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# Consumer surplus and pricing of transport infrastructures: The legacy of Jules Dupuit

Alain Bonnafous *, Yves Crozet

*University of Lyon, LAET, France*

## 1. Introduction

From Jules Dupuit's article (1844) to the works of Maurice Allais, the advances made in public economics have often been inspired by poignant issues relating to the transport sector. However, their results apply to every facet of public economics, especially any area bringing together public finance and commercial revenues. Indeed, if one were to raise the question of how a university should be financed by sharing the burden between the taxpayer and its users, one finds oneself facing the same problem as that of the optimal combination between the level of a toll and the subsidy required to finance a highway or railway project. Regarding both transport economics and the more general concept of surplus, the Nobel prizewinner Maurice Allais frequently emphasized the contribution made by Jules Dupuit (Baumstark and Bonnafous, 2010). When mentioning the issue of tariff differentiation, he wrote, for example, (Allais, 1989): “*Jules Dupuit, a precursor little known for too long, demonstrated extraordinary perspicacity in his two dissertations of 1844 and 1849 on transport infrastructures, and opened a king's highway for economic thought*”.

The list of Maurice Allais's citations in praise of the master is long. Perhaps this was in reaction to the lack of importance given to Jules Dupuit in French economic literature despite the fact that few around the world contest his role as the father of economic calculation. Fittingly, since 1992 the *WCTR* has awarded the Jules Dupuit prize instigated by Marc Gaudry and Antti Talvitie. The purpose of this paper is to illustrate the importance and modernity of Jules Dupuit's discoveries, especially in the works of French engineer-economists of whom Maurice Allais was the brilliant epitome in the 20th century.

Maurice Allais, Nobel Prize 1987 (1981) is particularly clear regarding the epistemological dimension of Dupuit's contribution. He underlines: “*the efforts that the meditation of Dupuit's work, thirty years ago, could have saved me, in particular by freeing me from the clutches of the marginalist school whose dogmatism has substantially slowed down the development of economic thinking*”.

Jean Tirole (2014), in his acceptance speech for the Nobel Prize mentioned: “*Industrial organization has a long tradition: first theoretical, with the work of French “engineer-economists” Antoine Augustin Cournot (1838) and Jules Dupuit (1844)*”.

In the following parts of this paper, we will show how Jules Dupuit addressed different kinds of utilities, anticipating the concepts of consumer surplus but also deadweight loss and finally price differentiation. We will show how these concepts can be introduced in the evaluation of transport infrastructures and their optimal pricing.

## 2. Absolute utility, net utility and lost utility

The entire work of Jules Dupuit is a huge response to the questions with which he was confronted in his capacity in administration and in the debate in which he was opposed to some of his colleagues of the “Ponts et Chaussées”. It entails formulating tools capable of assessing the interest of public works, in particular when such interest is not covered by revenues. However, his questioning went well beyond: “*Transport routes raise a multitude of economic questions on which we are far from reaching agreement: questions of fact, questions of principles. What routes are the most advantageous? How can their utility be monitored and measured? Who must pay the capital costs? Who must build them? Who must operate them?*” (Dupuit, 1873).

In order to give an answer to these questions, Dupuit proposed to draw a marginal utility curve identified to a demand curve (named by Dupuit *courbe de consommation)*. In some graphs summarized in the Fig. 1 (see below), he was therefore able to present his key concepts of *absolute utility*, *net utility* and *utility loss*.

When the price (P) is null, the absolute utility is at its maximum as the quantity of goods consumed (N). Dupuit was here anticipating the fact that some public goods have to be offered freely. But a price equal to zero does not represent a cost equal to zero. When we multiply the average production cost (p’) by the related demanded quantities (n’) we can obtain the production cost but also the net utility and the lost utility.

At a time when economists did not yet use equations, no one is better

* Corresponding author.
*E-mail address:* alain.bonnafous@let.ish-lyon.cnrs.fr (A. Bonnafous).

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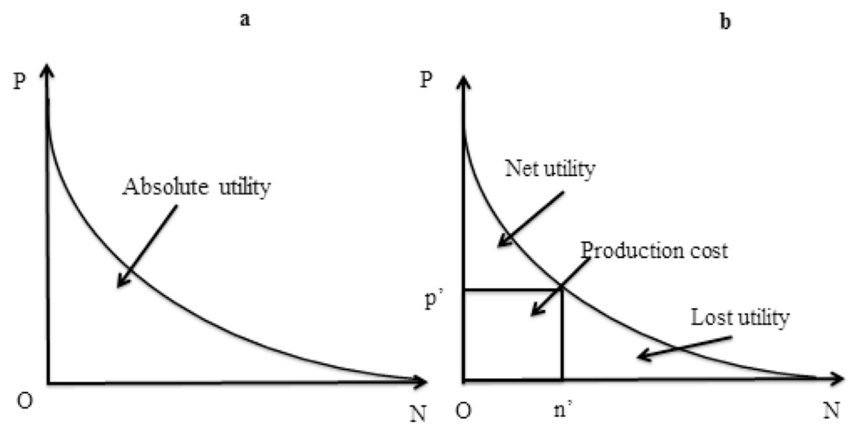


**Fig. 1.** From utility curve to net utility and utility loss.

qualified to summarize these results than Dupuit (1844) himself: "*The utility of a transport route is at its maximum when the toll or price is null. When the toll is non-null, the utility is shared in three parts: 1) the utility lost by those who do not consume it due to the price; 2) the utility received by the person who receives the price; 3) the utility remaining for consumers.*"

As indicated by Allais (1989), Dupuit was returning to the classical definition of the object of economics: the use of limited resources to satisfy the unlimited needs of men. This perception is subject to consensus in public economics and obviously requires the measurement of both the constraint of scarcity and the degree of satisfaction. Almost from the outset, the latter was identified as having collective utility, but the prevailing academic reserve of the 19th century asserted that it could not be measured. Jules Dupuit's notion of net utility resolves this problem. It was clear to Maurice Allais that this engineer from the elite "Ponts et Chaussées" was the founder of the notion and he devoted long passages to it in his *General Theory of Surplus*. According to Maurice Allais, the three essential contributions of Dupuit are the following:

- the concept "net utility", i.e. consumer surplus in the modern economics;
- the concept of "lost utility", i.e. deadweight loss;
- fundamental intuitions relating to price differentiation, i.e. Ramsey-Boiteux pricing.

It is therefore clear that we can turn Dupuit's reasoning and recommendations into a welfare analysis very powerful to understand what is at stake in the domain of transport infrastructures.

## 3. From consumer surplus to public utility

The well-known articles of Dupuit (1844, 1849), were, in the middle of the nineteenth century at the heart of a lively theoretical debate on the measure of utility. Dupuit was a strong opponent of the dominant conception of measuring utility inspired by J. B. Say based on trading prices observed on the market, and thus on production costs (Bordas, 1847). He destroyed this conception with a single sentence: will a road that costs "*half as much due to the skill of an engineer also have half as much utility*?"

As we have seen, he proposed to take into account the preference of individuals by assessing the monetary sacrifices to which they are ready to consent to satisfy their desires. It is then possible to bestow a precise expression of utility as do modern methods based on revealed preferences and willingness to pay.

The great advantage of the concept of consumer surplus is to transform private gains into a public utility and finally into a Cost-Benefit-Analysis of the welfare gains or losses. For example, if we consider a bridge, it can be assumed that the passage over it can be subjected to a toll that will be varied progressively. At each level of price, certain users will inevitably give up using it, thereby revealing its utility to them when their willingness to pay changes to refusal to pay.

By proposing such a protocol, Dupuit shed light on a very simple phenomenon. Any tax collected for the use of a public good, e.g., a bridge, results in excluding some of its users. The result is what was called by Dupuit "lost utility" because some potential users cannot cross the bridge. In modern economics, this loss of consumer surplus is designated as the "deadweight loss" that is to say this part of the surplus that is neither obtained by the potential buyers nor captured by the producer. As a consequence, since the public value of a good depends on the sum of utilities gained by the users, any exclusion of a user leads to reducing the value of the public good concerned. When there is no toll, under condition of other scenarios to which we shall return in what follows, the public utility of the bridge for the users is maximal and the deadweight loss is null. The higher this tax becomes, the higher the number of users excluded, since the utility conserved is shared between the toll revenues and the utility that remains for those willing to pay for it. The level of use falls until cancelling itself completely, as does the public utility of the infrastructure.

Dupuit did nothing less than establish what would become the fundamental Cost-Benefit-Analysis equation. Indeed, in the meaning of, and subject to, the usual assumptions of economic calculation, the variation of public utility between a reference situation denoted 0 and a situation to be evaluated denoted 1 (which can, for example, be differentiated by the absence or presence of a structure, or by two different toll prices) is written as follows:

$$\Delta U = \Delta C + \Delta R - \int_0^1 T \cdot dp \quad (1)$$

Where: ΔC is the variation of the cost of the transport system between situation 0 and situation 1.

ΔR the variation of the revenue.

and $-\int_0^1 T \cdot dp$ the variation of the consumer surplus, $T$ being the quantity of transport service consumed at price $p$. Thus we find exactly what Dupuit had recommended. Besides the mathematical formalization, the only theoretical difference evident in the contemporary approach is that this result is obtained on the basis of welfare theory, the first complete demonstration linking the surplus of the user to the welfare gain being established only belatedly (Lesourne, 1972, 1975). In the field of transport the cost C is no only the price paid by the users, as in Dupuit's analysis, but the generalized cost that is to say the monetary cost plus the cost of time. The latter depends on the value of time of travelers usually introduced today in Cost-Benefit Analysis.

If we were to limit our reading of Dupuit to this result, it could be understood as a demonstration of the public utility of a zero toll. Obviously, the problem is not quite so simple. In the case of a zero toll the absolute utility of the bridge is the sum of the absolute utilities of the users. The relative utility is obtained by "*deducting the maintenance costs* *and interest on the capital spent on construction*" (Dupuit, 1844).

- But what about the impacts of taxes levied on some other markets to finance the cost of the bridge? A tax is not only a transfer of surplus to the public budget; it is also the source of a deadweight loss due to the reduction of consumption imposed by the tax. Dupuit estimated that the deadweight loss associated with excise taxes was proportional to the square of the tax (Ekelund, 1968). It is important to underline here that Jules Dupuit did not mention any producer surplus because there is no supply curve in his graphs. As demonstrated by Arnold Harberger (1964) the modern assessment of the deadweight loss takes now into account both consumer and producer's surplus. It is the case in our equation (1).
- And what about the risk to limit the number of transport infrastructures because of the scarcity of public funds? The view of Dupuit was that the government should produce the maximum amount of utility possible. Thus Dupuit recommended to set-up something like a pricing scheme, associated with a price differentiation, in order to maximize the welfare. But what is the optimal level of the toll?

## 4. Optimal toll and scarcity of public money

Once again, we cite Dupuit (1844) to go to the heart of the matter:

> "It is understood that to deal with the question of whether or not to impose tolls, it is necessary to examine by which taxes they must be replaced and what the effects of these taxes will be; this would be no less than a generalized theory of taxes. Therefore this article cannot have an immediately practical conclusion; …"

The pricing of infrastructure use is a very old question and has been the subject of a great deal of literature, particularly on transport economics and energy economics, resulting in a recommendation on which agreement is fairly general. It can be summed up as follows: seen in the short term, pricing at marginal welfare cost leads, under ordinary assumptions, to a first order optimum. When demand is affected by a limitation of capacity, the need to invest to limit congestion and its social costs lead to incremental costs or long term marginal costs corresponding to higher prices. For all that, they are not always sufficient to cover the average costs if the fixed costs are high, a frequent characteristic of network activities.

Consequently this price with a long-term marginal welfare cost must be modified to increase revenues. The modification that causes the first order optimum to diverge as little as possible is that which deforms the structure of the demand as little as possible. The result, known as Ramsey-Boiteux pricing (Oum and Tretheway, 1988), then consists in increasing the price for a segment of the demand by as much as the elasticity of demand at this price is low (Boiteux, 1956). This is therefore a second order optimum in that the welfare function is optimized subject to the constraint of the capacity to finance debt using public funds. The public budgetary constraint is related to the fact that public decision makers are always facing a trade-off between the cost of public spending and the cost of taxation. The cost of taxation is not only a burden equal to the revenue of the tax. We have to take into account an "excess burden" adding the surplus lost by the consumers (deadweight loss) and by the producers.[1]

We situate ourselves in this perspective of modern economics by considering that, in the welfare function, public money must be assigned to a scarcity coefficient that we denote $\varphi$. The definition specifies that $\varphi$ is the dual variable of the public financing constraint which is the price of public money in the classical analysis (Bonnafous et al., 2006). $\varphi$ is defined by the following ratio. The numerator is the excess burden of the tax plus the revenue of the tax. The denominator is the revenue of the tax. Therefore $\varphi$ is equal to 1 if the excess burden is null and is > 1 when there is an excess burden.

$\varphi$ can also be understood to be an implicit scarcity coefficient revealed by the decisions of the State relating to tolls (Bonnafous, 2010). We shall limit ourselves to varying within a range of reasonable values a little further on. We also hypothesize that the pricing that must be determined is constant which, initially, corresponds to a necessary working hypothesis but also to the most frequent concrete cases of tolls which are identical for all users and are invariable over time.

The following assumption allows us to avoid the problem of integrating external costs into a Ramsey-Boiteux pricing logic. We thus assume that the non-monetary components of the marginal cost (including the environmental components) are covered by taxes collected by the state. In the case of transport, one can imagine that this will take the form of taxes on oil products and that the corresponding revenues will not be assigned to the transport system beyond covering the marginal operating cost.

Thus, in this analysis the share of funding ensured by the users of a highway can only result from toll revenues. The result of this working hypothesis is not only that it eliminates environmental costs, conveniently assumed to be internalized by fuel taxes, but also the problem of congestion charging. The difficulty of the latter restriction was far less problematic than it is today in many countries including France, since the new infrastructures franchised or partially financed by tolls rarely equip congested routes. Thus, our analysis is outside the dominant problem treated by the literature of the last decades, which was remarkably synthesized by Robin Lindsey (2012), and which deals with the question of the optimal pricing and of the optimal capacity of the infrastructure in a situation of congestion.

In the following paragraphs, in relation with Dupuit's developments, the problem of the optimal toll is therefore reduced to the sole issue of arbitrating between the paying user and the taxpayer, the contribution paying user being an internalized share of the surplus they enjoy by using the infrastructure. This also corresponds perfectly to the alternative between the toll and the tax formulated by Dupuit.

With this supposed balance between external costs and taxes, the evaluation of a project can be formulated in a very simplified: the variation of public utility, or welfare function linked to a project ($\Delta U$), is therefore only a function of the discounted subsidy (which can be defined as the difference between the discounted investment and operating costs $C$ and the discounted revenues of project $R$) and the discounted surplus of users $S$. This function is therefore written as:

$$\Delta U = \phi \cdot Sub + S = \phi(R - C) + S \quad (2)$$

Unless otherwise indicated, we assume that the revenue is always less than the costs and that a subsidy is always necessary. This corresponds to the great majority of current highway and railway projects in Europe.

Since the discount calculations were performed at a constant price, we assume that toll $p$ is unchanged over the discount period and that the present demand $d$ can be expressed by a linear function of $p$ written as:

$$d = d_0 - \beta \cdot p \quad (3)$$

The assumption of a linear demand curve may appear as a strong hypothesis. In reality, if it is a toll-dependent demand on a route that competes with a toll-free route, the linear approximation is statistically acceptable, as has been shown (Bonnafous, 2011).

The result is the present revenue:

$$\mathrm{R} = \mathrm{do.p} - \beta.\mathrm{p}^2 \quad (4)$$

As for the present surplus of users, for a price level $p$, it is written as:

$$S = \frac{\beta}{2}\left(\frac{d_0}{\beta} - p\right)^2 \quad (5)$$

[1] In Jules Dupuit's paper, there is a demand curve but not supply curve. He is not mentioning any producer surplus.

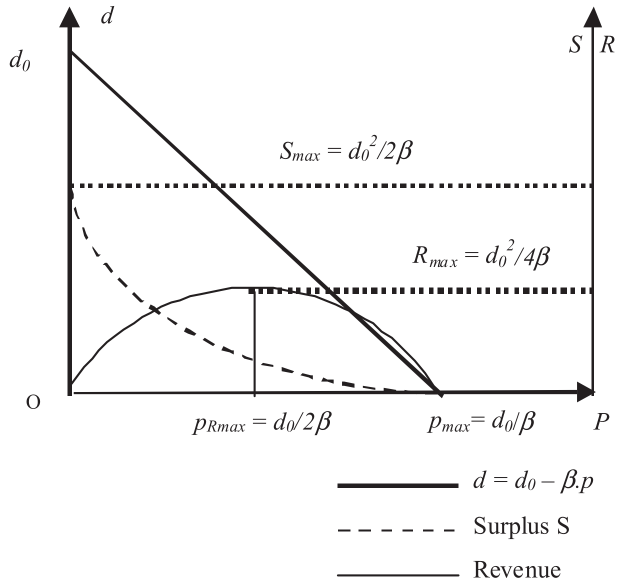


**Fig. 2.** Demand function, Consumer surplus and Revenue.

The last three equations are shown in Fig. 2 below. Certain characteristics of this highly stylized economic reasoning can be identified: the "maximum" toll for which demand vanishes which is equal to $d_0/\beta$ and the toll that maximizes the revenue which is half of the latter and for which the value of this maximum revenue is $d_0^2/4\beta$.

Equations (4) and (5) allow explaining the variation of public utility defined by equation (2) which is presented as a second order function of the toll:

$$\Delta U = -\phi \cdot C + \frac{d_0^2}{2\beta} + (\phi - 1)\cdot d_0 \cdot p + \beta \cdot \left(\frac{1}{2} - \phi\right)\cdot p^2 \tag{6}$$

The social performance of the project will therefore be maximal for a toll $p_{Umax}$ that maximizes this function, thus which cancels its derivative:

$$(\Delta U)' = (\phi - 1)\cdot d_0 + \beta \cdot (1 - 2\phi)\cdot p \tag{7}$$

i.e.:

$$p_{U\max} = \frac{\phi - 1}{2\phi - 1} \times \frac{d_0}{\beta} \tag{8}$$

The toll which maximizes the project's utility is therefore null when $\varphi$ is equal to 1 and between 0 and $d_0/2\beta$ when $\varphi$ is higher than 1. Both cases are shown in Fig. 3 in which equation (2) has been rewritten in equation (9).

$$\Delta U + \phi C = \phi R + S \tag{9}$$

We can therefore put on the same vertical axis the two members of the equation (9). This apparently strange manipulation has the merit of clearly associating the revenue of the toll and the consumer surplus. Thanks to that, the trade-off is very clear between, on one hand the efficiency of public spending, measured by the consumer surplus, and on the other hand the revenue of the toll. When $\varphi = 1$, any increase in the toll decreases $\phi R + S$.

This corresponds to the mechanism clearly demonstrated by Jules Dupuit (1844, 1849): the reduction of the surplus (*lost utility*) that results from this increase is always higher that the increase in revenue. Our hypothesis of a linear demand function and in the case of the same toll applied to all the users,[2] the maximal revenue equal to $d_0^2/4\beta$ only

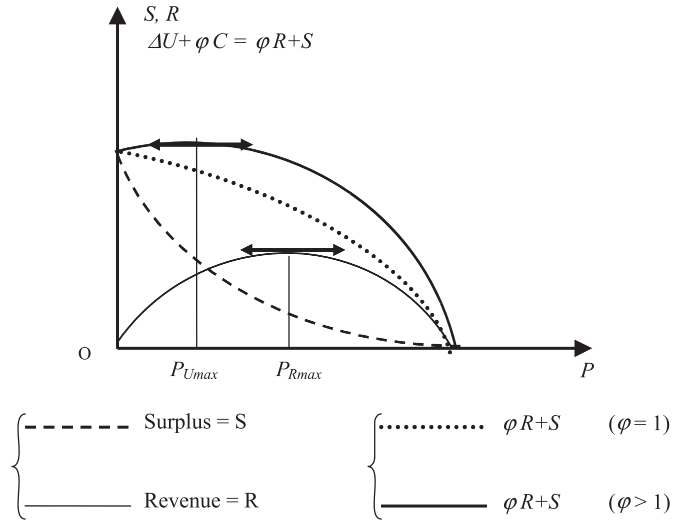


**Fig. 3.** Welfare function and scarcity coefficient of public funds.

represents half the maximum surplus that the users enjoy when no toll is applied.

But what if $\varphi$ is higher than 1? As indicated by the shape of the curve at the top of the graph, there is a non-null optimal toll ($P_{Umax}$) that maximizes $\varphi R + S$ that is to say the net present value of the project. This optimal toll is a function of $\varphi$. The zero toll is optimal only when $\varphi = 1$. But as soon as $\varphi$ is higher than 1, there is a non-null optimal toll which is a growing function of $\varphi$.

This formalization is nothing other than a mathematical redrafting of the analyses of Jules Dupuit and simply reinforces his conclusions. As identified so well by him, these analyses are based on the hypothesis of a single toll. They are strengthened if the utility of differentiated tolls is taken into account.

## 5. Price differentiation and infrastructures financing

The idea of variability of preferences was very important for Jules Dupuit. Today, in the field of transport economics, we would speak about the statistical distribution of time value. He was clearly aware of this and it led him to set out the principles of what was to be called price discrimination. As revealed by the long citation below, he shows that welfare loss is not fundamentally linked to the status of the company that operates the infrastructure but its capacity to segment its clientele.

> "A footbridge is built between two densely populated districts of a city, it cost Fr150,000, and the revenue of Fr0.05 per passage is only Fr5,000. It is a bad investment, since the entrepreneur who had borrowed most of the Fr150,000 cannot pay the interest on the loan and will soon be ruined. The bridge is sold to an intelligent man (…). He notices that his bridge links the district where the factories are located to that where the workers live (…). The bridge greatly shortens the distance to be travelled, but a sacrifice of 10 centimes a day is far too high with respect to their wage. By asking them only 1 centime per passage, no one would hesitate to procure this satisfaction, and therefore a thousand new daily passages a day would be generated, which at a rate of 1 centime would produce a daily revenue of Fr10 francs and Fr3,000 for the three hundred working days of the year. The aim now is to generate this additional revenue without reducing that of Fr5,000 generated by the price of Fr0.05 (…).The owner of the bridge could insert a clause in his price worded as follows: for pedestrians wearing cap, overalls or jacket, the price is reduced to Fr0.01 (…) he will certainly obtain the revenue of Fr3,000 raised from the new passages; but it is likely that the revenue of Fr5000 will fall by a certain amount, because a certain number of

[2] We know that only fully discriminative pricing would allow internalizing the entire consumer surplus.

users at Fr0.05 will benefit by virtue of their clothes, from the reduction which is not intended for them.(…) Thus he could stipulate that the reduction will only be in force in the morning and in the evening during the opening and closing times of the workshops, or that it will only be applicable to workers holding proof of entitlement. Whatever the combination adopted, the result will be to increase the revenue generated from the toll as a function of how well the users are differentiated as they attach a different value of utility to the bridge they use." (Dupuit, 1849).

This reasoning shows that a perfect discrimination, or 1st degree discrimination (Phlips, 1987) would reduce the welfare loss to zero by charging different prices for different buyers without any true cost differential to justify the different price. But due to the fact that is impossible to reach this first degree of price discrimination we observe today in the field or air transportation a 2nd degree price discrimination. Low-cost but also major airlines developed a "yield-management" system including a schedule of declining prices for different quantities. Using this strategy the companies can extract some of the consumer surplus without knowing much about the individual consumer. Incidentally, this suggests that private companies and even a private monopoly are not, by nature, in conflict with the public interest. Therefore, the preference for public management loses one of its justifications. A strong regulator is more efficient than public authorities to monitor a sector in relation with the maximization of welfare.

It remains that this idea of price differentiation suggests that there can be an advantage for the public authorities to base the pricing of infrastructure consumption on a discriminating principle which consists in "*asking a price for a service rendered not because it has a cost for the person who renders it, but a sum corresponding to the importance that the person to whom the service is rendered attaches to it*" … "*Therefore according to whether you adopt such or such a toll system, the bridge can or cannot be built, it will be a good or poor deal for the builder, and it will be useful or useless for the public.*" (Dupuit, 1849).

The rail access charges (RAC) scheme applied in France since the end of the 1990′ is exactly in line with Dupuit's recommendations. For high-speed tracks, a long-run marginal cost is applied by the rail infrastructure manager. The RAC take account of the investment cost, including financial charges. The rule is a full cost principle in order to limit the burden on the public finances of extending the HSR network (400 km in 1981, 2700 km in 2017). It is as if the main objective of the French government, namely the extension of the HSR network, has to be largely financed by high rail access charges.

In addition to the goal of protecting the public finances, the HSR pricing system also attempts, following a Ramsey-Boiteux approach, to take account of the elasticity of demand in order to achieve the best trade-off between efficiency goals and budgetary needs (Crozet and Chassagne, 2013).

- In line with Dupuit's recommendation, the first stage is to calculate, for a particular line, the total revenue which is required in order to cover investment costs.
- The second stage consists of calculating the pricing modulations, i.e. the mark-ups that can be applied by varying the access charges over time. The mark-ups are based on the elasticity of demand on one hand and on the other hand on the scarcity coefficient of public funds.

It should be noted that when it adopts this approach with regard to train operator, the rail infrastructure manager is merely applying the same yield management approach which the high-speed train operator (SNCF) imposes on its clients a 3rd degree price discrimination (Phlips, 1987). In this case, the firm is able to extract the consumer surplus of those who might not otherwise pay the standard rate. Third degree price discrimination relies on the firm being able to separate the segments of the demand, for instance during peak of off-peak hours. The result is that the price of a ticket between Paris and Lyon varies by a factor of four depending on whether the journey takes place in the peak period or the off-peak period. The outcome is that, on the Paris-Lyon line, which is the line with the highest passenger traffic, the access charges can amount to six times the marginal cost. The Paris-Lyon high-speed line is also the most profitable line for rain infrastructure manager and for SNCF.

The main result of high RAC on Paris-Lyon is a wide cross-subsidisation system between high-speed relations. On lines with lower passenger traffic, access charges can only reach the marginal cost during off-peak period. It is clear that this opportunity of yield management results in reducing the welfare loss linked to the toll and thus considerably strengthens the social utility that a toll can provide if public funds are scarce. Paraphrasing Jules Dupuit, we can conclude that because (not in spite) of high rail access charges during peak periods on lines with a dense traffic, it has been possible to finance the development of the French high-speed rail network. The same rationale had been adopted for the extension of the motorways network.

## 6. Conclusion

The works of Jules Dupuit shed light on three key concepts of economic calculation: consumer surplus, welfare gains and losses and the opportunity cost of public funds. The first two are very often used to justify the pricing of infrastructures and price differentiation. One allows increasing public welfare insofar as it helps to increase the level of public investment. The other contributes to reducing the welfare loss that could result from pricing. Thus, whereas upon initial examination the optimal pricing of a transport infrastructure should be that of gratuity, as Adam Smith led to understand at the end of the 18th century, it is preferable to implement pricing for certain infrastructures. This is the case in particular when new and expensive infrastructures must be installed quickly like the construction of the French highway network (nearly 10,000 km in forty years) and the high speed train network (more than 2500 km in forty years).

Due to the fact that the funding of new infrastructures is currently facing numerous obstacles, notably because of their profitability and the scarcity of public funds, the third contribution made by J. Dupuit deserves to given central place in the analysis. The opportunity cost of public funds must be introduced in the economic calculation, whether for comparing the social utility of the different projects or for determining the optimal pricing of an infrastructure, whether a highway or railway. The definition and measure of this opportunity cost of public funds is now a central issue of research.

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