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**The Social Cost of Road Congestion in Ile-de-France Region (and France):  
Empirical Evidences from the Paris Ring-Road<sup>1</sup>**

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**Abstract:**

The aim of this article was to assess specific problems concerning traffic congestion access to the city of Paris. First, we attempted to evaluate the evolution of the congestion cost for the Paris Ring-Road (PRR), the major urban highway surrounding the French capital, during the period from 2000-2007. A speed-density methodology was implemented which enabled us to differentiate the external costs of road congestion between speed-classes of 5 km/h. These results were useful to subsequently propose the order of magnitude of time losses at national and regional scales, as well as marginal pricing schemes which could potentially be used in order to correct road congestion externality on the PRR.

Our empirical investigation concluded that, in 2007, the PRR was more costly for central Paris area (130 M€) compared to that of seven years earlier (117 M€). The deterioration of traffic conditions, symbolized by the mean speed fall (- 5.2 %), dominates the infrastructure least used (- 2.2 %). Based on these figures, the social cost of road congestion is thought to reach about 0.2 % of the French GDP. This ratio becomes three times higher once reported on a regional scale and underlines that road congestion is an important issue for Ile-de-France. Finally, despite their analytical limitations, the proposed taxes clearly illustrate the challenges related to road-pricing strategies.

**Keywords:** Paris Ring-Road, Road Congestion, Speed-Density Relationship, Road-Pricing

**JEL Classification:** R40, R41, R62

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## 1. Introduction

Economists frequently present road congestion as a “*non-market interaction*” particularly relevant to understand urban dynamics. If the concentration of people and economic activities within a limited area results in efficiency gains (Duranton and Puga 2003), road congestion is in fact one of the major “*push-forces*” characterizing urban agglomerations (Thisse and Lafourcade 2006). By increasing the cost of moving people (Glaeser and Kahn 2004), this impacts the spatial structure of cities and influences their productive advantages (Anas and alii. 1998). More recently, congestion issues have subsequently become critical because of global warming and concerns linked to sustainable development: pollutant emissions indeed increase as traffic speed decreases. Consequently, the fight against greenhouse gaz primarily deals with the excessive use of private cars in urban areas where road congestion has to be relieved (OCDE 2005, European Commission 2007).

Nevertheless, and in spite major interest<sup>3</sup>, economic scientific research has to date been unable to homogenously assess this socio-spatial phenomenon. Therefore, important differences occur in the way road congestion is measured (Lindsey and Verhoef 2000, Parry and alii. 2006, De Palma and Zaouali 2007). Time losses related to the over-use of transportation infrastructures have been reported to range between 2 % and 0.1 % in the GDP of developed countries (De Palma and Zaouali 2007). The extent of market failures generally conditions the force of public intervention. Consequently, these academic divergences may seem puzzling. In the French case, challenges related to road congestion could impact respectively either 36 billions euros or 180 millions euros. By focusing on one specific transportation infrastructure, this research attempts to produce empirical information allowing us to propose a credible order of magnitude for road congestion costs.

The main object of our study was the Paris Ring-Road (PRR). This urban highway surrounding the French capital is a strategic interface for the socio-economical life of the Parisian agglomeration, one of the wealthiest geographical areas worldwide (Davezies 2008, Gilli and Offner 2009). The infrastructure is known for being one of the most frequented roads in Europe. Therefore, the cost of its congestion is of major interest for at least three

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<sup>3</sup> One other major concern linked to road congestion relates to “*oil dependency*” (Parry and alii. 2006), even if this dimension strongly depends on the national provision sources.

reasons. First, because our calculations were conducted for the years 2000 and 2007, the evolution of PRR's congestion should be considered accurate. Motorized traffic conditions in Paris city have recently experienced a particular evolution (Prud'homme and Kopp 2008) and watching what happens to the PRR could logically be relevant. Second, figures on this transportation infrastructure could be used as a useful benchmark concerning the magnitude of the social waste due to road congestion. Finally, if urban road-pricing is implemented in the Ile-de-France Region (Lindsey and De Palma 2006, Bureau and Glachant 2008), the PRR would certainly become a perfect candidate. This factor, of course, must take into consideration the various challenges at stake.

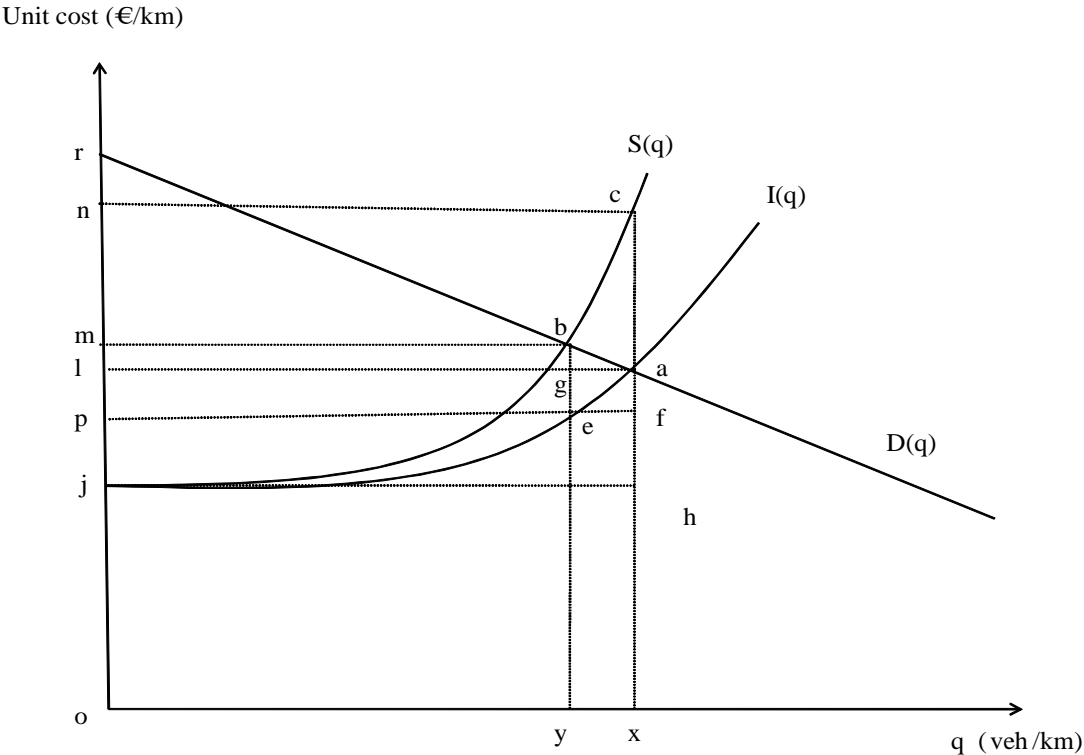
In order to assess these different questions, we organized our research as follows. Section 2 presents and discusses the methodological framework used in this article to estimate congestion costs. Based on Prud'homme and Sun (2000), we applied a speed-density model which, combined with an extensive database, enabled us to differentiate congestion costs as regards speed-classes of 5 km/h. Section 3 describes the PRR and the context characterizing up-to-date traffic conditions in the greater Paris area. We equally report the data and the parameters involved. In section 4, we estimated congestion costs for the PRR and analysed their 2000-2007 evolution. This section will equally contain sensitivity tests since we "*disaggregated*" our approach as regards temporal and geographical scales. Section 5 summarized results and attempted to extrapolate them on both national and regional levels. Finally, the discussion regarding PRR road-pricing is presented in section 6. Although the principal forces of our model do not rely on that specific issue, it however permits one to illustrate some lessons stressed by other studies on that topic.

## **2. Congestion Modeling**

Congestion modeling has inspired both engineers and economists for decades (Lighthill and Whitham 1955, Walters 1961, Vickrey 1969). Time wasting occurs when an infrastructure cannot effectively deal with a certain level of traffic. Whereas engineers have been more interested in the supply side, i.e. the physical constrain capacity, economists have in contrast been more likely to concentrate on travel demand. In order to estimate social waste which occurs in the PRR, the traditional Pigouvian framework is used below. This focuses on the social wastes resulting from the divergence between effective and optimal equilibriums.

Because motorists do not internalize the entire consequences of their actions, they impose time losses on others: private and social costs on the market of displacements differ. In order to illustrate this, let us consider Figure 1.

Figure 1 – Equilibriums on the Market of Displacements



The market equilibrium is reached at the intersection of the demand curve ( $D(q)^4$ ) with the private cost curve ( $I(q)^5$ ), i.e. point  $a$ . It is however sub-optimal because of road congestion. The traffic that would maximize the collective welfare indeed lies at the intersection of  $D(q)$  with the social cost ( $S(q)^6$ ), i.e. point  $b$ . As a consequence, there is an “*excess*” of  $xy$  motorists on the road. After the  $y$  point, each additional vehicle generates a social cost greater than its social benefit. We can thus define road congestion as the cost supported by society when the use of the transportation infrastructure is  $x$  instead of  $y$ . The corresponding “*dead weight loss*”

<sup>4</sup> The demand is expressed as an inverse function of the road use cost. We used a linear demand function whose slope can be deduced from the price elasticity of the road use ( $\epsilon$ ):  $D(q) = b + a \cdot q$  with  $b =$  fixed cost if the road is empty and  $a = p/(\epsilon \cdot q)$  in a point  $(q,p)$

<sup>5</sup> The private cost is composed of a fixed cost ( $I_0$  ; mainly fuel, insurance and deterioration of the vehicle) and of a time opportunity cost ( $w$  ; main component of the so-called “*generalized cost*”).  $I(q)$  varies inversely with the traffic speed ( $s(q)$ ) because of travel duration:  $I(q) = I_0 + w/s(q)$ .

<sup>6</sup> The social cost function is obtained by adding the private cost and its derivative multiplied by the quantity of road use:  $S(q) = I(q) + I'(q) \cdot q$ .

can be estimated by evaluating the variation of economic welfare associated to each situation (=prbe-lra=plge-gba, Quinet and Vickerman 2004). According to this vision, the market of displacements is characterized by sub-optimality as soon as the demand of road use is positive. Note equally that the road space is considered here as a public commodity whose quality of service, i.e. the time necessary to travel, depends on traffic conditions. It can be synthesized by the speed-density relationship ( $s(q)$ <sup>7</sup>) which reflects either the infrastructure's physical capacity or drivers' habits. It is possible to interpret this relation as the distance separating two vehicles for a given speed. The speed-density function, or the speed-flow<sup>8</sup> depending on the output chosen<sup>9</sup>, provides the basis of the "*fundamental diagram*" (Walters 1961, Evans 1992). By linking the level of road use to private and social costs, this technological relationship allows us to shape functions and subsequently, to measure externalities.

Relying on the partial equilibrium framework, this type of approach belongs to the so-called "*static*" family of congestion modelling (Verhoef 1999). As noted by the advocates of "*endogenous congestion*" (Vickrey 1969, Arnott and alii. 1990, Lindsey and Verhoef 2000, Leurent 2005), the "*static*" methodologies fail in integrating to the decisional process of drivers the "*scheduling costs*" related to predicable bottlenecks, i.e. late or early arrivals<sup>10</sup>. Despite this limitation, we are nevertheless convinced of our methodology's interests. In fact, considering behavioural adjustments seems necessary in order to correctly assess the impact of changing travel conditions on the modal choice of commuters or on the re-localisation of households within the intra-urban equilibrium framework<sup>11</sup>. The aim of this article is more

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<sup>7</sup> We retain here a linear specification:  $s(q) = s_0 + d \cdot q$  with  $s_0$  = speed if the road is empty ( $q=0$ ).

<sup>8</sup> The flow (veh/h) is the product of the speed (km/h) with the density (veh/km).

<sup>9</sup> The choice of the relevant output to study road congestion has led to a strong debate among transportation researchers. In this article, although Figure 1 retains the density for sakes of comprehension, calculations rely on vehicle\*kilometer (vkm) measurements. This unit of counting is thought to take better into account the social utility of travel activity because merging the number of vehicles and the length of each displacement.

<sup>10</sup> Drivers who are daily confronted with bottlenecks when entering an infrastructure change their displacement's habits by adapting their departure/arrival hours. From a theoretical point of view, total "*scheduling costs*" are said to be equal to the total travel time costs (Arnott and alii. 1993). Empirical investigations have proved that they are non negligible for drivers (Small 82, De Palma and Fontan 2001).

<sup>11</sup> "*Dynamic*" models are equally useful to understand the observed growing duration of peak-periods, to introduce individual heterogeneity in the analysis (Arnott and alii. 1993), to assess the impact of traffic information on drivers' habits (Arnott and alii. 1999) or to fully appraise the effect of road-pricing on the level of traffic. In opposition to the static situation, it in fact better catches the inducted road usage resulting from improved traffic conditions.

humble. It just seeks to propose a reasonable order of magnitude for social losses due to road congestion. The methodology presented above seems thus sufficient for that purpose. Second, the “*picture*” of the PRR traffic conditions we will give in section 4 may be more relevant than others inside the “*static*” congestion family, for conceptual and practical reasons.

Some authors prefer in fact to define road congestion as the difference between the effective number of hours spent on the infrastructure and the one which would prevail in cases of an “*empty road*”<sup>12</sup> (Bouladon 1991, Quinet 1994, European Commission 1995). However, one easily understands why such a definition is inappropriate. It completely denies the social utility of the transportation infrastructure<sup>13</sup> and ignores the demand side of the reasoning. In fact, it does not take for referential the optimal equilibrium. A variant of this theoretical misspecification is furnished by studies which estimate road congestion by comparing effective travel times and what travel times would be under “*free-regime*”<sup>14</sup> (INFRAS 2000, Schrank and Lomax 2005, COMPETE 2006). One other rival definition of road congestion could be qualified as “*fiscal*”. It stipulates that congestion losses may be approximated by the amount of taxes that would lead to the optimal situation (Newberry 1990). From Figure 1, one can easily deduce the optimal tax that would force motorists to fully internalize impacts of their private decisions (=be). For the “*fiscal*” vision to be true, areas *pemb* and *bca* should be equal. As we will see in section 5, there are no reasons for this equality to be satisfied<sup>15</sup>. Above all, our approach seems particularly accurate since it takes into account one major criticism traditionally addressed to “*static*” models, namely the uniqueness of the equilibrium on the market of displacements.

Speed-density or speed-flow methodologies indeed consider behaviours of motorists as exogenous and tend to recognize a sole demand curve (Verhoef 1999). Outputs and traffic speed are therefore supposed to remain constant and the equilibrium reached is unique. Such

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<sup>12</sup> This configuration is derived from the speed-density relationship. It corresponds to the traffic speed when the density is zero.

<sup>13</sup> As well as its funding.

<sup>14</sup> Road use on a given infrastructure can be characterized by three types of traffic regime (Hall and alii. 1992). “*Free-regime*” corresponds to the situation where drivers are not numerous on the road and the traffic speed is therefore high. In situation of “*transition regime*”, the infrastructure receives its maximal charge, a queue is formed and the flow is equal to the road capacity. Finally, during “*crowded regime*”, the flow and the speed progressively decline until the moment where all vehicles are stopped.

<sup>15</sup> “*Even if such definition relies on the good referential (the sub-optimality), it mistakes the end (to reduce the congestion) with the mean (the tax)*” (Prud’homme and Sun 2000).

specification seems inappropriate. According to the speed-flow relationship, to a given traffic speed in fact correspond two different levels of road use: one over “*free-regime*” and one over “*crowded-regime*”. It therefore follows that the intersection of the demand curve with the private cost curve coincides with a double equilibrium. Because of non stationary forces, the one corresponding to “*hypercongestion*”, i.e. over “*crowded regime*”, is generally forgotten in “*static*” models (Verhoef 1999, Button 2004).

Conversely, we are able to use here an extensive database which allows us to distinguish the PRR’s use as regards speed-classes of 5 km/h. We can thus differentiate the demand curve thanks to an accepted elasticity<sup>16</sup>. Given that effective and optimal quantities depend on the demand curve’s level, we will distinguish several social costs. Consequently, we will better highlight the fact that the marginal vehicle is more costly for society when it accesses an infrastructure which is already crowded. Even if this differentiation process is not “*micro-founded*”, it nevertheless constitutes a notable methodological improvement. Finally, because our database can be exploited according to temporal or geographical dimensions, we will shed light on *when* and *where* road congestion mainly occurs on the PRR. We will equally adjust with parameters involved and geographically differentiate the speed-density relationship in order to provide sensitivity tests.

### 3. PRR’s Presentation and Data

*The Paris Ring-Road (PRR)* - Built on “*old fortifications*” and finished in 1973, the PRR is an urban highway 35 kms in length surrounding the municipality of Paris. Like many industrialized countries, France faced, during the seventies, the co-development of the automobile system and sub-urbanization (Brueckner 2000). The aim of the PRR was to relieve Parisian streets from the excess of vehicles and to help the spatial re-organization of people and activities that the State just decided to enhance with the creation of “*new towns*” (Sheamur and Alvergne 2003). However, the PRR became a victim of its own success and its circulation routes were rapidly crowded (Gérondeau 1977). The demographic and economic hegemony of the Parisian territory, as well as the radiocentric organization of the national road system, are some rationales to justify the fact that, in 2000, the region concentrated 89 %

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<sup>16</sup> By observing the effective equilibrium, point a on Figure 1, we first deduce the slope ( $a = p/(\epsilon \cdot q)$ ) and then b.



of national queues (URF 2007). Although the increase of motorized displacements mainly occurred in the “*Grande Couronne*”, i.e. the “*second belt*” of the agglomeration, over last decades (EGT 2002), central Paris and the PRR were responsible for 33 % of these wastes of time in 2000 (29 % of national queues). In line with these figures, the infrastructure is often taken as a symbol of congestion distress within the French collective imagination<sup>17</sup>.

Since 1995, concrete action has been engaged in order to reduce this problematic “*car dependency*” (Newman and Kenworthy 1989, Dupuy 2006). At the regional level, financial efforts were mainly oriented to the modernization of public transit and a better configuration of radial networks. At the municipal level, the mayor of Paris decided in 2001 to couple a “*regulation by quantities*” (Prud’homme and Kopp 2008), i.e. narrowing of the road space available for private cars by about 25 %, with a stimulation of alternative transportation modes<sup>18</sup>. Available data clearly highlight effects of these policies. After a long stagnation, the railway public has vigorously been re-born at both regional and municipal levels (RATP 2007). The use of private cars in central Paris has simultaneously decreased by 20 % between 2000 and 2007 (Bilan des Déplacements 2007), as well as the level of pollutant emissions (- 32 %<sup>19</sup>, Airparif 2006). However, in accordance with the desired political orientation, time losses have risen because of the induced speed fall by about 11 % (Prud’homme and Kopp 2008). Due to its links with the central city, as well as the importance relying on transportations issues in the current debate on the “*Grand Paris* ” (Crozet 2007, Gilli and Offner 2009), i.e. the reform of the territorial governance of the Parisian agglomeration, it seems to us of interest to examine what has happened on the PRR during this period.

*Traffic Data* - The empirical support has been provided by the Division de la Voierie et des Déplacements, Section Tunnels, Berges et Périphérique de la Ville de Paris. Data were obtained from receptors incorporated into the road structure and refer to what has happened during the last 6 minutes (240 periods per day) on each 500 meters-long section of the PRR

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<sup>17</sup> The PRR is equally said to constitute a physical barrier between central Paris and its suburbs. It symbolises the lack of territorial cohesion among the Parisian agglomeration (Pinçon-Charlot 2008). In order to solve this problem, it has been planned to progressively cover the PRR. Works have even begun on some sections of the infrastructure.

<sup>18</sup> Several developments have been engaged. Buses now benefit from dedicated lanes, a system of rent-bicycles and a new line of street-car have been inaugurated. The parking pricing-scheme has equally evolved in favour of residents.

<sup>19</sup> This last evolution cannot be completely attributed to the municipal policy. In fact, it has mainly been engendered by technological progress and norms related car engines (- 26 %, Airparif 2006).

(71 sections). The unit of counting is called “*section-period*” (s-p). It has been decided to restrict observations to Tuesdays and Thursdays of June and October<sup>20</sup>. Although it offers us a rich empirical support, this database has required an intense work of cleaning. It was in fact composed of many broken-series that would have made impossible for any serious comparison. Some geographical sections had no observation at all, others were incomplete<sup>21</sup>. For our estimates to be reliable, we need a complete distribution of the observations, that is to say, the exact full number of s-p for the two years and for each section/day. As a consequence, we have divided the original database into the smallest ones, each of them according to temporal and geographical dimensions<sup>22</sup>. This process has enabled us to sort and to consider the sole comparable observations. We had then to accurately compare the number of journeys that would constitute our sample and the number of observation posts in each geographical area<sup>23</sup>. Table 1 presents descriptive statistics on the PRR traffic<sup>24</sup> as well as the speed-density relationship calculated for the entire infrastructure<sup>25</sup>.

*Table 1 – Descriptive Statistics and PRR’s Speed-Density Relationship*

<b>Traffic conditions</b>					
<b>2000</b>			<b>2007</b>		
<i>Daily Traffic (M vkms)</i>	<i>Av. speed (km/h)</i>	<i>Av. density (veh/km)</i>	<i>Daily Traffic (M vkms)</i>	<i>Av. speed (km/h)</i>	<i>Av. density (veh/km)</i>
7,830	45.9	175	7,661	43.5	185
<b>Speed-density relationship</b>					
$s(q) = 90.285 - 0.253 * q$					
(0.007)			(0.000)		
					R2 = 0.75

*Source:* Author’s calculations after the work of cleaning realised on the database of the Division de la Voierie et des Déplacements, Section Tunnels, Berges et Périphérique de la Ville de Paris.

PRR traffic conditions have undergone an evolution similar, in trend, as those of central Paris. If the number of vkms driven daily has fallen between 2000 and 2007 (- 2.2 %), it has not been accompanied by any improvement in the service’s quality: the average speed has

<sup>20</sup> These dates have been chosen because they are qualified as representative by municipal agents.

<sup>21</sup> The same can be said about the temporal dimension.

<sup>22</sup> Five periods (00-07h, 07-10h, 10-17h, 17-20h, 20-00h) and four areas (North, East, West, South) were retained.

<sup>23</sup> We have finally retained 6 days per year (3 in June, 3 in October) and 49 sections (on 71 possible). Observations are then extrapolated to the whole PRR and to 300 days a year.

<sup>24</sup> Both circulation senses have been merged.

<sup>25</sup> We obtain it by leading a simple regression, corrected of heteroskedasticity, on data obtained from our sample and corresponding to a single day of observation.

decreased (- 5.2 %). Although the magnitude differs<sup>26</sup>, this tendency is comparable to the one given by official data. Note furthermore that the average speed is about a half of that which would correspond to the “*empty road*”. Above all, figures in Table 1 have led us to believe that the PRR has shifted between 2000 and 2007 from the “*transition regime*” to the “*crowded*” one. It is in fact possible to rewrite the speed-density relationship as a flow-speed function,  $f(s) = 356.86*s - 3.95*s^2$ . The flow then reaches its maximum when the derivative of this equation is null, that is to say, when  $s$  equals 45.2 km/h. The speed evolution passes through this point and, consequently, traffic conditions on the PRR seem to be characterized currently by “*hypercongestion*”<sup>27</sup>. Despite the vkms’ decrease, one may legitimately expect congestion losses due to PRR’s over-use to have increased between observation dates.

It should equally be pointed out that the traffic decrease on the PRR is minor compared to the one registered for inner Paris, whatever the source retained. Because the traffic *in* and *around* the city are necessarily linked, two rationales can be advanced to justify this. First and most obvious, although there exist other transportation modes to cross the metropolitan territory, the PRR always constitutes a major node of the regional road system. Its frequency seems therefore less elastic because of the sub-urbanization process still experienced by the Parisian agglomeration (Gilli 2009, Gilli and Offner 2009). By considering an average trip on the PRR of 8 kms, it can thus be calculated that more than 950,000 vehicles travel via the infrastructure every day. One can also deduce<sup>28</sup> from EGT (2002) that the PRR accounts for 6.4 % of vkms daily which take place in the region using a private car, ratio that has to be compared to the sole 70 kms of road within it. Second, the infrastructure might currently receive some former Parisian motorists. As suggested in Prud’homme and alii. (2009), displacement costs in central Paris may have become so expensive in some city areas that motorists would now receive incentives to use the PRR instead of the capital’s streets. The average traffic speed on

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<sup>26</sup> According to Indicateurs Généraux (2007), the traffic has declined by 7 % (2,283 M vkms in 2000 and 2,120 M vkms in 2007), the average speed by 10 % (51.2 km/h in 2000 and 46 km/h in 2007). Such divergence, relatively important, may originate from the panel’s nature and from the necessary work of cleaning preformed on the database. Our sample might therefore under-estimate the traffic evolution, a possibility that should be taken into consideration during the presentation of estimate results. We were unfortunately unable to learn how the broken-series were treated during the extraction of data providing the Indicateurs Généraux.

<sup>27</sup> According to traffic speeds given by Indicateurs Généraux (2007), the PRR in 2007 was over “*saturation regime*” and cloth to tip over “*crowded*” one.

<sup>28</sup> From EGT (2002) we know that 44 % of the 35 M displacements carried-out daily in the region were motorised. We obtained the number of vkms by multiplying it with the average travel range (6.4 km), transformed into distance based on a 0.25 coefficient. This produces about 123.2 M vkms.

the PRR is in fact 2.5 times higher than the actual one in central Paris. This possible “road transfer” might consequently soften the decline that would have normally prevailed and, inversely, trigger the congestion cost on the PRR.

*Parameters* – Estimates rely on two types of information: some tutelary values (especially the time opportunity cost) and the demand elasticity of road use. According to the Boiteux report (2001, actualized in 2004 and 2005), i.e. the official report used in France for transportation studies, the mean value of a displacement ( $w$ ) performed with a private car across the Parisian agglomeration was equal to 9.3 €/h in 2000. By assuming a consumption growth rate of 2 %, one obtains a time opportunity cost of 10.2 €/h in 2007<sup>29</sup>. The use of mean parameters ignores however displacements motives. To overcome this limitation, we will consider a second value of the time. For travels driven during peak-periods, we will retain the one related to Home-Work displacements, namely 12.2 €/h. Following the same method to up-date this value, it becomes 13.4 €/h for 2007. These values are for only one passenger. We will therefore consider the occupation rate of vehicles, i.e. 1.3 (Orfeuil 2008). Moreover, it is known that 23 % of the PRR’s traffic concerned goods delivery in 2000 (Bilan des Déplacements 2001). Official reports advise in this case to retain a value of the time equal to 31.4 €/h. It should not be indexed annually<sup>30</sup>. This differentiation of displacement motives will lead us to find a coefficient which will be applied to congestion costs expressed in terms of  $vkm$ <sup>31</sup>. Concerning the second component of the generalized cost, the fixed cost ( $I_0$ ), this is said to be equal to 0.30 €/vkm in 2006 (Orfeuil 2008). Because the price index of motorized displacements experienced a 14.5 % increase between 2000 and 2006 (Insee 2007), we considered an initial value of 0.26 €/vkm. The last parameter we are interested in is the demand elasticity of the road use ( $\epsilon$ ), i.e. the commuter’s sensitivity to displacement costs. We retained a usual elasticity of - 0.8 (Goodwin 1992, Litman 2006). In order to provide sensitivity tests, we will equally consider an alternative demand elasticity equal to - 0.4 for trips carried-out during peak-periods. This can be justified by the potential “constrained” nature of trips at these periods of the day. All parameters are remembered in Appendix.

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<sup>29</sup> “This value of the time evolves from one year to the other with respect to the unit consumption’s expenditures of the households, (...), with an elasticity of -0.7” (Instruction Cadre 2004).

<sup>30</sup> It « comes back to consider that productivity gains will compensate the charges’ increase resulting from a better respect of social and road legislations » (Instruction Cadre 2004).

<sup>31</sup> Considering the general case, we find 1.367 (=  $(23*31.4+77*1.3*9.3)/(100*1.3*9.3)$ ) for 2000 and 1.315 (=  $(23*31.4+77*1.3*10.2)/(100*1.3*10.2)$ ) for 2007.

#### 4. Congestion Costs on the PRR

*General approach* - The first calculations' stage consists in finding gaps between effective and optimal quantities of road use, i.e. between  $x$  and  $y$  on Figure 1. For this purpose, we equalize social cost functions and demand functions which have been *ad hoc* obtained due to the travel elasticity<sup>32</sup>.

Table 2 – Gaps between Effective and Optimal Situations on the PRR

Effective Situation			Optimal Situation		
Speed (km/h)	Density (veh/km)	Flow (veh/h)	Speed (km/h)	Density (veh/km)	Flow (veh/h)
2.5	347	867	13.9	302	4,191
7.5	327	2,454	23.0	266	6,115
12.5	307	3,843	28.8	243	7,000
17.5	288	5,035	33.4	225	7,506
22.5	268	6,028	37.4	209	7,818
27.5	248	6,824	41.0	195	7,985
32.5	228	7,423	39.9	199	7,948
37.5	209	7,824	47.5	169	8,032
42.5	189	8,027	50.8	156	7,927
47.5	169	8,033	54.4	142	7,719
52.5	149	7,841	57.6	129	7,437
57.5	130	7,451	61.4	114	7,005
62.5	110	6,864	65.2	99	6,459
67.5	90	6,079	69.3	83	5,751
72.5	70	5,096	73.6	66	4,857
85.8	18	1,521	85.8	18	1,521

Source : Author's calculations.

As predicted by the methodology, the PRR is almost constantly used in a sub-optimal way. This over-use is however not homogenous. It reaches its maximum (30 %) between 15 and 35 km/h and it progressively declines for superior speed-classes. As a consequence, social costs imposed by vkms in these speed-classes will tend to be negligible. Even if it corresponds to the highest social utility of the infrastructure, the traffic speed which allows the maximum flow on the PRR (45,2 km/h) is also associated with welfare losses. We now have the entire information necessary to calculate congestion costs. Unit costs are obtained by estimating the variation of economic surplus corresponding to each speed-class ( $=prbe-lra=plge-gba$ ). Then,

<sup>32</sup> See note 16.

we apply unit costs to the correspondent number of vkms. An example based on the 5-10 km/h speed-class is given in Appendix.

Table 3 – PRR's Congestion Costs

Speed (km/h)	2000				2007			
	Distrib (%)	Traffic (M vkms)	Unit costs (€/vkm)	Congestion (M €)	Distrib (%)	Traffic (M vkms)	Unit costs (€/vkm)	Congestion (M €)
2,5	0.15	3.59	2.613	12.86	0.19	4.30	2.866	16.16
7,5	1.20	28.13	0.646	24.86	1.34	30.71	0.709	28.51
12,5	2.81	65.70	0.305	27.38	2.94	67.45	0.334	29.52
17,5	3.72	87.12	0.173	20.64	3.83	88.07	0.190	21.92
22,5	3.66	85.74	0.108	12.66	3.83	88.03	0.118	13.65
27,5	3.59	84.11	0.070	8.04	3.63	83.44	0.077	8.37
32,5	3.38	79.23	0.031	3.36	3.27	75.08	0.034	3.34
37,5	2.88	67.52	0.031	2.83	2.69	61.77	0.034	2.72
42,5	2.53	59.59	0.020	1.67	1.98	45.55	0.022	1.33
47,5	2.14	50.36	0.014	0.94	1.82	41.86	0.015	0.82
52,5	2.02	47.76	0.009	0.56	2.19	50.26	0.010	0.61
57,5	2.71	63.85	0.005	0.48	3.74	85.87	0.006	0.68
62,5	3.83	90.30	0.003	0.40	7.88	181.08	0.004	0.84
67,5	5.82	136.98	0.001	0.34	15.58	358.09	0.002	0.93
72,5	8.19	192.53	0.000	0.25	20.16	463.21	0.001	0.64
85,8	51.38	1,206.50	0.000	0.00	24.94	573.37	0.000	0.00
<b>Total</b>	<b>100</b>	<b>2,349</b>		<b>117.2<sup>a</sup></b>	<b>100</b>	<b>2,298</b>		<b>130.1<sup>a</sup></b>

Source: Author's calculations.

Note: a: adjusted with the coefficient taking into consideration the differentiation of displacements' motives.

According to the figures in Table 3, the PRR was more expensive in 2007 for the Parisian public as a transportation infrastructure, either in absolute or relative terms. Time losses due to its over-use had reached 130.1 M€, an amount corresponding to a 13 M€ (+ 11 %) increase compared to 2000 (117.2 M€)<sup>33</sup>. In fact, more hours were “consumed” in 2007 on the PRR (53 Mhs) as regards 2000 (51 Mhs). Of course, the congestion cost's annual growth rate could be considered as weak (+ 1.5 %), and even greater once corrected of which could be sometimes termed its “artificial” component (+ 0.8 %), i.e. the time opportunity cost's update<sup>34</sup>. However, introducing remarks on road congestion lead us to negatively assess these

<sup>33</sup> We have performed calculations by using statistics supplied by Indicateurs Généraux (2007). We find congestion costs equal to 116 M€ in 2000 and to 122 M€ in 2007. The possible bias resulting from the sample's construction seems therefore not to have a major influence on estimates' results even if it should be moderated. In fact, to perform “true” calculations we should have corrected the vkms' distribution, but we were unable to do it.

<sup>34</sup> To up-date the time opportunity cost, we have considered an annual growth rate of consumption's expenditures equal to 2 %. We made this choice because of ignorance concerning the “real” growth

results. Even to smaller extent, notably compared to what has been observed for traffic conditions within Paris (Prud'homme and Kopp 2008), this increased cost of moving people could restrict the territorial development of the agglomeration. In order to illustrate this, consider that the shift towards “*crowded-regime*” on the PRR dominates the traffic decrease. Equal to 0.050 €/vkm in 2000, the mean congestion cost thus rises to 0.057 €/vkm in 2007 (+ 14 %). Within our model, this deterioration implies a change of the vkms’ distribution. Two main evolutions concerning this should be underlined.

We first observed an important fall in the median speed: it passes from 85 km/h in 2000 to 67.5 km/h in 2007. Following studies on that topic (Corbett and Simon 1999, ONISR 2006), we can explain this by the progressive introduction, since 2004, of 8 speed-cameras on the PRR. More than 334,600 motorists have thus been fined for speeding in 2007 (Bilan des Déplacements 2007). While this road policy has an impact on the mean traffic speed (by modifying drivers’ habits)<sup>35</sup>, it does not have any significant implication in terms of congestion costs since superior speed-classes are associated with low unit costs<sup>36</sup>. Conversely, worst effects of speed decline are reflected in the distribution beginning. The relative share of vkms driven below 20 km/h has grown from 7.9 % to 8.3 %. This evolution, despite its weakness, has even been coupled with an absolute increase of the number of vkms driven at such speeds<sup>37</sup>. This change mechanically increases the extent of the social waste. The congestion cost resulting from these “*slow*” vkms has thus experienced a 12 % increase over the period (85.7 M€ in 2000 and 96.1 M€ in 2007). In order to better highlight this, we now consider the PRR under the temporal and geographical dimensions.

*Temporal and Geographical “Disaggregations”* - During the database’s construction, we have considered two peak-periods (07-10h and 17-20h), others referring to off-periods (00-

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rate, which could be considered as generous. By mobilizing the “*economic base theory*”, Davezies (2008) in fact shows that Ile-de-France’s per head income tended to grow slowly over last decade, despite major economic performances.

<sup>35</sup> One other explanation could be drawn from the increased share of displacements realized in the Parisian area with the use of two-wheels (Kopp 2009). This transportation mode in fact necessitates more vigilance from motorists because of accidents’ risks.

<sup>36</sup> The distribution’s settling induces thus a small increase of 2 M€ for speed-classes which was between 50 and 75 km/h and an “*economy*” of 0.3 M€ for the greater one.

<sup>37</sup> It passes from approximately 184.5 M vkms in 2000 to 190.5 M vkms in 2007 (+ 3.2 %).

07h, 10-17h and 20-00h)<sup>38</sup>. Remember that alternative demand elasticity and time values are applied for estimates performed over peak-periods. We have equally decided to calculate several speed-density relationships<sup>39</sup> (see Appendix) for the geographical areas which have been defined (North, East, South, West)<sup>40</sup>. This process allows one to disregard the implicit assumption of transportation infrastructure's homogeneity. Some sub-sections of the PRR are in fact structurally smaller and experience more traffic difficulties<sup>41</sup>. Table 4 describes the results.

Table 4 – Temporal and Geographical “Disaggregations”

	2000				2007			
	Traffic (M vkms)	Av. speed (km/h)	“Slow” <sup>b</sup> (%)	Congestion (M€)	Traffic (M vkms)	Av. speed (km/h)	“Slow” <sup>b</sup> (%)	Congestion (M€)
<i>Temporal “Disaggregation”</i>								
Peaks	723	30.4	17.3	85.9	737	28.6	17.7	100.5
Off-peaks	1,626	57.3	3.7	40.2	1,561	54.4	4.0	44.9
<b>Total</b>	<b>2,349</b>	<b>45.9</b>	<b>7.9</b>	<b>126.1<sup>a</sup></b>	<b>2,298</b>	<b>43.5</b>	<b>8.3</b>	<b>145.4<sup>a</sup></b>
<i>Geographical “Disaggregation”</i>								
North	695	53.8	4.6	22.8	685	49.7	5.5	26.9
East	595	47.7	7.0	43.8	569	43.3	7.9	53.8
South	548	37.9	12.3	42.6	527	33.9	14.7	51.2
West	511	45.0	8.6	27.0	516	49.8	5.9	19.7
<b>Total</b>	<b>2,349</b>	<b>45.9</b>	<b>7.9</b>	<b>136.2<sup>a</sup></b>	<b>2,298</b>	<b>43.5</b>	<b>8.3</b>	<b>151.6<sup>a</sup></b>

Source: Author's calculations.

Notes: a: adjusted with the coefficient taking into consideration the differentiation of displacements' motives. b: share of vkms driven under 20 km/h.

From the temporal point of view, figures in Table 4 confirm the predominance of peak-periods concerning the PRR congestion costs. While they received 32 % of the total number of vkms in 2007, these periods concentrated 69 % of time losses. One can furthermore remark that the worsening of traffic conditions recorded at the global level has happened during peak-periods. The average speed has thus decreased by 4.8 %, leading to a congestion over-bill of 17 % between 2000 and 2007<sup>42</sup>. Even if it may come from the database specificities, it is also

<sup>38</sup> Sub-periods have been compiled to calculate vkms' distribution. This “disaggregation” process is therefore for relative simplification and does not aim at examining details as how the PRR's traffic has changed, minute after minute, which would necessitate a dynamic approach.

<sup>39</sup> Congestion unit costs directly depend on the technological function's slope.

<sup>40</sup> North section goes from “Porte de Champerret” to “Porte Chaumont” (10 kms), East section from “Prés Saint Gervais” to “Porte Canal” (8 kms), South section from “Quai d'Ivry” to “Quai d'Issy” (10 kms) and, finally, West section from “Pontaval” to “Porte des Ternes” (8 kms).

<sup>41</sup> Since the road priority is given to vehicles entering the PRR, this differentiation might equally give insights about the dynamism of different zones.

<sup>42</sup> Note that the extent of this growth is (artificially) amplified by the higher value of the time.



noticeable that this evolution is joined with a small increase (+ 1.9 %) of the total number of vkms driven on the PRR during the peak-periods, conversely to what is observed for off-periods (- 3.9 %). This result may be in accordance with the “*endogenous congestion*” theory since the adjustments of commuters confronted to bottlenecks may explain the observed growing duration of peak-periods in many urban agglomerations (Boiteux report 2001, Berthier 1998). By spreading departure/arrival times on a wider range, transportation infrastructures are used in a more intensive manner and receive more vkms. This observation is equally compatible with the already mentioned assumption of “*road report*” from the Parisian streets towards the PRR.

From the geographical point of view, we notice that time losses are more important on the eastern and southern sub-sections of the PRR<sup>43</sup>. Congestion costs have increased there by 22 % and 20 % respectively. Whereas the extent of the market failure calculated for the eastern sub-section can be mainly explained by more significant unit costs<sup>44</sup>, the one corresponding to southern PRR describes intrinsic difficulties of this geographical zone (see Appendix). Difficulties that may be otherwise exacerbated. Because of the road space narrowing required to install a new street-car line on dedicated lanes, the traffic speed on the southern Maréchaux boulevards (parallel and 400 meters away from southern PRR) has strongly declined between 2003 and 2007 (- 17 %). According to Prud’homme and alii. (2009), the “*missing*” vkms on Maréchaux boulevards<sup>45</sup> appear to be potential candidates in order to explain why the southern PRR has embedded itself within “*crowded regime*”<sup>46</sup>. Even if one cannot fully consider this as the geographical side of the phenomenon commented previously<sup>47</sup>, the important (and growing) share of “*slow*” vkms driven on that part of the infrastructure (14.7

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<sup>43</sup> These two sub-sections counts for 65 % of the total time waste generated on the PRR.

<sup>44</sup> By considering the 5-10 km/h speed class, unit congestion costs for eastern, northern, southern and western areas were equal to 0.882 €/vkm, 0.717 €/vkm, 0.693 €/vkm and 0.713 €/vkm in 2007 respectively. These figures are coherent since unit costs are inversely dependent on the speed-density relationship slope (see Appendix).

<sup>45</sup> Traffic on Maréchaux boulevards has strongly declined (- 31 %) whereas the modal report towards the street-car has been proved to be very limited (2.6 %). 42.000 vkms are thus daily “*missing*”. See Prud’homme and alii. (2009) for more details.

<sup>46</sup> According to geographical speed-flow relationships, the inflexion point for southern PRR is at 42.9 km/h. The eastern PRR has shifted from “*transition*” to “*crowded-regime*” (inflexion point at 45.5 km/h).

<sup>47</sup> Each sub-section being an “*opened-system*” (conversely to the PRR considered on its all), the decrease of the number of vkms driven on the southern PRR (- 3.6 %) does not necessarily mean one least used of the infrastructure on that geographical area. In fact, the flow decrease associated to an increase of the density mechanically translates into a decline of the number of vkms driven on that sub-section.

% in 2007) forces us not to ignore this possible “*road-transfer*”. Inversely, the speed increase (+ 11 %) resulting from the decline of vehicles density on the western sub-section has engendered a small growth of the vkms driven on that part of the PRR (+ 1 %). In fact, the traffic regime can be characterized there of “*transition*” again<sup>48</sup>. It therefore follows an important fall of the share of “*slow*” vkms driven there and a major economy in terms of congestion cost (- 25 %).

Finally, differentiating parameters offers alternative values to well-being losses<sup>49</sup>. The congestion cost obtained in the temporal case thus reaches 145.5 M€ in 2007, an amount 12 % higher than the one previously calculated. It can be deduced from these figures that congestion cost’s elasticities as regards demand sensitivity and time opportunity cost are respectively equal to 0.11 and 0.57<sup>50</sup>. Concerning the geographical “*disaggregation*”, it implies a total waste equal to 151.5 M€ (+ 14 %). Even if the elasticity of congestion cost as regards speed-density relationship slope does not appear robust, the physical capacity of roads seems to influence estimates in a similar manner as the time opportunity cost.

## 5. The Magnitude of Road Congestion Costs

According to results presented in this article, the PRR was in 2007 more congested and more expensive for society than seven years earlier. In spite of a reduced use (- 2.2 %), the worsening of traffic conditions has engendered a growth of the time spent on its “*tarmac*”. Above all, the observed speed fall (- 5.2 %) suggests that the PRR is currently used, on average, over “*crowded regime*” (or is cloth to tip on it). These results have to be confirmed by further studies. But if this trend continues, one could expect difficulties related to PRR’s congestion to worsen, negative conclusion from regional perspectives. In fact, the speed fall concomitant to road congestion on the PRR may affect the over-productivity of Ile-de-France by reducing the “*effective size of labor market*”, i.e. the number of jobs that can be matched

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<sup>48</sup> Western PRR has shifted from crowded regime to transition one (inflexion point at 46.2 km/h). The northern PRR has stayed over free-regime (46.5 km/h).

<sup>49</sup> The temporal scenario combines two opposing forces. Whereas one weakest elasticity reduces gaps between effective and optimal quantities of road use (and consequently the social waste induced by infrastructure’s over-use), the higher tutelary value corresponding to Home-Work displacements raises the bidding of time losses.

<sup>50</sup> One could expect the time opportunity cost’s elasticity to be higher. This “*low*” value is explained by the (recommended) non-indexation of the time opportunity cost for displacements related to goods delivery.

under  $x$  minutes of displacement (Prud'homme and Lee 1999, Cervero 2001)<sup>51</sup>. In the same logic, because the cost of moving people across the Parisian territory is progressively increasing, “*push-forces*” could become significant enough to make the agglomeration really explode in excessively de-concentrated “*sub-centers*”. Despite their normative scope, the importance of Ile-de-France's economy within the national system of social redistribution forces us not to neglect these types of arguments (Davezies 2008)<sup>52</sup>. From a more positive point of view, this would certainly imply future troubles linked to the motorized mobility.

Concerning the extent of the social waste, our results range between 130 M€ and 150 M€. Of course, these amounts are closely linked to functional forms related to shape demand, costs and speed-density functions. However, the manner in which we have conceptually defined road congestion or differentiated demand curves are some rationales to convince readers that our methodology can be considered as relevant. Calculations using the “*empty road*” approach thus result in a social waste equal to 370 M€<sup>53</sup> for 2007. If one retains aggregated congestion costs, as those proposed by INFRAS (2000), time losses due to the PRR's over-use would reach 1,050 M€<sup>54</sup>. The gap between methodologies is therefore enormous. Without giving them a universal scope, we can nevertheless mobilize our figures to propose an order of magnitude to road congestion costs. For that, we need further information, as well as some assumptions. According to URF (2007), central Paris and the PRR were, in 2006, responsible for 26 % of queues recorded at the national level (33 % at the regional level)<sup>55</sup>. We equally know that vkms driven on the PRR correspond to 33.5 % of those driven in Paris (Kopp 2009). Unfortunately, we currently lack information on the respective importance of congestion costs *in* and *around* the French capital. Consequently, Table 5 presents two variants: the first considers that the road congestion is relatively as costly (per vkm) in both

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<sup>51</sup> The « *effective size of labor market* » can be seen as a media by which externalities resulting from spatial concentration are spread across the urban territory. It depends on the traffic speed, the city size and density (Prud'homme and Lee 1999).

<sup>52</sup> Davezies (2008) explains that productive advantages of Ile-de-France permits to redistribute 8% of the national GDP to others regions.

<sup>53</sup> If the traffic speed were equal to 90.3 km/h, 25.4 Mh would have been necessary to realize 2,298 M vkms. It would then correspond to an “*economy*” of 27.4 Mh, i.e. 370 M€ once valorized at 10.2 €/h and corrected by the coefficient taking into consideration the displacements for delivery goods.

<sup>54</sup> INFRAS (2000) proposes social costs (for highways) equal to 2.032 €/vkm in case of “*congested road*” or to 1.907 €/vkm in case of “*dense road*”. If one applies former ones to vkms effectively driven under 15 km/h and later ones to vkms driven between 15 and 45 km/h, a bill of 1,051 M€ is reached.

<sup>55</sup> Because of the lack of information, we will consider these “*queues*” as road congestion, although the definition retained by the French Gendarmerie Nationale (quoted by URF 2007) differs from ours.

zones while the second stipulates that traffic difficulties in Paris are relatively 2 times superior. In a comparative perspective, we also present results associated to INFRAS (2000) external costs.

Table 5 - Order of Magnitude for Congestion Costs

	Aggregated case		Geographical case		INFRAS	
	P=PRR	P=2*PRR	P=PRR	P=2*PRR	P=PRR	P=2*PRR
<i>Paris+PRR</i>	518	906	603	1,056	4,188	7,326
<i>France</i>	1,994	3,487	2,322	4,061	16,109	28,175
<i>Ile-de-France</i>	1,571	2,748	1,829	3,200	12,692	22,199
<i>nat. GDP<sup>d</sup></i>	0.11	0.20	0.13	0.23	0.90	1.58
<i>reg. GDP<sup>e</sup></i>	0.30	0.53	0.35	0.62	2.46	4.30
<i>reg. Income<sup>f</sup></i>	0.40	0.70	0.47	0.82	3.24	5.67

Sources: Author's calculations from INFRAS (2000), URF (2007) and Kopp (2009).

Notes: d: 1,780,000 M€. e: 516,200 M€. f: 391,600 M€.

Even if the numerous assumptions made force to the cautious, our data and our methodology suggest that social losses due to roads' over-use equal, in France, around 0.2 % of the national GDP. On the one hand, this result does not enter in contradiction with the fact that road congestion is an expensive issue for French society. Because of the lack of coordination during individual displacements choices, a non negligible share of available societal time is daily sacrificed on transportation infrastructures, reality often exacerbated by psychological distress (Santos and Bharkarb 2006). On the other hand, figures presented above tend to moderate accusations against the unlimited cost of the motorized mobility, for what concerns time losses at least. As well as can be calculated that wastes due to sub-optimality on the PRR are equal to only 4 % of the total well-being it generates<sup>56</sup>, ratios in Table 5 are far away from the 2 % of national GDP sometimes advanced (European Commission 2001). This conclusion does not aim at defending any types of economical interests or territorial development's patterns. On the contrary, by providing empirical information, we only seek to render the French debate on the motorized mobility more "secular", as hoped by some academics convinced otherwise by the necessity of habits' changes (Orfeuill 2008). To illustrate this, one may notice from some figures that challenges related to road congestion become more critical on the regional scale. Once applied to regional GDP or Income, social losses become three

<sup>56</sup> The total well-being generated by the PRR is composed by the number of hours driven (52.8 Mh=544 M€), expenditures related to car use (689 M€) and the economic surplus of consumers, i.e. the difference between their willingness to pay and the effective cost of road use. One can evaluate this later at 2,000 M€, figure that amounts the total well-being at 3,233 M€.

times higher and constitute a major concern for Ile-de-France region. Therefore, the interest relies on correcting this market failure. Because an increase of capacities *via* physical investments does not constitute a successful solution within our theoretical framework<sup>57</sup>, let-alone in reality (Duranton and Turner 2008), we end this article with a brief reflection about the “*regulation by prices*”.

## 6. Marginal Pricing on the PRR<sup>58</sup>

Even if road-pricing cannot yet be implemented on the PRR<sup>59</sup>, political willingness may soon be likely to modify rules of game (Conseil d’Analyse Stratégique 2008). In fact, time losses are not the sole external effect resulting from the use of private cars (Quinet 2004, Parry and alii. 2006, De Palma and Zaouali 2007) and the growing environmental constraints constitute a severe call for changes. According to Figure 1, the tax that would force motorists to internalize road congestion is equal to  $be$ , i.e. the marginal cost characterizing the optimal situation ( $=S(q_{opt})-I(q_{opt})$ ). Based on that framework, Table 6 presents several schemes of marginal pricing. The two first columns consider congestion charges, the second focusing on the sole peak-periods. The two followings integrate, under an additive form, external costs related to noise, accidents, pollutants and greenhouse effect (Lindsey and De Palma 2006)<sup>60</sup>. Because CO2 emissions depend on the traffic speed, taxes presented in the last column are derived from a methodology which combines the speed-density relationship with an emission-speed one (Prud’homme and alii. 2009, see Appendix). In that latter case, a ton of CO2 is valorized at 32 € (Conseil d’Analyse Stratégique 2008).

Before commenting on results, let us remember that pricing schemes resulting from speed-density methodologies are not the most relevant ones to fully estimate effects on the level of

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<sup>57</sup> Analysis presented on Figure 1 corresponds to a given infrastructure. Any improvement of the road capacity results in a shift to the right of the  $I(q)$  and  $S(q)$  curves. It then corresponds to a decline of costs and leads to an increase of effective and optimal quantities. As a consequence, the sub-optimality is still present.

<sup>58</sup> Analysis regarding road-pricing on the PRR would necessitate further study which cannot be substituted by this last section alone. It would be a pity not to tackle this point since it constitutes the logical progression of this present research.

<sup>59</sup> According to the French law, road-pricing schemes are only allowed to cover funding necessary to new investments. For a review, see Raux and Souche (2004) or Conseil d’Analyse Stratégique (2008).

<sup>60</sup> These external costs remain constant ones. Lindsey and De Palma (2006) retain them from Quinet (2004) and Unite (2001).

road use. Even if a decrease of 10.5 %<sup>61</sup> can be calculated for the whole PRR (-12.6 % for sole peak-periods), vkms induced by better traffic conditions are in fact hardly discernible with the “static” framework (Verhoef 1999). Despite this limitation, figures in Table 6 offer interesting insights.

Table 6 – Marginal Road-Pricing on the PRR

	<b>Congestion Taxes</b>	<b>Peak-periods Taxes</b>	<b>“Full” Taxes (1)<sup>g</sup></b>	<b>“Full” Taxes (2)<sup>h</sup></b>
<i>Taxes’ range (€/vkm)</i>	4.05 – 0.00	5.31 – 0.00	4.15 – 0.11	4.15 – 0.10
<i>10-15 km/h (€/vkm)</i>	0.77	0.99	0.87	0.87
<i>40-45 km/h (€/vkm)</i>	0.16	0.20	0.27	0.26
<i>Toll Revenue (M€)</i>	250.5	218.7	475.6	442.0

Sources: Quinet (2004), Unite (2001), Prud’homme and alii. (2009), Conseil d’Analyse Stratégique (2008).

Notes: g: external costs derived from Quinet (2004) and Unite (2001), see Appendix. h: CO2 unit costs from Prud’homme and alii. (2009), see Appendix.

First, congestion taxes vary as regards traffic conditions. A trip of 8 kms on the PRR would thus imply a toll equal to 7.2 € if the traffic speed were of 12.5 km/h. This travel would cost 2.2 € when driven at 42.5 km/h<sup>62</sup>. This result highlights a first complexity linked to marginal pricing strategies. The extreme volatility of pricing schemes would in fact necessitate expensive technologies and it may excessively disturb drivers making their displacements’ choices. Second, time losses represent the main component of tolls. External costs related to noise, accidents, pollutants and greenhouse effect, once added, exceed congestion tax only above 50 km/h. Differentiating CO2 emissions as regards traffic speed marginally alters this result<sup>63</sup>. One may then legitimately wonder about this fact which seems to be in contradiction with the primacy accorded to environmental problems. Consider thus that social losses due to CO2 emissions on the PRR represent only 14 % of the congestion waste<sup>64</sup>. Finally, it can be drawn from Table 6 that the “fiscal” definition of road congestion is not verified. In the

<sup>61</sup> From Table 3 we know gaps between effective and optimal level of road use, i.e. between  $x$  and  $y$  on Figure 1. We therefore correct the effective demand by this gap.

<sup>62</sup> Due to methodological specificities, congestion marginal costs even become excessively expensive for worst traffic conditions (Verhoef 1999), as illustrated by the first speed-class.

<sup>63</sup> According to our methodology, CO2 emissions on the PRR have only decreased by 8,000 tons between 2000 and 2007, i.e. an economy valorized at 0.3 M€ (see Appendix). Even if it is biased because of engines’ progresses (and the possible traffic over-evaluation), this result is *ceteris paribus* coherent with the observed speed fall. Inferior speed-classes are in fact associated with more emissions and, in 2007, compensate progresses realized otherwise.

<sup>64</sup> Following this argument, one understands that transportation projects would more often satisfy economical appraisals thanks to time gains they induce rather than environmental benefits they generate.

simplest case, toll revenues appear twice as high (250 M€) compared to the extent of time losses. This result illustrates well one major difficulty linked to the implementation of road-pricing, namely its social acceptability (Rothengatter 2003, Raux and Souche 2004). In fact, introducing a toll on the PRR would induce surplus' transfers between the different types of commuters (Bureau and Glachant 2008). Such "*regulation by prices*" could worsen the (already) unequal accessibility to the regional labor market among social categories (Donzelot 2004, Wenglenski 2007, Gobillon and Selod 2007) and, thus, restrain the public support to this type of intervention.

Despite of what seems to be major limitations, solutions are nevertheless available to make road-pricing an effective regulation tool. Progresses related to NITCs and successful experiments of dynamic pricing offer first reasonable perspectives to facilitate drivers' adjustments (De Palma and alii. 2005). In order to improve the social acceptability, a practical option would consist in implementing road-pricing progressively on the regional road network (Lindsey and De Palma 2006). Introducing tolls on the PRR first, despite the symbol it would constitute, could in fact excessively disturb drivers' habits and portfolios. Most of all, toll's revenues should be used to finance quantitative and qualitative improvements of public transits in Ile-de-France (Small 1992, Crozet 2007). These fiscal transfers would of course exacerbate in the short run respective contributions of travellers to transportation activity by making the (already over-taxed) motorists pay for the (already subsidized) public audience (Orfeuil 2008). However, due to difficulties linked to infrastructures' funding in Ile-de-France region, amounts presented in Table 6 could offer to drivers effective possibilities to shift towards cleaner transportation modes<sup>65</sup>. Improving the accessibility of public transits to the jobs centers would certainly constitute a major channel of policies successes.

To conclude, note that alternative actions to road-pricing may equally be relevant in order to relieve road congestion. From our figures, it can in fact be calculated that increasing the vehicle occupation rate to 2 (instead of currently 1.3) would induce a fall of vkms driven on the PRR approximately equal to 33 %<sup>66</sup>. Even if this result suffers from above documented

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<sup>65</sup> To illustrate this, consider that one year of "*full*" toll revenues would be sufficient to cover the creation of one street-car line as that mentioned by Prud'homme and alii. (2009).

<sup>66</sup> Note first that 2,298 M vkms correspond to 2,531 passenger\*kms (pkms). Suppose then that we keep constant the global mobility (in terms of pkms) as well as displacements due to goods' delivery

limitations concerning “static” analysis, it constitutes an appreciable perspective. This “non-market intervention” would thus save a congestion waste of 50 M€<sup>67</sup>. One therefore easily understands the interest relying in exploring options related to co-driving in particular (Small and alii. 2006), and to cooperative practices among commuters in general (Orfeuil 2008)<sup>68</sup>.

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(529 vkms=529 pkms). If one applies a vehicles’ occupation rate equal to 2, the 2,002 pkms previously traveled transform into 1,001 vkms. The total PRR use becomes 1,530 vkms.

<sup>67</sup> If one applies a total traffic on the PRR of 1,530 vkms to general congestion unit costs, a social waste equal to 80 M€ is found.

<sup>68</sup> Finally, debates on sustainable development too often focus on transportation issues whereas concrete solutions have equally to be found in the real estate’s domain. Focusing on the Parisian agglomeration, Korsu and Massot (2006) have calculated that building housings in order to bring closer people and jobs, especially in the central area, could save about 8 % of daily regional displacements. In addition, this strategy would soften land speculation, other major “push-forces” stressed by urban economics.



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## Appendix

Table 7 - Estimates Parameters

	2000	2007
Fixed cost (€/vkm)	0.26	0.30
Av. time value (€/h)	9.3	10.2
House-Work time value (€/h)	12.2	13.4
Delivery goods time value (€/h)	31.4	
Share of delivery goods (%)	23	
Road demand elasticity	-0.8 / -0.4	

Sources: Ministère de l'Équipement, des Transports, de l'Aménagement du territoire, du Tourisme et de la Mer (2004), Orfeuil (2008), Insee (2007), Bilan des Déplacements (2001), Goodwin (1992), Litman (2006).

### Calculation of the PRR's congestion cost in 2007 for the 5-10 km/h speed-class

We know coordinates of points necessary to calculate (LGEP-AGB) area on Figure 1:

$$X = 327 \text{ veh/km}$$

$$Y = 266 \text{ veh/km}$$

$$L = I(327) = 1.66 \text{ €/km}$$

$$M = S(266) = 2.04 \text{ €/km}$$

$$P = I(266) = 0.74 \text{ €/km}$$

We therefore obtain:

$$\text{Kilometric cost}_{5-10} = \text{LGEP} - \text{AGB} = Y*(L - P) - (M - L)*(X - Y)/2 = 232.01 \text{ €/km}$$

It corresponds to the cost generated by 327 vehicles, driving one kilometer on the PRR at a traffic speed of 7.5 km/h instead of 23.0 km/h. We transform this in unit congestion cost (€/vkm) by dividing it by the number of vehicles present on that kilometre, i.e. the density:

$$\text{Unit cost}_{5-10} = 232.01/327 = 0.709 \text{ €/vkm}$$

It is then enough to multiply this unit cost by the total number of vkms driven into this speed-class:

$$\text{Congestion cost}_{5-10} = 0.709 * 30,713,000 = 28.51 \text{ M€}$$

This figure represents what has been lost by society in 2007 due to the fact that 30.7 M vkms have been realized on the PRR at a traffic speed reduced because of road congestion. We have finally to correct this social waste. In fact, one vehicle is occupied by 1.3 passengers (Orfeuill 2008). Moreover, 23 % of PRR's traffic results from goods' delivery (Bilan des Déplacements 2001) whose time value is more expensive (31.4 €/h instead of 10.2 €/h). A simple calculation (see note 42) conducts to find a 1.315 coefficient. The "true" social waste caused by road congestion on the PRR at the traffic speed of 7.5 km/h is:

$$\text{Congestion cost}_{5-10} = 28.51 * 1.315 = 37.49 \text{ M€}$$

*Table 8 - Geographical Speed-Density Relationships*

<i>Northern PRR</i>	$s(q) = 93.119 - 0.249 * q$ (0.152) (0.001)      R2=0.76
<i>Eastern PRR</i>	$s(q) = 90.990 - 0.246 * q$ (0.140) (0.001)      R2=0.78
<i>Southern PRR</i>	$s(q) = 85.353 - 0.264 * q$ (0.141) (0.001)      R2=0.74
<i>Western PRR</i>	$s(q) = 92.392 - 0.251 * q$ (0.110) (0.001)      R2=0.79

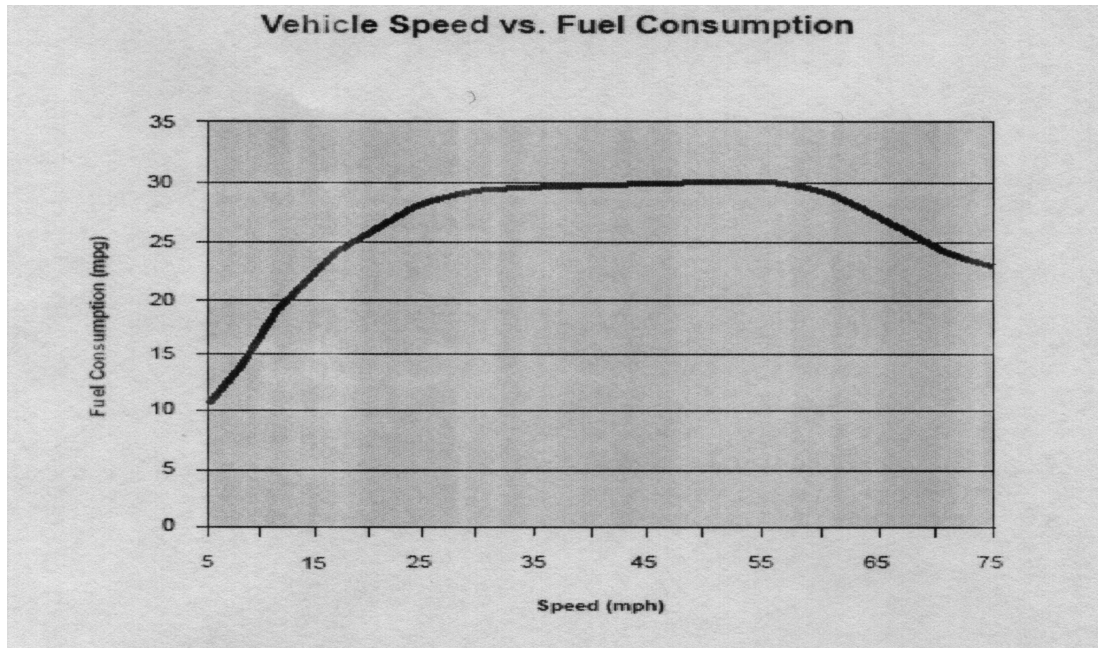
*Source:* Author's calculations.

It may be observed that speed-density relationships do not fundamentally diverge across PRR's sub-sections. The one related to the southern area offers the lowest maximum speed ( $s_0=85.4$  km/h), result coherent with the fact that it is composed on its main part by only two circulation lanes. Inversely, the road capacity appears superior for northern ( $s_0=93.1$  km/h) and western ( $s_0=92.4$  km/h) sub-sections.

#### *The PRR's emission-density relationship*

The fuel consumption is a function of the velocity. The graph hereafter shows it clearly. It is infinite when speed is zero and decreases regularly when speed increases, up to 40-50 km/h. It stagnates then between 40-50 km/h and 90-100 km/h and increases again beyond this limit.

Figure 2 – Relationship between Speed and Fuel Consumption



Source: [www.fueleconomy.gov/feg/drive-Habits.shtml](http://www.fueleconomy.gov/feg/drive-Habits.shtml)

Note: the fuel's consumption is measured in miles per gallon (i.e. in kilometer per liter) which explains the inverted form with respect to a graph expressed in liters per kilometer.

One can deduce the function that connects fuel consumption and speed by considering the point where the curve cuts the y-axis<sup>69</sup> and the point that corresponds to a speed of 30 miles/hour<sup>70</sup>. Once this function derived, one multiplies it by the CO2 emissions associated with 1 liter fuel consumption (2.35 kg):

$$\text{For } s < 50 \text{ km/h (expressed in kg/km): } \text{CO}_2(s) = 0.624 - 0.00925*v$$

$$\text{For } s > 50 \text{ km/h: } \text{CO}_2(s) = 0.16$$

This function is derived for private cars. Actually, the traffic on the PRR includes approximately 23 % commercial vehicles, which emit on average twice as much CO2 than cars. In that case, it will be advisable to multiply the obtained estimate by a coefficient of 1.13 (= (0.23\*2+0.67\*1)). It is then possible to cross the emission-speed equation with the speed-density relationship. One obtains the quantity of CO2 emitted as a function of the density of the road:

$$\text{CO}_2 = f(s) = \lambda + \mu * v \quad (\text{with } \lambda = 0.624 \text{ and } \mu = -0.00925)$$

$$s = g(q) = \alpha + \beta * q \quad (\text{with } \alpha = 90.3 \text{ and } \beta = -0.253)$$

<sup>69</sup> s = 5 miles/h = 8.04 km/h ; fuel consumption = 10 miles/gallon = 0.23 liter/km

<sup>70</sup> s = 48.27 km/h ; fuel consumption = 30 miles/gallon = 0.078 liter/km



This gives us:

$$\text{For } s < 50 \text{ km/h: } \text{CO}_2 = h(q) = \lambda + \mu \cdot \alpha + \mu \cdot \beta \cdot q = 0.00234 \cdot q - 0.2111$$

$$\text{For } s > 50 \text{ km/h: } \text{CO}_2 = 0.16$$

We then can apply the number of vkms driven into each speed-class and sum it to obtain the whole quantity of CO<sub>2</sub> yearly emitted on the PRR, without forgetting the coefficient considering commercial vehicles. Since a ton of CO<sub>2</sub> can be valorized at 32 € (Conseil d'Analyse Stratégique 2008), we are able to find the environmental cost of one vkm as regards speed-classes.

*Table 9 – CO<sub>2</sub> Emissions on the PRR*

Speed (km/h)	Density (veh/km)	CO <sub>2</sub> (q) (kg/vkm)	Traffic2000 (M vkms)	Traffic2007 (M vkms)	CO <sub>2</sub> 2000 (tons)	CO <sub>2</sub> 2007 (tons)	CO <sub>2</sub> unit cost (€/vkm)
2.5	347	0.601	3.595	4.306	2,160	2,587	0.026
7.5	327	0.555	28.127	30.713	15,598	17,031	0.025
12.5	307	0.462	65.701	67.453	33,396	34,286	0.023
17.5	288	0.416	87.120	88.070	40,254	40,692	0.022
22.5	268	0.370	85.750	88.032	35,656	36,605	0.020
27.5	248	0.277	84.109	83.450	31,084	30,840	0.018
32.5	228	0.231	79.232	75.090	25,617	24,277	0.017
37.5	209	0.185	67.523	61.772	18,709	17,115	0.016
42.5	189	0.160	59.595	45.558	13,756	10,516	0.014
47.5	169	0.160	50.380	41.867	9,299	7,728	0.013
52.5	149	0.160	47.764	50.265	7,642	8,042	0.005
57.5	130	0.160	63.861	85.871	10,218	13,739	0.005
62.5	110	0.160	90.303	181.091	14,448	28,975	0.005
67.5	90	0.160	136.983	358.100	21,917	57,296	0.005
72.5	70	0.160	192.537	463.212	30,806	74,114	0.005
85.8	18	0.160	1,206.50	573.374	193,040	91,740	0.005
<b>Total</b>			<b>2,349</b>	<b>2,298</b>	<b>569,068</b>	<b>560,010</b>	

Sources: Author's calculations from Prud'homme and alii. (2009), Conseil d'Analyse Stratégique (2008).

According to Table 9, 0.56 M tons of CO<sub>2</sub> have been emitted because of PRR's use in 2007. Once valorised at 32 €/per ton, the PRR's social cost due to greenhouse effect amounts at 18 M€ (14% of the congestion waste). This guardian value of the CO<sub>2</sub> is actually higher than alternatives ones. The Stern Report (2006) advises thus to retain a value of 25 €/ton and consider that one ton was exchanged at 10 € on BlueNex, the European spot market of CO<sub>2</sub>, in

Februar 2009. With these values, the social cost of CO2 emissions on the PRR would respectively reach 14 M€ or 5.6 M€ (i.e. 11 % and 5% of congestion externality).

This methodology is also interesting for analytical purposes. In fact, it allows one to differentiate CO2 emissions as regards traffic speed<sup>71</sup> and better highlight changes. CO2 emissions on the PRR have thus weakly decreased (- 2 %) between dates. Because of the speed fall, a more important share of PRR’s traffic is nowadays realized into inferior speed-classes, i.e. the more polluting ones. This can explain the weakness of the evolution<sup>72</sup>. Above all, this methodology offers more precisions concerning CO2 unit costs.

### *Marginal taxes on the PRR*

We now present different pricing schemes for the “*regulation by prices*” on the PRR. We first consider the sole time losses, for the general case and during peak-periods (with a higher time value). We thereafter integrate (under an additive form) others external costs due to noise, accidents, greenhouse effect and pollutants (“*full taxes*”). These last ones, as in Lindsey and De Palma (2006), are drawn from Quinet (2004) and Unite (2001), except for last column of Table 11 whose CO2 unit costs are derived from the methodology presented above.

*Table 10 – External Costs linked to Noise, Accidents, Greenhouse Effect and Pollutants*

<b>Externality</b>	<b>Noise</b>	<b>Accidents</b>	<b>Pollution</b>	<b>Greenhouse</b>	<b>Total</b>
Value (€/vkm)	0.0056	0.0348	0.0422	0.0244	0.107

*Sources: Quinet (2004) and Unite (2001).*

<sup>71</sup> We do not have found any similar equation for the French case. But Renault communicated to us that, in urban areas, passing from 10 km/h to 20 km/h induced an “economy” equal to 25 %. Our estimate results in a 17 % economy, amount not so far away.

<sup>72</sup> This evolution is certainly under-evaluated. In fact, it supposes constant unit CO2 emission whereas technological progresses have made vehicles’ engines become cleaner (Airparif 2006).

Table 11 – Different Marginal Pricing Schemes for the PRR

<b>Speed (km/h)</b>	<b>General Case (€/vkm)</b>	<b>Peak-periods (€/vkm)</b>	<b>“Full Taxes” (1)<sup>g</sup> (€/vkm)</b>	<b>“Full Taxes” (2)<sup>h</sup> (€/vkm)</b>
2.5	4.046	5.315	4.153	4.155
7.5	1.316	1.707	1.423	1.423
12.5	0.767	0.993	0.874	0.872
17.5	0.530	0.685	0.637	0.634
22.5	0.392	0.506	0.499	0.495
27.5	0.305	0.394	0.412	0.407
32.5	0.327	0.422	0.435	0.427
37.5	0.197	0.254	0.304	0.295
42.5	0.159	0.204	0.266	0.256
47.5	0.127	0.163	0.234	0.222
52.5	0.103	0.132	0.210	0.191
57.5	0.080	0.102	0.187	0.168
62.5	0.062	0.079	0.169	0.150
67.5	0.046	0.059	0.153	0.134
72.5	0.033	0.041	0.140	0.121
85.8	0.000	0.000	0.107	0.095

Sources: Author's calculations from Quinet (2004), Unite (2001) and Prud'homme and alii. (2009).

Notes: g: external costs derived from Quinet (2004) and Unite (2001). h: CO2 unit costs based on Prud'homme and alii. (2009).