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Alain Bonnafous. A new theoretical approach to highway tolls: a Jules Dupuit toll. 2024. halshs-04426303

HAL Id: halshs-04426303

<https://shs.hal.science/halshs-04426303>

Preprint submitted on 7 Feb 2024

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Keywords: Fundig toll, Tolloed highway, MCF.

J.E.L. Classification: D61, H21, H43



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Janvier 2024

ISSN : 2741-8103

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A new theoretical approach to highway tolls: a Jules Dupuit toll

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Abstract

Whereas the literature on optimal road pricing has mainly focused on the issue of dealing with congestion, in most cases road tolls have been introduced in view to financing new projects. The question of optimal toll is therefore that of a trade-off between the user-payer and the taxpayer, in the same way as it was raised by Jules Dupuit in the middle of the 19th century. Keeping in this spirit and on the basis of several simplifying assumptions that are suitably verified in the real world, a calculation of an optimal toll is proposed in the case of a single project considered for construction. This toll is a function of the marginal cost of public funds. However, in the case of the combined optimisation of a programme of several projects and their pricing, the optimal toll of each project no longer depends on its financial characteristics.

Résumé

Alors que la littérature sur la tarification routière optimale s'est principalement concentrée sur la question de la gestion de la congestion, dans la plupart des cas, les péages routiers ont été introduits afin de financer de nouveaux projets. La question du péage optimal est alors celle d'un arbitrage entre l'usager-payeur et le contribuable, ainsi qu'elle a été soulevée par Jules Dupuit au milieu du XIXe siècle. Dans cet esprit et sur la base de plusieurs hypothèses simplificatrices convenablement vérifiées dans le monde réel, un calcul de péage optimal est proposé dans le cas d'un projet unique. Ce péage est fonction du coût marginal des fonds publics. Cependant, dans le cas de l'optimisation combinée d'un programme de plusieurs projets et de leur tarification, le péage optimal de chaque projet ne dépend plus que de ses caractéristiques financières (recette maximale et subvention minimale).

JEL Classification: D61 H21 H43

Key words: Fundig toll, Tolloed highway, MCF.

1. Introduction

“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?”

These few lines were written 150 years ago by Jules Dupuit in an article on roads for an economic dictionary (Dupuit, 1873), a few decades after having initiated the concept of user surplus and laying the foundations of cost-benefit analysis in his two seminal articles of 1844 and 1849. It is no coincidence that Kenneth Button, in a survey on road pricing (2004) recalled this work, “as without it, today’s understanding of the problem of traffic congestion and congestion charging would probably be different”.

However, this legacy is not obvious when we examine the recent literature on road pricing. It certainly deals with the double optimization of capacity and road pricing as Jules Dupuit did, but with differences that depend on the circumstances. In the age of the car, the most worrying aspect of transport is that of congestion, especially in urban areas. In a brief and rich summary titled *“Road pricing and investment,”* Robin Lindsey (2012) made an observation that will lead us to better situate our contribution: *“The practice of tolling roads to cover their construction and maintenance costs*

dates back to Roman times. This funding role remains important today. However, most of the road pricing literature has focused on the demand management role of tolls in controlling congestion."

Indeed, the literature on congestion charging is abundant, although in the real world actual application is rare. In Europe, for example, 60 years after the famous article by William Vickrey demonstrating the collective utility of urban tolls (1963), only seven cases can be observed: followed the example of the three main Norwegian cities that introduced this system in the 1990s, London in 2003, Stockholm in 2006, Milan in 2007 and Gothenburg in 2016.

In the rest of the world, twenty years after Singapore's seminal initiative in 1975, only some congestion tolls have been implemented, as for high occupancy lanes in the US. This was initiated in 1995 when the California State Route 91 (SR-91) Express Lanes opened: time-varying tolls designed to keep lanes free from congestion were implemented. Nevertheless, the primary motivation for tolling these lanes was that the state did not have the money to expand SR-91 (Boarnet & DiMento, 2004).

Compared to these few cases of congestion pricing, we observe on all continents several hundred cases of motorways with funding tolls. In this sense, this paper will not be located in the main stream of the literature (Santos & Verhoef, 2011) but will focus on the most frequent realities, which is to say on the problem of the funding role of the pricing.

Thus, on these sections of toll highways, with rather interurban characteristics, we rediscover the pertinent questions asked by Jules Dupuit and cited in the first lines above. We reutilise them to better specify the issue dealt with.

1.1. What routes are the most advantageous?

On every continent, the development of trade and the domination of road transport has led to new needs for highway links. In each country, several projects are generally candidates and the first obligation of decision-makers must be to define their optimal programming. Of course, it is necessary to make the distinction between investment programmes optimised by planners on the basis of benefit-cost ratios and the actual programmes decided by politicians.

Jonas Eliasson and Mattias Lundberg (2012), for example, demonstrated that the Swedish Transport Investment Plan 2010–21 was concretised by political decisions taken almost independently of the planner's economic evaluations. In France, regarding the planning of 39 railway projects during the same period, 2010-2021, a systematic comparison was performed between the actual ranking of the projects and their optimal theoretical ranking (Bonnafous & al., 2017): the ranking effectively decided presented less than 10% of the Net Present Value that the optimal programme would have provided, that is to say a programme constrained by the same time series of public subsidies but according to a ranking of projects based on a decreasing value for money ratio (NPV/Subsidy).

This political "transformation" is obviously an important subject but we set it aside here by following the standard assumption of benevolent decision-maker. Our analysis will be made in the framework of reflection on theoretically optimal recommendations. The latter, when concerning pricing, are obviously not independent of the NPV/Subsidy ratio that permits ranking a programme of projects, since there is clearly a close link between toll revenue and needs for subsidies. We will therefore be led to formalising this link in section 6 further on, and show that optimising the programme has impacts on toll optimisation.

1.2. How can their utility be monitored and measured?

Even those who do not know the works of Jules Dupuit can accept his response since it was the very first formulation of the cost benefit analysis (CBA), except for three differences. The first is, that for Jules Dupuit, the aim was to maximise a collective utility that did not yet benefit from the theoretical

power contributed by the mathematical formulation of the welfare function and the general equilibrium model.

The second difference is that the demand used by Dupuit was only a function of the transport price and not of its generalised cost. However, considering a generalized cost allows the price and transport time to be taken into account. This is how Jacques Lesourne was able to establish the first theoretical demonstration (1972) of the fact that the variation in users' surplus is indeed a component of the variation in the welfare function.

The third difference is that the notion of external effects appeared many years after the analyses performed by Jules Dupuit. However, it should be emphasised that their inclusion in the cost benefit analysis occurred progressively and efficiently as knowledge increased.

Everything that follows in this article should be considered in the framework of the initial issue posed by Jules Dupuit, but by using when needed the convenience of the mathematical formalisation of the standard economic analysis.

1.3. Who must pay the capital costs?

This is obviously the central question that we propose to deal with. Between gratuity, which implies that the infrastructure is financed solely by the taxpayer, and pricing at full cost, implying financing solely by the user, there is evidently a whole array of situations among which the optimal toll can be determined.

The main reason for raising the crucial questions posed by Jules Dupuit in this article stems from the fact that he was the first, by reasoning in terms of users' surplus, to show that a non-null toll involves a "social loss" but which can be justified by the scarcity of public funds. We start with this demonstration which will return in section 2 in order to detail the issue we attempt to solve.

Thus, we will be led to briefly recalling in this section what the literature has contributed to this concept of scarcity of public funds, and to propose a solution that permits overcoming the uncertainties that burden its measurement.

1.4. Who must build them? Who must operate them?

These questions, already asked in the 19th century, are obviously highly topical today with the boom observed in Public-Private Partnerships (P3s). There are many reasons, well established in the literature, for explaining this evolution. They are recalled in section 3 since these reasons explain that today, most toll highways are financed, built, and operated by a P3 system.

We therefore specify in this section that, from both the empirical and theoretical standpoints, it is reasonable to treat the issue of optimal toll by situating oneself in the case of P3 and considering that the case of public operators (a public entity or a non-profit private company) are only particular cases of P3.

The items of response regarding this issue of optimal toll will be based on several working assumptions used to simplify the mathematical formalisation. These hypotheses will be specified in section 4 as will be the sources of the data used to illustrate the analysis through numerical results representing the real world.

In section 5 we use these bases to deal with a simplified case of a single highway section whose construction has been decided and which is in competition with a slower but toll-free itinerary.

In section 6, we situate our reflection in the more general case of a group of projects in view to optimising their ranking and pricing by subjecting this optimisation to a Value for Money objective function. Finally, several conclusions are given in section 7.

2. The Jules Dupuit Funding Toll and the Scarcity of Public Funds

For reasons outlined in the previous section, we are led to formulating the issue of optimising a funding toll in a configuration similar to that dealt with by Jules Dupuit, but with a graphic presentation that did not exist in his era. Either a new road or bridge that saves time in comparison to an existing itinerary and for which the aim is to determine the level of optimal toll. In figure 1a, the structure is assumed to be free whereas in figure 1b a toll of level p is introduced, thereby reducing demand to a level n and implying the removal of users.

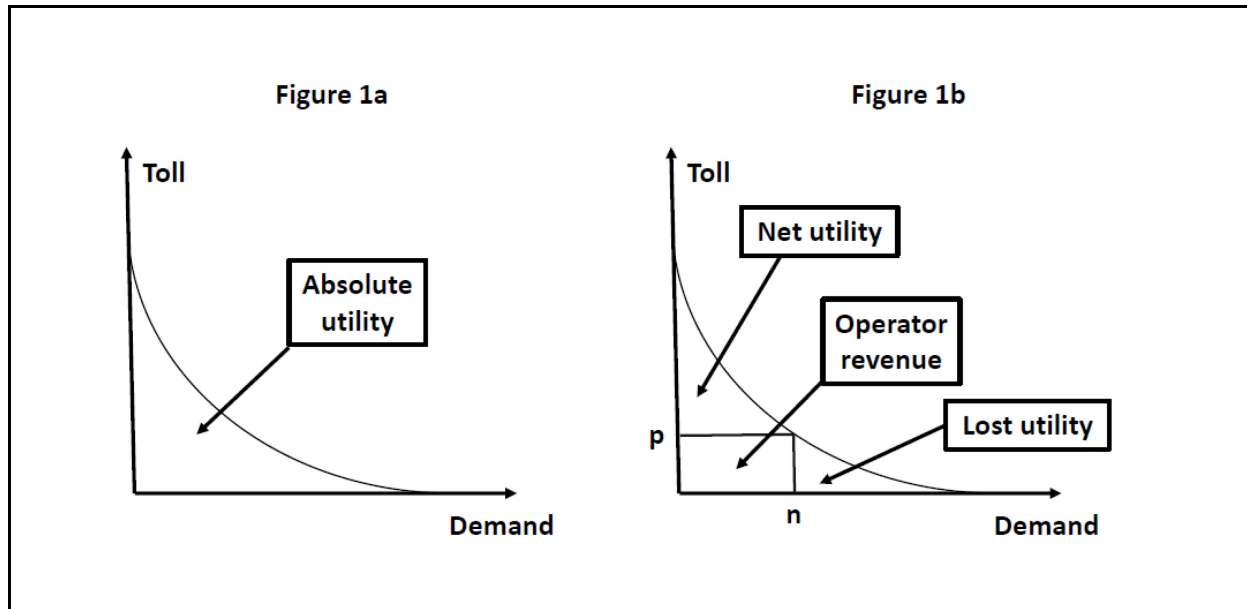


Figure 1: From the demand curve to net utility and lost utility.

Although at that time economists used neither equations nor graphs, only accounting tables of prices and quantities, no one is better qualified to summarize these results than Dupuit himself (1844): *“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.”*

In modern economics, utility loss is called “deadweight loss” that is to say the share of the surplus that is neither obtained by the potential buyers nor captured by the producer. This expression of deadweight-loss suggests that a non-zero toll automatically results in a loss of collective utility. However, as Jules Dupuit observed (1844), it is not so simple because in this case the costs of the infrastructure must be financed by public funds, which led him to ask a very modern question: *“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 practicable conclusion;...”*. This sentence suggests carrying out a research programme that was not to take place until long after it was written. The question is indeed that of the Marginal Cost of Public Funds (MCF), the term used most frequently to designate the distorting effects on the economy of an additional tax.

A subsidy, denoted Sub , which can be consecutive to the choice of a null-toll, is assumed to be financed by a tax of the same amount whose distorting effects on the economy result in a variation of welfare ΔW , W being the standard welfare function. A scarcity coefficient of public funds, denoted φ , can therefore be defined by $\varphi = -\Delta W/Sub$. If the tax has no distortion effect, this coefficient is equal to 1; if it has an effect, φ is different from 1 and is most often higher.

Note that in the literature, whether general (Laffont & Tirole, 1986) or applied in a transport context (Petersen, 1994), so that the social cost of one unit of public expenditure is noted $(1 + \lambda)$. For reasons of mathematical simplification in calculations in sections 5 and 6, we will use $\varphi (=1 + \lambda)$ rather than λ .

2.1. Very diverse evaluation of MCF

Despite the fact that all the authors in public economics had, like Dupuit, highlighted the problem, it was not until the 1970s that the first numerical evaluations were performed. Thus, Edgar Browning (1976) assumed that the additional public expenditure was offset by a tax on labour income and based his thinking on reasonable estimations of the wage elasticity of labour supply. He deduced *“that the marginal cost of public funds for taxes on labour income in the United States ranges from \$1.09 to \$1.16 per dollar of tax”*.

A little later, still for the United States, an estimation using a computable general equilibrium model and considering various tax options (Ballard & al., 1985) provided more troubling results: *“The welfare loss from a 1 percent increase in all distortionary tax rates is in the range of 17 to 56 cents per dollar of extra revenue, when we use elasticity assumptions that we consider to be plausible”*. The authors commented that *“this suggests that many projects accepted by government agencies in recent years on the basis of cost-benefit ratios exceeding unity might have been rejected if the additional effects of distortionary taxes had been taken into account.”* For the subject that concerns us, it should be remembered that these results also suggest, as formulated in section 4, that a non-null toll can increase the welfare function.

Regarding the evaluation methods currently employed in industrialised countries such as those eligible for loans from the World Bank, we know that they did not wait for these academic results to weight public expenditure with a public fund scarcity coefficient. Thus, many works have been carried out to rank as well as possible the magnitude of this coefficient that is reasonable to retain.

Here, we mention only two to illustrate our thinking. Firstly, a report by Jean-Jacques Laffont (1999) for the World Bank observed, on the basis of a review of available works, that the evaluation of φ ranged between 1.3 to 1.5 in industrialised countries, but attained magnitudes higher than 2 in developing countries for which these estimations were made. Secondly, a more recent work, which had the merit of treating 38 sub-Saharan African countries with the same model, Auriol & Warlters, (2012) confirmed a considerable dispersion of estimations, either as a function of the countries studied, or as a function of the 5 tax families considered. For example, according to the hypothesis of tax on labour income, the estimations of φ according to country ranged between 1.18 to 2.55. It can be noted that the evaluation proposed by OECD countries are not less dispersed (Kleven & Kreiner, 2003, Barrios & al., 2013).

2.2. Such a complex alternative

Note that there is an alternative way of dealing with the scarcity of public funds that allows us to hope for less dispersed and perhaps more easily measurable results. It consists in defining the MCF as the social marginal value of public resources, within the meaning of the value of the Lagrange multiplier on the government budget constraint.

It corresponds to the reality of transport investment policies: the ministry responsible for programming these investments is given an annual budget envelope constituting the constraint that investment choices must abide by. In a classical optimisation calculation under constraint, the cost of the public fund corresponds to the dual value of the constraint. Although this conception of MCF has been used only occasionally according to certain authors (Jacobs, 2018), it has been frequently treated in comparison and in association with the standard approach (Dahlby, 2008). Strict conditions of equality have been established between evaluations performed using the two methods but they have never been verified.

We retain from this alternative conception of MCF that, theoretically, it requires the evaluation of the coefficient φ_t specific to each year t , whether for the calculation of the Net Present Value of a project (Maurice & Roquigny, 2013) or the estimation of the time series of an optimal toll. Establishing such time series is obviously complex and can only provide uncertain results.

In practice, to our knowledge, there is no evidence in the documents recommending official evaluation methods that this solution has ever been chosen. A particular value of the public fund scarcity coefficient is generally officially prescribed and it is this reference value of the MCF (generally unique) which is used in the calculations of updated balance sheets.

2.3. The solution of a variable scarcity parameter of public funds

By situating ourselves in Jules Dupuit's problem of an optimal financing toll, we know that we must formalise the problem by introducing this MCF denoted φ . To compare the theoretical results with data relating to real situations, we simply consider a series of numerical values of φ covering the range of measures proposed by the literature. The results will be presented according to a rationale of calculation of the sensitivity of tolls thought to be optimal at the value of φ which we vary from 1 to 1.8. The MCF used remains compatible with the two options above, whether the ratio of the variation in welfare to the variation in taxes or the value of the Lagrange multiplier on the government budget constraint. Thus, we provide a response to the question: What is the role of a public fund scarcity coefficient in toll optimisation according to its numerical value?

3. The P3 system considered as the general case

The following analyses are based on a certain number of working assumptions that require detailing. They seem to correspond quite well to concrete cases of new highway links equipped with toll gates. Thus, the first working assumption, already mentioned, consists in considering that the P3 system is the general case for new toll roads.

3.1. The advantages of P3s

They can be seen on every continent (Beria & al., 2015, Boardman & al., 2016) but they are particularly present in the European Union. New roads, bridges, tunnels and highways that have been built with (and often due to) toll systems correspond to more than 30,000 km of interurban highways operated by 123 companies that in most cases are private (ASECAP, 2022). These highways therefore have characteristics that do not situate them within the dominant paradigm of the literature on tolls:

- Contrary to older investments, they are not concerned by daily problems of congestion, especially since sections in dense urban areas often have no tolls.
- These structures are added to a historic road network and do not pose problems of acceptability regarding tolls, contrary to the introduction of a toll on an already existing section or in an urbanised area (Verhoef & al., 1997; Raux & Souche, 2004).
- Road pricing is accepted as a component of their financing, since it is accepted that without these receipts, their commissioning would occur much later (or never). The last point, emphasised in the literature long ago (Gomez-Ibanez & al., 1991) also corresponds to better acceptance of the principle of payer-user.

The development observed of P3s systems for toll structures was initially called into question due to the fact that the Weighted Average Cost of Capital (WACC) is liable to be excessive (Gross & Garvin, 2011, Fernandes & al., 2012) if it is not offset by greater efficiency.

3.2. The issue of the Weighted Average Cost of Capital (WACC)

When the operator in charge of the project is a public entity, or a non-profit private company, this operator is not supposed to make profits, but should cover the investment, maintenance and operating costs, including the financial charges of its loans, through commercial revenue. The latter

can comprise tolls paid by the users, or a shadow toll paid by the public authority. It is assumed that a possible deficit is compensated by the public authority. In the case of P3, the mechanism is the same, except that the private operator may have more expensive loan conditions than a public operator and must ensure the remuneration of its equity, and therefore generate a profit.

Consequently, the WACC is higher in the case of a P3. Although the literature has pointed to considerable variances capable of exceeding 300 basis points or bps (Fernandes & al., 2012, Vecchi & Hellowell, 2013), it appears that the magnitudes observed more recently are closer to 200 bps (McKinsey, 2017, Bonnafous & Faivre d'Arcier, 2018). The question raised is therefore that of knowing whether a private operator can offset this additional cost through more efficient management.

Systematic work has been carried out on the basis of 17 toll highway files in France that consists in establishing the gains required to offset 200 bps of additional WACC in a case of P3 (Bonnafous & Faivre d'Arcier, 2018), as this variance corresponds precisely to the situation observed in concession contracts. The result is that regarding several parameters, the private operator can easily ensure a performance that offsets the 200 bps of WACC. For example, in most cases, it simply needs to reduce construction costs by 13% at most; or reduce the lead-time of the construction by 15% at most. If the efforts combine for the parameters determining the internal rate of return (IRR), then the effects combine and in the 17 cases, the 200 bps were offset by a gain of at least 10% for each of the parameters considered.

Overruns of costs and lead-times in the case of a public operator are increasingly well documented. By way of example, mention can be made of a recent study of a Canadian case focusing on 39 traditional projects and 27 P3 projects (Zhang & al., 2020). Concerning the construction costs, the authors noted: "About 75% of P3 projects were delivered on budget, whereas about 80% of traditional projects involved various degrees of construction cost overruns". And concerning the delays: "The average total schedule creep of the traditional projects is estimated to be 428 days. In contrast, the average construction schedule delay in P3 projects is -24 days, meaning on an average, P3 projects actually complete ahead of the contracted deadline by 24 days."

Among the many comparable results, we mention a study evaluating P3 in the United States, based on seven value for money studies (Kweun & al., 2018), that assessed the advantages of a P3 system for the public purse and which confirmed its advantage.

Therefore, we consider in what follows that the issue of optimal toll can be posed in the case of a P3 system. Where necessary, we specify the outcome of the results in the case of a concession managed by a public entity.

4. Working assumptions and real world-values

The following analyses are based on working assumptions that have the dual advantage of corresponding to real situations and of simplifying calculations. Regarding the real situations the first of these assumptions consists in considering that the question of the optimal toll is raised by a new road added to an itinerary without a toll. We will assume in everything that follows that there is no congestion on these new road.

4.1. A new toll road added to an itinerary without a toll

This configuration is used systematically in the literature on toll roads, at least since Arthur Pigou (1920), and in particular by all the authors on congestion tolls cited in this article. But this configuration is also that of concrete situations in which new projects equipped with tolls are considered. They generally concern traffic up to now catered for by existing roads without tolls.

In this case, as soon as the physical characteristics of the competing itineraries are known, we know how to simulate the distribution of traffic between them, something that is obviously practiced

systematically in *ex ante* evaluations of projects: the evaluator establishes a demand function on the new route that expresses the traffic as a function of the toll level.

In the case of the French highway system, a model has been developed for this configuration, making it possible to represent evaluations of such a project in various concrete situations. The model is known as SIMCALECO and was developed by the LAET (Chevasson, 2007) in order to test all the impacts on project evaluations of the trade-offs comprised in official evaluation methods, such as the numerical values retained for the nuisances. Here, we use it to compare our results with real toll values.

Indeed, this model is capable of performing all the evaluations recommended by official French texts pertaining to highway projects. These calculations are based on the values of some 140 parameters necessary to carry out this type of assessment (value of CO₂, safety or comfort coefficient, etc.). In a reference scenario that we have chosen for this exercise and which represents an “average project”, we consider a section of highway of 90 km that has been added to an existing road of 110 km. Before the highway was commissioned, the road accommodated 13,000 vehicles a day (counted in private cars equivalent) transferable to the highway section; the investment and operating costs and the toll are those observed for the 2000s in France; the assignment of traffic between the road and the highway under concession is simulated by a LOGIT model.

The use of these simulations representative of real situations makes it possible to understand the following results, as well as validate a working assumption of particular value in what follows.

4.2. The assumption of the linearity of the demand function

For the sake of clarity, the assumption according to which the traffic on the highway is a linear function of the toll was chosen initially, since it allows simplifying the calculations considerably. The situation represented by the SIMCALECO model shows that this assumption is pertinent, at least for the levels of the tolls actually charged. Indeed, figure 2 suggests that a linear adjustment (by least squares) over the entire range of the demand function would not be acceptable. However, this adjustment becomes perfect ($R^2 > 99\%$) in the range of values that cover acceptable toll levels (from 0 to 18 cents per v-km).

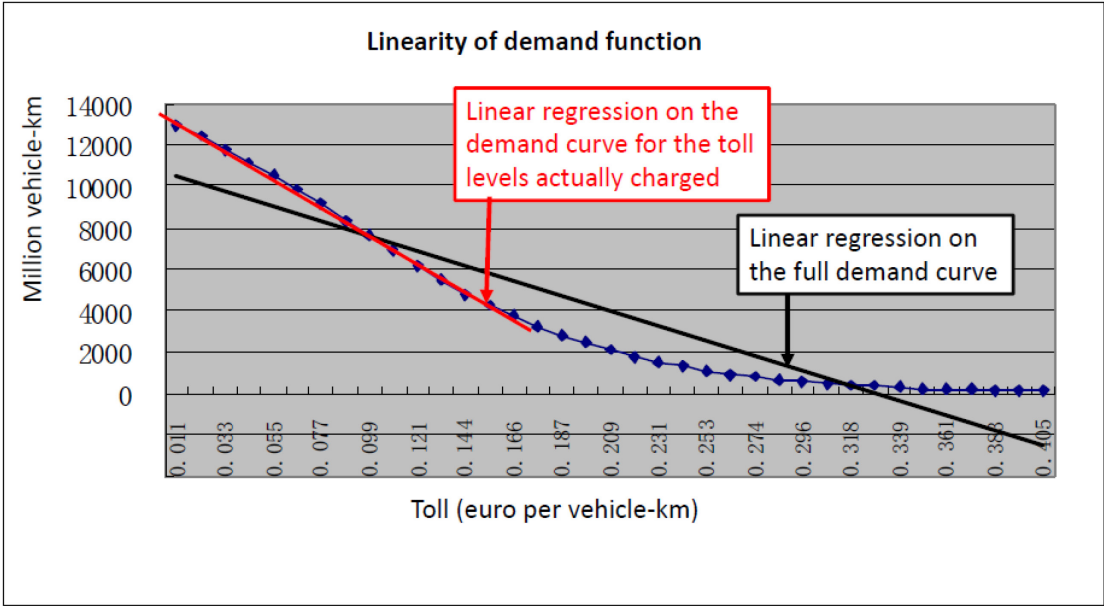


Figure 2: Relevance of the assumption of linearity of the demand function.

Note that the measurement error made by choosing this linear demand function concerns the measurement of users' surplus (net utility in the meaning of Dupuit) and more particularly the users'

surplus ready to pay very high tolls. This “error” has no effect on the measurement of a variation of the surplus between two levels of toll, nor on a marginal calculation of toll optimisation from the moment that the latter is situated between 0 and 18 cents.

4.3. The toll function is strictly a financing function

We are assuming that the function of the toll is to finance the highway on which it is collected, which amounts to considering that the pricing of the use of a road network (chiefly taxes on fuel) covers the marginal external costs.

In the same way as for the previous assumption, this obviously allows significantly simplifying the optimal toll problem, as we will see in the following section. Its pertinence can be seen from two angles.

The first question consists in asking whether this assumption is confirmed by the tax system in force. Highly precise work by Georgina Santos (2017) concerning 22 European countries, showed that “a number of countries could be considered to be on the right path already regarding petrol taxation”, but a large majority of countries fail to ensure the coverage of the externalities considered (climate change, air pollution, congestion, accidents and noise).

This leads to a second rather naïve question: For all that, is it up to the toll on a new infrastructure to correct these deficiencies? The answer is obviously no, especially since a highway has a very positive effect on externalities linked to safety. But above all, in the reality of decisions to invest and charge, the toll is defined as a financing toll. It is therefore justifiable to seek its optimal value within this sole financial dimension, therefore according to a rationale of second best.

5. What is the optimal toll in the case of a new structure?

In this section we ask the question: At what level should the toll be set for a new highway structure whose construction has been decided and for which it is necessary to know how its financing will be shared between the user and the taxpayer?

5.1. The optimization of the discounted welfare function

Taking the working assumptions above, the evaluation of a project can be formulated in a very simplified way: the variation in the welfare function for the project ΔW , depends solely on the discounted subsidy multiplied by the public funding scarcity coefficient φ and the discounted user surplus S . The subsidy is defined as the difference between the discounted investment and operating costs C and the discounted revenue from the project R . This function is therefore written as follows:

$$\Delta W = \varphi \cdot \text{Sub} + S = \varphi(R - C) + S \quad (1)$$

It is noteworthy that the discounted revenue is frequently lower than the costs, thus making subsidies necessary. This is generally the case of most of the more recent highway and railway projects in Europe. Since the discounting calculations are performed at constant prices, we assume that toll p remains unchanged over the discounting period and that discounted demand d (equal to d_0 when p is zero then a slope $-\beta$ as a function of p) can be expressed by a linear function written as:

$$d = d_0 - \beta \cdot p \quad (2)$$

This results in discounted revenue:

$$R = d_0 \cdot p - \beta \cdot p^2 \quad (3)$$

Regarding the discounted user surplus, for a price level p , it is written as:

$$S = \frac{\beta}{2} \left(\frac{d_0}{\beta} - p \right)^2 \quad (4)$$

Equations (1), (2) and (4) can be represented on the same graph insofar as it shows the respective variations of ΔW , R and S , as a function of the same variable p . To facilitate the interpretation of Figure 3 below, function $(\Delta W + \varphi.C)$ is represented as an ordinate, C being considered a constant value independent of the toll.

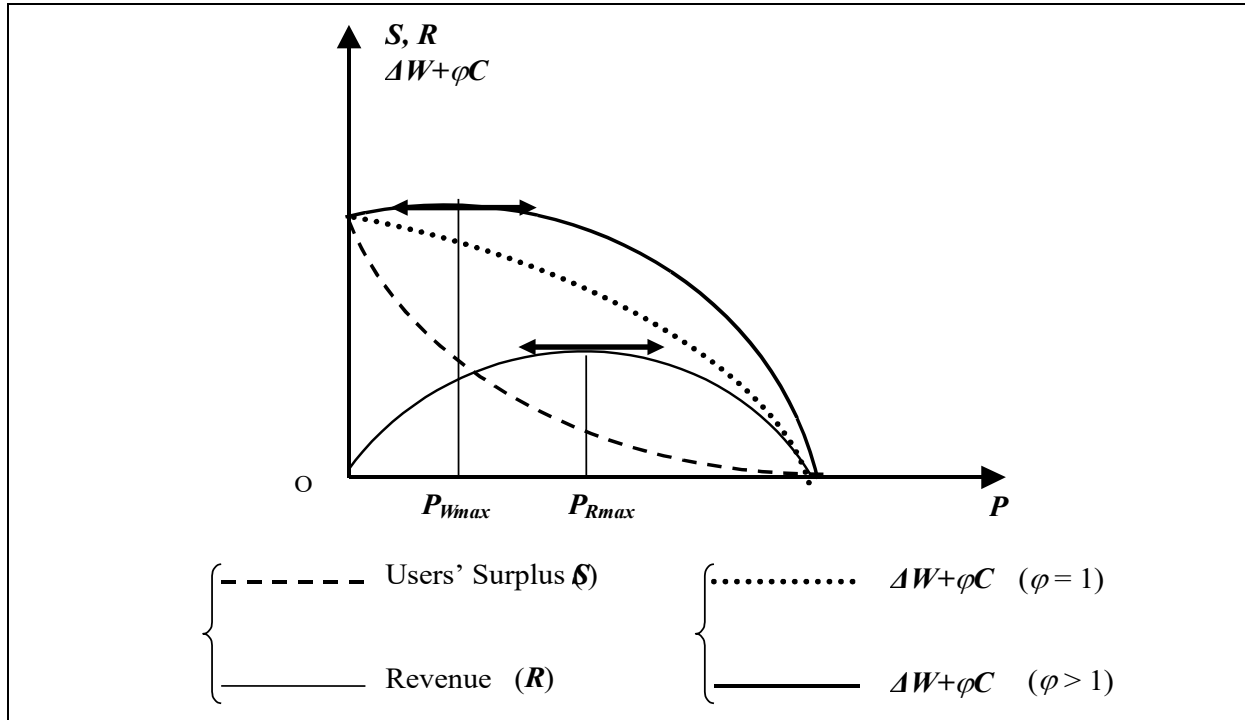


Figure 3: The utility function for two values of the public funding scarcity coefficient.

According to whether we consider the welfare function without scarcity of public funds, or this function with a scarcity coefficient higher than 1 or the revenue function, we obtain three optimal tolls:

- The first is no toll. As was been clearly stated by Jules Dupuit, in the case where the scarcity of public funding is not considered, ($\varphi=1$) the welfare function, which he referred to as social welfare, has a maximum value when $p = 0$. If a toll were introduced in this case, the resulting decrease in the user surplus (the "loss utility" of Figure 1) would always be greater than the increase in revenue. According to our hypothesis that the demand function is linear, it is easy to demonstrate that the maximum revenue, for example, is equal to only half the maximum user surplus when the toll is zero. We know, from Jules Dupuit (1849), that the full user surplus could only be internalized with discriminatory pricing. Otherwise, the welfare function can only decrease with the price when $\varphi=1$.
- If we take account of the scarcity of public funding, the welfare function does not decrease for the lowest toll values: in our graph, when the toll increases from 0 to P_{Wmax} the welfare function increases when $\varphi>1$. Beyond P_{Wmax} the loss of user surplus, expressed by a decrease of S , begins to dominate and the welfare function decreases. Once again, although he used neither equation nor curve, Jules Dupuit understood this collective utility of the toll in the case of insufficient public funds. The value of the toll which maximizes ΔW can be deduced easily from equations (1), (2) and (4):

$$P_{W \max} = \frac{\varphi - 1}{2\varphi - 1} \times \frac{d_0}{\beta} \quad (5)$$

- Lastly, if we consider only the monetary components of the project, we observe that the toll which maximizes revenue (denoted by $P_{R \max}$) is higher: it is easy to deduce from equation 3 that this toll is equal to exactly half the toll that cancels demand (the value for which all traffic transfers onto toll-free routes) and which is written as:

$$P_{R \max} = \frac{d_0}{2\beta} \quad (6)$$

5.2. Real world values

In order to compare these theoretical results with real toll values as observed in practice, let us return to the case of the French highway network and the standard project set out in section 4. The SIMCALECO model (Chevasson, 2007) allows giving real values to equations (5) and (6) and calculating $P_{W \max}$ and $P_{R \max}$. This confirms that $P_{W \max}$ depends on the public funding scarcity coefficient φ , as shown in Figure 4.

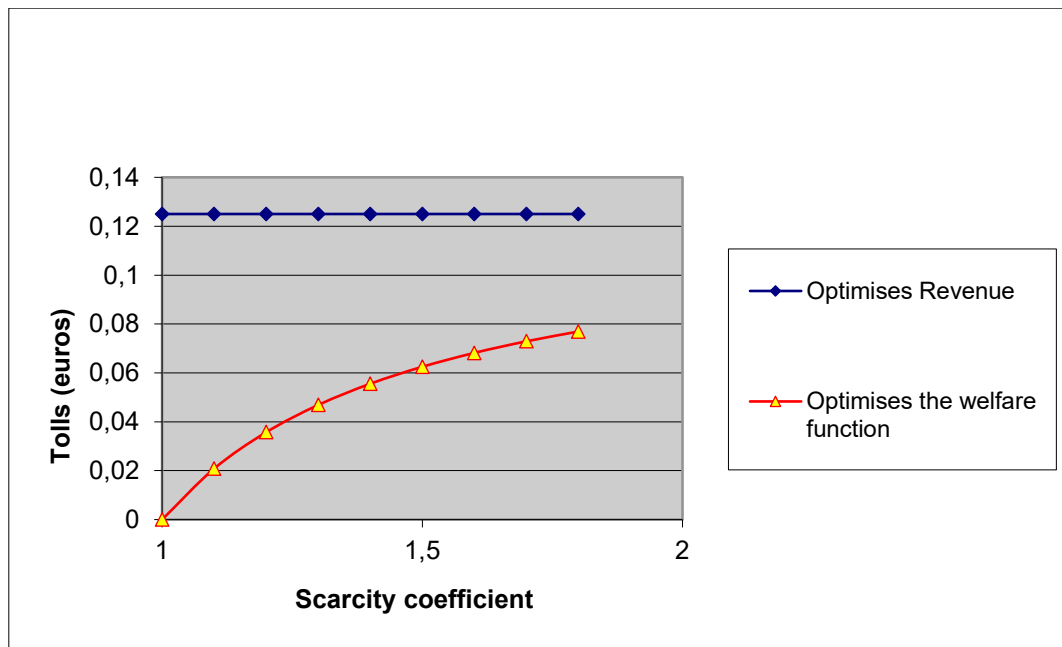


Figure 4: The two optimal tolls as a function of the public-funding scarcity coefficient.

The toll per vehicle-km observed in the 2000s on existing French highways corresponds to a value of 0.064 € (with inflation-related corrections). Figure 4 shows that this toll was barely more than half the toll that would maximize revenue. If we interpret it as a toll that maximized the welfare function, it would correspond to a value of the scarcity coefficient φ of almost 1.5, which is fairly reasonable compared with the available estimates of φ in transport policy (Ponti & Zecca, 2007). This suggests that the implicit scarcity coefficient used to determine the tolls prior to the French reforms of the 2000s (Bonnafous, 2015) was higher than the coefficient of scarcity that was officially fixed at 1.3 in order to evaluate investments (Ministère de l'Équipement, 2004 & 2005). This said, the calculation of the toll has never explicitly set out to maximize the welfare function.

The finding is more meaningful for the tolls on recent franchises: allowing for price increases (compared to tolls on the date of construction of SIMCALECO), the 14 cent toll on the A88 (opened in 2010) would be exactly equal to toll $P_{R \max}$ in our numerical example which maximizes the revenue, and the 11.3 cent toll on the A65 highway (also opened in 2010) would be 19% below this. In view of

the likely fluctuations in the evaluations of P_{Rmax} in concrete cases, our estimate (12.5 cents in 2005) should be taken as an order of magnitude – but one that is surprisingly close to the tolls that have been introduced on highway sections opened recently (Bonnafous, 2015).

Recent franchises were built in France in a macroeconomic context characterized by large public finance deficits. Everything therefore happened as if the toll policy had been determined with abnormally high scarcity coefficients for public funds.

6. From optimizing for a single project to optimizing a "programming toll"

By reasoning on the basis of a single project for which the goal is to determine the optimal funding toll, we naturally opted for the welfare function as the objective function. However, optimisation becomes more complex if we consider the perspective of the economic regulation of investments, in view to ensuring the coordinated utilisation of the different orders, in particular the programming of the investments and their pricing (Bonnafous, 2010).

This entails that the planner must consider several candidate projects in order to establish their optimal ranking under the constraint of a time series of available budgets, which cannot be done without making an assumption about tolls: with low tolls, the budgetary constraint will be considerable and few projects can be financed; with higher tolls this constraint is looser and a higher number of projects can be financed, but with a large number of users squeezed out and thus deadweight loss. It is therefore necessary to achieve consistency through a dual optimisation: that of the choice of investments and that of their pricing.

6.1. Another objective function

This leads us to raise the question of optimal pricing, not as it was dealt with in the previous section, that is to say the pricing that maximises the variation of the welfare function linked to a particular project, but in the way it contributes to maximising the welfare function *of a programme of projects that must be carried out under a budgetary constraint*.

The issue of the optimal ranking of candidate projects under budgetary constraint has received relatively little attention from the literature. A solution was however demonstrated by both numerical simulation (Bonnafous & Jensen) and by theoretical simulation (Roy, 2005): the ranking that maximises the Net Present Value (*NPV*) of a projects programme is the ranking of the projects according to the decreasing values of Value for Money ratio (in the meaning of the *NPV/Sub* ratio).

We note in passing that these works showed that, under the same budgetary constraints, the order of carrying out projects according to the decreasing ratio of the socioeconomic internal rate of return (*ERR*) resulted in an *NPV* for the complete programme lower than that of an order of execution according to the decreasing financial rate of return (*IRR*). In addition, this order results in a global *NPV* lower than that of the optimal ranking according to decreasing values of *NPV/Sub*. A pricing consistent with such an optimisation will therefore be that which optimises the *NPV/Sub* ratio. It is therefore necessary to resume the previous calculations with this objective function.

Equations (1) and (3) allow us to express the variation of the welfare function ΔW in the form of a function of the second degree of toll p :

$$\Delta W = -\varphi.C + \frac{d_0^2}{2\beta} + (\varphi - 1).d_0.p + \beta.\left(\frac{1}{2} - \varphi\right).p^2 \quad (7)$$

To express the financing constraint, it should be remembered that the level of the subsidy, as formalised in section 5, is written as a function of p :

$$Sub = C - R = C - d_0.p + \beta.p^2 \quad (8)$$

With an available budget B , a certain number of projects can be subsidised and the process then consists in determining the toll that optimises the net present value of the projects carried out under this constraint. This entails optimising the NPV per public euro invested as mentioned previously and therefore, by using equations (7) and (8), to determine the toll that maximises:

$$\Delta W / Sub = \frac{-\varphi \cdot C + \frac{d_0^2}{2\beta} + (\varphi - 1) \cdot d_0 \cdot p + \beta \cdot \left(\frac{1}{2} - \varphi\right) \cdot p^2}{C - d_0 \cdot p + \beta \cdot p^2} \quad (9)$$

The derivative of this function requires a rather complex calculation but which can be considerably simplified to give:

$$\frac{d(\Delta W / Sub)}{dp} = \frac{d_0^3 - 2C \cdot \beta \cdot d_0 + 2(C \cdot \beta^2 - \beta \cdot d_0^2) \cdot p + \beta^2 \cdot d_0 \cdot p^2}{(2\beta)^2 (C - d_0 \cdot p + \beta \cdot p^2)^2} \quad (10)$$

The surprising message provided by this equation is that the public funds scarcity coefficient φ has disappeared, meaning that the *optimal toll of the programming does not depend on the public funds scarcity coefficient*.

The numerator, a function of the second degree in p , accepts two real roots: on the one hand the value d_0/β which is a trivial root corresponding to the level of toll for which demand is cancelled (likewise the receipt and the surplus users, as indicated by equations (3) and (4)); on the other hand, a root that is a value obviously lower than d_0/β and which optimizes the function of equation (9) and corresponds to the "optimal programming toll". We denote this toll as P_{op} which optimises the social yield of the investment programme under a public financing constraint:

$$P_{op} = \frac{d_0}{\beta} \left(1 - \frac{2C \cdot \beta}{d_0^2}\right) \quad (11)$$

To situate this toll in relation to that which maximises the receipt ($P_{Rmax} = d_0/2\beta$), we can introduce the value of the maximum receipt ($d_0^2/4\beta$), denoted R_{max} , and the corresponding subsidy value, denoted Sub_{min} , which is therefore the minimum subsidy equal to $(C - R_{max})$. Equation (11) is therefore written as:

$$P_{op} = \frac{d_0}{2\beta} \left(1 - \frac{Sub_{min}}{R_{max}}\right) \quad (12)$$

The interpretation of this P_{op} using equations (11) and (12) provides a wealth of information, some of which can be detailed.

6.2. Several theoretical lessons from these results on concession contracts

The most significant result provided by equation (12) is obviously the independence of P_{op} in relation to the public funds scarcity coefficient, contrary to P_{Wmax} (equation 5). This optimal programming toll depends only on the cost of the project and the parameters that characterise the demand function.

This result, formalised by equation (12), can be interpreted in terms of the project's financial efficiency: when it is higher, the maximum receipt covering a large share of the costs, there is a

collective advantage in drawing the optimal programming toll closer to the maximum receipt toll. If the maximum receipt is higher than the costs, the subsidy is null and P_{op} becomes P_{Rmax}

In this case, a concession contract between the public authorities and the operator does not require a specific clause regarding the toll, even if the aim is to protect users from excessive tolls, since the operator has no interest in applying a toll higher than P_{Rmax} . On the contrary, the contract can foresee the sharing of operating surpluses between the conceding party and the concessionaire.

Reciprocally, when the financial profitability of the operation is low, the minimum subsidy becomes high and, if it reaches the level of the maximum receipt, P_{op} is null. In this case, the toll does not provide a gain in welfare and we find ourselves typically in a partnership contract with a regular payment to a private partner, as is practiced for a toll-free highway section. Equation (12) thus suggests a precise rule: a structure without toll (and with a possible partnership contract) is the right solution when the discounted maximum revenue cannot cover at least half the discounted cost.

6.3. Magnitudes in a concrete case

As in the previous section, we return to the case of a French highway network and the standard project based on the SIMCALECO model in order to compare these theoretical results with the real toll values observed.

The representation of the objective function, as expressed by equation (9), confirms that the optimal toll is the same whatever the level of the public fund scarcity coefficient and thus not a curiosity linked to calculation errors.

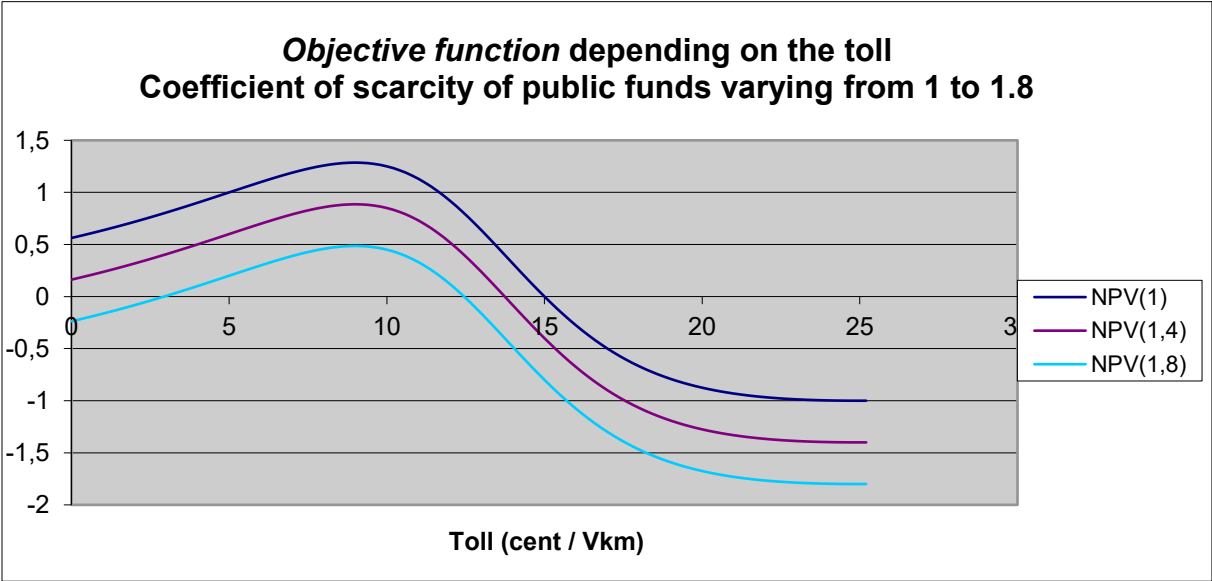


Figure 5: $\Delta W/Sub$ as a function of the toll and the scarcity coefficient of public funds.

We can also situate the three optimal tolls mentioned above as a function of φ (Figure 6). We note that if the toll that optimises the NPV of a programme (P_{op}) is never higher, as we have shown, than the toll that optimises the revenue, it can be lower than that which optimises the NPV of a specific project.

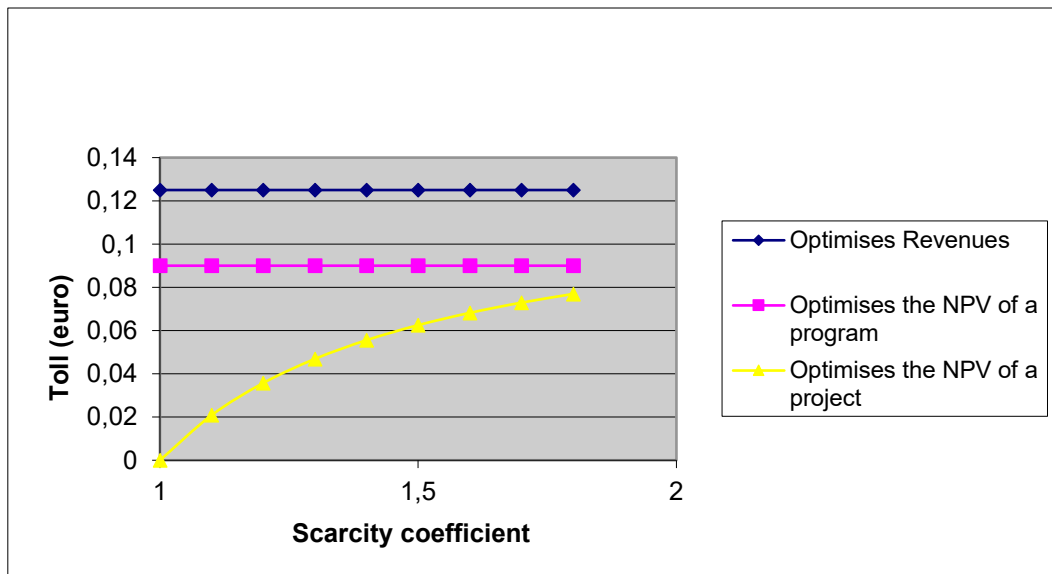


Figure 6: The two optimal tolls as a function of the public-funding scarcity coefficient.

The main merit of this series of curves is that it gives us a representation of several orders of magnitude in the case of an investment quite similar to an “average” highway case. For example, it shows us that if we consider a scarcity coefficient of 1.3 as currently and officially recommended in France (Ministère de l’Équipement, 2005), the optimal project toll should be around 0.05 euros per V.km. However, the optimal toll of the programme should be around 0.09 euros whereas the toll practiced is close to 0.07 €. For a project not requiring subsidies, like that mentioned by us, these P_{op} should be in the region of 0.125, i.e. much higher, which is quite close to the tolls of certain new links, as already mentioned.

6.4. A pricing principle that does not exclude adaptations

On this basis, in the reality of a system of programming new toll highways, such an optimal programming toll can be calculated in the framework of *ex ante* evaluations that precede the decision to invest and determine the numerical values of the parameters or variables of equations (11) and (12). In the case of private concessions, this toll simply becomes one of the data of the call for tenders intended to designate the concessionaire. In the case of a public concession or an operator with the status of public agency, this optimal toll can be imposed on the basis of the same calculations. It is simply likely that the estimator of the minimum subsidy S_{min} will be higher than in the case of a private operator if we retain the analyses mentioned in section 3 that suggest less efficiency from public operators. This will lead to slightly a different sharing of financing between the user and the taxpayer at the expense of the latter.

This rationale of financing toll is obviously not incompatible with price modulations during exceptional periods, for example during the weekends of the major summer holiday migrations characterised by congestion on part of the toll network. Thus, varying prices could be considered for an entire network, capable of reducing losses of time linked to congestion by implementing spatial and temporal modulations of tolls. The literature provides theoretical solutions, including in the case of a concession (Verhoef, 2007).

However, it is clear that such pricing mechanisms may be difficult to implement in reality since they imply agreements and compensations immediately they involve a network on which several concessionaires intervene. It is no coincidence that the rare success stories correspond to cases in which price modulations have been implemented on sections managed by the same operator, for example in France on the highways operated by SANEF (Gómez-Ibáñez & Small, 1994).

Other adaptations of prices can also be considered in the direction of diversifying tariffs according to different segments of demand with different price elasticities, in line with the reasoning of Marcel Boiteux (1956). Naturally, this will require adjustments to the highly simplified analysis proposed here.

7. Conclusion

It appeared reasonable to call the financing toll obtained here the “Jules Dupuit Toll”, since it is clear that it is based on the toll problem which Jules Dupuit was the first to formulate, as explained in section 2. Very paradoxically, we obtain a result that calls into question what he wrote about such a toll: “*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*”. But our result suggests that if one reasons from the perspective of programming a number of projects for which an optimal ranking must be programmed as well as the respective optimal tolls, the latter no longer depend on the public fund scarcity coefficient, thus the question of knowing “*by which taxes they must be replaced and what the effects of these taxes will be*” is no longer pertinent.

However, it remains crucial to determine the successive budgetary envelopes devoted to such investments, though this is quite another question. In the clear academic tradition to which we adhere, transport economics considers this envelope as an exogenous constraint under which one can only seek a second best optimum.

For the rest, we suggested a pricing principle, in the sense of optimal sharing between users and taxpayers. It was completed with indications on the types of public-private partnerships according to the economic performances of the projects. They ensure the necessary and strategic coherence between the choice of investments, their evaluation and the key to their financing.

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