Parking enforcement and travel demand management

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Abstract

This article deals with the on-street non-free parking policy. The aim is to show how parking meter violation challenges the travel demand management policy. The literature widely admits that only the increase in the enforcement effort both deters drivers from offending and contribute to moderating car use. Nevertheless, the link between the parking non-compliance, the enforcement effort and the travel demand has never been examined. We show that when the parking meter violation behaviour, the fine level choice, modal split and travel demand are connected, the fine increase paradoxically supports car use and encourages parking violation in the case of large parking congestion in particular.

Keyword

Travel policy, Modal choice, Parking policy, Parking behaviour, Parking non-compliance, Enforcement effort

1. Introduction

The literature has widely shown that parking pricing is a key feature of the urban traffic policy (Button and Verhoef, 1998; Verhoef, Nijkamp and Rietveld 1995), especially when the aim is to moderate commuting (Higgins, 1992; Shoup, 1997). Yet parking meter offence is seldom dealt with. For instance, the survey by Young, Thompson and Taylor (1991) refers neither to parking violation nor to parking enforcement. However, Cullinane and Polak (1992) show how significant the volume of parking offences is, which makes it necessary to analyse both the offender's behaviour and the relevance of policies designed to deter parking offence.

Indeed in 1990, two thirds of the road offences in France were related to parking. The non-payment of the parking fees was particularly heavy. In Lyon, the vehicles for which the parking fee was not paid accounted for 80% of the parking offences in 1993 (Lyon Parc Auto, 1994). In Amsterdam, more than 50% of the commuters regularly take the risk of not paying for the parking fee and 67% of the parked hours are not paid (Mulder, 1985).

Despite the actual importance of parking meter violation, there are few theoretical studies on the question. However, since parking pricing is a part of the travel demand management policy, parking meter offence directly challenges the efficiency of the travel policy. Nevertheless, there are no rigorous analyses of enforcement effort to be applied within the framework of the travel policy.

However, the Adiv and Wang (1987) and Elliott and Wright (1982) analyses show that - as expected – the parking non-compliance level increases as the enforcement effort decreases. This result is obtained by considering that from the driver's point of view, illegal parking is one category of parking supply among several others. The parking choice is made as a rational economic choice (as a portfolio choice). The driver assesses the expected illegal parking cost (taking into account the enforcement probability and the fine level) *versus* certain legal parking cost (taking into account the parking charge only). The calculus includes walking time from parking to final destination but *excludes the travel demand context as traffic level or parking congestion*. Then, the driver opts for the "cheapest" alternative between illegal and legal parking. That theoretical result is empirically confirmed by both American (Adiv and Wang, 1987) and English (Elliott and Wright, 1982) data. Consequently, it seems to be an accepted fact that an increase in the enforcement effort deters parking offence.

The aim of this article is to show that the planner should not trust that single relation between enforcement effort and non-compliance insofar as he assumes no link between the parking violation behaviour and travel demand. Actually, there are no answers concerning the impact of a fine increase on travel demand. Moreover, given the relation between a parking fee increase and travel demand, it is not obvious whether a fine increase is really the best answer to reduce car use when drivers do not pay for parking. Indeed, the Glazer and Niskanen (1992) and Arnott and Rowse (1999) analyses show that an increase in parking charge may yield an increase in parking turnover, which creates an additional parking supply and supports driving demand. Against all odds, parking fee increase reinforces both parking congestion and road congestion. Therefore, without a rigorous theoretical analysis concerning the impacts of the enforcement effort variation on travel demand, it is not reasonable to state that such an effect does not exist when the fine increases.

We recall in section 2 the aims of the parking pricing policy. Section 3 shows to what extent parking meter violation challenges travel policy. Section 4 presents some arguments against the consensus in favour of a systematic fine increase. In particular, we show that the financial outlook should be distinguished from an economic approach when the aim of the parking policy is to contribute to the travel demand management. Section 5 presents the main results of an economic analysis showing that a fine increase implies a growth in road congestion and encourages non-compliance. We suggest further developments in a conclusive point

2. The parking pricing policy

2.1. The theoretical foundations

According to Calthrop, Proost and van Dender (2000), there exist two sources of inefficiency in urban transport. First, the driving cost does not reflect the actual travel cost. This market failure is dealt with road pricing. Secondly, few individuals pay for parking. Shoup (1995) underlines that the free parking policy in the United States is generally much more implemented than parking controls. Rennes and Orfeuil (1997) assess to 37% the charged on-street parking supply in Paris only.

However, the Verhoef, Nijkamp and Rietveld (1995) analysis proves the theoretical role of parking pricing in the traffic regulation policy. When the travel cost reaches the level where the marginal social cost equals the marginal private benefit, the social travel costs are internalised and the travel demand reaches a Pareto optimal level. In particular, the total marginal social cost adds the parking social cost to the marginal social cost, which leads to reduce the optimal number of trips. Thus, the travel pricing level should apply both to road traffic and parking. Different kinds of argumentation may justify the parking pricing implementation. We rank here these arguments with respect to three possible theoretical outlooks:

- *Parking pricing moderates road traffic but it is to be distinguished from traditional tolls*. The parking price aim is not only to cover the parking social costs, but it is also to constrain demand so as to yield an optimal allocation of resources. The public road system is "a scarce resource" and pricing is a way of giving it a price. Then, from the point of view of Bonnafous (1991) and Button (1982), parking pricing is "a soft toll" – *i.e.* easier to implement and, according to Arnott, de Palma and Lindsey (1991), a more acceptable toll for commuters than road pricing. Moreover, it provides funds for investments in parking supply.
- *Parking pricing yields a second-best optimum on the trip market when no road pricing*. This conclusion has been largely developed in Verhoef, Nijkamp and Rietveld (1995) and Button and Verhoef (1998). When traffic is not priced, drivers express demand for trips according to their private cost only without considering the marginal social cost. In economic terms, the travel market is thus inefficient. Therefore, according to Small (1992), it seems natural to conclude that free parking exacerbates this under-priced driving. Then, a parking fee equal to the marginal social cost would at least regulate parking demand. In this way, parking pricing may lead to achieve a second-best on the travel market by internalising parking externalities. Nevertheless, Glazer and Niskanen (1992) show that if parking pricing reduces the driver’s welfare by curtailing his parking time, the number of drivers being able to park increases. The new drivers’ benefits may overall exceed the losses of the already parked drivers in particular when, all other thing being equal, the marginal utility of the new parking users exceeds the willingness to pay of the already parked users. Therefore, parking

pricing may generate a net social welfare increase. In this way, according to the terms used by Schaefer (1994), parking pricing becomes a "trip-end toll".

- *Parking pricing may be theoretically regarded as an efficient traffic management tool as well as road pricing*. In the absence of road pricing, parking pricing could internalise all the trip-related costs. Parking pricing would therefore yield a first-best optimum. Drivers would be led to pay the actual parking cost - *i.e.* all the social costs related to parking including the trip costs upstream from parking. Nevertheless, Verhoef, Nijkamp and Rietveld, (1995) show that parking pricing cannot compete with road pricing in terms of efficiency. Indeed, road pricing maximises the social welfare as it varies according to the trip characteristics - *i.e.* trip length, travel time, route choice, *etc*. These characteristics determine the marginal social cost of travel. On the other hand, parking pricing only acts upon the number of trips and modal choice, but never upon route choice or trip length. Consequently, if intellectually parking pricing is potentially able to yield a social optimum, it is to be admitted that parking being located at the end of a trip, it cannot internalise the external costs upstream parking. One efficient solution is to charge all the average traffic cost externalities. However, Verhoef, Nijkamp and Rietveld (1995) illustrate the inefficiency of that last solution. For example, a part of the parking fees could correspond to the average external costs due to chemical effluents. Such a pricing would appear as a grant to the benefit of the longest trips which throw out the most effluents into the atmosphere to the detriment of least polluting trips. Although the two kinds of trips would decrease indeed, this tax would be socially inefficient. Finally, according to the authors, this example shows that parking pricing is efficient if the travel externality internalised is road congestion only.

2.2. Parking pricing and traffic regulation

Although parking pricing may yield a social optimum on the urban trip market, some restrictions are necessary to ensure success. Assuming that parking pricing has an impact on modal split, Gillen (1977) analyses the opportunity to substitute road pricing to parking pricing. He shows that, *ceteris paribus*, a parking fee variation has a rather low impact on modal choice (its elasticity measure of the driving demand with respect to the parking fee amounts to – 0,31). Even though this analysis is dated, its conclusion remains interesting and it is confirmed by recent analyses (see K.T. Analytics, 1995; Shaw, 1997; Pratt, 1999). They indicate that the elasticity of parking varies typically between - 0.1 and – 0.3, with significant variation depending on demographic, geographic, travel choice and trip characteristics. Hensher and King (2001) also predict how an increase in parking prices in one location will shift cars to park at other locations, or travellers to shift to public transit (conclusion coming from cross-elasticity analyses). So, drivers faced with the parking fee increase may indeed switch to another trip mode or change their parking mode. Motorists substitute a relocation of their parking place for a modal shift. Only drivers already parked far from their final destination switch to another transportation mode. Moreover, the elasticity decreases with the distance to the city centre, simply because demand is lower there. Therefore, Gillen (1978) emphasises an overflow effect of parking pricing since, for a given distance, parking congestion is moved towards periphery. An efficient parking pricing must be continuous on a broad urban area (Gillen, 1977). Thus, according to Button (1998), if parking pricing may have effects on traffic, it also has an impact on space use. For example, Arnott, de Palma and

Lindsey (1991) show that the optimal parking pricing, which differs according to the parking location, partially reduces congestion. To lower their travel cost, drivers do not change their transportation mode, but try to park further indeed. The authors conclude then that the benefit in traffic management remains finally relatively poor.

Generally speaking, the social optimum seems to be obtained by combining parking pricing and road pricing. Calthrop, Proost and van Dender (2000) show that this couple of policies used in a complementary way is the best way of yielding an optimum. Their theoretical simulations allow to conclude that both the parking pricing level and the road pricing level must be determined simultaneously. For Van der Waerden, Borgers and Timmermans (1998), an efficient policy should be a mixture between road pricing and parking pricing. They show that this solution makes it possible to collect more than three quarters of the maximum potential welfare. This result comes from the fact that, on the one hand, parking pricing eliminates the inefficiency stemming from the parking market failures but, on the other hand, road pricing cuts down travel congestion. So, for the authors, this policy remains advantageous because road pricing does not tax the within city trips whereas parking pricing taxes the city centre trips.

Nevertheless, the Glazer and Niskanen (1992) model shows that in theory, if parking pricing is likely to increase the overall drivers' surplus, this increase in parking fee cuts each driver's parking time. Consequently, the parking time reduction generates an higher parking turnover and leads to increase parking supply. So, the increase in parking charge may contribute to increase both traffic demand and road congestion.

To conclude, parking pricing is theoretically an actual tool of travel management but its economic efficiency remains relative and it should go with road pricing. Yet, parking policy is to play a part in the traffic calming policy only if it is assumed that drivers comply with the parking tariff constraints. Under the opposite assumption, what would then be the role of parking meter offences in the travel policy? Which parking enforcement effort would it be necessary to implement to reach the aims of the travel policy?

3. Parking meter violation and urban mobility

Given the role played by parking pricing in travel policy, parking meter violation interferes in the expected results of pricing policy. *In economic terms*, the problem lies in the interdependence between parking fee, enforcement effort, parking non-compliance and travel demand. This interdependence turns parking enforcement into a real tool of the travel regulation policy. Therefore, both pricing and enforcement effort influence the efficiency of parking policy on the one hand, and, on the other hand, the success of traffic management.

Given the relative scarcity of empirical studies considering the specific impact of parking offences on mobility, one cannot say that the analysis of parking meter violation is a priority in the implementation of an effective travel policy. Nevertheless, a few studies provide facts and clues for further studies.

In London, half of the reduction in the total travel speed downtown is due to parking offences (Elliott and Bursey, 1979). Assuming full enforcement, the reduction in the trip length in the urban area would have amounted to 20%. May (1985) shows that parking non-compliance induces higher traffic and additional congestion. In addition, Rigby (1983) highlights that the road congestion induced by the parking non-compliance penalises the quality of urban transit.

Indeed, parking non-compliance really seems to influence mobility. However, those data are quite old. Therefore, the lack of recent works seems to prove that there exists a consensus on the link between parking non-compliance and mobility: parking violation stimulates both car use and congestion. From the viewpoint of road traffic management, the only policy to be applied is the increase in the enforcement effort, in particular the fine increase. Yet, no rigorous theoretical analyses related to the economic determinants of parking meter violation make it possible to draw such a conclusion. Therefore, it seems necessary to study the economic determinants of the parking meter violation behaviour. From such an analysis, we should be able to state on the impact of the fine increase both on non-compliance and driving demand.

A first determinant seems to be the low degree of monitoring, control and repression. The figures are explicit. In Paris, out of 100 cars in parking offence, 9 are fined (Dupuy, 1995). In Lyon, 7.6% of the offences are fined (LPA, 1994) and 6% of the vehicles not paying for the parking fee are fined. Those figures seem to be explained by the 25% fall in the number of tickets per place and per month for parking offences in France between 1985 to 1995. The decrease seems to be explained by the 20% increase in the number of places per traffic warden who enforced parking controls over the same period (Perrière, 1997). Therefore, it seems easy to connect the importance of parking non-compliance with an enforcement effort decrease.

Then, the answer which is generally given to the question of the main determinant of parking meter violation is the weakness of the enforcement effort. As far as the travel policy is concerned, the argument is the following. If the aim is to fight against parking offence to ensure the efficiency of parking pricing, it is advisable to reinforce the enforcement effort, in particular the amount of the fine, so that the driver may think he had better pay for the parking fee.

However, Adiv and Wang (1987) underline the lack of knowledge concerning the individual behaviour as regards parking meter. In particular, they underline the lack of analyses dealing specifically with the elasticity of the offending parking demand with respect to both parking fee and enforcement effort. Consequently, *no one can state that the behaviour of an individual faced with an increase in the enforcement effort is systematically to comply with parking regulations.* This is the reason why May (1982) claims for a better knowledge of the individuals' reactions to the enforcement effort so as to adapt repression measures which are compatible with the aims of travel management. Moreover, *there are no studies stating that an increase in the enforcement effort has a positive effect on car use*. The main problem is that there are no analyses dealing with the relation between parking non-compliance, enforcement effort and road congestion.

4. The increase in the enforcement effort: not really a good answer

The financial loss derived from the offences for the parking supply manager justifies fighting against parking non-compliance. According to a report by the French Ministry of Transportation, the average rate of payment of the parking fee is about 200 to 900 hours per place over a year in French cities (DRAST, 1998) while a well respected non-free parking should generate 1 200 hours paid per place per year.

Half the parking supply is considered to be profitable only (Bernard, Carles, 1999). According to the authors, it seems urgent to increase the enforcement effort.

Yet, several remarks challenge this logic. First of all, there is no reason to think that the criterion of the parking profitability may be a sufficient argument. Admittedly, it is reasonable to advance that parking managers have a private advantage in the parking supply being profitable. Nevertheless, *in economic terms*, achieving a higher profitability is not a relevant argument to conclude that the increase in the enforcement effort has a positive impact on the traffic calming policy.

The second remark comes from a comparison which can be established between the effect of a parking fee increase and an enforcement effort increase. The theoretical results of the Glazer and Niskanen (1992) queuing model show that a parking fee increase may cause an increase in road congestion. Indeed, the authors show that a parking fee increase induces each driver to park for a shorter time. So, the increase in the parking charge contributes to arise the parking supply use contributing finally to create an additional parking supply. Thereby the parking charge increase means heavier traffic. In the same way, nothing justifies claiming that an enforcement effort increase automatically results in reducing car use.

Nevertheless, assuming that parking meter non-compliance is actually explained by the enforcement effort decrease, Perrière (1998) affirms that the fine level is not a sufficient incentive for the parking pricing compliance. Perrière (1997) notices that the on-street parking fine in France was equivalent to 10 parked hours in 1995 while it was equivalent to 20 parked hours in 1985. So, according to Perrière (1998), considering the mechanism fixing the fine level for the Parisian transit system - 24 times the average travel fare - the same logic should govern the calculation of the fine for parking meter violation. From 11 euros, the parking fine should pass to 30 euros – *i.e.* 24 times the one hour parking fee in France. This statement seems really questionable and, without relevant economic arguments, it must be opposed that there is no reason for comparing the parking market with the Parisian transit market. For example, it does not make sense to conclude that the elasticity of offences to enforcement effort is identical on the two markets.

Considering the general arguments justifying the fine increase, it should be acknowledged that nothing actually proves that such a policy is economically relevant. *Without a rigorous analysis of the parking violation behaviour, it can not be concluded that the fine increase deters parking violation and calms traffic automatically*. Consequently, given the role of parking in travel demand, it is necessary to deal with the question of the offending parking enforcement with the analysis of the link between parking non-compliance and travel demand.

5. The analysis of the parking meter violation behaviour: some unexpected results

5.1. A parking meter violation model

In the face the deadlock of parking enforcement with regards to the aims of travel policy, a theoretical representation of the non-compliance behaviour may lead to some sort of conclusion. The aim is to understand the individual non-compliance behaviour to improve enforcement effort.

This analysis rests on a parking behaviour model (Arnott and Rowse, 1999) presented in Appendix 1. Although this model does not deal with the question of non-compliance, it formalises the link between parking conditions and travel demand. It shows how a parking pricing that internalises parking congestion changes the structure of travel demand[1]. Such a formalisation is a coherent theoretical framework for integrating the question of parking meter violation.

Formally, the model shows the existence of a social optimum of parking. In the case of low parking congestion, the implementation of parking pricing decentralises the social optimum by internalising parking congestion. Besides, the model shows that there is an impact of parking conditions - *i.e.* congestion and parking fee - on modal share and on travel demand. More precisely, in the case of very high parking congestion, the equilibrium fee does not decentralise the social optimum. Arnott and Rowse (1999) then consider a parking fee variation. In this high congestion state, a parking fee increase reduces congestion in such a way that it paradoxically favours car use confirming then the results of the Glazer and Niskanen (1992) analysis.

A development of the Arnott and Rowse (1999) model founded on *the economics of crime* (Becker, 1968) integrates the parking meter non-compliance behaviour (Petiot, 2000, 2002). Briefly, the driver chooses whether to pay or not to pay for the parking fee when he parks. If he does not pay, he faces the risk of a monetary sanction. If he is controlled, he pays for a fine which deteriorates the welfare he gets. If he pays for the parking fee, he gets the welfare produced by his parking minus the

1 In the Arnott and Rowse (1999) model, commuter chooses between travel or not from home to destination in order to realise an activity. He chooses to travel comparing the total travel cost (which depends on the total travel time) to the utility provided by the activity. If he decides to travel, he chooses to walk or to drive with respect to the total travel time for each mode of transport. The total travel time by car is equal to the travel time (including the time for searching a parking place) and the parking time. The higher the parking congestion, the longer it takes to find a parking place. So, the total travel time by car increases with respect to the parking congestion.

fee. From the agent's viewpoint, the model assumes therefore that *the offending parking is a rational economic choice*. A traditional cost-benefit calculation between the payment and the non-payment of the parking fee determines the agent's choice. The agent rationally chooses the option which gets him the maximum of welfare. He compares the expected benefit he gets when he chooses not to pay with the certain benefit he gets when he chooses to pay for the parking fee. He chooses the option which curtails his expected travel cost. The purpose of the sanction is to make the fined offender bear the cost of the externality of congestion he generates when he parks but which he refuses to bear when not paying. Either the agent pays for the optimal parking fee and takes part in the internalisation of the parking externality process or he offends and does not contribute to this process if he is not controlled. When the driver is convicted guilty, he must pay for a fine whose level internalises the externality of congestion he generates while parking. When paying for the fine, the agent bears all the external costs he generates while parking, proportionally to the probability of being controlled.

For the purposes of analysis, we make a number of hypotheses:

- *Parking is assumed to be legal*. The illegality involved is merely the non-payment of parking. It is interesting to see to what extent failure to pay parking fees directly reduces the ability of parking fees to restrict car use by modifying modal split and the level of travel. In this case, the fine has the same function for the person who does not pay the parking fee as the parking fee does for the person who pays – *i.e.* it makes them bear the social costs their travel generates;
- *When apprehended a non-payer will automatically be prosecuted.* The situation where the non-payer is apprehended without being prosecuted is not considered, neither is the situation where the non-payer is prosecuted only after being

apprehended several times. The probability of being apprehended and the probability of being punished are therefore the same;

- *The duration of stay without paying the fee is the same as the length of time required to perform the activity*. Non-paying parking involving a different time from that required to perform the activity is therefore not considered, and neither is the situation where drivers park for longer than they have paid for. When the driver parks he only considers the duration of stay necessary to perform his activity. The decision to pay or not to pay the parking fee is made by considering the probability of being punished solely during this time;
- *The probability of punishment remains constant over the time it takes to perform the activity*. It does not depend on the duration of stay to the extent that the driver parks throughout this period and only during this period. When making a decision, the driver therefore makes a calculation on the basis of the duration of stay required for the activity. The probability of being apprehended is discreet over this period and it is assumed to be known by the driver. Furthermore, *the fine is a lump sum*. The case of a fine that depends on the duration of stay is not considered. This conforms with reality and simplifies the calculations;
- *The user's choice does not depend on the cost of enforcement.* The purpose of the model is not to determine an optimum level of parking meter violations and enforcement, but, less ambitiously, to analyse the behaviour of those committing parking meter violations;
- *The model only considers the behaviour of a risk-neutral driver.* It is obvious that analysis should consider the heterogeneity of driver behaviours with regard to risk. However, the purpose of this paper is to model the behaviour of the risk-

neutral driver sufficiently accurately to provide a basis for future developments which will deal with different levels of risk aversion.

Let A denote the “fee non-payment” decision. For this action, the states of nature are “*apprehended and punished*” and “*not apprehended*”. The consequences of these states of nature are respectively “*obtaining the satisfaction provided by parking net of the fine*” and “*obtaining the satisfaction provided by parking*”. A discreet random variable Q_j links the two random events, Q_1 "being apprehended and punished” and Q_2 "not being apprehended ". It ascribes what is assumed to be a fixed probability distribution of being apprehended to the user $q_{j,j=1,2}$ such that $0 \leq q_j \leq 1$ where $\sum_j q_j = 1$.

Within the Arnott and Rowse (1999) model framework, if the driver does not pay the parking fee, the mean monetary benefit derived from the trip is expressed by $q(\beta - F((\bar{x}_A - \tilde{x}_A)/\bar{x}_A)) + (1-q)\beta$, where $\bar{x}_A$ is *the maximum mean travel distance accepted by non-payers*, $\tilde{x}_A$ is *the maximum walking distance accepted by non-payers*, β is the monetary benefit derived from the trip and F is the level of the fine. The first term of the expression is the mean benefit derived from the decision not to pay the fee when the driver is punished. In this case, the satisfaction is equal to the gross gain provided by the activity at the destination minus the fine. The fine is weighed by the proportion of trips made which actually generate parking - *i.e.* $((\bar{x}_A - \tilde{x}_A)/\bar{x}_A)$ the modal share of driving. The mean satisfaction of the punished non-payer is weighted by the probability q of being prosecuted. The second term expresses the benefit derived from the decision to park without paying the fee if the driver is not apprehended. This is the mean level of satisfaction of the unpunished non-payer, that is to say the gross gain generated by the trip, weighed by the probability $(1-q)$ of not being prosecuted. The user derives no additional satisfaction from the pleasure of not paying the fee. The benefit received by the unpunished non-payer is the gross benefit derived from the trip.

When the behaviour of a risk-neutral driver is represented by a linear increasing utility function of the type $U(x)=x$, the non-payer maximises the trip's hourly expected utility, which is expressed as follows:

$$\max_{\bar{x}_A,\tilde{x}_A,d_A} EU_A = q\left(\frac{\beta - F\left((\bar{x}_A-\tilde{x}_A)/\bar{x}_A\right)}{L_A}\right)+(1-q)\left(\frac{\beta}{L_A}\right), \qquad (1)$$

where $F>0$, and L_A is the total travel time of non-payers.

If we state that $\Delta \equiv L_A\,\bar{x}_A$ and $\mathrm{X}_A = \beta - F\left((\bar{x}_A-\tilde{x}_A)/\bar{x}_A\right)$, d_A *is the distance the non-paying driver cruises to find a parking space,* T_1 is the travel time if the trip is made by foot and T_2 is the travel time if the trip is made by car (see Appendix 1), the first order conditions are as follows:

$$\frac{\partial EU_A}{\partial \tilde{x}_A} = \frac{1}{\Delta_A}\left[q\left(F-\frac{\mathrm{X}_A}{L_A}(T_1-T_2)\right)+(1-q)\left(\frac{-\beta}{L_A}(T_1-T_2)\right)\right]=0; \qquad (2a)$$

$$\frac{\partial EU_A}{\partial \bar{x}_A} = \frac{1}{\Delta_A}\left[q\left(\beta-F-\frac{\mathrm{X}_A}{L_A}(T_2+l)\right)+(1-q)\left(\beta-\frac{\beta}{L_A}(T_2+l)\right)\right]=0; \qquad (2b)$$

$$\frac{\partial EU_A}{\partial d_A} = -\frac{1}{\Delta_A}\left[q\frac{\mathrm{X}_A}{L_A}\left(\frac{\partial T_2}{\partial d_A}\right)-(1-q)\frac{\beta}{L_A}\left(\frac{\partial T_2}{\partial d_A}\right)\right]=0. \qquad (2c)$$

Equation (2a) indicates that the non-payer selects a value for $\tilde{x}_A$ which will lead to the use of a transport mode which minimises the expected cost of the trip. Equation (2b) means that the non-payer selects $\bar{x}_A$ so that the trip by car provides an expected benefit which covers the opportunity cost of the trip. Lastly, equation (2c) shows that the non-payer selects the cruise distance in order to look for a parking space d_A so that the value of the time spent walking to the destination does not exceed the opportunity cost of making the trip by car.

We shall identify certain theoretical states of congestion for which an increase in the parking fine leads to a reduction in satisfaction which is smaller than the increase in satisfaction derived from the reduction in the parking time caused by an increase in the fine. In order for this kind of situation to exist, the marginal utility of parking time must be greater than the marginal disutility of the fine. Furthermore, if the effect that the change in the parking time has on the change in the utility is greater than the effect of the change in the fine on the change in utility, that is to say if:

$$\varepsilon_{W_A} = \frac{\partial EU_A}{EU_A} \bigg/ \frac{\partial W}{W} > \frac{\partial EU_A}{EU_A} \bigg/ \frac{\partial F}{F} = \varepsilon_F \,, \qquad (3)$$

then the reduction in the parking time, with a constant parking fee, will provide an increase in satisfaction which is greater than the reduction in satisfaction that results from the increase in the fine. If these conditions are satisfied, the impact of a change in the fine on the travel time is such that a benefit is derived from non-payment of the fee. *So, theoretically, there are actually situations in which an increase in the fine encourages non-payment of parking fees*. This casts doubt on the idea that an increase in enforcement automatically deters illegal parking. The confusion comes from the fact that it is general practice to ignore the fact that a change in the level of the fine can have an impact on the parking turnover rate, therefore on the parking time and travel time.

If now we denote the decision "*to pay the parking fee*" by $\bar{A}$, there is only one certain outcome, which is "*obtaining the satisfaction provided by parking net of the parking fee*". The monetary benefit derived from the trip is expressed by $\left(\beta - p\left(\left(\bar{x}_{\bar{A}} - \tilde{x}_{\bar{A}}\right)/\bar{x}_{\bar{A}}\right)\left(W_{\bar{A}}\left(P, d_{\bar{A}}\right) + l\right)\right)$ where $\bar{x}_{\bar{A}}$ is the mean maximum travel distance for those paying the fee, where $\bar{x}_{\bar{A}}$ is the mean maximum distance of travel accepted by those paying the fee, $\tilde{x}_{\bar{A}}$ is the mean maximum walking distance accepted by those not paying the fee, $\tilde{x}_{\bar{A}}$ is the mean maximum walking distance accepted by those paying the fee, l is the duration of the activity in question, $\left(W_{\bar{A}}(P,d_{\bar{A}})+l\right)$ is the mean parking time for those paying the fee and p is the hourly parking fee (see Appendix 1).

Those paying the fee maximise their expected hourly utility, which is certain:

$$\max_{\bar{x}_{\bar{A}},\tilde{x}_{\bar{A}},d_{\bar{A}}} EU_{\bar{A}} = \frac{\beta - p\left(\left(\bar{x}_{\bar{A}}-\tilde{x}_{\bar{A}}\right)/\bar{x}_{\bar{A}}\right)\left(W_{\bar{A}}(P,d_{\bar{A}})+l\right)}{L_{\bar{A}}}, \tag{4}$$

where $L_{\bar{A}}$ is the total travel time of users who pay the parking fee.

If $\Delta_{\bar{A}} \equiv L_{\bar{A}}\,\bar{x}_{\bar{A}}$, $\mathrm{X}_{\bar{A}} \equiv \beta - p\left(\left(\bar{x}_{\bar{A}}-\tilde{x}_{\bar{A}}\right)/\bar{x}_{\bar{A}}\right)\left(W_{\bar{A}}(P,d_{\bar{A}})+l\right)$ where $d_{\bar{A}}$ is the distance a person paying the parking fee cruises for parking, the first order conditions are:

$$\frac{\partial EU_{\bar{A}}}{\partial \tilde{x}_{\bar{A}}} = \frac{1}{\Delta_{\bar{A}}}\left[p\left(W_{\bar{A}}(P,d_{\bar{A}})+l\right) - \frac{\mathrm{X}_{\bar{A}}}{L_{\bar{A}}}\left(T_1 - T_2\right)\right] = 0\,; \tag{5a}$$

$$\frac{\partial EU_{\bar{A}}}{\partial \bar{x}_{\bar{A}}} = \frac{1}{\Delta_{\bar{A}}}\left[\beta - p\left(W_{\bar{A}}(P,d_{\bar{A}})+l\right) - \frac{\mathrm{X}_{\bar{A}}}{L_{\bar{A}}}\left(T_2 + l\right)\right] = 0\,; \tag{5b}$$

$$\frac{\partial EU_{\bar{A}}}{\partial d_{\bar{A}}} = \frac{\left(\bar{x}_{\bar{A}}-\tilde{x}_{\bar{A}}\right)}{\Delta_{\bar{A}}}\left[-p\frac{\partial\left(W_{\bar{A}}(P,d_{\bar{A}})\right)}{\partial d_{\bar{A}}} - \frac{\mathrm{X}_{\bar{A}}}{L_{\bar{A}}}\frac{\partial T_2}{\partial d_{\bar{A}}}\right] = 0\,. \tag{5c}$$

Equation (5a) indicates that the driver who pays the fee chooses $\tilde{x}_{\bar{A}}$ in order to select the mode with the lowest cost. Equation (5b) means that a trip is only accepted by those who pay the fee when the opportunity cost of travel time does not exceed the net benefit provided by the trip for the selected value of $\bar{x}_{\bar{A}}$. Lastly, equation (5c) indicates that the selected distance the driver cruises for parking $d_{\bar{A}}$ prevents the value of the walking time to the destination from exceeding the opportunity cost of the total travel time.

The driver's decision involves selecting A or $\overline{A}$ on the basis of a choice between the expected benefit and the certain benefit of paying the parking fee. If we apply the Von-Neumann and Morgenstern (1944) expected utility maximisation criterion, the optimum choice of the risk-neutral driver, denoted by I, is written as follows:

$$EU(I) = \max_{\overline{x}_A, \tilde{x}_A, d_A, \overline{x}_{\overline{A}}, \tilde{x}_{\overline{A}}, d_{\overline{A}}} \left\{ EU(A); EU(\overline{A}) \right\}. \tag{6}$$

The driver derives greater satisfaction from not paying as opposed to paying the parking fee if the expected utility of non-payment is higher than the utility of payment.

We can therefore calculate the equilibrium parking fine on the basis of the approach described by Arnott and Rowse (1999) which lets us assess an optimum price which minimises the total mean travel time. The purpose of the punishment is to ensure that those who do not pay the parking fee pay for the congestion externality that their parking generates and which they attempt to avoid by not paying the parking fee. When non-payers are apprehended, they must pay a fine. It seems obvious that when paying the fine drivers should pay for all the external costs which they generate by parking, in proportion to the probability of their being apprehended.

The equilibrium fine F^e is calculated by combining the social optimum equilibrium conditions (equation system (A7a) – (A7d) in Appendix 1) and the non-payer equilibrium conditions equation system (2a) – (2c). The equilibrium fine, in the case of an exogenous probability of apprehension q, is expressed as follows:

$$F^e = \frac{\beta \ E^*\left(W^* + l\right)}{q\left[L^* + E^*\left(\left(\overline{x}^* - \tilde{x}^*\right)/\overline{x}^*\right)\left(W^* + l\right)\right]}, \tag{7}$$

where E^* is the externality at the optimum. The optimum fee is then:

$$p^* = \frac{E^* \beta}{L^* + E^*\left(\left(\overline{x}^* - \tilde{x}^*\right)/\overline{x}^*\right)\left(W^* + l\right)}. \tag{8}$$

By substituting (8) in (7), we express the lump sum equilibrium fine as follows:

$$F^e = \frac{p^*\left(W^* + l\right)}{q}. \qquad (7')$$

5.2. The theoretical results

For a risk-neutral agent, the model shows that *there are theoretical states of congestion for which the fine increase favours both non-compliance and car use*. In those states, the fine increase involves a decrease in commuter welfare which is less significant than the welfare increase produced by the parking time reduction. The necessary condition is that the marginal disutility of parking time is higher than the marginal disutility of the fine. Moreover, the effect of the parking time variation on the commuter welfare is stronger than the effect of the fine variation (this condition is expressed by equ. 4). For a constant fee, the fine increase may produce an advantageous decrease in the parking time.

Under those conditions, the fine increase has such an impact over the total travel time – in particular over the parking time – that driving and not paying for the parking fee become the most advantageous choice. Theoretically, a profitable impact of the fine increase on the decision to offend is possible. This result challenges the idea that the enforcement effort increase has both an automatic deterrent effect on the non-compliance choice and a positive effect on driving. The error comes from the fact that the question of the possible impact of the fine on the occupancy rate of the parking supply – *i.e.* over the parking time - is generally ignored.

The theoretical simulations of the model show that in the case of hypercongestion of parking, with a fixed optimal fee, if the commuter offends, the fine increase initially discourages driving. But, as the fine increase contributes to reducing the congestion level, driving becomes more advantageous.

The welfare decrease resulting from the fine increase is largely compensated by the welfare increase resulting from the individual expected travel time benefit. Expressing the maximum accepted walking distance –a modal share indicator[2] – as a function of the fine, the simulations show that the maximum walking distance decreases with the fine (Fig. 1). In other words, the increase in parking fee boosts driving. Despite the fine increase, the effect of this increase on the commuter's welfare is more than compensated by the effect of the travel time benefit. Therefore, in the hypercongestion state presented here, the more the enforcement effort increases, the greater is the advantage the risk-neutral commuter gets from driving and not paying for the parking fee.

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[2] In the model (see Appendix 1), $\tilde{x}.$ is the maximum accepted walking distance and $\bar{x}.$ the maximum accepted journey distance. The expression $\frac{(\tilde{x}. - \bar{x}.)}{\bar{x}.}$ represents the modal share of driving and $\tilde{x}.$ may be therefore considered as an expression of the modal share of walking.

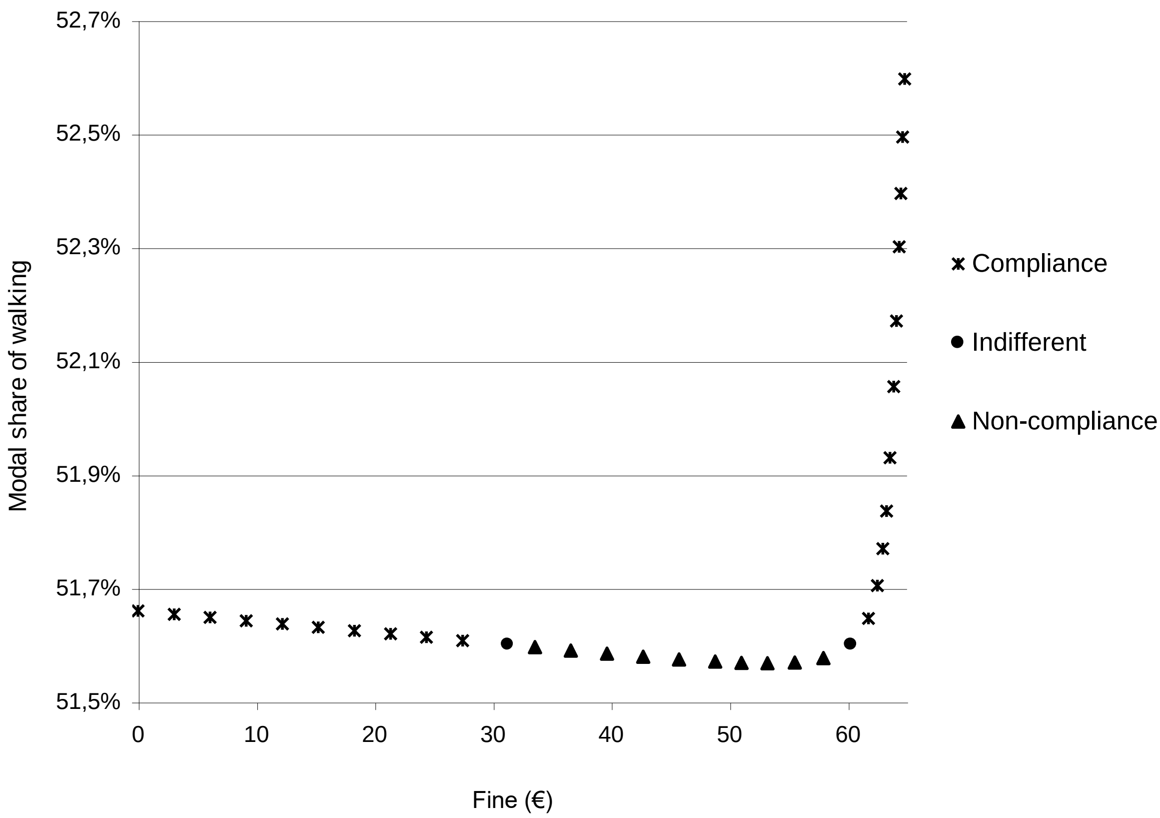

Fig. 1. Modal share of walking with respect to fine level (hypercongestion state of parking)[3]

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3 In this simulation, parameterisation has been based on the French travel context (Madre and Maffre, 1995). The activity length is fixed to 5.5 hours and 30 minutes. The values have been selected such that the longest outward trip does not exceed 5.3 kilometres. We have assumed a population density of 2 678.26 inhabitants per km^2. The parking space density is 125 spaces per km^2. Walking speed has been fixed at 5 km per hour. The speed by car has been fixed at 13.4 km/h. The working time value is equal to 12.31 euros. The probability of control for this parking time amounts to 11%. At the social optimum, the congestion rate amounts to 93.8% and the average parking time amounts to 5 hours and 32 minutes. Each parked commuter produce a social travel time loss equals to 39 minutes. Without pricing, the rate of vacant parking places amounts to 0.34%. The optimal fee internalising the parking externality amounts to 1.2 euros per hour of parking. Therefore, each parking user should pay 6.63 euros for the total parking time.

For a fine of less than 31.26 euros (See Appendix 2), the utility derived from the decision to pay the parking fee is greater than the expected utility of the decision not to $\left(EU_A / EU_{\bar{A}} < 1\right)$. In this case, it is therefore more advantageous for the driver to pay the parking fee. However, the non-payer's expected satisfaction increases with the level of the fine. This first paradox is a consequence of the contrasting effects which an increase in the fine has on the expected utility of the non-payer and on the non-payer's travel time. An increase in the level of the fine directly reduces the non-payer's expected satisfaction $\left(\partial EU_A / \partial F < 0\right)$. It nevertheless leads to a reduction in the parking space occupancy rate. Drivers therefore find a parking space nearer to their final destination. The reduction in the time spent walking from the parking space to the destination (W_A) therefore increases the non-payer's expected utility ($\partial EU_A / \partial W_A < 0$ but the effect is positive as $\partial W_A < 0$). However, the change in the expected utility which results from the reduction in the duration of parking is greater than the change in the expected utility that results from the increase in the fine $\left(\partial EU_A / \partial F < \partial EU_A / \partial W_A\right)$. In other terms, *the marginal disutility of the fine is more than compensated for by the marginal utility of the parking time*. Ultimately, non-payers lose less from an increase in the fine than they gain from a reduction in parking time caused by the increase in the fine. Overall, an increase in the fine is responsible for an increase in the expected satisfaction of non-payers. When the parking fine amounts to 31.26 euros, it makes no difference to users whether they pay the parking fee or not ($EU_A / EU_{\bar{A}} = 1$).

Between 31.26 euros and 53.19 euros, an increase in the fine always encourages car use. Furthermore, it becomes advantageous not to pay the parking fee $\left(EU_A / EU_{\bar{A}} > 1\right)$. Above 31.26 euros, the increase in the fine therefore encourages the driver not to pay the parking fee. In addition, when the fine is set at 53.19 euros, non-payers maximise their expected satisfaction. This second paradox can also be explained by the effect of an increase in the fine on parking time. Between 31.26 euros and 53.19 euros, the parking occupancy rate falls from 99.34% to 97.95%. Parking time therefore falls by approximately 15 minutes and cruise time for looking for parking by approximately 4 minutes. Consequently, the time saving leads to an increase in the number of accepted trips ($\Delta\bar{x}_A = +0{,}10\%$) and a drop in the number of walking trips ($\Delta\tilde{x}_A = -0{,}06\%$). Here too, an increase in the fine encourages car use. Furthermore, the reduction in the travel time is such that the expected gain becomes greater than the certain gain which is derived from paying the parking fee.

Between 53.19 euros and 60.27 euros, it is advantageous not to pay the parking fee up to a fine of 60.27 euros at which price the driver again becomes indifferent to paying the parking fee or not $\left(EU_A / EU_{\bar{A}} = 1\right)$. The non-payer's expected utility falls as the fine rises. The non-payer continues to gain walking time and cruise time for looking for parking because the parking occupancy rate falls from 97.95% to 93.86%. However, these time savings no longer make up for the direct loss caused by the increase in the fine. This now discourages car use. While it is true that the effect of the change in duration of stay on the non-payer's satisfaction remains positive $\left(\varepsilon_{W_A} = 0{,}0002\right)$, it is now lower than the negative effect that the change in the fine has on the non-payer's satisfaction $\left(\varepsilon_F = -0{,}0051\right)$. However, the non-payer's expected gain remains higher than the legal parker's certain gain. When the parking fine amounts to 60.27 euros, it makes no difference to users whether they pay the parking fee or not ($EU_A / EU_{\bar{A}} = 1$).

Between 60.27 euros and 64.83 euros, in spite of the shorter walking times (which fall by approximately two minutes) and shorter cruise times for looking for parking (which fall by approximately 40 seconds), the increase in the fine discourages car use and non-payment of parking. The cost of parking in this case becomes sufficiently high for the number of accepted trips to fall ($\Delta \bar{x}_A = -3{,}05\%$) and the number of walking trips to rise ($\Delta \tilde{x}_A = +1{,}97\%$). In view of the respective average speeds of these modes, the journey time therefore tends to increase (by approximately two minutes). However, the marginal disutility of the travel time $\left(\partial EU_A / \partial L = -1{,}5471\right)$ is considerably higher than the marginal utility of parking time $\left(\partial EU_A / \partial W = -0{,}0047\right)$. Furthermore, the non-payer's expected utility becomes lower than the legal parker's certain utility. The increase in the fine therefore discourages non-payment of parking fees and private car use.

Therefore, *ceteris paribus*, while the fine increase discourages car use in the case of hypercongestion, in fact it contributes to producing an additional parking supply - *i.e.* it reduces congestion. It reduces the threshold distance where commuter starts cruising for a parking place as well as the average walking time to destination. On the whole, it reduces the total travel time. The fine increase reinforces car use. The effect works up to a fine level above which the state of hypercongestion disappears.

Thus it is not possible to state that a fine increase has a mechanical effect on parking violation and travel demand. The traditional proposal of systematic fine increase both to deter non-compliance and moderate car use may be theoretically rejected.

6. Discussion

If the literature has largely shown that parking policy is a key feature of travel demand management, this article clearly shows that the lack of interest for the question of the parking enforcement effort has to be deplored. However some studies show that parking violation is far from being negligible. Parking meter violation challenges the parking pricing efficiency itself, which justifies the analysis of the enforcement effort and highlights the need for a rigorous analysis of the parking meter violation behaviour.

Then the planner wishing to reduce car use must enforce parking regulations. It is traditionally agreed that the adapted tool in front of parking meter non-compliance is the increase in the enforcement effort, in particular the fine increase. Furthermore the studies dealing with this question show that fine decrease generally produces a parking violation upsurge. However, there is no link with travel demand, and if the aim of parking pricing is to reduce car use, the increase in the enforcement effort against parking regulations non-compliance should be accompanied by an impact study on travel demand.

However, some theoretical models have shown that a parking fee increase encourages driving by creating an additional parking supply. Assuming a parallel with this parking charge effect, it is not reasonable to conclude that the automatic effect of a fine increase is both to deter parking violation and to reduce car use.

This article attempts to explore an original outlook of the parking enforcement policy linking offending behaviour and travel demand management. The theoretical simulations of a parking meter violation behaviour model linking the fine level choice, the non-compliance behaviour, modal split and travel demand show that in the case of quite large parking congestion, the fine increase paradoxically boosts car use and encourages parking violation. Of course, if this challenging conclusion holds from an intellectual point of view, only the confrontation with actual data would confirm those theoretical results. Anyway, the way is now open. Moreover, if this conclusion contradicts the consensus on the enforcement policy to be implemented, it remains theoretical and it should be handled carefully given the assumptions of the model which depend on simplifying assumptions about enforcement policy, commuters behaviour and travel choice. In the future, the researches should thus tackle both theoretical improvements and empirical tests.

For example, in the model, only the risk-neutral behaviour is analysed. In reality, the economics of crime shows that a risk-averse agent reacts more strongly to a change in the fine level than he does to a change in the probability of control. A variation in one or other of the repression measures does not have the same effect on the decision to offend according to the agent’s reaction to risk (neutrality, preference or aversion). Beyond the problem of the reaction degree to a change in the repression measures, taking into account the behaviour towards risk should make it possible to assess the weight of the agent’s wealth on his parking violation behaviour, and hence to deal with the question of whether the aversion towards risk is increasing or decreasing with wealth.

The theoretical model of the parking meter violation behaviour should be also enriched to be included into a road congestion model. For example, it would be quite relevant to consider the parking meter violation behaviour within the framework of a trip chain which necessarily weighs on modal split. It is then advisable to approach the parking meter violation behaviour, on the one hand, according to each parking pattern dictated by the daily activity pattern and on the other hand, according to the result on the agent’s wealth obtained at the end of the parking period which enabled him to carry out the activity preceding the activity at the origin of the parking under study.

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Appendix 1 – The Arnott and Rowse (1999) model

Journey time

If x denotes the distance from home to destination, $\tilde{x}$ the maximum accepted walking distance, and $\bar{x}$ the maximum accepted journey distance, the total travel time for an individual is written as follows:

$$L(\tilde{x},\bar{x},P,d)=\frac{1}{\bar{x}}\left[\int_0^{\tilde{x}} T_1(x)\,dx+\int_{\tilde{x}}^{\bar{x}} T_2(x,P,d)\,dx\right]+l+\frac{\pi r}{\mu\bar{x}}. \qquad \text{(A1)}$$

It is made up of the expected travel time $\frac{1}{\bar{x}}\left[\int_0^{\tilde{x}} T_1(x)\,dx+\int_{\tilde{x}}^{\bar{x}} T_2(x,P,d)\,dx\right]$, the duration l of the activity and the expected waiting time at home for a trip opportunity $\pi r/\mu\bar{x}$ (where r is the radius from the centre of the city which is assumed to be a circular city – home and destination are located on the circumference of this circle, μ is the parameter of a Poisson distribution that describes the rate of arrival of trip opportunities).

For a trip opportunity, if the driver chooses to walk, the journey time for the round trip, at an exogenously fixed mean walking speed w, is equal to the time taken to cover twice the distance between the home and the destination at the walking speed:

$$T_1(x)=\frac{2x}{w}. \qquad \text{(A2)}$$

If the traveller decides to use the car, the journey time consists in the time spent driving from home to the place of parking and the walking time from the place of parking to the destination. Furthermore, the travel time in the car, that is to say the journey time without the walking time during the end journey, consists of the time spent cruising for a vacant space and the travel time as such, *i.e.* without this cruise time. The speed of the car journey, denoted by v, is fixed exogeneously and assumed to be constant and identical for the trip and when looking for a space, irrespective of the traffic density. Thus, the expected driving time is the sum of two components. The first is the travel time in the car (a consequence of the difference between the total travel distance and the distance d the user chooses to cruise for a parking space). The second is the amount of time the driver expects to spend cruising for a parking space. We express the expected driving time for the return trip as follows:

$$R(x,P,d)=\frac{2(x-d)}{v}+\frac{2}{vP} \quad \text{, for } x \geq d \text{ ,} \tag{A3}$$

where P is the mean density of vacant parking spaces.

The expected walking time during a return car trip can be expressed as follows:

$$\begin{aligned} W(P,d) &= 2\int_0^d \frac{d-y}{w} P\, e^{-Py}\, dy + 2\int_d^{+\infty} \frac{y-d}{w} P\, e^{-Py}\, dy \\ &= \frac{2}{w}\left(\frac{2\,e^{-Pd}}{P}+d-\frac{1}{P}\right) \end{aligned} \quad , \tag{A4}$$

where y is the actual cruise distance and $P\,e^{-Py}\,dy$ is the probability of finding a vacant parking space in the time that elapses between y and $y+dy$.

The expected return car travel time is therefore written as follows:

$$\begin{aligned} T_2(x,P,d) &= R(x,P,d)+W(P,d) \\ &= \frac{2x}{v}+\frac{4\,e^{-Pd}}{wP}+2\left(d-\frac{1}{P}\right)\left(\frac{1}{w}-\frac{1}{v}\right). \end{aligned} \tag{A5}$$

The social optimum

In the Arnott and Rowse model (1999), the objective of the planner is to minimise the mean journey time. The program is written thus:

$$\min_{\tilde{x},\bar{x},d,P} L \quad \text{such that } L = \frac{1}{\bar{x}}\left[\int_0^{\tilde{x}} T_1(x)\,dx + \int_{\tilde{x}}^{\bar{x}} T_2(x,P,d)\,dx\right] + l + \frac{\pi r}{\mu \bar{x}}, \qquad \text{(i)}$$

$$\text{and } L = \frac{\Gamma(W(P,d)+l)(\bar{x}-\tilde{x}/\bar{x})}{D-P}. \qquad \text{(ii)} \quad \text{(A6)}$$

where (ii) is the equilibrium condition with Γ representing the population density per unit distance and D the parking space density per unit distance.

If we introduce λ as a Lagrangian multiplier, the first order conditions are:

$$\frac{\partial L(\bar{x},\tilde{x},P,d)}{\partial \tilde{x}} = \frac{1}{\bar{x}}\left[(1-\lambda)(T_1(\tilde{x}) - T_2(\tilde{x},P,d)) - \lambda\frac{\Gamma(W(P,d)+l)}{D-P}\right] = 0, \quad \text{(A7a)}$$

which can be also expressed as:

$$T_1(\tilde{x}) = T_2(\tilde{x},P,d) + E(W(P,d)+l), \qquad \text{(A7a')}$$

where E is the delay experienced by other drivers per unit time the driver in question spends parked;

$$\frac{\partial L(\bar{x},\tilde{x},P,d)}{\partial \bar{x}} = \frac{1}{\bar{x}}\left[-(1-\lambda)(L(\tilde{x},\bar{x},P,d) - l - T_2(x,P,d)) + \lambda\frac{\Gamma(W(P,d)+l)}{D-P}\frac{\tilde{x}}{\bar{x}}\right] = 0 \quad \text{(A7b)}$$

which can be expressed as:

$$T_2(\bar{x},P,d) + l + E(W(P,d)+l) = L(\tilde{x},\bar{x},P,d) + E(W(P,d)+l)\left(\frac{\bar{x}-\tilde{x}}{\bar{x}}\right); \quad \text{(A7b')}$$

$$\frac{\partial L(\bar{x},\tilde{x},P,d)}{\partial d} = \frac{\bar{x}-\tilde{x}}{\bar{x}}\left[(1-\lambda)\frac{\partial T_2(x,P,d)}{\partial d} + \lambda\frac{\Gamma}{D-P}\frac{\partial W(P,d)}{\partial d}\right] = 0; \quad \text{(A7c)}$$

$$\frac{\partial L(\bar{x},\tilde{x},P,d)}{\partial P} = \frac{\bar{x}-\tilde{x}}{\bar{x}}\left[\begin{array}{l}(1-\lambda)\dfrac{\partial T_2(x,P,d)}{\partial P} \\ +\lambda\dfrac{\Gamma}{D-P}\left(\dfrac{\partial W(P,d)}{\partial P} + \dfrac{W(P,d)+l}{D-P}\right)\end{array}\right] = 0, \quad \text{(A7d)}$$

and which gives the value of λ.

If we replace λ in equation (A7a) by the value obtained from equation (A7d), it is straightforward to obtain the expression for the expected parking congestion externality:

$$E = \frac{-\partial T_2(x,P,d)/\partial P}{((W(P,d)+l)/(D-P)) + (\partial W(P,d)/\partial P)} . \tag{A7b}$$

The parking equilibrium with a parking fee

According to Arnott and Rowse (1999), the program for the user with a parking fee is written thus:

$$\max_{\bar{x},\tilde{x},d} V(\tilde{x},\bar{x},d,p,P) = \frac{\beta - p((\bar{x}-\tilde{x})/\bar{x})(W(P,d)+l)}{\frac{1}{\bar{x}}\left[\int_0^{\tilde{x}} T_1(x)\,dx + \int_{\tilde{x}}^{\bar{x}} T_2(x,P,d)\,dx\right] + l + \frac{\pi r}{\mu\bar{x}}} . \tag{A8}$$

Let $\Delta \equiv L\bar{x}$. In this case the first order conditions are written as follows:

$$\frac{\partial V(\bar{x},\tilde{x},d,p,P)}{\partial \tilde{x}} = \frac{1}{\Delta}\left[p(W(P,d)+l) - V(T_1(\tilde{x}) - T_2(\tilde{x},P,d))\right] = 0 ; \tag{A9a}$$

$$\frac{\partial V(\bar{x},\tilde{x},d,p,P)}{\partial \bar{x}} = \frac{1}{\Delta}\left[\beta - p(W(P,d)+l) - V(T_2(\bar{x},P,d)+l)\right] = 0 ; \tag{A9b}$$

$$\frac{\partial V(\bar{x},\tilde{x},d,p,P)}{\partial d} = \frac{\bar{x}-\tilde{x}}{\Delta}\left[-p\frac{\partial W(P,d)}{\partial d} - V\frac{\partial T_2(\bar{x},P,d)}{\partial d}\right] = 0 . \tag{A9c}$$

Decentralisation of the social optimum

The pricing leads drivers to pay the social cost of parking financially. It is obtained by comparing the systems (A7a)-(A7c) and (A9a)-(A9c) which gives:

$$\frac{p^*}{V^*} = \frac{\lambda^*\Gamma}{(1-\lambda^*)(D-P^*)} \text{ or } p^* = V^* E^* , \tag{A10}$$

where * denotes the value at the social optimum. The price is equal to the parking externality per unit time multiplied by the value-of-time. As V is a function of p, Arnott and Rowse (1999) express equation (A10) using equation (A8) which gives:

$$p^* = \frac{E^* \beta}{L^* + E^*\left(\left(\bar{x}^* - \tilde{x}^*\right)/\bar{x}^*\right)\left(W^*\left(P^*, d^*\right) + l\right)}. \qquad \text{(A10')}$$

Appendix 2 – Simulations results

Table. 1. Simulation results (hypercongestion state of parking)

F (€)	11*	31,26	53,19	60,27	64,83
$EU_{\bar{A}}$	10.23375	10.23375	10.23375	10.23375	10.23375
EU_A	10.23371	10.23375	10.23379	10.23375	10.23317
ΔEU_A		+ 0.00004	+ 0.00004	- 0.000035	- 0.00058
$\partial EU_A/\partial F$	- 0.00084	- 0.00087	- 0.00089	- 0.00087	- 0.00005
ε_F	- 0.0009	- 0.0025	- 0.0045	- 0.0051	- 0.0003
W_A (mn)	36.88	22.71	7.38	2.46	0.16
ΔW_A (mn)		- 14.17	- 15.33	- 4.91	- 2.30
$\partial EU_A/\partial W_A$	- 0.0774	- 0.0805	- 0.0831	- 0.0809	- 0.0047
ε_{W_A}	0.037	0.014	0.002	0.0002	0.0000007
L_A (h)	6.610	6.599	6.586	6.583	6.615
ΔL_A (mn)		- 0.680	- 0.789	- 0.185	+ 1.922
$\partial EU_A/\partial L_A$	- 1.5481	- 1.5508	- 1.5539	- 1.5546	- 1.5471
d_A (km)	2.265	1.395	0.453	0.151	0.01
Δd_A (mn)		- 3.896	- 3.833	- 1.737	- 0.631
$\partial EU_A/\partial d_A$	- 0.5775	- 0.5578	- 0.5378	- 0.532548	- 0.5527
P	0.51	0.83	2.56	7.67	118.41
Parking space occupancy (%)	99.59	99.34	97.95	93.86	5.43
$\bar{x}_A$ (km)	2.882	2.885	2.888	2.885	2.797
$\Delta\bar{x}_A$ (%)		+ 0.11	+ 0.10	- 0.10	- 3.05
$\tilde{x}_A$ (km)	2.737	2.735	2.733	2.735	2.789
$\Delta\tilde{x}_A$ (%)		- 0.07	- 0.06	+ 0.06	+ 1.97
Private car use rate (%)	48.36	48.40	48.43	48.40	47.39
$EU_A/EU_{\bar{A}}$	0.999996	1	1.000004	1	0.99994
Rational decision (VNM criterion)	Pay	Indifferent	Not pay	Indifferent	Pay

*The current fine level for parking meter violation in France.

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