On the Marginal Cost of Road Congestion: an Evaluation Method with Application to the Paris Region

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SUMMARY ABSTRACT

The paper analyzes the sensitivity of the marginal congestion cost on a roadway network to the level of aggregation in space, from utmost disaggregate to utmost aggregate. Simulation and aggregation are based on a static network assignment model.

Keywords

Marginal cost. Road congestion. Cost aggregation. Congestion indicator. Assignment model.

1. INTRODUCTION

When using a private motorcar, the driver has vehicle ownership and use expenses, he/she also uses time and is subject to tiredness and discomfort. These represent the 'private costs', those incurred by the user. Similarly, a transport company or a public transport passenger is also subject to the same costs. A variable part of these costs is related to the road being occupied by other vehicles that impede users, delay them and increase their discomfort: this is the phenomenon of congestion where the number of users degrades the service's quality. Congestion also has environmental effects: the reduced speeds in urban areas increase energy consumption, greenhouse gas emissions and emissions of most pollutants. The types of congestion, their associated costs and their quantitative significance on different mainly urban networks have been the subject of many studies: a summary and further details are provided in the Cemt-OECD report (2007).

In economic theory, congestion is an external effect of which it is appropriate, based on the principle of 'polluter pays' , to internalise the external cost by making the user who creates the problem pay the corresponding marginal social cost in order to obtain a financial resource that is intended to compensate the 'damage' experienced by other users (Pigou, 1920). The marginal cost of congestion is the monetary value of the time lost by other users. This marginal cost is not just a charge that is imposed but is also, for the network management, a signal of the need to reduce traffic intensity by relieving a given road or by increasing its capacity. This signal is a valuable indicator for decision-making especially in the socio-economic evaluation of transport investment projects (Piarc, 2007). The marginal costs of road congestion in urban areas in France has been used to evaluate the benefit of a public transport projects for road users by multiplying the resulting reduction in road traffic in the modal report by a congestion coefficient estimated at 7.5 minutes /uvp.km (Hautreux et al, 1969 ; Boiteux et al, 1994). The French Department of Transport commissioned us to update the coefficient's values and to evaluate spatial and time variations in the marginal costs on the greater Paris road network (Leurent et al, 2009).

In this paper, we consider the marginal congestion costs as a signal to be used as a decision-making aid when planning a road network. Our aim is to establish indicators of marginal

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congestion costs at several levels of aggregation and several spatial scales: from the local level of a specific road to the level of the overall network via sub-networks and by road type and/or geographic sector. We provide a method for aggregating local marginal costs and demonstrate how to use the indicators by applying them to the Paris road network.

To evaluate local marginal costs, we use a model that assigns traffic to the road network in order to simulate traffic for each part of the network and deduce the marginal cost.

This article's body is split into six sections. Section 2 provides the aggregation concepts and method. The following sections show it being applied to the Paris road network: a description of the network (section 3) is followed by mapping of local marginal costs for a given period (section 4), aggregation by road type and geographic sector (section 5) and mapping zone related indicators to detect zones that are the biggest contributors to congestion (section 6). We conclude by discussing the scope and limitations of the indicators (section 7).

2. CONCEPTS AND METHODS

2.1 Defining marginal congestion costs

Let us consider a road a with length L_a and a traffic volume of x_a vehicles during a given period of time H. Each additional vehicle on this section of the network induces an additional distance covered of L_a and wasted time for every other user. Let $T_a = \mathrm{t}_a(x_a)$ be the road travel time for a user as a function of the level of volume, x_a. Each additional vehicle results in wasted time for every other user of $\delta T_a = \mathrm{t}_a(x_a+1) - \mathrm{t}_a(x_a)$.

The time wasted for the total local traffic flow is the total of the individual delays and is equal to

$$\begin{aligned}\Delta T_a &= x_a.\delta T_a = x_a.[\mathrm{t}_a(x_a+1) - \mathrm{t}_a(x_a)] \\ &= x_a.\frac{\mathrm{dt}_a}{\mathrm{d}x_a}\end{aligned}$$

When expressed in relation to the distance covered, which is L_a, the marginal cost for an additional traffic unit is

$$c_a = \frac{\Delta T_a}{L_a} = x_a.\frac{\mathrm{dt}_{a1}}{\mathrm{d}x_a},$$

with $\mathrm{t}_{a1}(x_a) = \mathrm{t}_a(x_a)/L_a$ being the time-volume function per unit distance.

This is a physical indicator, expressed as time, for the marginal cost. We can easily deduce a financial indicator in monetary terms from this by multiplying it by a unit value for the time spent travelling.

2.2 Example of a BPR type time-volume function

The BPR (1964) time-volume function is as follows, where t_{a0} is the free flow travel time per unit of distance, κ_a is the road's capacity (the maximum volume per time period), β_a and γ_a are congestion sensitivity parameters:

$$\mathrm{t}_a(x_a) = L_a t_{a0}[1 + \gamma_a (\tfrac{x_a}{\kappa_a})^{\beta_a}]$$

This provides a marginal cost per unit of traffic of:

$$c_a = \frac{t_{a0}\gamma_a\beta_a}{\kappa_a}(\tfrac{x_a}{\kappa_a})^{\beta_a - 1}.$$

For a 'possible' situation such as $x_a \le \kappa_a$, the marginal cost is regulated by $\hat{c}_a = t_{a0}\gamma_a\beta_a / \kappa_a$; this means that the greater the capacity, the smaller the marginal cost.

2.3 Time and space variations

The above formulae provide the marginal costs based on the characteristics of a part of the network and the traffic volume during a given period. For the same road, the ratio of marginal costs between the busiest period with $x/\kappa = 1$ and the quietest period with $x/\kappa = 0.5$, using a typical value of $\beta = 6$, is $2^5 = 32$, which demonstrates the need to identify these types of periods and treat them without aggregation.

Two roads with the same time-volume function but where one is in the centre of the network and the other is at the periphery will have respective loads that are significantly different for a given time period and the marginal costs will be even more so: spatial differences have to be dealt with individually by identifying the road types (with distinct time-flow rate functions) and the network's geographical sectors.

2.4 Aggregation by sub-network

To link marginal costs to a sub-network, the concept of marginal user has to be defined. This is not an additional unit on a given part of the network but a traffic unit, usually 1 uvp.km. For a sub-network consisting of a sub-unit z of arcs a, each arc counts for $L_a x_a$ in the statistical population of traffic units with 'marginal potential' in terms of causing congestion; in terms of the effects of congestion, the unit marginal cost for the arc a is given by $c_a = \frac{x_a}{L_a}\frac{\mathrm{d}t_a}{\mathrm{d}x_a}$.

The size of the population causing congestion is

$$\mathbf{xL}_z = \sum_{a \in z} L_a x_a .$$

The average marginal cost is

$$\bar{c}_z = \sum_{a \in z} \frac{L_a}{\mathbf{xL}_z} x_a \frac{x_a}{L_a}\frac{\mathrm{d}t_a}{\mathrm{d}x_a} = \frac{1}{\mathbf{xL}_z}\sum_{a \in z} x_a^2 \frac{\mathrm{d}t_a}{\mathrm{d}x_a}$$

This formula demonstrates that a simple aggregation that uses all the arcs as a statistical population and provides $\mathrm{E}_z[c_a] = \frac{1}{|z|}\sum_{a \in z} x_a \frac{\mathrm{d}t_a}{\mathrm{d}x_a}$ is incorrect.

We get a similar variation in the distribution of units with marginal potential,

$$\mathrm{E}[\chi^2] = \frac{1}{\mathbf{xL}_z}\sum_{a \in z} L_a x_a (\frac{x_a}{L_a}\frac{\mathrm{d}t_a}{\mathrm{d}x_a})^2 = \frac{1}{\mathbf{xL}_z}\sum_{a \in z} \frac{x_a^3}{L_a}(\frac{\mathrm{d}t_a}{\mathrm{d}x_a})^2 .$$

2.5 Aggregation by trip end zone

When applying this to the Paris network during the peak evening period on a working day, we observed that the local indicators had very large spatial variations, in a range of 1 to 100. Equally, aggregated indicators by sub-network varied within a range of 1 to 10. These extremely large variations do not facilitate territorial analysis of congestion.

This is why we have specified indicators by zone, attaching the journeys that originate (irrespective of their destination) in each zone during the period being analysed to the zone and retracing the travel costs experienced or caused, respectively, on the network. Using q_{od} for the volume going from zone o to zone d, G_{od} as the overall cost per journey, D_{od} as the distance from origin to destination on the network and E_{od} as the external cost per journey between origin and destination, the principle zone related indicators are:

- $I_o^G = \frac{\sum_d q_{od} G_{od}}{\sum_d q_{od}}$ the average overall cost,
- $I_o^{G/D} = \frac{\sum_d q_{od} G_{od}}{\sum_d q_{od} D_{od}}$ the overall average cost per distance unit,
- $I_o^E = \frac{\sum_d q_{od} E_{od}}{\sum_d q_{od}}$ the average marginal cost,
- $I_o^{E/D} = \frac{\sum_d q_{od} E_{od}}{\sum_d q_{od} D_{od}}$ the average marginal cost per distance unit,

with $E_{od} = \frac{1}{q_{od}} \sum_r x_r E_r$, x_r being the volume assigned to the route r from o to d, and $E_r = \sum_{a \in r} x_a \frac{dt_a}{dx_a}$ the total external cost of congestion throughout the length of the route.

3. THE PARIS ROAD NETWORK AND THE ASSOCIATED MODEL

3.1 Greater Paris

Greater Paris had a population of 11 million people in 2007 and covered about 1,200 km². Every working day, the population makes 37 million journeys, 44% of them in private cars, covering a distance of 120 million veh.km. There is significant road congestion with periods of saturation that last up to 14 hours per day on the inner multi-lane ring road (the ' Boulevard Périphérique de Paris').

3.2 The time-volume functions

Traffic observations were conducted in 1997 using a sample of roads in the Paris region which included motorways, urban clearways and urban arteries with various capacities.

Sixteen sights were chosen using the ‘selection criteria of geographic location, road type and location of measurement stations'. Specifically, the following road types were surveyed: (1) an urban clearway - A13 to the right of Saint-Cloud; (2) a high capacity artery: dual carriageway with no traffic lights - RN7 to the right of Orly; (3) an artery: dual carriageway with traffic lights and reduced capacity - RN7 to the right of Villejuif. For each site, road traffic was measured by a double electromagnetic loop which recorded the number of vehicles classified by length and the average speed per length class. A 30-day data set was used from each sensor, any obvious errors were removed and it was limited to non-saturated traffic conditions. This data was subjected to statistical analysis of the time-volume function, deducing time from the speeds and volumes from vehicle numbers per 6-minute period.

Table1 shows the estimation obtained by Cohen et al (2001) for the parameters of a BPR type time-volume function and also for a Davidson type function provided by the formula $t_{a1}(x) = t_{a0}[b - a\frac{x}{\kappa}]/[b - \frac{x}{\kappa}]$.

Tab. 1. Adjustment to the time-volume function in the Paris region

Function	Road type	Urban clearway	Artery without traffic lights	Artery with traffic lights
Time-volume	Site	A13 St Cloud	RN7 Orly	RN7 Villejuif
Free-flow unit time	t_{a0} (min/km)	0.51	0.82	1.1
Capacity	κ (pcu/h)	6,600	4,000	4,000
BPR	γ	0.37	0.51	1.00
	β	7.15	3.54	4.00
DAVIDSON	b	1.09	1.28	1.33
	a	0.97	0.81	0.66

Source: Cohen et al (2001).

3.3 Modelling the road network

The French Transport Minister has developed a traffic model to help plan the transport network in the Ile de France region that includes greater Paris: this model is called MODUS and is a model that creates journeys in five stages: trip generation, spatial distribution, temporal distribution, modal choice and assignment to a network for the chosen method (Dreif, 2006).

The road network traffic assignment model is a static model using two periods: the peak evening travel period on a working day and a time between peak hours. The road network is represented by 15,000 nodes and 40,000 arcs with Davidson type time-volume functions. For travel demand, the survey field is split into 1,300 traffic assignment zones; the origin-destination matrix for the evening peak period (average time from 16:30 to 19:00) contains 1,300,000 trips per hour.

In our digital applications, we used TRANSCAD software to simulate road traffic by converting the Davidson functions from the DAVISUM software used by the Transport Minister in the MODUS model into BPR functions. We estimated BPR type time-volume functions using the exponent β with an order of 6 and a factor γ with a value range of 0.1 to 1.0 from the most urban roads to the roads of highest capacity.

4. LOCAL CONGESTION COSTS

The marginal costs per unit distance on the Paris road network during the peak evening travel period are very variable. Figure 1 shows the value ranges as different colours and the thickness of each arc represents vehicle volumes (which provides an approximate indication of the road's capacity and type).

A large proportion of green arcs can be seen where the marginal costs are very low, less than 0.1 minute/veh.km. The value of 7.5 minutes/veh.km, which has been the norm in France since 1970, has been exceeded by the majority of the arterial arcs within the city of Paris and the immediate suburbs where these arcs have a lower capacity than the urban clearways and other major boulevards.

The marginal costs for roads with high capacity are low in the periphery and moderate in the centre. The highest marginal costs occur with popular roads with average capacities

In the period between peak travel (figure 2), marginal costs are low or very low.

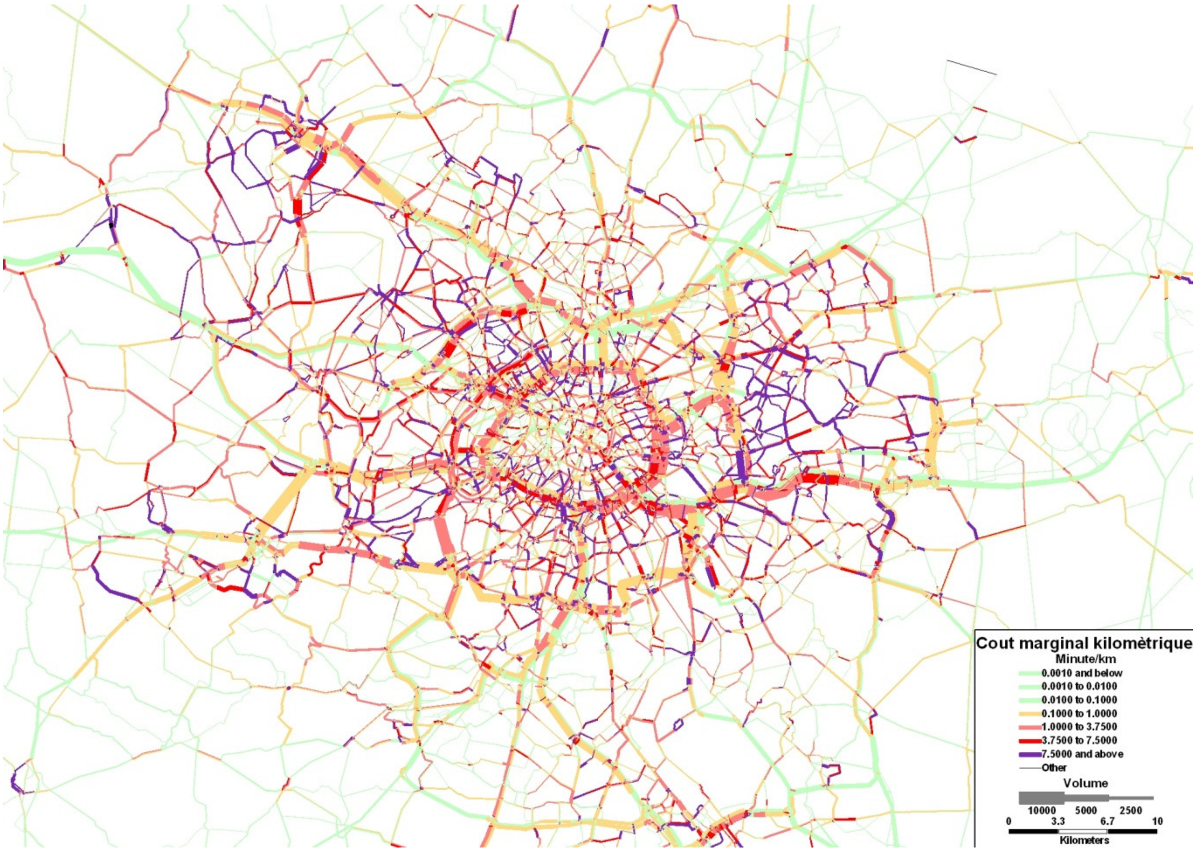

Fig. 1. Social marginal costs in the peak evening period, 2002

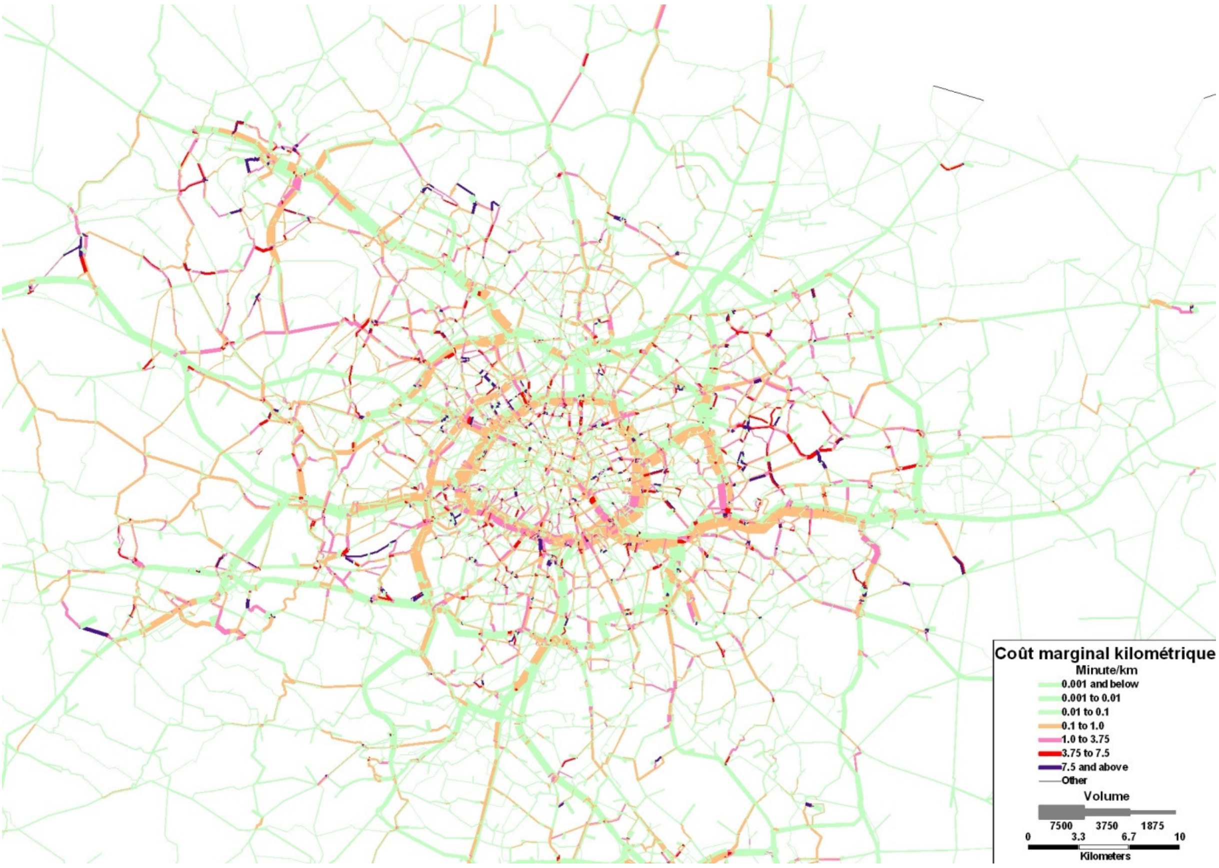

Fig. 2. Social marginal costs in the between-peak period, 2002.

5. AGGREGATION BY SUB-NETWORK

5.1 Network segmentation

We have divided the road network into several sub-networks by crossing two criteria. Firstly; by road type based on its physical configuration, how it is used and interaction between the main flow and all other factors. Secondly, by geographic sector, especially the degree of urbanisation.

We have identified three road types:

1. motorway roads with access limited to motor cars, including highways and urban clearways.
2. major arteries with uncontrolled access but high capacity (around 2,000 vehicles/h in each direction).
3. smaller arteries with uncontrolled access and reduced capacity (around 1,000 vehicles /h in each direction).

We have identified four geographic sectors:

1. the central zone of the city of Paris ('Paris intra-muros') with high density,
2. the close suburbs ('petite couronne'), the periphery near the centre that is still dense,
3. the far suburb s ('grande couronne'), the more distant periphery with reduced density,
4. the roads farthest from the centre in the suburbs.

5.2 'Crude' aggregated marginal costs

Table 2 shows the average marginal costs by sub-network and by period: bold for the peak evening period and italics for the period between peak periods. We note that the marginal costs decrease by road type the further they are from the centre. The marginal costs between road types are generally lower for larger roads. This is because the larger roads have been designed to easily handle high traffic volumes.

We also measured marginal cost variances for sub-networks: the relative dispersions vary by 1 - 2 for roads with limited access and from 10 - 25 for smaller arteries, which is very high. For the whole network, the relative dispersion is 26 which retrospectively justifies breaking it down into sub-networks.

Tab. 2. Average marginal cost per sub-network: peak / *between peak* **period (min/km).**

Road type Geographic sector	Limited access motorway	High capacity popular artery	Smaller popular artery	Consolidated total
Paris	**2.18** *0.,51*	**5.40** *0.93*	**47.7** *4.66*	**24.4** *2.33*
Close suburbs	**1.04** *0.13*	**4.42** *0.85*	**44.6** *4.39*	**19.3** *1.93*
Far suburbs	**0.27** *0.02*	**1.37** *0.21*	**26.5** *2.59* **8.97** *0.94*	**11.7** *1.18*
Consolidated total	**0.75** *0.13*	**2.68** *0.49*	**33.1** *3.24* **8.48** *0.92*	**14.4** *1.46*

5.3 'Net' aggregated marginal costs

The high values for smaller popular arteries differentiate them from other roads and lead us to question their veracity. Intuitively, we would expect smaller capacity roads to be more liable to congestion so the nature of the difference is not a surprise but its size is. In fact, these roads are of a type that has been less finely encoded in the MODUS assignment model, in the same way as a peripheral road that is far from the arterial network is less detailed in the model than one in the centre of Paris. The roads in the centre of communes and flows between demand zones are represented less finely, often aggregated with parallel adjacent roads and local traffic generators in order to simplify the description. Under these conditions, the encoded road parameters and assigned volumes are less representative of the field reality and there is a risk that this falsifies the marginal costs calculations. Not all are effected but it tends to produce artificially high values around over large centres that represent a moderately sized demand zone by a single entry point. These high values dominate the lower values in the average value formula (with weighting provided by x_a^2).

This is why we reprocessed all the data using the following conditions: capped load rates (ratio between volume and capacity based on an equilibrium assignment with no capacity limit) at 120% to evaluate the marginal cost and limited volumes on each road ([2]). The averages obtained are shown in table 3 for the peak evening travel period. The capping does not cause any changes in the period between peak periods.

We observed that imposing a ceiling by reducing values that are outside relevant levels does not significantly change the conclusions in respect of major roads, limited access roads or

[2] Based on an assignment with no explicit capacity constraint.

high capacity popular roads. This is probably because these roads are represented more finely in the model. However *for smaller popular roads*, whilst the results are the same during the period between peak travel periods, during *peak travel periods the values and greatly reduced*: they fall by 8 to 4 min/uvp.km depending on their distance from the centre.

These values are close to the values recommended by the European research group (IMPACT, 2008).

Tab. 3. Average modified external cost by segment during peak period.

Road type Geographic sector	Limited access road	High capacity popular artery	Smaller popular artery	Consolidated total
Paris	2.15	3.94	7.69	5.11
Close suburbs	1.01	4.39	9.35	5.05
Far suburbs	0.27	1.35	4.59 2.84	2.54
Consolidated total	0.74	2.57	6.29 3.07	3.35

In minutes/uvp.km.

6. AGGREGATION BY TRIP END ZONE

We calculated the indicators for the overall cost per unit per unit of distance (figure 3) and the marginal cost per unit of distance (figure 4) for the peak evening travel period. These maps show very clearly the zones that are subject (or emit, respectively) the greatest congestion effects per unit of traffic.

A geographical structure is clearly visible: the costs are higher in clearly identified parts of greater Paris to the west of the city of Paris, in the Hauts-de-Seine (92) and Yvelines (78) départements. The values remain low to the east of greater Paris. These maps also suggest that transport capacity should be developed in the western part of greater Paris or that more public transport should be developed to reduce car traffic.

Comparing the two maps demonstrates a certain relationship between congestion reception (figure 3) and emission (figure 4) but with high external costs that are significantly higher than the general costs by a factor of two or even three. This suggests that in the Ile de France, road traffic congestion is already partially internalised in terms of time within the traffic flows.

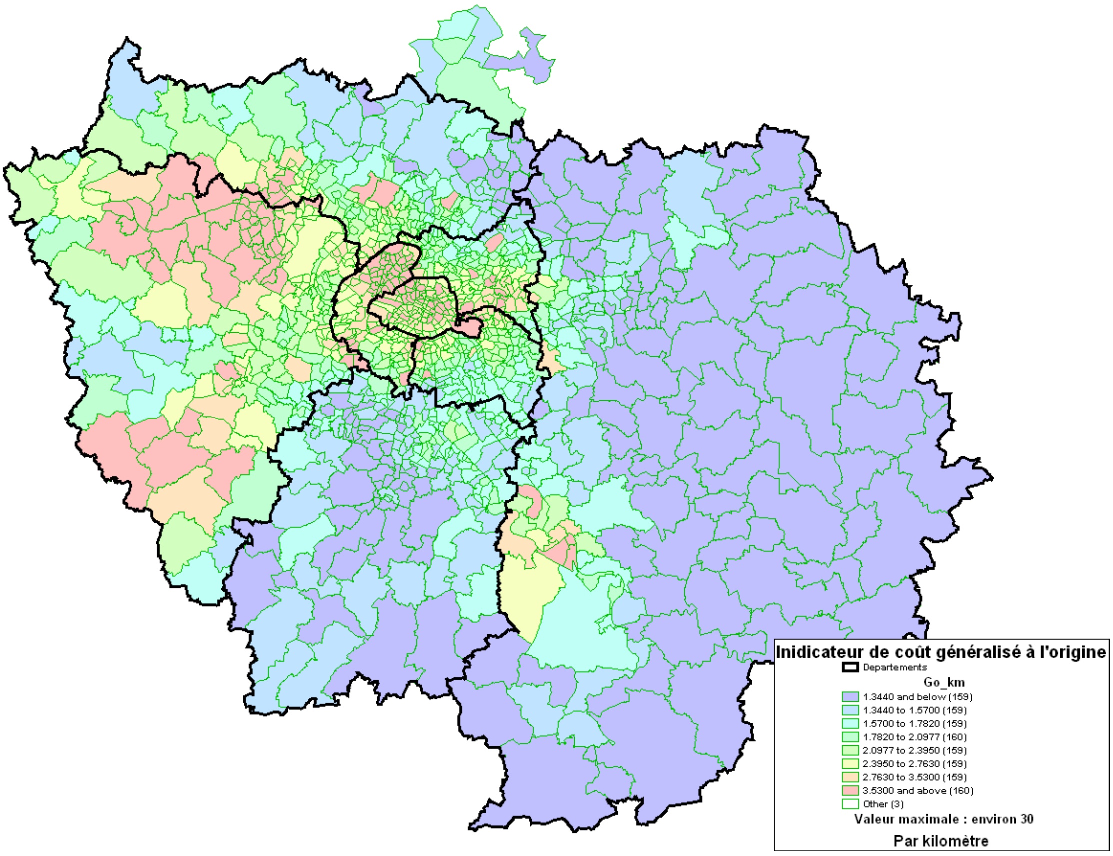

Fig. 3. Overall cost per unit of distance by departure zone in peak evening period, 2002.

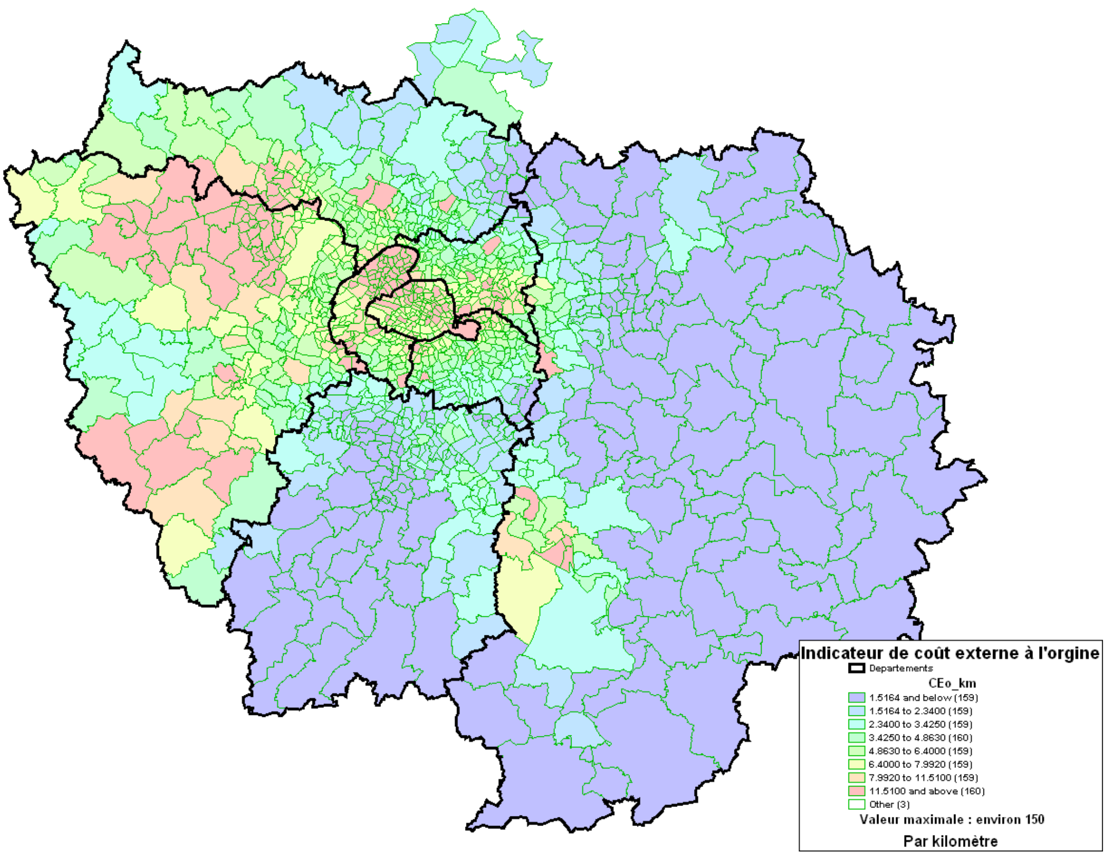

Fig. 4. External cost per unit of distance by departure zone in peak evening period, 2002.

7. CONCLUSION

We have specified the indicators for marginal congestion costs with several spatial scales: part of network, sub-network or origin-destination zone. These indicators are intended to help planning decisions for the road network by detecting and positioning the most acute needs.

In our use of it for the Paris road network, we observed that the indicators had a very high variability even within a same geographic sector or for two roads near to each other which were of the same road type. By differentiating sub-networks by road type and geographic sector, we obtained average marginal costs by sub-network that consistently showed: higher costs in denser zones, lower costs for high capacity roads. The indicators by origin zone allowed us to locate the origins with the most intense effects which will help design projects to reduce congestion.

Overall, the local and aggregated analyses have demonstrated the value of indicators at various scales for evaluating a large and complicated urban area and road network.

Our indicators are based on a *static* road network traffic assignment model at a given time period. In reality, traffic is dynamic in terms of journey numbers, traffic volumes and local circulation: we deal with the dynamic variations to marginal costs in other articles (Leurent, 2005 a-b ; Aguiléra and Leurent, 2009).

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