Maintenance Incentives in Highway Concession Contracts

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Abstract

In most European countries, the private sector has a direct or indirect participation in the construction, overhaul, maintenance or operation of highways, normally through concession contracts with a pre-specified duration. The company which is granted the concession contract is normally remunerated through direct payments by road users (road tolls) or through payments by the concession authority, normally as a function of observed road traffic. In this context, it is important to understand the incentives of the concession company to maintain a highway in proper conditions (normally a requirement of the concession contract) whilst at the same time it seeks to maximise its profits. We model the profit-maximisation problem faced by the concession company throughout its concession contract in the case where (i) it is remunerated directly by users, (ii) demand is a function of road quality and (iii) maintenance is costly. We find that concession companies have incentives to "shirk" on their maintenance duties and let road quality degrade early in their concession contract; later on, because at the end of the contract the motorway must be in good working conditions, the concession company invests more heavily in maintenance. We test these results by analysing how they vary with the road depreciation rate, demand, economies of scale and the duration of the concession contract.

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1 Introduction

The use of concession contracts "by which a public authority grants specific rights to an organization (whether private or semi-public) to construct, overhaul, maintain and operate an infrastructure for a given period" (Bousquet and Fayard (2001)) is a common practice in most European Countries when dealing with road infrastructures, and, in particular with highways. The organization which is granted the concession contract is normally remunerated through direct payments by road users (road tolls) or through payments by the concession authority ("shadow toll"), normally on the basis of the traffic observed on the motorway.

In many cases, the company granted the concession is charged with making the investments required to create the service at its own cost and operate the service at its own risk, for a limited period. However, there are several possible variations to the infrastructure concession, and it may be possible to have the public authority funding the project and later making the infrastructure available to the concession company, who must be responsible for managing the operation of the motorway.

As a general rule, the concession company is responsible for the execution of work, and the supply of services throughout the period of concession. In this paper, we focus on the issue of maintenance, which has received little attention in the literature (see Vickerman (2004)). We attempt to construct a model reflecting the incentives of the concession company to maintain a highway in proper conditions, whilst at the same time it seeks to maximise its profits. We model the profit-maximisation problem faced by the concession company throughout its concession contract in the case where i) it is remunerated directly by users (road tolls), ii) demand is a function of road quality and iii) maintenance is costly. We will consider that the company has no part in the construction phase of the infrastructure, and is
only responsible for the operation of the motorway, which, at the beginning of the contract will be in an almost-as-new condition.

The timing of the rehabilitation actions is a "fundamental aspect of the road maintenance planning" (Dekker et al (1997)). "On the one hand one must rehabilitate the roads before the damage is bothering the motorists; on the other hand one must not repair the roads too soon as it is quite expensive to maintain small road-sections" (idem). Road maintenance activity is characterised by economies of scale. In fact, the cost of maintenance per square meter decreases when the repaired area becomes larger, i.e., it is less costly to carry out a one-off larger repair than to spread out the maintenance task over several small repairs.

A popular discussion is one which concentrates on issues such as whether private sector operators will put profits before safety. This would imply, however, that there would be no revenue implications of operating an unsafe or under-maintained network, or at least that these implications would be smaller than any cost saving. "Since most infrastructure has an expected life greater than the typical franchise granted to an operator, there might be an incentive to depreciate the asset more rapidly if there is no penalty for the condition at the end of this period" (Vickerman (2004)). This is why most concession contracts refer to the infrastructure being transferred, at the end of the period of concession, in good working order.

Vickerman (2004) analyses maintenance in privatised infrastructures, namely for the road network and the rail network. In particular, he discusses the definition of the optimal level of maintenance, and the incentives which might ensure that the infrastructure operator maintains the infrastructure in this optimal state. Vickerman (2004) considers that "those maintaining and operating networks will have a better knowledge of their long-term potential to deliver a given level of service than those regulating that provision". The risk and effort
which the agent employs is unobservable, assuming asymmetric information and incomplete contracts. In what concerns road maintenance, however, as suggested by Decker et al (1997), the deterioration of a road is observable, since "inspections are relatively cheap to perform".

In this paper, we present an optimal control model which determines the optimal path of the intensity of road maintenance efforts by the concession company, during the period of concession. The company will receive the road, at the beginning of the contract, in an almost-as-new condition and will have to return it, at the end of the period, in the same condition. The road quality at any time $t$ will depend on the depreciation rate, assumed to be constant, and on the intensity of road maintenance. We find that concession companies have incentives to "shirk" on their maintenance duties and let the road quality degrade early in their concession contract; later on, because at the end of the contract the motorway must be in good working conditions, the concession company invests more heavily in maintenance. In other words, the company will underinvest in an initial stage relative to the depreciation rate, leading to a deterioration of the road, but will more than compensate for this in a later stage by investing more heavily in maintenance so as to bring the quality of the road towards the original level.

The paper is structured in the following way: section 2 describes the model and provides the optimal solution for the concession company; section 3 analyses these results by making use of a Phase diagram, where the dynamics of the problem are analysed in more detail; finally, section 4 concludes.

## 2 The model

We assume the concession company must maximise its profits over a given planning horizon $[0, T]$, the concession period, in continuous time.
Revenues are given by demand (number of road users) multiplied by the road toll, \( p \) which we assume is fixed throughout the concession period and exogenous to the concession company. Demand is given by:

\[
D_t(p) = K_t(a - bp)
\]

where \( K_t \) is road quality at time \( t \). We assume that \( K_t \in [0,1] \), where \( K_t = 1 \) means that the highway is in an almost-as-new state and cannot be further improved and \( K_t = 0 \) means that the highway is in poor conditions and cannot get any worse than that. Therefore, demand is a decreasing function of the road toll and an increasing function of road quality. The following relationship is assumed to hold: \( a > b \).

Let \( Q_t \) denote the intensity of road maintenance efforts by the concession company. \( Q_t \in [0,1] \), where \( Q_t = 0 \) implies that no maintenance is carried out in period \( t \) and \( Q_t = 1 \) implies that in a given period the concession company fully restores the road into an almost-as-new condition.

The concession company is assumed to have the following cost function for each period \( t \):

\[
C(Q_t) = cQ_t - Q_t^2
\]

with \( c > 2 \). This cost function conveys the idea that average costs are a decreasing function of maintenance efforts, as suggested by Dekker et al (1997). Economies of scale in road maintenance arise with this cost function if \( c > 2 \), as assumed. Therefore, it is less costly for the concession company to carry out a given maintenance task \( Q_t \) in one single period than to spread it out over two or more periods.
We assume that there is a constant depreciation rate of road quality given by \((1 - \delta)\). Therefore, if road quality at period \(t\) is \(K_t\), in the following period it will be given by \(\delta K_t\). We assume \(\delta \in [0, 1]\).

The maximisation problem of the concession company is:

\[
\max_{Q_t} \int_0^T \left[p[K_t(a - bp)] - cQ_t + Q_t^2\right] dt
\]

s.t. \(\dot{K} = (\delta - 1)K_t + Q_t\)

\(K_0 = 1\)

\(K_T = 1\) \hspace{1cm} (3)

where \(\dot{K}\) is the instantaneous rate of growth of road quality at any point in time. At this point, we have opted not to constrain the optimisation problem, for example imposing the restrictions that \(Q_t \geq 0\) or that at any point in time \(K_t \leq 1\). By doing so, we wish to analyse the dynamics of this simple setup and understand how the imposition of such contraints would affect the results.

In order to solve this optimal control problem, where the concession company must decide on a given path of \(Q_t\) over the planning horizon \(t \in [0, T]\), we set up the Hamiltonian:

\[
H = p[K_t(a - bp)] - cQ_t + Q_t^2 + \pi(t)\left[(\delta - 1)K_t + Q_t\right] \hspace{1cm} (4)
\]

The stable path must satisfy the following first order conditions
Applying the first order conditions to our maximisation problem yields:

\[
\frac{\partial H}{\partial Q_t} = 0 \\
\dot{\pi}(t) = -\frac{\partial H}{\partial K_t} \\
\dot{K} = \frac{\partial H}{\partial \pi(t)}
\]  

(5)

Substituting the first condition into the second yields:

\[
\dot{\pi} + (\delta - 1) \pi = -p(a - bp)
\]  

(7)

This is a linear differential equation. In order to solve it, we multiply both sides by \(e^{(\delta-1)t}\) and integrate:

\[
\pi = \frac{p(a - bp)}{1 - \delta} + Ce^{(1-\delta)t}
\]  

(8)

where \(C\) is assumed to be the constant of integration. Substituting into the first equation yields:

\[
Q_t = \frac{c}{2} - \frac{p(a - bp)}{2(1 - \delta)} - C\frac{e^{(1-\delta)t}}{2}
\]  

(9)

Finally, substituting this equation in the third first order condition and rearranging yields:
\[ \dot{K} + (1 - \delta) K_t = \frac{c}{2} - \frac{p (a - bp)}{2 (1 - \delta)} - C \frac{e^{(1-\delta)t}}{2} \]  

(10)

Again, this is a linear differential equation. Multiplying both sides by \( e^{(\delta-1)t} \) and integrating yields:

\[ K_t = \frac{c}{2 (1 - \delta)} - \frac{p (a - bp)}{2 (1 - \delta)^2} - C \frac{e^{(1-\delta)t}}{2 (1 - \delta)} + D e^{(1-\delta)t} \]  

(11)

where \( D \) is a constant of integration. These equations for \( K_t \) and \( Q_t \) contain the path over time of the state and costate variables of this optimal control problem. In particular, the equation \( Q_t \) describes the optimal path (profit maximising) of maintenance efforts of the concession company throughout the planning horizon. Given that path, and given that road quality depreciates over time, the equation \( K_t \) describes the path of the state variable given the optimal choice of \( Q_t \). If the optimal \( K_t \) is an increasing function of time, then the incentives of the concession company are such that it invests in maintenance in any given period by more than the road depreciates; by contrast, if \( K_t \) is a decreasing function of time, then the optimal choice of \( Q_t \) is such that maintenance investment is not sufficient to restore, in any given period, road quality back to the previous period’s conditions.

Using the last two restrictions, the starting point and the end point of the state variable, \( K_t \), it is possible to solve for values of \( C \) and \( D \). In particular, we know that at the start of the concession, the highway is handed over to the concession company in an almost-as-new condition, i.e. \( K_0 = 1 \); we also know that at the end of the concession contract, the concession company must hand over the highway in an almost-as-new condition (this is generally not the case in most concession contracts, which vaguely specify that the highway must be in "usable" conditions), i.e. \( K_T = 1 \). Using the optimal equation for \( K_t \), this implies that the
following equations must hold:

\[
K_0 = \frac{c}{2(1 - \delta)} - \frac{p(a - bp)}{2(1 - \delta)^2} + D = 1 \tag{12}
\]

\[
K_T = \frac{c}{2(1 - \delta)} - \frac{p(a - bp)}{2(1 - \delta)^2} - \frac{C}{2(1 - \delta)} + De^{(1-\delta)T} = 1 \tag{13}
\]

Solving this system of equations yields:

\[
C = \frac{1 - e^{(\delta-1)T}}{e^{(\delta-1)T} - e^{(1-\delta)T}} \left[ 2(1 - \delta) + c - \frac{p(a - bp)}{1 - \delta} \right] \tag{14}
\]

and

\[
D = 1 - \frac{c}{2(1 - \delta)} + \frac{p(a - bp)}{2(1 - \delta)^2} + \frac{1 - e^{(\delta-1)T}}{e^{(\delta-1)T} - e^{(1-\delta)T}} \left[ 1 + \frac{c}{2(1 - \delta)} - \frac{p(a - bp)}{2(1 - \delta)^2} \right] \tag{15}
\]

These equations fully characterise the optimal (stable) path of \(Q_t\) and \(K_t\) over the planning horizon. In particular, by substituting equation (14) into equation (9), we obtain the optimal path chosen by the concession company for its maintenance efforts throughout the concession contract. In particular, it can be shown that \(Q_t\) is an increasing function of time. This suggests that the concession company will invest increasingly more in maintenance as the concession approaches its end.

Also, by substituting equations (14) and (15) into equation (11) we obtain the pattern of evolution of road quality throughout the concession period given the optimally chosen values of \(Q_t\) for all values of \(t\). In particular, it can be seen that \(K_t\) is a decreasing function with time for low values of \(t\) and an increasing function with time for higher values of \(t\). This suggests that the optimally chosen values of \(Q_t\) are low in the initial periods when compared to road depreciation; therefore, road quality decreases. However, later in the concession, maintenance efforts increase sufficiently so as to be higher than road depreciation.
and therefore to slowly restore road quality. When the concession expires, the road is fully restored to an almost-as-new condition, as specified in the maximisation problem.

3 Graphical analysis of results

In order to understand the dynamics of the system, we can draw a phase diagram. Using the first first order condition, we know that:

$$Q_t = \frac{c}{2} - \frac{\pi(t)}{2}$$  \hspace{1cm} (16)

Differentiating with respect to time yields:

$$\dot{Q} = -\frac{\pi(t)}{2}$$  \hspace{1cm} (17)

Substituting the second first order condition into this equation yields:

$$\dot{Q} = \frac{p(a - bp) - (1 - \delta)c}{2} + (1 - \delta)Q_t$$  \hspace{1cm} (18)

If we set $\dot{Q} = 0$, we will find the values of $Q_t$ such that no growth over time is observed. This yields:

$$Q_t = \frac{c}{2} - \frac{p(a - bp)}{2(1 - \delta)}$$  \hspace{1cm} (19)

This is the first element we need in order to draw the phase diagram. The second element comes from one of the restrictions. We know that:

$$\dot{K} = (\delta - 1)K_t + Q_t$$  \hspace{1cm} (20)
Therefore, if we set $\dot{K} = 0$, we will obtain the values of $Q_t$ (as a function of $K_t$) such that no growth in road quality is observed through time. This yields:

$$Q_t = (1 - \delta) K_t$$

(21)

We can plot these two equations into the $(Q_t, K_t)$ space in order to understand the dynamics of the system. This is done in Figure 1.

These two equations partition the space into 4 regions. In region I, the dynamics of the system are such that $\dot{K} > 0$ and $\dot{Q} > 0$. Therefore, if the starting point value of $K_t$ and $Q_t$ was in this region, the optimal path would follow a righwards and downwards trajectory, crossing the $\dot{K} = 0$ line at some point in time. If the starting point values were in region IV, the dynamics of the system would show that in that region $\dot{K} > 0$ and $\dot{Q} > 0$; therefore,
the optimal trajectory would be rightwards and upwards. If the starting point values were
in region II, the dynamics of the system show that $\dot{K} < 0$ and $\dot{Q} < 0$; therefore, the optimal
trajectory would lead us in a downwards and leftwards direction.

The interesting cases are those in region III, given that the starting point value of $K_t$ is
1. Here we see that depending on the equation which describes $\dot{Q} = 0$, and in particular the
point where it intersects the vertical axis, we obtain a stable optimal path. In particular, it
appears to be the case that for some value parameters of $c, a, b, p$ and $\delta$ that intersect would be
negative. Therefore, the starting point value of $Q_t$ would be negative, which is non-sensical in
our context (it would be equivalent to negative maintenance in any given period). Although
this is true, we can still analyse the dynamics of the system and understand what would
happen if we were to impose the restriction that $Q_t \geq 0$ at any point in time. Assuming the
intersect of the $\dot{Q} = 0$ line is negative, and at $K_0 = 1$, the dynamics of the system, for the
above values of $Q_t$ obtained from the maximisation problem we know that $Q_t$ is increasing
with time. Therefore, it must be the case that the optimal path more to the left describes
the optimal trajectory. This suggests that $\dot{K} < 0$ and $\dot{Q} > 0$ whilst the values are within
region III, i.e. the concession company invests in maintenance but not enough to restore
road quality to its previous period’s condition. In other words, the concession company lets
the highway degrade during the first periods of the concession contract.

This is true even in the "odd" case of negative values for $Q_t$. Indeed, if one were to impose
the restriction that $Q_t \geq 0$, then the optimal path would be given by the optimal path more
to the right in the Phase diagram, i.e. starting at a value of at least 0 and then letting the
system dynamics rule. This would show that the same happens as in the case above; in the
first periods the concession company would underinvest in maintenance and let road quality
degrad.
When the path crosses the $K = 0$ line, it must have an infinite slope. It then enters region IV, and follows a rightward and upward direction. In this region, maintenance investment continues to grow but now such growth is more than sufficient to offset the natural road depreciation given by the parameter $\delta$. Therefore, $\dot{K} > 0$ and the concession company continues to invest in road maintenance so as to reach the point $K_T = 1$ when the concession contract expires and it must have the highway in perfect working conditions (almost-as-new).

This analysis does not, for the time being, look in more detail at what would happen to the optimal path in the following interesting limiting cases:

- What happens as the planning horizon tends to infinity, i.e. $T \rightarrow \infty$; this is equivalent to a "permanent" concession contract rather than one with a given end point;

- What happens as road depreciation grows large or small, i.e. when $\delta \rightarrow 0$ or $\delta \rightarrow 1$;

- What happens as price (road toll) increases or decreases, i.e. when $p \rightarrow a/b$ or $p \rightarrow 0$;

- What happens when economies of scale increase, i.e. as $c \rightarrow \infty$;

- What happens as the end point changes, i.e. when the concession company can hand over the highway at the end of the concession period in a less than almost-as-new condition.

- Finally, what happens when the concession authority imposes (directly or indirectly) a minimum threshold for $K_t$.

The analysis of what happens when the restriction $Q_t \geq 0$ is imposed has not yet been derived analytically, but can be seen by looking at the phase diagram.
4 Conclusion

This paper addresses a pertinent issue in highway concession contracts: are maintenance incentives in concession contracts such that highways are always in good working conditions? As Vickerman (2004) notes, popular discussion concentrates on issues such as whether private sector infrastructure operators put profits before safety. Naturally, such bold statements assume implicitly that the infrastructure operator is unaffected by such decision, i.e. its profits are not reduced as a consequence. This would indeed be the case if the possible loss of revenue was more than off-set by potential cost savings.

In order to analyse this issue, we have set up a model where such a trade-off emerges. On the one hand, maintaining highways in good working quality increases the number of users which may decide to use it; however, such maintenance has a cost, as economies of scale are assumed to exist. Therefore, it is less costly to carry out maintenance tasks in one go rather than spread it out into smaller tasks over time.

In this setup, and imposing the restriction that the concession company must hand over the highway in an almost-as-new condition at the end of the concession, we find that the concession company has incentives to invest less in maintenance in the first periods of the concession but will invest increasingly more as time evolves. This investment is not sufficient to maintain road quality in those first periods, and therefore road quality degradation is observed. Later on, as maintenance efforts increase, these will off-set the depreciation effect and road quality inverts its trend and starts increasing in such a way as to be in an almost-as-new condition at the very end of the concession.

Our model allows for a richer analysis of other issues surrounding concession contracts. In particular, starting from this basic model, it is possible to analyse how these maintenance
incentives depend on the assumed exogenous variables, particularly the road depreciation rate, road tolls, economies of scale and the quality level of the highway at the end of the concession (imposed by the contracting authority). This analysis will be left for future research.
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