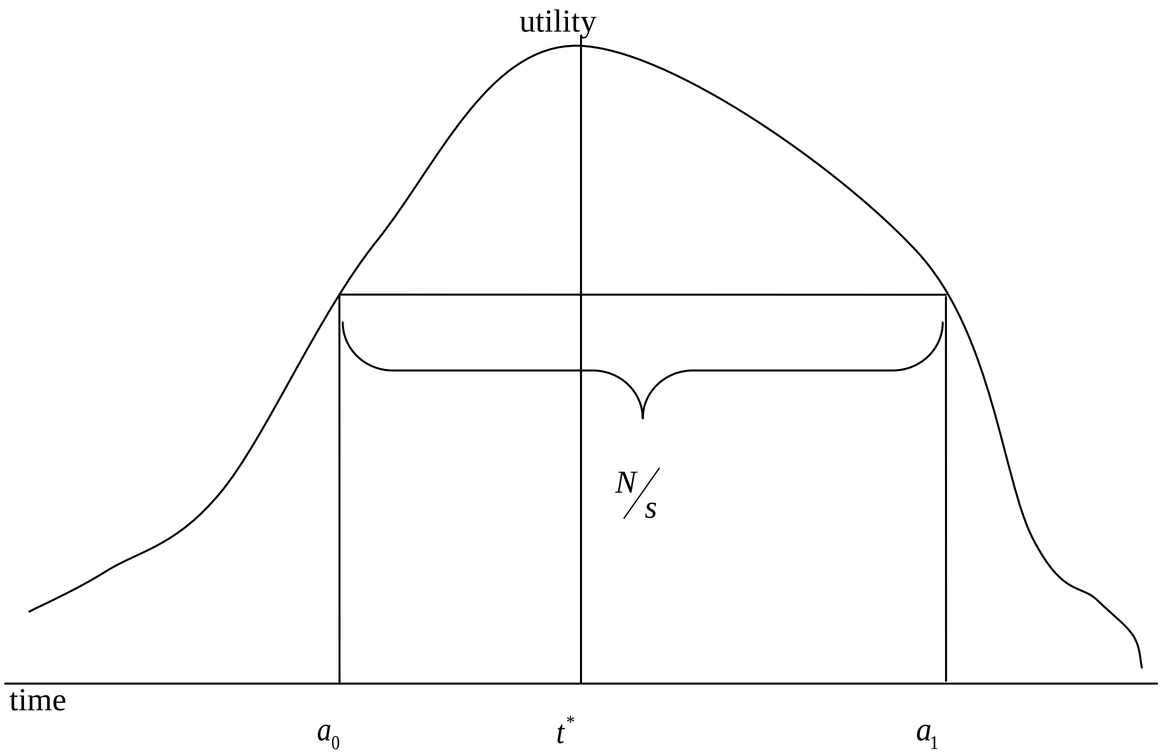


Figure 5 The function v and the equilibrium departure interval

Equations (10) and (11) determine the equilibrium utility of travelers as a function of the number of travelers and the bottleneck capacity. It is then straightforward to derive the marginal external congestion cost and the marginal benefit of capacity expansion.

As in the basic model, there is always a queue during the interval I and a traveller arriving at the bottleneck at time a exits at time $a_0 + R(a)/s$. Travellers are identical so they achieve the same scheduling utility in equilibrium

$$v(a_0) = u\left(a, a_0 + \frac{R(a)}{s}\right).$$

Consider now a time varying toll $\tau(\cdot) \geq 0$ charged at the time of arrival at the bottleneck. We restrict attention to tolls that have $\tau(a_0) = \tau(a_1) = 0$ and are zero outside the departure interval I. This means that equations (10) and (11) still apply. If the toll is not too large, then Nash equilibrium exists with departures still in the interval I.[8] Therefore the equilibrium utility $v(a_0)$ is the same as in the no-toll equilibrium. As in the basic model, the optimal toll maintains the departure rate at capacity. The optimal toll is then given by $\tau(a) = v(a) - v(a_0)$ for $a \in I$ and zero otherwise.

The conclusions regarding elastic demand extend to the case of general scheduling preferences. That is, the optimal toll is still $p = \tau - u$, which is the same as in the case of inelastic demand. The conclusions regarding optimal capacity and self-financing also carry over to the general case. That is, if capacity is supplied at constant cost and optimally chosen, then the optimal toll exactly finances the capacity cost.

In this section we provided a brief description of the theoretical models related to travel behavior modeling. These theories are applied in the simulation models we have used for Ile-de-France and many other cases. In the next section we present some basic characteristics of the study area.

[8] Provided that the toll does not decrease too quickly. A quickly decreasing toll may induce travelers to avoid certain departure times, which leads to unused capacity.

3 Data (network, O-D matrix, traffic count, etc) and geography of Ile-de-France

In this section we present various data about our study area Ile-de-France. Most of these data are related to the traffic network and the demand which are closely related to travel behaviour modelling. This section will help us to have an overall idea about the present situation of the study area.

Our study area Ile-de-France embraces Paris and its suburbs. It covers about 12000 sq. km. Ile-de-France occupies 2% of the surface area of France and represents 19% of the population, 22% of the jobs and 29% of the GDP of the country (de Palma, Motamedi, Picard, & Waddell, 2005). We subdivide the study area in three regions: Paris, the inner suburbs called inner ring and the outer suburbs called outer ring. Table 1 gives the details on the areas studied:

Table 1: Description of the study area

Region	Description
Paris (P)	Surface area 105 sq.km Population 2193000 Mode of transport: Auto, Metro, Bus, Regional train
Inner ring **(Petit Courronne, PC)**	It consists of three departments around Paris: les Hauts-de-Seine, la Seine-Saint-Denis and le Val-de-Marne. Mode of transport: Auto, Metro, Bus, Regional train
Outer ring **(Grande Couronne or GC)**	It consists of four departments: la Seine-et-Marne, les Yvelines, l'Essonne and le Val-d'Oise. Mode of transport: Auto, Bus, Regional train

3.1 Population

According to the Census data in the year of 2008, the city of Paris has about 2.2 million inhabitants, on a regional total of 11.7 million. The population of Paris is estimated to not grow over the next 30 years but the total population will approximately grow about 0.3% yearly (this rate has been 0.4% for Paris and 0.7% for the region during the preceding 9 years). Regarding the suburbs, 46% of the population lives in the near suburbs and 54% in the outer ring. In each ring the population is approximately equal among the departments.

Out of Paris there are 38 communes with a population of more than 50 000, 31 of them are situated in the near suburbs and 7 in outer ring. These communes can be considered as poles of population over the region.

3.2 Employment

The total number of jobs is 5.6 million on 2008. That has grown by a rate of 1.2% per year during last 9 years. About 1.77 million jobs are concentrated on Paris and it has increased over the precedent years. The employments are equally distributed between near suburbs and outer ring but there is a clear concentration in the two western departments Haut-de-Seine and Yvelines.

Outside of Paris, there are 8 communes with more than 50 000 employments. Three of them constitute the zone La Défense. Three others (Boulogne-Billancourt, Saint-Denis and Levallois-Peret) are immediate neighbors of Paris at West and North. Roissy at North-Est is where the great international airport is situated and Créteil is a great pole at South-East.

3.3 The road network

The road network is organized into a hierarchy that is densely interconnected and often congested. The express network of the region is composed of 590 km of motorways and 250 km of expressways, with a total of 4 500 lane-km. Road traffic flows attain the highest levels known all over the country. But thanks to the efficient road network, and despite the traditional rush-hour traffic jams, traffic conditions are on the whole remarkably good for a metropolis of this size. The average duration of a car trip is 19 minutes, and no more than 25 minutes for commuter trips by car (de Palma, Motamedi, Picard, & Waddell, 2005). The mode market shares for the home based work trips in 2001 are: 50% Private cars, 36% Transit and 14% Bicycle/walk.

The public transportation network is diversified into:

- a main radial railway network, especially the RER lines (high speed train service between Paris and the suburbs)
- a subway network that provides comprehensive and timely service in the city centre
- a bus network to complement the rail services

At present within the neighbourhood of Paris, the available tolled roads are Highway A1 (the southern end at Roissy near Charles-de- Gaulle airport and towards Belgium), Highway A14 to the west or Paris (Montesson: Colse to Nanterre), Highway E5/A13 to the west of Paris (Buchelay and Heudebouville). But the only toll road that belongs to our study area Ile-de-France is Highway A14.

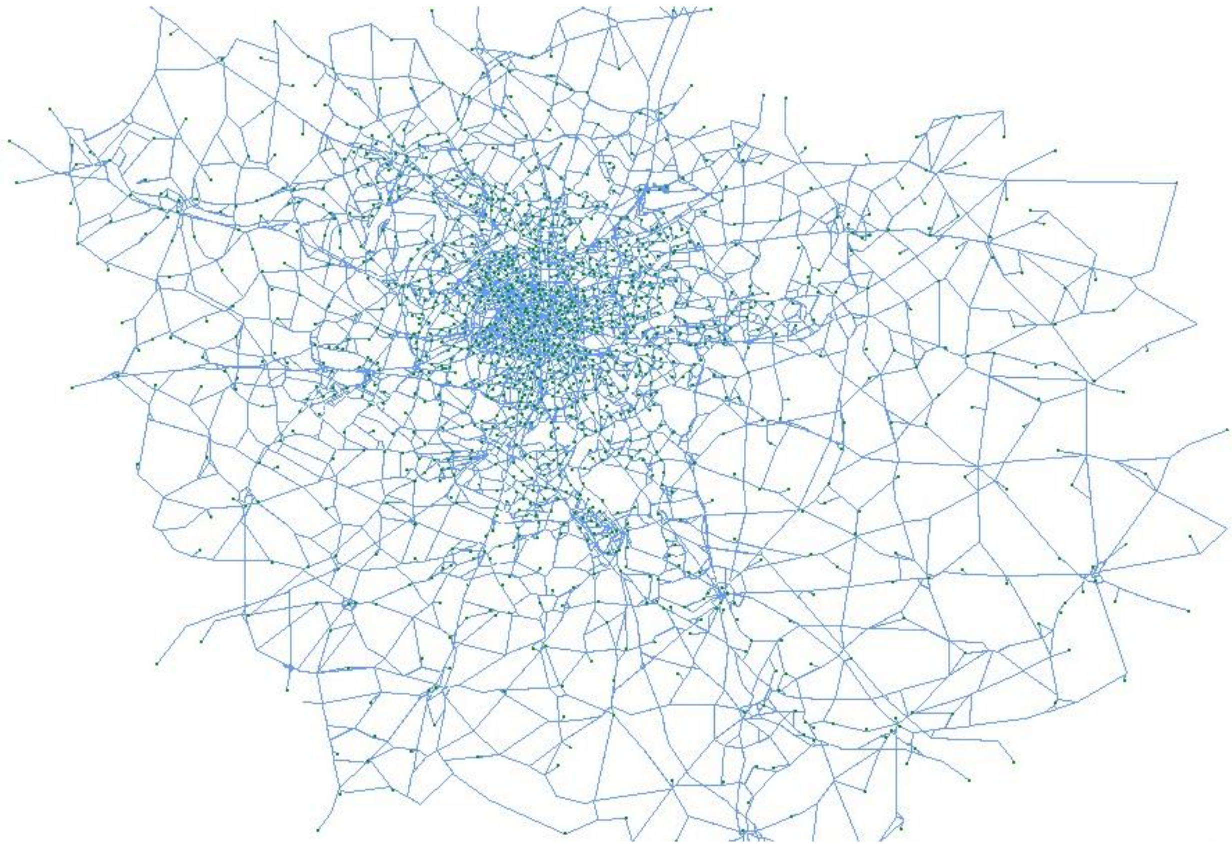


Figure 6: Road network of Ile-de-France

3.4 Transportation Demand

Total number of trips generated inside the region was estimated at about 35.16 million per day in 2001 and at 36.9 million in 2005. It is projected to be 41.37 and 43.61 on 2025 and 2035 by the static model MODUS (DREIF, 2008). The individual mobility of Ile-de-France inhabitants has remained unchanged since 1976, which is equal to 3.5 trips per person and per day (Debrincat et al., 2006). The geographical distribution of the trips among the three rings of the region is presented in Table 2. In this table OUT represents the trips originating out of Ile-de-France that enter the GC and the table only considers trips in the morning.

Table 2: OD trips in and between zones in 2007 in morning

	P	PC	GC	OUT	
P	627 423	282 691	79 365	18 368	1 007 847
PC	620 169	1 089 765	1 729 990	19 055	3 458 981
GC	418 142	527 238	1 504 671	38 341	2 488 392
OUT*	116 484	94 052	159 413		369 949
	1 782 218	1 993 746	3 473 439	75 765	7 325 168

The road network is organized into a hierarchy that is densely interconnected and often congested. The express network of the region is composed of 590 km of motorways and 250 km of expressways, with a total of 4 500 lane-km. The mode market shares for the home based work trips (2001) are: 50% Private cars, 36% Transit and 14% Bicycle/walk. Table 3 shows the number of trips that are exclusively made by car among the regions. As can be seen, in the center of Paris, public transport has a large market share.

Table 3: Share of the trips made exclusively by car

	P	PC	GC	OUT
P	14%	26%	41%	68%
PC	22%	56%	44%	58%
GC	21%	59%	80%	83%
OUT	32%	8%	85%	

3.4.1 Trip purpose and timing

The trips are classified in 8 trip purpose categories. Trips purposes are originally identified by the trip origin and trip destination as Home, Workplace, Shop, Leisure or Personal affaire. Origin–destination couples are aggregated in 8 classes based on similarity in the behavior and equally distribution of trip frequency. Table 4 presents trip purposes classes (1 to 8) based on trip origin and destination and Figure 7 presents the trips frequency in each trip purpose class.

Table 4: Trip purpose 8 categories (Source: DREIF, 2008)

Origin	Destination				
	Home	Work	Shopping	Leisure	Personal affairs.
Home		1	3	7	3
Work	2	5	5	5	5
Shopping	4	5	6	6	6
Leisure	8	5	6	6	6
Personal affairs	4	5	6	6	6

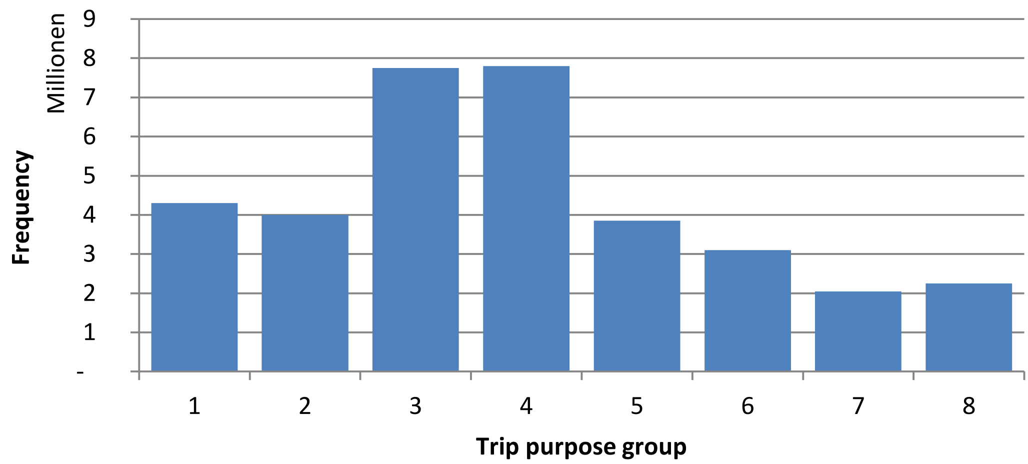


Figure 7: Distribution of trip purpose of 8 categories Source: (DREIF, 2008)

It is observed that the trips related to shopping are the most frequent one. Work related trips are in the next place. But this ranking would be different for motorized trips. About 4 million trips are for Home to work purpose the mostly happen during the morning period.

3.4.2 Mode share

Over the region, 46% of trips are carried out by cars, 20% by public transit system and 34% by other modes like walk and bike. The trip distance is the most important determinant of the mode share. Non-motorized modes are essentially used for short distances (less than 5 km). Part of public transit increases with distance but it is stabilized when the distance is greater than 5 km. Figure 8 presents the modal shares with respect to the trip distance according to the travel survey 2001.

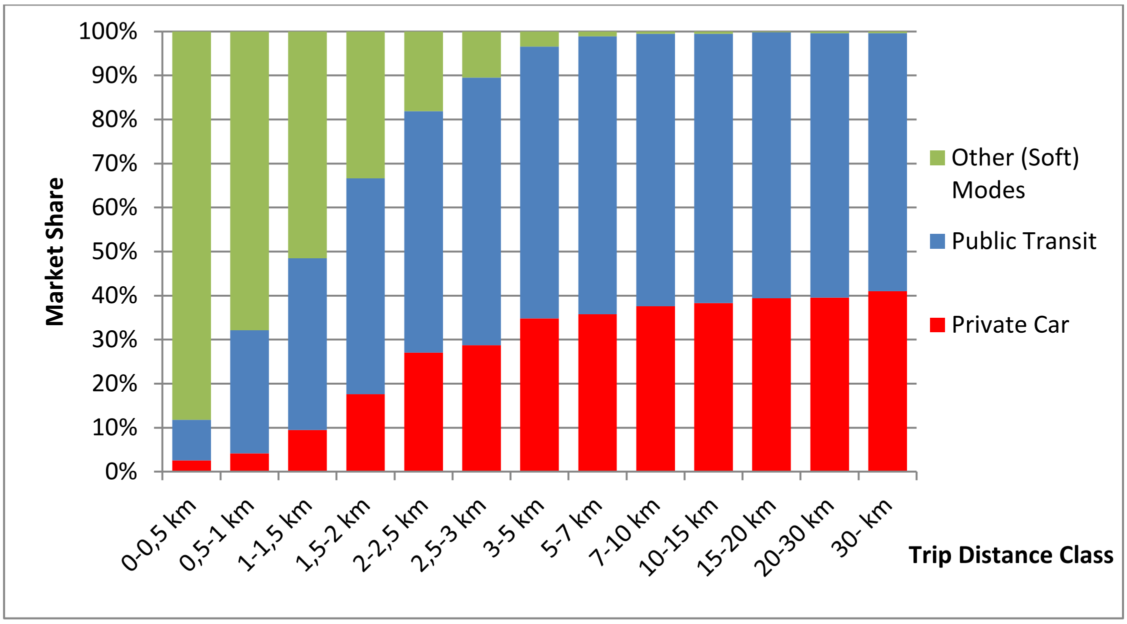


Figure 8: Market shares of different modes

Ile-de-France is a big traffic network which could be difficult to manage by any traffic models if not well planned beforehand. In the next sections we provide details about some popular transport models used for Ile-de-France and some major policy analysis done by them.

4 METROPOLIS: a day to day adjustment dynamic model

METROPOLIS is a traffic planning software which uses event based dynamic simulation. It was developed in Geneva by André de Palma, Fabrice Marchal and Yurii Nesterov (de Palma, Marchal and Nesterov, 1997) and later on applied at the University of Cergy-Pontoise by de Palma and Marchal (de Palma and Marchal, 2002). It is based on simple economic principle, explained originally by Vickrey (1969) and Arnott, de Palma, Lindsey (1993a). METROPOLIS describes the joint departure time and route choice decisions of drivers. Each vehicle is described individually by the simulator. However, the modelling of congestion on the links is carried out at the aggregate or macroscopic level. On the supply side a congestion function describes the travel delays of the links. The demand is represented at microscopic level and each trip is modelled accordingly to its choices of mode, departure time and route of travel. METROPOLIS features a two-stage nested logit model with a binary choice between auto and public transport in the outer nest, and a continuous choice of departure time for the auto mode in the inner nest so that trips are not allocated into pre-defined discrete time intervals such as peak and off-peak.

In the project SustainCity[9], MOTRPOLIS has been used for the transport analysis of Ile-de-France and MATSIM has been used for other two cities: Belgium and zurich.

4.1 The generalized supply

The congestion function

The model needs a congestion function to define the travel time over the links. METROPOLIS provides the possibility to introduce any relevant function with a flexible form based on the traffic flow and capacity of the links. The delay at intersections is considered in the link travel time and to obtain that either the capacity of the links or the maximum permitted speed of the vehicles should be modified. The usual forms of congestion function used in METROPOLIS are Bottleneck, Bureau of Public Roads (BPR) or DAVIS. In this study bottleneck function was used to describe congestion in the network.

[9] www.sustaincity.org

Spill-back effects

Spill-back effects can be considered in METROPOLIS. In absence of this effect, only vertical queuing has been considered since the density *D* has no upper bounded. To improve congestion model, the roads are allowed to bear up to a maximum density D_{max} that depends on the average length of the vehicles and road length. If a vehicle wish to enter a saturated road link where $D=D_{max}$, it has to wait for some period t_w until the downstream link can accommodate any new incoming vehicles. Horizontal queuing is not trivial to implement in an even based simulator like METROPOLIS, because the waiting time t_w is exogenous to the link traffic variables and it only depends on the downstream network condition (Marchal, 2001)

4.2 The generalized cost function

Each traveler has a scheduling cost expressing his/her preferences concerning the timing of the trip. Travelers are assumed to have a preferred arrival time t* and they dislike arriving earlier or later at the destination. Travelers also prefer the trip to be as quick as possible.

The generalized cost function can be defined as: Cost, C(t) = travel time cost + cost of arriving early or late. The cost function is presented in equation (12), and the distribution of the schedule delay costs are presented in Figure 9.

$$C(t) = \alpha . tt_c(t) + \beta . \left[\left(t^* - \Delta / 2 \right) - \left(t + tt_c(t) \right) \right]^+ + \gamma . \left[\left(t + tt_c(t) \right) - \left(t^* + \Delta / 2 \right) \right]^+ , \qquad (12)$$

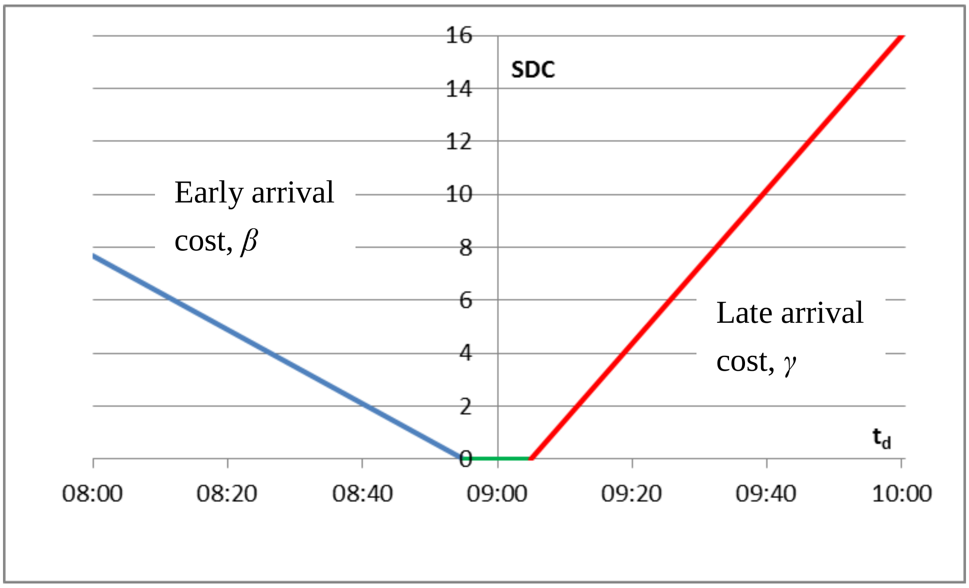


Figure 9: Schedule delay cost

where, $A^+ \equiv Max(0, A)$ .The first term in the above equation represents the travel time penalty; the second and third term represents early or late arrival penalty respectively. And

$\mathrm{C(t)}$: Generalized cost for car user whose departure time is t from the origin
$\mathrm{tt_c(t)}$: Travel time for a departure at t from the origin
$\mathrm{t^*}$: Desired arrival time at destination
α : Value of time
β : Unit penalty associated to early arrival
γ : Unit penalty associated to late arrival
Δ : Flexible time period without penalty

Typically, the user faces the following trade-off: either he arrives close to the desired arrival time and incurs a lot of congestion or he avoids the congestion and arrives too early or too late compared to his desired arrival time.

4.3 Hierarchical choices: the nested logit model

In METROPOLIS the demand is represented at microscopic level and each trip can be simulated. The users' characteristics which are necessary for the modeling are presented below:

- Value of time
- Schedule delay penalty (early and late)
- Desired arrival/departure time distribution
- No penalty period
- Logit scale parameters
- Mode choice parameters
    - Value of time for Transit
    - Penalty or fee

The individual values are drawn from the given distribution. In simulation, each trip will be followed individually in its choices of mode, departure time and route choice (direction at each crossing).

Mode choice

Mode choice is described by a discrete choice model. The generalized cost associated to public transport (VB) is defined as:

$$V_B = \alpha_{PT} \cdot tt_{PT} + C_{PT},$$

where,

α_{PT}= Value of time spent in public transport (PT)
tt_{PT} = Generalised travel time in PT

C_{PT} = Fixed penalty associated to PT.

The mode choice could be modeled either in short run or long run choice. In long run, the user chooses the mode considering the average maximum expected utility (logsum) offered by the car network in comparison with the other modes. In short run the user chooses her mode after choosing her departure time and consider the car utility at that precise time.

Departure time choice and route choice

Car users have to select their departure time. The choice of departure time for public transportation is not described by the model, since the public transportation travel times are external inputs to METROPOLIS. The departure time choice model for car is a continuous logit model, either deterministic or stochastic. In the deterministic version the individual selects the departure time that minimizes the generalized cost function. In the stochastic version used in METROPOLIS, the *P(t) dt* probability of choice of the departure interval [*t*, *t+dt*] is given by a continuous model logit:

$$P(t)dt = (1 / A) * \exp(-C(t)/\mu^T)dt,$$

where, the parameter $\mu > 0$ measures the heterogeneity of the departure time choice, and *A* is the accessibility which can be defined as there is no MUT here, $A = \mu^T ln \int_{T_0}^{T_1} \exp(-C(u)/\mu^T)du$.

METROPOLIS uses a model of route choice based on point-to-point dynamic travel times. The user selects the dynamic shortest path from the origin node to the destination node. The decision will be based on the real time situation of the immediate link and memorized information about the rest of the network up to the destination.

The choice of a route at the origin is only based on the minimization of historical travel times. Consider a user whose origin zone is *O* and who is reaching the intersection *N*. Intersection *N* has 3 downstream links whose directions are D_1, D_2 and D_3. The final destination of the user is zone D_f. In METROPOLIS, it is assumed that the user chooses the direction D_i (i = 1, 2 or 3) that minimizes the remaining travel time to destination. That travel time is the sum of the current travel time on the link downstream of *N* plus the historical travel times from D_i to D_f. The situation is described in Figure 10.

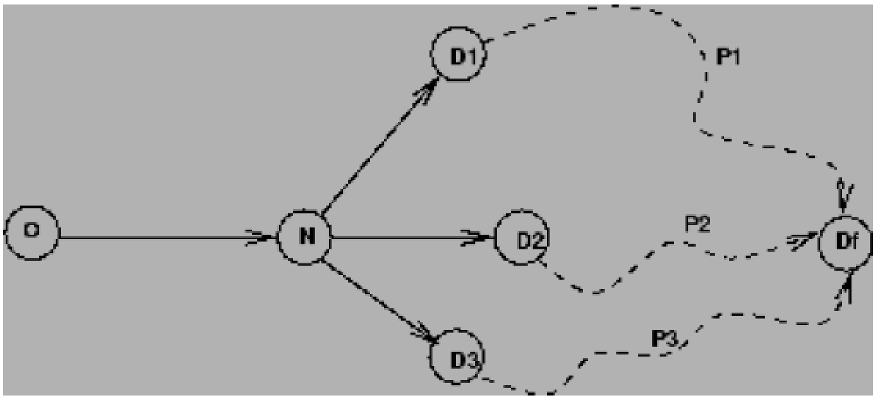


Figure 10: Route choice decision (Source: METROPOLIS manual 1.5, 2002)

It is assumed that the travel time on the next link to take is observable and anticipated by the user. It is expressed by the following equation:

$$tt_{j\,D_f}\,(t) \;=\; tt_j^s\,(t) + \; tt_{D_j\,D_f}^H\,(t + \; tt_j^s\,(t))$$

In this expression, H-indices refer to historical travel times and S-indices refer to the simulated travel times (i.e. current) on the links downstream from *N*. Historical travel times are those used to reach D_f by using the routes P_1, P_2 and P_3 from nodes D_1, D_2 and D_3. This combination of current and historical values allows:

- To model that users perform route diversion if any disturbance (e.g. incident) occurs,
- To avoid an all-or-nothing route choice model: the situation is different for each user since the simulated conditions vary from one vehicle to another in the same intersection and over a very short time.

It is also possible to use a stochastic direction choice. In this case the choice probabilities are given by a logit type function specified by its own heterogeneity parameter μ_r.

$$\Pr(i) = \frac{\exp\left(-tt_i(t)/\mu_r\right)}{\sum_{j=1}^{3}\exp\left(-tt_j(t)/\mu_r\right)}.$$

4.4 Learning model

The software uses a learning process where users acquire knowledge about their travel and uses this information to modify their trip for the next day. It should be noted that one is day corresponds to one iteration in METROPOLIS. This process operates as follows:

- The first day, the users have a naive knowledge: they make the assumption that there is no congestion in the network. The users start their journey relatively late and all attempting to arrive at their preferred time by using the fastest route. The congestion caused by this concentration phenomenon is very high.

- Learning from the experience, second day they start their journey either much earlier or later and select longer routes. Consequently, the congestion is reduced but the arrivals are too far away from the schedule time.

- The process continues until it reaches a stable state. The users acquire information about their experienced route and after each iteration, the collected information's are either stored as historical travel data or update the previous data.

The process can be illustrated by following equation

$$X_{d+1}^{H} = f\left(X_{d}^{H}, X_{d}^{S}\right),$$

where,

X_{d}^{H} : The historical information acquired on day d

X_{d}^{S} : Represents the traffic conditions effectively simulated/incurred on day d.

Several functions *f(.)*are available. METROPOLIS uses Exponential, Linear, Quadratic or Genetic function for learning process.

4.5 Data requirement for METROPOLIS

Coded network

The network representation in metropolis is similar to any static traffic models. It consists the co-ordinates of the zones and intersections. The links will connect the points (zones or intersections). The links can contain only one line in one direction, therefore number of lanes comes as an extra input. An average value of capacity is used for road section having more than one lane and it is in the form of veh/hr/lanes.

All the points are considered as either intersection or zones. So when importing the network from another traffic model that contains nodes which are not belongs to either intersections or zones, care should be taken to avoid having unnecessary intersections in the network. We also need maximum permitted speed for each links.

Static O-D matrix

Metropolis use a static O-D matrix as the input for the model, but it re-generates the demand according to the behavioural parameters of the individual and preferred time of travel distribution.

User parameters

The dynamic model needs some behavioural parameters to be estimated in addition to the static model parameters. These parameters can be estimated from the result of an interactive survey based on Stated / Revealed Preference approach. Considering the difference of the survey costs, this approach is not included in usual travel surveys and implies new specific survey. Such a survey will be designed taking into account the model to be constructed later. An adaptation will be necessary to use the survey data designed for one model to provide the parameters of the other one. The behavioural parameters are:

- Value of time
- Early arrival penalty
- Late arrival penalty
- Desired arrival/departure time distribution
- No penalty period
- Logit mu for departure time
- Mode choice parameters

Calibration data

The collected field data, which could be useful for calibrating the model are listed below:

- Vehicular flow in some specific links
- Distribution of flow during the simulation period in some specific links
- Travel time for some specific O-D or part of road sections
- Distribution of travel time during the simulation period
- Previous idea or survey about the modal share, etc
- Revenue collection
- Level of congestion from other available models

4.6 Simulation result of Ile-de-France in METROPOLIS

The Ile-de-France network is coded with 1289 internal zones. 50 zones represent the entry/exit points of the region with the exteriors in public or road transportation system (including the international airports and inter-regional train stations).

The road network is coded by 43 857 links within them 4 462 are the connectors. This coding has been aimed to provide a detailed model able to produce detailed information about the traffic flows necessary for engineering studies on the transportation infrastructures.

The model has been calibrated[10] using field measurements from the situation without charging. Field data contained flow measurements for 606 selected links, travel time for 124 selected OD pairs, distribution of departure and arrival time and network average travel time. The calibrated network is considered as the base scenario. To reduce the runtime, the demand has been reduced to 10% of the original travel demand in the morning period (6AM – 10AM). The capacity of the network was also adjusted to reflect the original picture. The aggregate/average result for the base case scenario is presented in Table 4 and 5.

Table 5: Network aggregate/average results

	Base scenario	Description
Number of car trips[11]	608 686	Number of car trips considering one individual per vehicle
PT share (%)	47.83%	Percentage of individual who chose Public Transport alternative
Travel time (min)	19.03	Average travel time by car (from origin to destination)
Travel cost (€)	10.00	Average travel cost by car (from origin to destination)
Schedule delay cost (€)	3.34	Average schedule delay cost
Toll revenues (€)	0	No toll was present in base situation
Consumer surplus (€)	-9.285	User surplus (logsum for auto and public transportation)
Equity (€)	5.94	Standard deviation of accessibility
Early arrivals (%)	53.80	Percentage of drivers arriving earlier than their desired arrival time
On-time arrivals (%)	20.50	Percentage of drivers arriving on time (within in 10 min of his desired arrival time)
Late arrivals (%)	25.70	Percentage of drivers arriving later than their desired arrival time
Congestion (%)	51.14	The ratio of actual arrival time (T) to the free flow travel time (T_0), Congestion $C = (T-T_0)/T_0$
Speed (km/hr)	46.82	Mean speed by automobile
Mileage (10^6 veh-km)	8.47	Total vehicle kilometers driven by auto

[10] To know the detail calibration process the interested readers can see the working paper of de Palma, Motamedi and Saifuzzaman (2012).

[11] Based on 10% of the morning travel demand.

Table 6: Externalities[12] for private transport (for 10% of demand)

	Low valuation	High valuation
Auto noise[13] (€)	22,104	47,256
Auto accidents (€)	294,972	294,972
Auto pollution (€)	76,305	357,049
Greenhouse emissions (€)	105,861	206,472
Social cost of public funds[14] (€)	-	-
Total external costs[15] (€)	499,242	905,749
External costs per driver (€)	0.82	1.49

The Regional survey (EGT 2001) which was the base for MODUS model showed the average car trip is about 19 min long for Ile-de-France region. The simulation suggests an average travel time for the simulation period (6-10 AM) is 19.03 min which supports the survey data. The mode shares for the home based work trips calculated from the survey EGT 2001 were: 50% Private cars, 36% Transit and 14% Bicycle/walk. As the mode choice model of METROPOLIS only consider auto and public transport, a modal split between auto and public transport is observed as 52.2% and 47.8% respectively. Average car travel cost is about €10.0. The congestion index—defined as the ratio of queuing delay to free-flow travel time on the route taken—has an average value over the network of 51.1%. The average cost of schedule delay is €3.3. About 20.5% of drivers arrive on time, about 53.8% arrive early, and the remainders are late. The combined external costs of noise, accidents, pollution and emissions (all of which are assumed to be proportional to distance travelled) amount to about €0.82 per driver for the low unit values for external costs and €1.50 per driver for the high unit costs.

4.7 Interaction between METROPOLIS and Urban model

METROPOLIS will be coupled with UrbanSimE (Waddell, 2007) to produce transport related inputs for the urban model. Similar experiences with other transportation models like Visum, Emme/3 and MatSim have been performed. This section describes the integration process in details. It also describes the data transformations required for each step. All data are

[12] The unit values for externalities are reported in de Palma and Lindsey, 2006.

[13] The external costs of Auto noise, accidents, pollution and greenhouse emissions are proportional to veh-km travelled and the standard unit values are reported in Table A1 in Appendix.

[14] Social cost of public fund: toll revenue multiplied by the marginal cost of public funds. For this study MCPF was set equal to 0.14 which was used in the macroeconomic models developed by the 'Bureau du Plan' (de Palma and Lindsey, 2006).

[15] Total external costs: sum of costs from noise, accidents, pollution, greenhouse and marginal cost of public funds for auto trips.

stored in databases and managed by MySQL. The interface is developed in Java and runs on both Linux and Windows environments.

The interaction of the two simulation software can be simply described as following: UrbanSimE provides the population and employment of different geographical units (in the case of Paris 1300 Communes over the region). The interface computes an Origin-Destination matrix. Then METROPOLIS calculates the accessibility of different zones based on the updated OD matrix, UrbanSimE uses this new accessibility measures values to simulate the evolution of population and employment. As the urban system evolves slower than transportation system, the interaction between METROPOLIS and UrbanSimE is not performed each year, rather it is flexible for adjusting the scales. The developed interface handles all the data transfer, data modification and runs the simulation automatically according to a pre-defined simulation plan.

The METROPOLIS UrbanSimE interface in short 'MetroSim' performs all the data transfer and their modification. It is GUI based and can be used in future for work with other software. We have selected file based data transfer method. The data transfer plan can be described in a simple diagram as shown in Figure 11.

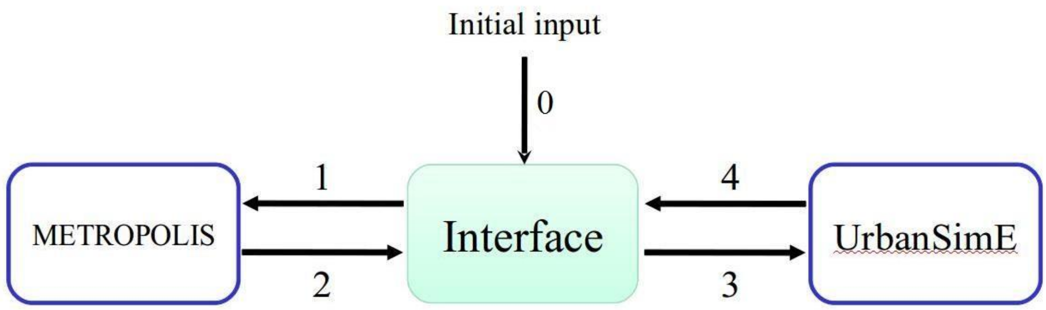


Figure 11: Data transfer plan

Step 0): The data about OD demand and PT travel time will be loaded in the interface database. The data file could text or xml file or MySQL database.

Step 1): Interface will send travel demand for METROPOLIS along with PT travel time and other simulation parameters and start the simulation process.

Step 2): After the simulation, METROPOLIS will provide the O-D travel time and user surplus for each user to the interface database. As these data are stored in METROPOLIS MySQL database, the interface will transfer the data to its own MySQL data store for further processing.

Step 3): The interface calculates accessibility based on the travel time and user surplus data generated by METROPOLIS and send it as an input to UrbanSimE. It also sends other simulation parameters and starts the simulation in UrbanSimE for a certain number of years.

Step 4): After the simulation UrbanSimE will provide the modified population and employment for each commune. The interface will store these data to its MySQL database and calculate the new OD demand for METROPOLIS. Then Step 1 starts again and the process continues for a certain number of iterations.

This process runs multiple simulations in METROPOLIS and UrbanSim simultaneously and transfers the necessary data between the two models. The process is automatic and an interface is build from where the simulations can be controlled. As the data structure is different for the two models, the interface will automatically do necessary data transformation.

In the next section we provide the details of estimation for travel behavior modeling parameters in Ile-de-France. These parameters are used in most of the transport models used for Ile-de-France transport analysis.

5 Estimation of behavioral parameters

Two famous surveys are conducted to estimate the travel behaviour parameters for Ile-de-France. The first one is MADDIF, which was conducted in the year 2000. The estimation result from this survey has been used in most of the transport models of Paris region. The other survey MIMETIC is comparatively new (conducted at the end of 2011) and was aimed to update the estimations of MADDIF.

5.1 Project MADDIF

Travel behaviour parameters are essential for transport modelling. The most common parameters are value of time for car and for public transport (α_{car}, α_{PT}), schedule delay penalty (early arrival penalty β and late arrival penalty γ). Other parameters used are logit scale parameter of the departure time choice model μ, the desired arrival time distribution, t*, no penalty period Δ. These parameters should be estimated by a stated and/or revealed preference surveys and need some interactive surveying method that is usually not included in travel surveys. For the case of Ile-de-France a specific survey was designed and conducted in 2000 under the project MADDIF (Multimotif Adaptée à la Dynamique des comportements de Déplacement en Ile-de-France), see (de Palma and Fontan, 2000 and de Palma and Fontan, 2001). In that survey the respondents were asked by phone about information's concerning their morning trips for the same day. The survey was administered during May and June 2000. The phone calls have been processed from 5 to 8 PM. About 4230 individuals answered the questionnaire.

The survey had four different sections (De Palma, Fontan, Picard, 2003). In the first section the respondent was asked about his departure and arrival time and constraints, selected mode and its characteristics, network knowledge and use of information on trip conditions, etc. This part helps us to model departure time choice. The second part of the questionnaire was concerned with the tradeoffs between two choices involving different departure times and different travel times (and thus different arrival times). The third part was related to scenarios of available modes and information. The last section was about the characteristics of the individuals and their household.

As the model has the capacity to consider several individual (trip) groups, during the estimation, it has been studied to find the best possible classification to represent optimally the population heterogeneity with acceptable quality of results. Classifications with respect to the geographical zones as origin or destination, to the trip purpose or the distance have been tried. The results will be discussed later in a dedicated section.

After estimating the schedule delay penalties for all the population (de Palma, Delattre, Marchal, Mekkaoui, & Motamedi, 2002), the β/α and γ/α are obtained as 0.51 and 0.81 respectively. β and γ are estimated parameters for arriving early and late. Dividing them by α normalizes the estimation, therefore, β/α and γ/α represents the flexibility of arriving early or late. The estimation of the total population shows that $\beta/\alpha > \gamma/\alpha$ which tells us that people of Ile-de-France prefers to arrive early than late, which totally make sense. But it is not wise to model with only one population sample, because the model may not show the true heterogeneity among the people. Therefore the population was classified in different samples depending on some certain criteria.

Different classification scheme was proposed i.e. with respect to residence area, purpose of trips, length of the trip and destination of trips. The most significant classification was jointly based on trip purpose and destination by merging Paris and near suburbs in a group. The detail results of these estimations based on different classifications are presented in the report of QUATUOR (de Palma, Delattre, Marchal, Mekkaoui, & Motamedi, 2002), interested users are suggested to read that report. In this report only the estimation result based on the final classifications is presented. The final classification is as follows:

Home to Work to Paris and Near Suburbs,

Home to Work and Outer Ring,

Other purposes

The result of final estimation is presented in Table 7.

Table 7: Behavioral parameters by O-D region

	Simple size	$\boldsymbol{\alpha}$	β	γ	$\boldsymbol{\beta}$/α	γ/α
Work to Paris and Near Suburbs	648	0.081 (0.015)	0.038 (0.007)	0.047 * (0.023)	0.469	0.580
Work to Outer Ring	509	0.130 (0.022)	0.084 (0.013)	0.175 * (0.045)	0.646	1.346
Other purposes	544	0.089 (0.019)	0.036 (0.008)	0.073 * (0.03)	0.404	0.820

Legend: * significant between 1% and 5%, Without any symbol : significant at less than 1%

Source: Final report of QUATUOR project (de Palma, Delattre, Marchal, Mekkaoui, & Motamedi, 2002)

The estimation samples included respondents declaring a precise desired arrival time. In the estimations, the significance of a no penalty time window at the arrival is testes and it is obtained as null.

In these estimations the logit scale parameter μ is normalized to 1. If one removes the assumption $\mu = 1$, previous estimates of dynamic parameters will be equivalent to α/μ, β/μ and γ/μ. For example, in the case of work-related travel to Paris and its inner suburbs were: $\alpha/\mu = 0.081$, $\beta/\mu = 0.038$ and $\gamma/\mu = 0.047$. The scale parameter μ can be obtained through a recent estimate of the value time, α, obtained for the population of the study area.

Following the econometric work done from the EGT 1998, motorists of the Ile-de-France have value of time α equals 85F/H (see (de Palma & Fontan, 2001)) i.e. α =12.96 Euros per Hour. So a simple calculation will provide that $\mu = 2.67$, $\beta = 6.09$ and $\gamma = 7.53$. Now the values are consistent with METROPOLIS specification. The final values of behavioral parameters according to METROPOLIS specification are presented in the following Table 8:

Table 8: Behavioral parameters for METROPOLIS estimated for three O-D classes

	Simple size	$\boldsymbol{\alpha}$ (Euro/hr)	β (Euro/hr)	γ (Euro/hr)	μ
Work to Paris and Near Suburbs	648	12.96	6.09	7.53	2.67
Work to Outer Ring	509	12.96	8.36	17.43	1.66
Other purposes	544	12.96	5.24	10.64	2.43

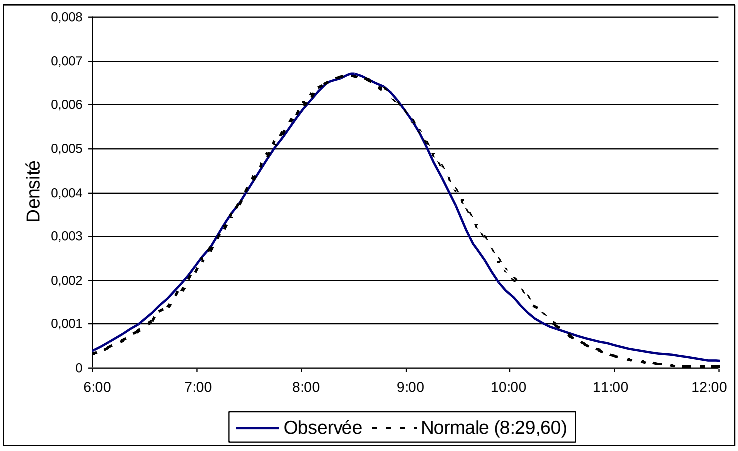
Desired arrival time

The distribution of desired arrival time for the same trip categories are also needed for dynamic modeling. The distributions are presented in Figure 12 as a combination of normal flows fitted by a kernel. In this figure the labels are in French; 'Densité' means density, Observée stands for observed distribution and Normale stands for fitted normal distribution and 'Résultat du mélange' refers to result of mixing of two graph. The distribution parameters are presented in Table 9.

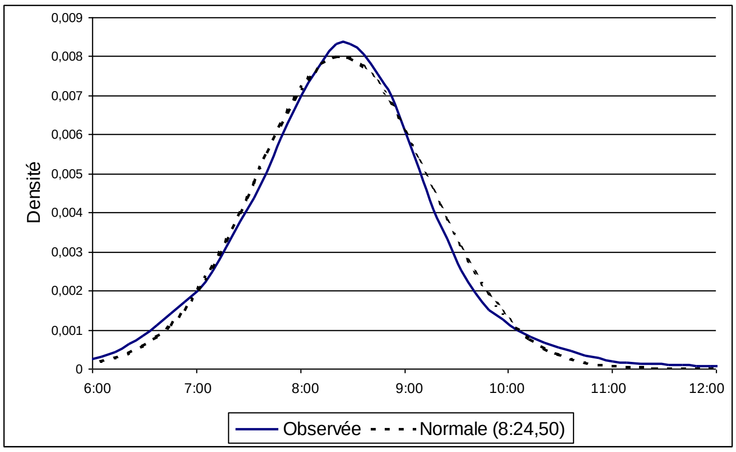
Table 9: Parameters of the fitted normal distribution in Figure 12

	Type of Distribution	Parameter of distribution	
		Mean	St. Dev.(minutes)
Work to Paris and Near Suburbs	Normal	8:29	60
Work to Outer Ring	Normal	8:24	50
Other purposes			
Group 1 (46%)	Normal	8:54	54
Group 2 (54%)	Normal	10:49	53

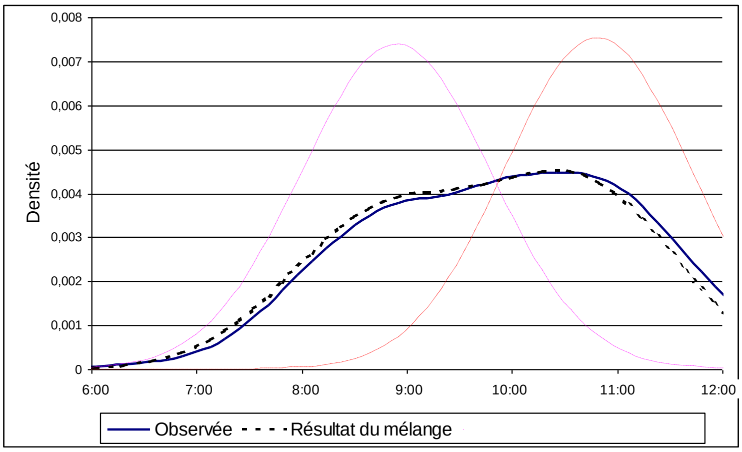
O-D pair: Work to Paris and Near Suburbs



O-D pair: Work to Outer Ring



O-D pair: Work to Outer Ring



Observée = Observed distribution, Densité = Density, Normale = Normal distribution, Résultat du mélange = Result of combined distribution

Source: QUATOUR report (de Palma, Delattre, Marchal, Mekkaoui, & Motamedi, 2002)

Figure 12: Distribution of arrival time for three different O-D pairs

5.2 Project MIMETIC

MIMETIC is a recent survey that was conducted in the Paris region in the end of 2011. It was a stated preference survey. Design of stated experiments was defined by means of nested choice situations to bracket, as in experimental economics, willingness-to-pay coefficients (Picard et al., 2012, de Palma et al., 2012). Although this survey is far more generic, it partly appears as the successor of one that was carried out more than 10 years before: MADDIF (de Palma and Fontan, 2000). One purpose of the survey was to update willingness-to-pay parameters to be used for transport policy simulation, especially schedule delay parameters. Initially, 3497 individuals were questioned about their residential locations, their automobile equipment, and some of the trips they carried out up to one week before they were surveyed. They were also questioned about their economic and socio-demographic conditions. Stated choice experiments were then built up on their actual travel behaviors. They pertained to mode choices, route choices, scheduling choices, parking choices, with and without explicit consideration of risky prospects. The purpose of this survey is not only to analyze transport-related individual decisions but also to infer on how decisions are made at the couple level. For details on data collection techniques and on the descriptive results of the whole project, see de Palma et al. (2012).

After removing observations with missing statistical information about some relevant socio-economic and demographic characteristics as well as observations with bugged information, the sample size for their study becomes 1814. Some of their descriptive statistics are reported in Table 10:

Table 10: Descriptive statistics of the selected sample

Label	Percent	Frequency
Respondent is a man	39.36	714
Respondent is a woman	60.64	1100
Respondent is single	26.9	488
Respondent has at least one child	44.27	803
Age: 15-24	10.25	186
Age: 25-49	69.13	1254
Age: 50-64	16.81	305
Age: >64	3.8	69
First income quartile	22.2	402
Second income quartile	28.11	510
Third income quartile	26.35	478
Fourth income quartile	23.37	424
flexible work hours	38.86	705
Respondent works full time	69.57	1262

Work-purpose trips	63.28	1148
Leisure-purpose trips	9.31	169
Other purposes	27.4	497
Mode used bus	10.09	198
Mode used: metro	18.41	334
Mode used : RER	25.24	458
Mode used: car (driver)	37.7	684
Mode used: car (passenger)	5.62	102
Mode used: (two -wheeler)	2.09	38
Sample size		1814

The table shows that 60.5% of travelers are women (39.5% are men). About 75% of the respondents declared to live with a partner. 50% declared to have one child or more. 69% are in between 25 and 49 years old, 10% in between 15 and 24 years old, 17% are in between 50 and 64 years old, and 4% are above 65 years old. The cumulative distribution of income is such that 22% of the individuals live in a household with a total income of less than 23000AC per year, 50% live in a household with a total net income less than 38000AC per year, and 75% live in a household with a total net income of less than 61000AC per year. 39% of the workers also declare they had flexible work hours and 70% report that they work full-time.

In an ongoing study Picard and de Palma (2013) estimated the value of time from the survey data of MIMETIC. The analysis was performed based on the responses to hypthetical scenarios where the travel cost and travel time are varied.

Table 11 reports the estimated weighted arithmetic mean and weighted median (geometric mean) of the marginal distributions of the value of travel time savings and the schedule delay costs. Weights are computed as proportions of respondent by mode of transport and trip purpose in the sample. The arithmetic mean is given for information only. For interpretation, we prefer to focus on median values. As the distribution is asymmetric and skewed to the right, the arithmetic mean is not very relevant, especially if skewness is strong as in our case. The median divides the population into two equally shared sub-populations of travelers below and above the stated values.

The table shows that public transport (PT) users have higher value of time than car users. Different trip purpose has different value of time. Females have higher VOT than male. Among different age groups, 36-45 age group has the highest value of time.

Table 11: Estimation results for Value of Time (VOT) in € per hour

Variable	Mean	Median	Std. Dev.	Min	Max
All	13.66	**11.88**	8.52	2.93	36.59
Mode					
PT	14.42	**12.01**	8.55	3.51	36.59
Car	12.81	**10.99**	8.41	2.93	35.38
Purpose					
Work	14.64	**12.17**	8.67	2.96	36.59
Pro meeting	16.07	**14.52**	9.46	3.00	35.32
Student	13.24	**11.57**	8.72	2.97	36.52
Trainee	15.15	**13.43**	8.16	3.17	29.92
Others	11.77	**8.26**	7.81	2.93	36.53
Sex					
Male	13.79	**11.75**	8.94	2.93	36.59
Female	13.55	**11.91**	8.16	2.94	36.57
Age					
<30	13.12	**11.64**	8.25	2.94	36.56
30-35	13.93	**11.95**	8.29	2.93	35.31
36-45	14.75	**12.31**	8.91	2.93	36.59
>45	12.81	**10.92**	8.44	2.93	36.56

Source: Picard and de Palma (2013)

6 Policy analysis

This section provides a brief overview of some policy analysis on travel behavior.

6.1 Road pricing

Road pricing has a big advantage over other transportation demand management policies. It encourages traveller's to adjust all aspects of their behaviour: number of trips, destination, mode of transport, departure time choice, route choice, as well as their long-run decisions on where to live, work and set up business. Road congestion is generally viewed to be the most costly external cost of travel in the Paris area. In a recent paper de Palma et al. (2013) the improvements in road pricing analysis for Paris region over the years was investigated. They analyzed in details different aspects of road pricing for the same location and same pricing scheme. Three different types of models have been investigated: theoretical mono-centric model (De Lara, et al., 2013), 4 step transport model MOLINO II (de Palma, Proost, Van der Loo, 2010), and dynamic transport model METROPOLIS.

6.1.1 Long term effect of road pricing (mono-centric model)

The theoretical mono-centric model captures the long term impact of congestion charging on housing and business location which have not received so much attention in the literature on road pricing. De Lara et al. (2013) considered the linear toll (proportional to travel distance) and the cordon toll (a toll paid once the driver crosses a given border). Both schemes are compared to the no toll case (base situation) and to the first best (where total housing and transport costs in the city are minimized). The linear toll is equivalent to an increase in the vehicle operating cost. It performs well with respect to the first-best solution but, since it applies identically to all trips and the number of trips is fixed, it is not likely to be relevant in practice. By comparison to the no-toll situation, optimal congestion pricing reduces the radius of the city and the average travel distance by 34% and 15%, respectively. Figure 13 shows the long term effect of congestion pricing in terms of household density.

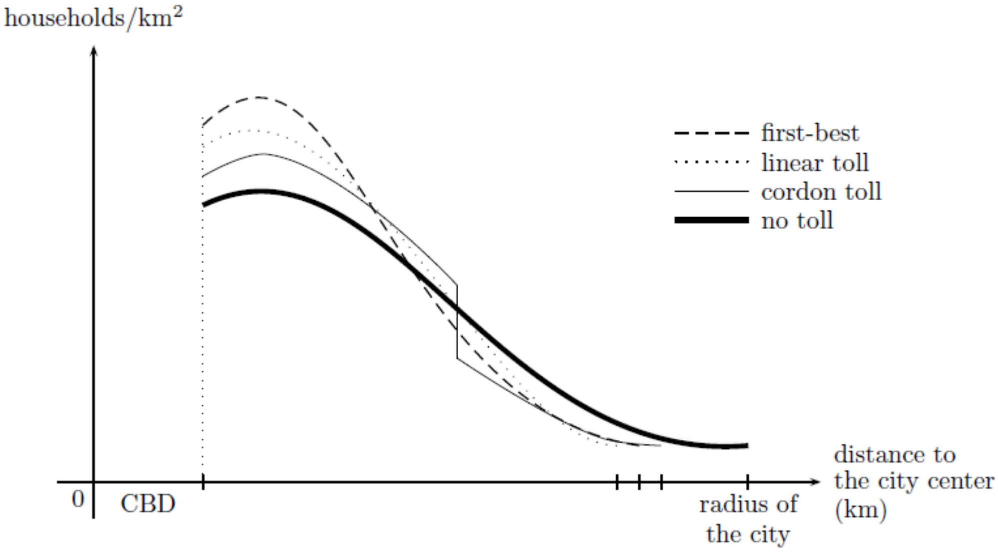


Figure 13: Long term effect of congestion pricing

(Source: De Lara, et al. 2013)

The radius of the city also decreases when a congestion toll is applied. This is the long run effect of toll, ignored by the two other models: METROPOLIS and MOLINO II. This an extra benefit induced by tolls, since more compact cities are more efficient cities from the point of view of transportation cost (envisaged in this model) but also more efficient in terms of construction costs, heating, and the like (not considered here). The effects on urban density are only considered in this model, not in the two other models.

A simulation output of the base case and several toll scenarios (cordon toll, linear toll and first-best toll) is presented in Table 12. All implementation and transaction costs of tolling are neglected in the presented results. In these scenarios 'No toll' represents the base scenario where no toll has been used, a toll of €22.5 has been charged at a circular distance of 22km from city centre for 'Cordon toll' scenario, and 'linear toll' requires that each household pays €210/km of daily trips per year. Congestion charging plays an effective role in improving the overall condition of the area in terms of travel time. Whenever a toll is charged, people will prefer to live closer to city centre to minimize overall travel costs. The linear toll decreases city radius by 36.5% compared to no toll situation, whereas cordon toll showed 24.2% decrease in city radius. Reduction in travel radius will also reduce the trip length. Trip distance decreased by 15.2% and 11.1% respectively for linear toll and cordon toll situation. The result suggests that linear toll is a better alternative than cordon toll although cordon toll is much easier to implement than other forms of tolls. The last column in this table indicates the impact of road pricing in terms of user surplus. The positive value of the surplus means that the households, who are assumed to share in the revenues of the toll, will benefit from the toll. The model finds that in the long term, with endogenous location, a linear pricing scheme (proportional to distance from CBD) produces 95% of the First Best results. A cordon toll is clearly less efficient as it produces only 63% of the First Best benefits.

Table 12: Simulation output of different toll scenario

	City radius (km)	Housing area (m^2)	Trip length (km)	Travel time (mins)	Change in surplus (€/yr/household)
No toll	73.423	84.236	22.075	37.7	0
Cordon toll	55.633	84.889	19.632	33.9	181
Linear toll	46.246	81.385	18.727	32.7	271
First-best	48.650	83.129	18.711	32.7	286

De Lara et al. (2013) also envisaged an extension of the monocentric model, where they consider two business centers. In this case, there is a specific hinterland of each city, as well as a region common to the two business center. Such an extension is needed to better capture the polycentric nature of the greater Paris.

6.1.2 Short term effect of road pricing (MOLINOII and METROPOLIS)

MOLINO II is a research software that has been used to evaluate the effects of a pricing or investment policy for Ile-de-France network. The model represents the Paris transport problem as a simplified network, exploiting the concentric symmetry in Paris. Four types of households (poor/rich and working/not working) live either in the center of Paris (Paris or P), the inner ring ("Petite Couronne" or "PC") or the outer ring ("Grande Couronne" or "GC"). Each household makes trips either inside the region they live or to other regions. To make these trips they combine different modes (car, bus, metro, RER) in function of the generalized cost of this mode or combination of modes. The generalized cost includes all monetary costs (vehicle, parking), in vehicle time costs. For public transport one adds the waiting costs, access costs and crowding costs. When several modes are combined one adds transfer costs. Production prices are taken as constant. The model is calibrated to the 2007 equilibrium (Moez, Proost, Van der Loo, 2013).

We consider a general capacity upgrade of public transport by 10% and combine this with a zonal toll and different public transport pricing scenarios. In total we consider 9 variants of zonal toll, pricing of public transport and investment in public transport. We analyze different versions of road toll systems for a toll of 1 €. This will allow us to select the best type of tolling system.

We consider two dimensions of alternative tolling systems: there is the choice between zonal toll and cordon toll and there is the choice of the area that is tolled. We consider five alternative toll systems for a toll of 1 €: (i) zonal charge within Paris (Z_P), (ii) within Petite Couronne (Z_PC) and (iii) within Grande Couronne (Z_GC), (iv) cordon charge around Paris (C_P) and (v) petite Couronnne (C_PC). By assumption we neglect transaction and implementation costs and assume all users of the transport system share equally in the toll revenues. The welfare changes are reported in Table 13.

Table 13: welfare changes (€/individual/year) for different 1 € toll systems

Pricing scenario	ΔW: poor	ΔW: rich	ΔW: average
Z_P	8.54	12.53	11.51
Z_PC	68.89	84.49	80.52
Z_GC	120.37	131.11	128.38
C_P	3.67	4.15	4.03
C_PC	-3.30	-15.37	-12.30

The average effect is a weighted average as 75% of the transport users are considered as rich and 25% are considered as poor. In almost all 5 road pricing schemes considered, users will see their welfare increase. There is one exception: the cordon toll around the PC does not generate a welfare gain. Overall, the zonal peak toll performs better than the cordon tolls. The main reason is that the cordon toll, whenever the cordon toll encompasses a larger area, leaves all car trips with OD within the zone unaffected. These types of trips will compensate the reduction of trips passing through the cordon. The zonal toll systems also produce much larger toll revenues because all trips are tolled. The largest welfare gain is obtained for the most extensive zonal system (around the Grande Couronne). Of course the larger zonal toll system will also be more costly to implement and monitor and this type of costs is not integrated in our analysis.

The overall impacts (aggregating both groups) are given in Figure 14. This graph gives an idea of the magnitude of the effects of all the different 1 € charging pricing schemes. We see that the effects of the zonal charges are much larger than those of the cordon charges.[16] The zone where the charge applies should be made as large as possible. Of course this neglects the larger implementation costs. For this reason we select the zonal toll around the PC for deeper analysis.

[16] As we noticed above, the cordon toll concerns only a minor part of the traffic when compared with the zone toll.

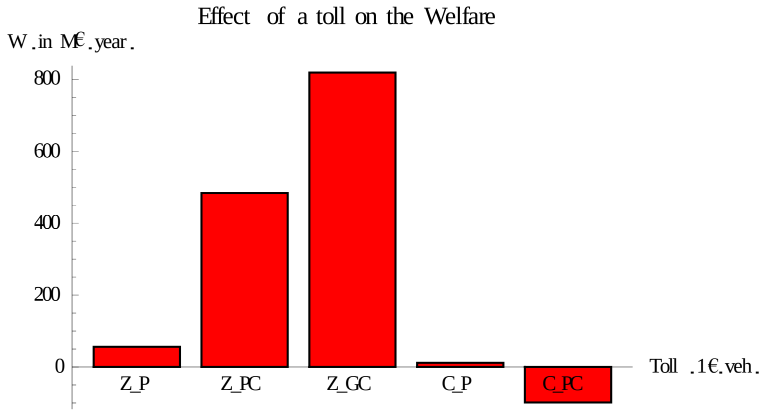


Figure 14: effects of a pricing scenario. Legend: Z_P = Zonal within Paris, Z_PC = zonal within petite couronne, Z_GC = zonal within grande couronne, C_P = cordon around Paris, C_PC = cordon charge around petite couronne.

METROPOLIS

METROPOLIS modelling features are described in details in Section 4 and, therefore, are not repeated again. METROPOLIS being a fully disaggregate model, can predict different aspects of the impact of road pricing. In this report we included the result of cordon pricing around Petit Couronne (PC) for €1 to € 22.5 with regular interval to find an optimum toll level where user benefit is maximum. The results for €1 and €22.5 cordon toll are given in Table 14.

Table 14: Aggregate result for cordon toll around inner ring

	Base scenario	**Toll = €1**	**Difference from Base**	**Toll = €22.5**	**Difference from Base**
PT share	47.83%	47.86%	0.02%	50.47%	2.6%
Travel time (min)	19.03	18.84	-1.0%	17.41	-8.5%
Travel cost (€)	10.00	10.00	0.0%	9.62	-3.9%
Schedule delay cost (€)	3.34	3.30	-0.9%	3.27	-2.0%
Toll revenues*** (€)	0	55 795	-	141 899	-
Consumer surplus (€)	-9.285	-9.293	-0.008	-9.490	-0.204
Net surplus** (€)	-9.285	-9.202	0.084	-9.244	0.041
Equity (€)	5.94	5.97	0.4%	6.48	9.1%
Early ratio (%)	53.80	53.46	-0.6%	53.53	-0.5%
On-time ratio (%)	20.50	20.72	1.0%	20.87	1.8%
Late ratio (%)	25.70	25.82	0.5%	25.60	-0.4%
Congestion (%)	51.14	50.21	-1.8%	45.04	-11.9%
Mileage (10^6 veh-km)	8.47	8.42	-0.6%	7.63	-9.9%
Speed (km/hr)	46.82	47.07	0.5%	48.56	3.7%

** Net Surplus = Consumer Surplus + Toll revenue/Number of car trips.
*** Toll revenue is obtained for number of car trips used in the simulation which is 10% of the original demand

It is observed from Table 14 that congestion charging has improved the overall network performance. With a toll of €22.5 all network performance indicators except user surplus showed better results than the unit toll. For all toll situations we observe a reduction in consumer surplus from no toll scenario. However, when the toll amount is redistributed, the net surplus increases i.e. individual starts to gain from tolling. The net surplus is higher for a small toll of 1 € than for a toll of €22.5 toll. Similar results for in-between toll values are not presented here. However, a summary table showing revenue collection, user benefit, environmental cost reduction and welfare gains is presented in Table 15, and the distribution of welfare gain for different toll amount is presented in Figure 15.

Table 15: Summary statistics for different level of congestion charging around inner ring

Toll description	User benefit[a] (€/individual/yr)	External cost reduction[b] (€/individual/yr)	Welfare gain[c] (€/individual/yr)
Toll = €1	50.10	11.55	61.65
Toll = €4	119.47	38.66	158.14
Toll = €8	143.67	55.48	199.15
Toll = €12	118.32	77.88	196.20
Toll = €16	81.71	86.26	167.97
Toll = €20	59.58	68.42	148.00
Toll = €22.5	24.66	92.69	117.35

[a] User benefit is yearly increase in net surplus from base situation for each user (considering 100% redistribution of the toll revenue).
[b] External cost reduction is calculated as the average reduction in external costs (noise, accidents, pollution, emissions and social cost of public funds) for car users.
[c] Welfare gain is the sum of user benefit and external cost reduction.

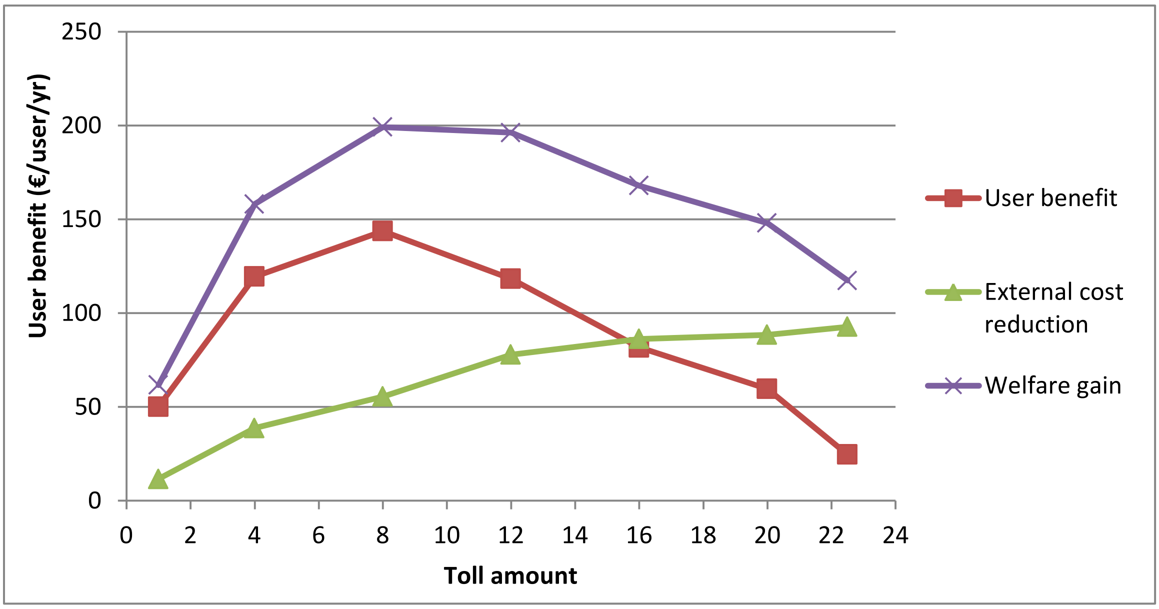


Figure 15: Distribution of user benefits

The figure shows us that increasing the toll amount will not always increase welfare gain. For cordon toll around PC, an optimal toll value could be in the range of €8 to €10.

METROPOLIS also compares the net gains per individual for a cordon toll for different locations. Overall we find that the gains are larger for those living in the central zone (within the cordon) than for those outside the cordon. The reason is that a smaller proportion of trips inside the cordon area pay the cordon toll but they share fully in the redistribution of toll revenues. In the monocentric model, there is perfect equalization of utility over location so all individuals are affected in the same way.

6.2 Impact of increased demand

In an ongoing research project we have increased the demand for working from home and observed its effect on the overall transport network. We have used METROPOLIS for this analysis. Please note that, percentage of people working is about 42% of the total travel in the morning simulation period (6AM to 10AM). We have increased the percentage of people working from home by 25%, 50% and 75%. The results are presented in Table 16.

Table 16: Simulation comparision for different tele-working demand

		Base	Scenario 1	Scenario 2	Scenario 3
		0% teleworking	25% teleworking	50% teleworking	75% teleworking
No of users		5027590	4428120	3879310	3324400
Travel time	min	17.40	15.01	13.64	12.88
Travel cost	€	5.97	5.23	4.87	4.70
Schedule delay cost	€	2.21	1.99	1.92	1.92
Consumer surplus	€	-11.48	-10.49	-10.00	-9.80
Equity	€	4.03	3.12	2.68	2.47
Early ratio	%	57.51	54.54	53.21	53.20
On-time ratio	%	19.03	20.77	21.00	20.53
Late ratio	%	23.46	24.69	25.79	26.27
Congestion	%	40.21	24.55	13.86	7.12
Speed	km/h	51.20	58.44	64.82	69.74

The result shows that increasing tele-working demand has dramatic effect on the level of congestion. If the demand increased by 75%, the level of congestion is expected to decrease by 82% from the base situation with no tele-working. Similarly the travel time can be decreased to a maximum of 26% and speed can increase to a maximum of 36%. All the other parameters also expected to improve with the level of increase in tele-working demand.

If we draw the demand vs Cost curve with the data given in Table 16, we will have a cost curve as a function of demand *C(N)*, and a marginal cost curve MC(N) as shown in Figure 16. It is a dynamic version of Figure 1. The curve $C(N)$ is an average cost curve expressing the cost that each traveler incurs. The curve $MC(N)$ is a marginal cost curve, expressing the marginal change in total cost following a marginal increase in the number of travelers; in other words: $MC(N) = C(N) + N \cdot C'(N)$.

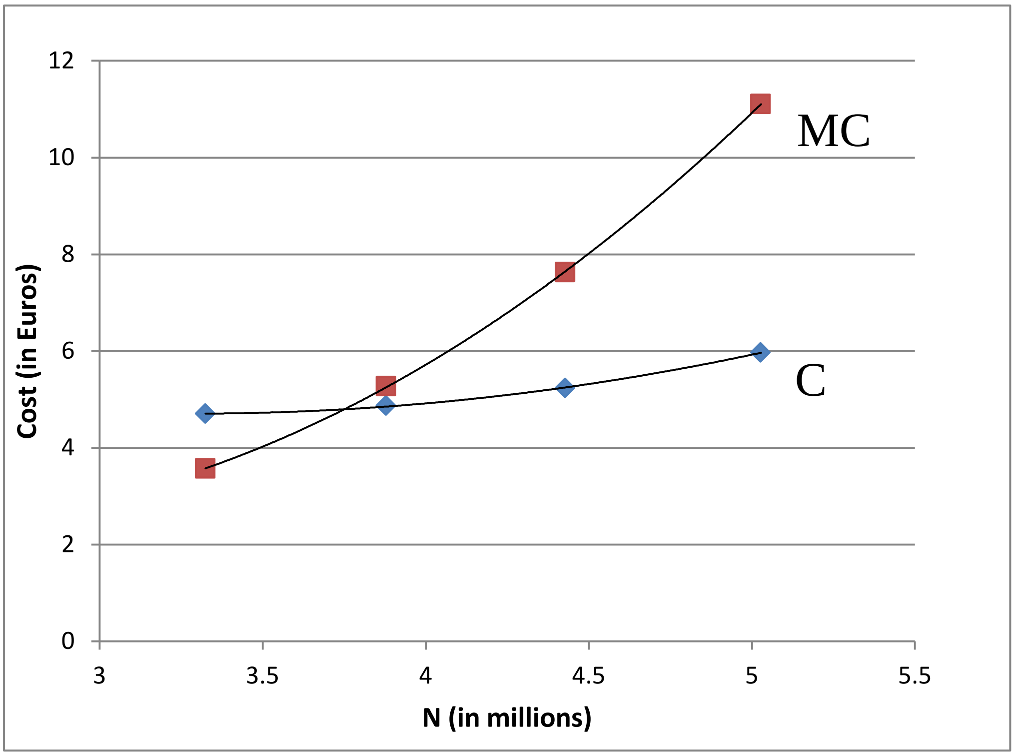


Figure 16: Demand vs Cost curve for a dynamic model

The equation of the polynomial fit are:

$$C(N) = 4\times10^{-13}N^2 - 3\times10^{-6}N + 9.1778$$
$$MC(N) = 1\times10^{-12}N^2 - 6\times10^{-6}N + 9.1778 \, .$$

From the theory we know that, the cost of travel can be expressed as

$$\text{Cost} = \alpha tt_o + \frac{\beta\gamma}{\beta+\gamma}\frac{N}{s} \equiv \alpha tt_o + \delta\frac{N}{s} \qquad (13)$$

Where, s is the total capacity of the network and tt_0 is the free flow travel time, i.e. travel time at no congestion. From linear regression using the data of Table 16, we get a relation between traffic flow and cost as described in the following equation:

$$C(N) = 7.4096\times10^{-6}N + 2.1065 \qquad (14)$$

From equation 12 and 13 we may say that $\alpha \cdot tt_0 \equiv 2.1065$. The value of time $\alpha = 12.96$ €/hr. Therefore, free flow travel time becomes $tt_0 = 9.8$ min. From a free flow simulation, we get free flow travel time as 11.8 min, which is very close to the regression analysis result.

6.3 Grand-Paris

Grand Paris is a major public transportation and urban development project in Paris area. About 160 km automatic subway will be added to the existing subway network in majority around the Paris city and in near suburbs. 75 new subway stations will be constructed. In comparison with currently active 220 km subway lines and 303 stations, the project is a considerable evolution in the public transportation system of the area. The total project's investment is estimated at about 30 billion Euros over more than 20 years (up to 2035). Principal characteristics of lines are presented in Table 17.

Table 17: Principal characteristics of the Grand Paris subway lines.

Line	Time headway at peak hour	Capacity	Commercial speed
Blue	85 s	38 000	45 km/hr
Red	120 s	32 000	60 km/hr
Green	150 s	6 000	65 km/hr

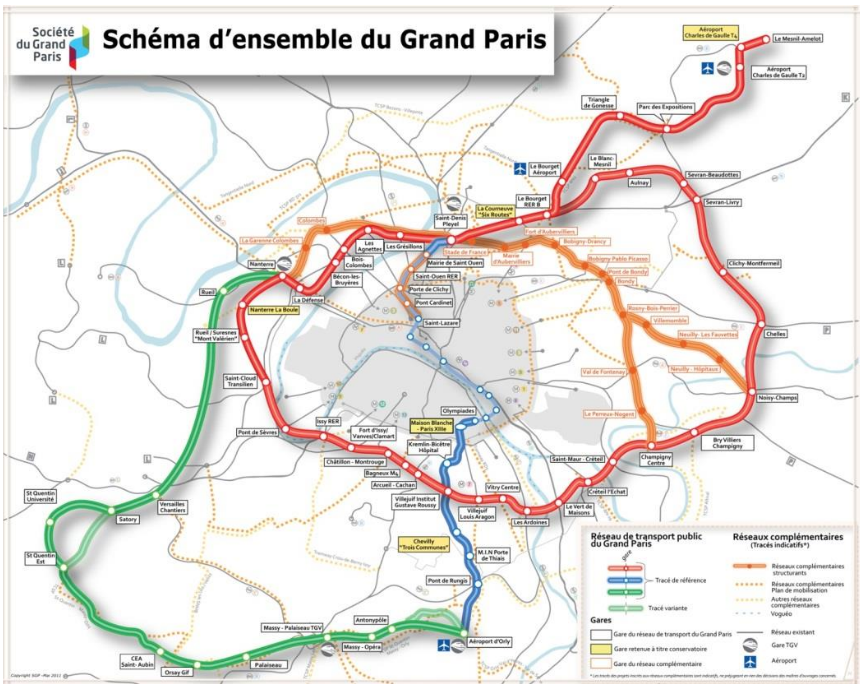


Figure 17: Grand Paris subway lines

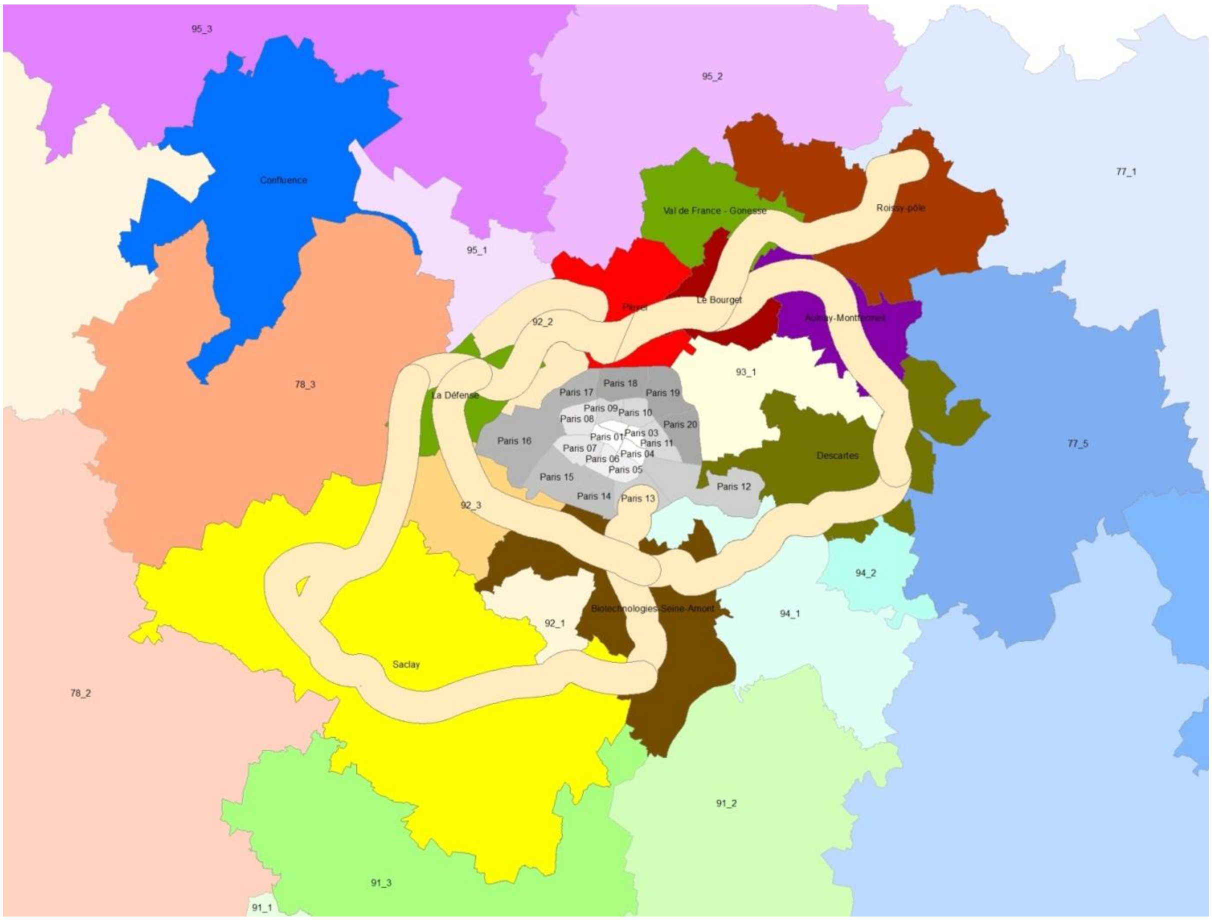


Figure 18: Grand Paris subway lines and urban policy zones arround Paris city (Pris: Gray zone)

The project is aimed to create a new regional dynamic and boost the Paris competitiveness and attractiveness with respect to important European and World metropolis like London and New York as well as Singapore or Shanghai. To achieve that objective the transportation infrastructure investment will be accompanied with relevant urban policies to assure the necessary urban evolution to offer relevant housing and activity floor space over the region. The region wide attractiveness gain is transformed to the increase of number of jobs and consequently of the population. Two limit scenarios are considered for this gain with minimum 1 million and maximum 1.2 million additional jobs over a 30 years period. The business as usual scenario estimates the additional jobs at about 800 000. For population the growth is estimated between 1.7 and 1.8 million in comparison to 1.6 million in BAU scenario. The urban policies are concentrated in about 10 poles around Paris where national and local authorities define common policies in a contractual framework named Territorial Development Contracts.

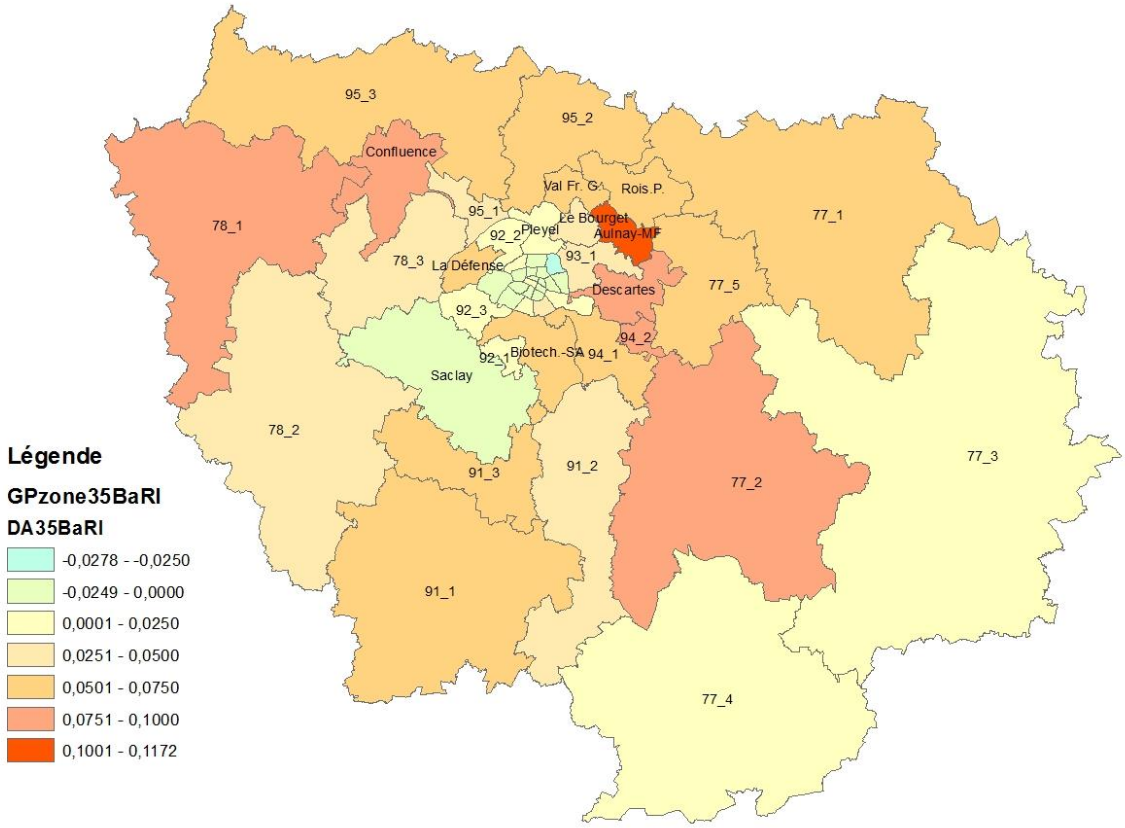


Figure 19: Difference of aggregate accessibility (users surplus) of great zones between low impact and BAU scenarios

Integrated transportation – Land Use simulations are conducted to evaluate the socio-economic effects of the project over the region. Two groups of simulations have been done:

1. Static traffic assignment with MODUS. Besides, in that set of simulations the demand is actuated in an off line manner. The simulation is done base on population and employment data that are not provided by land use model and that for the years 2009, 2025 and 2035.
2. Dynamic traffic assignment with METROPOLIS. The population and employment data have been updated each 3 years.

MODUS is actually the reference travel demand model of the region. In computation of O-D matrices for METROPOLIS, we have followed the same methodology as MODUS to keep the compatibility of results. The first sets of results are close enough as shown in Table 18.

Table 18: Results of integrated simulations, comparison of the number of additional jobs over period 2005 - 2035 in different scenarios.

Grand Paris Zone	**Ref**	**Low**	**High**	**Ref**	**Low**	**High**
	MODUS			METROPOLIS		
Aulnay-Montfermeil	2 390	19 650	22 052	2 381	19 021	21 260
Biotechnologies Sei.	77 924	93 887	135 201	75 856	90 885	128 976
Confluence	28 856	27 629	29 517	28 296	27 116	28 931
Descartes	40 688	72 798	83 037	39 719	69 696	79 001
La Défense	99 167	152 368	159 963	96 097	139 625	143 918
Le Bourget	15 644	46 839	54 501	15 092	42 416	49 640
Pleyel	58 299	90 651	99 985	55 980	85 043	93 163
Roissy-pôle	29 639	89 876	140 951	29 014	84 130	126 819
Saclay	35 521	125 465	150 095	35 187	121 294	144 125
Val de France – Gon.	6 041	7 186	18 009	5 963	7 075	17 315
Paris	112 918	91 083	94 982	112 138	90 575	94 430
CDT	394 169	726 349	893 311	383 584	686 302	833 149

In an ongoing research we are combining the travel model (METROPOLIS) and the urban model (UrbanSimE) together to get better prediction about the urban sprawl. METROPOLIS being dynamic in nature is expected to provide better accessibility data than other available static models. Accessibility being a key factor for the urban model, better accessibility data will certainly improve the prediction capability of the urban model. A combine simulation will be more interesting to study because at the moment the demand is fixed for the transport model which is not true in reality. It will not be the case for the combine simulation where the demand for travel will be predicted by the urban model and the accessibility of an area will be predicted by the transport model along with many other important results.

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