The race for telecoms infrastructure investment with bypass: Can access regulation achieve the first-best?*

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Abstract

We analyze the impact of mandatory access on the infrastructure investments of two competing communications networks, and show that for low (high) access charges firms wait (preempt each other). Contrary to previous results, under preemption a higher access charge can delay first investment. Constant access tariffs cannot achieve the first best. Optimal time-variant access tariffs may be increasing or decreasing over time. The first-best cannot be achieved at all through access tariff regulation if the follower's private incentives are dominated by business-stealing. Here access holidays can improve welfare by allowing for lower future access charges, which delay the second investment.

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1 Introduction

Over the last decades, one of the main goals of economic regulation has been to increase competition in markets that have traditionally been less competitive. At the same time, technological progress has come to be seen as a fundamental driving force of economic performance. In telecommunications, plans for the introduction of advanced networks generate such high expectations about new or improved services, and acceleration of economic growth and competitiveness, that not discouraging the necessary investments should be among regulators' primary concerns.

Regulators thus need to manage a trade-off between the two objectives of static and dynamic efficiency, which are often conflicting. While regulation for static efficiency aims to reduce market power based on existing infrastructure, it also reduces the rents on future investment. Hence, regulators face the difficult task of determining how to encourage networks to invest optimally without lessening competitive intensity.

In recent years, telecommunications markets have seen high rates of technological progress. Several substitutes for existing copper networks have been developed, all allowing the creation of new broadband services: bi-directional cable networks, fixed wireless local loops (FWA or WiMax), and upgraded cellular mobile networks. Most of these alternatives continue to involve large sunk costs and economies of scale, which makes it difficult for many firms to invest immediately.

One of the instruments used by regulators to reduce the temporary monopoly power of existing networks is to force them to give access. The idea is that rivals can first compete as service-based competitors, before they build their own networks and turn into facility-based competitors. This regulatory instrument has gained an important role since it started to be promoted more strongly in the United States after 1996 with the Telecommunications Act and in the European Union after the 1998 liberalization, especially in the form of the "unbundling of the local loop". According to the European Commission, service-based competition is a pre-requisite to have future facility-based competition. The achievement of the latter is desirable since it creates a high scope for product differentiation and innovation.

The issue of access regulation and investment is particularly important in the context of the Lisbon strategy. For example, in 2006 there was a dispute between the European Commission on the one hand, and the German telecoms regulator and Deutsche Telekom on the other, about mandating access to the VDSL network that Deutsche Telekom plans to build in fifty German cities. Deutsche Telekom claimed the right to an access holiday to this future network, and the regulator offered its support. The European Commission counter-argued that ex-ante regulation had to be extended also to this network, since the lack of competition in the German market could lead to the re-emergence of monopoly.

The academic literature on the relationship between access regulation and investment has started to address these concerns only recently. For example, Valletti (2003) claimed that this type of problems had not been studied sufficiently. However, he gives some clues towards understanding it by relating the issue with questions common to the literature on R&D.

Bourreau and Dogan (2005) consider a model of infrastructure investment in a telecommunications market with access regulation. One of the firms already owns an infrastructure, and thus only the other firm must decide if it wants to enter as a service-based or facility-based competitor. Therefore, the regulator simply has the problem of setting an access price such that the entrant duplicates at the socially optimal investment date. Bourreau and Dogan (2003) consider a similar model but allow for the use of a time-variant access price.

Gans (2001) considers a context similar to Katz and Shapiro (1987). Two firms compete to invest in a new technology, and there will be only one investment. In this case the regulator can induce the leader to invest at the socially optimal date, for which he uses the access charge.

Woroch (2004) provides a formal model of a technology race among network owners and service providers and studies the equilibrium broadband deployment pattern, allowing for duplication. He finds the equilibrium in terms of investment dates and analyzes the impact of mandatory access on the investment pattern, as we do in our paper. However he does not consider the presence of a regulator who maximizes social welfare as we do, and therefore does not consider the choice of a socially optimal access tariff

Hori and Mizuno (2006) consider a similar model, but they assume a stochastic growing demand instead of technical progress. In their model payoffs are always symmetric, contrary to ours where they may be different after investment (without discounting the access charge) depending on which firm was the first to invest. Besides this, they only allow the use of a usage charge. They obtain an equilibrium in a preemption equilibrium and conclude that the incentive for preemption can be enhanced by an increase in the access tariff.

Our model is based on the literature on technology adoption. The underlying assumption in all models is that investment cost declines over time, for example due to technical progress. The game is one of timing of investment, i.e. firms' only choices are their respective investment dates.

In Fudenberg and Tirole (1985) two or more firms adopt a new technology. Since they assume that it is better to be the first to adopt, the equilibrium outcome in the duopoly case is either preemption or joint adoption, both with rent equalization.

Katz and Shapiro (1987) consider a similar model where only one firm adopts and then offers a licence to the other firm. They show that preemption or waiting may occur in equilibrium. The waiting equilibrium arises due to a second-mover advantage, and the follower has a higher firm value.

Riordan (1992) considers the effects of regulation of entry and retail prices when both firms can adopt. Since the follower cannot access the first network access pricing is not an issue. Still, in spirit his paper is closest to ours in that it analyses how regulation affects investment dates.

Hoppe and Lehmann-Grube (2005) show how equilibria can be analyzed if the leader's profit as a function of its investment date has multiple local maxima or is discontinuous.

In our model there are two firms that intend to operate in a market, and new infrastructure must be built to allow these firms to offer services. Investment costs decline over time because of technological progress, and the construction of a second network, bypassing the first one, will be viable and socially desirable at some point in time. The second firm (the "follower") can access its rival's (the "leader's") infrastructure at a regulated two-part access tariff before it builds its own network. The follower's choice of investment will depend on the conditions of access.

More importantly, firms generally have two incentives for the first investment, a stand-alone incentive and a preemption incentive. The stand-alone incentive stems directly from the increase in profits after investment. In the absence of strategic effects, firms would choose investment timing by trading off earlier gains in profit against lower investment costs later on. The second incentive to invest is related to the advantage of being the first to invest. In fact, if a firm does not invest, a rival firm may do so and become the common provider. If being a leader is more profitable than being a follower, each firm has incentives to preempt the other firm's investment. If, on the contrary, being a follower is more profitable, both firms only have the stand-alone incentive to invest, and there is no race to become the leader.

We first determine the equilibrium in terms of investment patterns. Indeed, two types of equilibria are possible, preemption if there is a first-mover advantage caused by a high access charge, and waiting if there is a second-mover advantage due to a low access charge. In the preemption equilibrium the leader invests at the preemption date, while in the waiting equilibrium it invests at its stand-alone investment date. The follower always invests at its stand-alone investment date.

Both the leader's investment in a waiting equilibrium, and the follower's investment in both types of equilibria, occur earlier with a higher access charge. This happens because the stand-alone incentives to invest increase with the access charge. Yet, contrary to Hori and Mizuno (2006), the effect of the access charge on the leader's investment decision in a preemption equilibrium is ambiguous. Besides strengthening the stand-alone incentive, a higher access charge makes being the follower less attractive and therefore strengthens the preemption motive. On the other hand, since the follower invests earlier, the duration of service-based competition will be shorter, which lowers the returns on the first investment. This second effect may be stronger than the first two, and investment is delayed.

In a third step the regulator maximizes social welfare using the access tariff. Socially optimal investment by both leader and follower cannot be achieved with a time-invariant access tariff. This is intuitive since one regulatory instrument normally cannot achieve two independent goals. On the other hand, simply lowering or raising the access charge to a different level at some point in time may not lead to the social optimum, either, and paths involving more steps may be necessary. Furthermore, the optimal path may be either increasing or decreasing, depending on whether the follower has incentives to invest too early. The first best may not be achievable even with arbitrary access price paths if the follower's private incentives for investment are much stronger than its overall effect on welfare.

Finally, we extend our model to the case where duplication is either not socially or privately desirable. We show that our previous conclusions continue to hold. As a second extension, we show that access holidays can have two functions: Encourage investment when profits under competition are not enough; and help to achieve first-best investment when the follower invests too early.

The remainder of the paper is organized as follows. We describe the model in Section 2. In Sections 3 and 4 we obtain the equilibrium investment timing for both firms and analyze the impact of the access tariff. In Sections 5 and 6 we find the socially optimal investment timing and solve the regulator's problem. In Section 7 we consider some extensions, and in Section 8 we conclude.

2 The Model

We introduce a model where two firms, say firms A and B, compete for the construction of network infrastructure that allows them to offer new services. After one firm has built the infrastructure, it must give access to its rival at a regulated price. The regulator sets a two-part access tariff which consists of a usage charge a and an access charge $P \geq 0$. These are set ex-ante, i.e., when firms invest the access rules are already defined and known to both.

Here we only analyze the aspects concerning dynamic efficiency, assuming that the regulator has full information about the firms' technology and payoffs. Therefore, we assume that the usage charge a is used to maximize static efficiency, as in Gans (2001). Hence, we can think of the access tariff as just an access charge, and concentrate on its optimal choice.

The two firms that can build the infrastructure know that if a firm "wins" in the provision of the infrastructure it becomes the common provider, and if it "loses" it either pays for access or builds a bypass network. This setup can create a first-mover advantage which stimulates a preemption process. However, there may also be a second-mover advantage which will lead to a game where preemption does not occur. This second case arises since the follower benefits from the first investment through access and then invests later when technological progress has brought down costs.

Depending on the pattern of infrastructure investment, there are different market structures over time. When only one firm has invested, it must give access to the rival, and there is service-based competition. When both firms have invested, we have facility-based competition. Each firm's profit at a given point in time only depends on the investment pattern up to this date.

Firms' payoffs

We assume that firms are ex-ante symmetric, and that time is continuous. Hence, at the beginning of the game, when neither of the firms has invested, each earns flow profits of π_0. When one firm has invested and gives access, it obtains the leader's flow profit $\pi_{1L} + P$. If the follower asks for access it receives $\pi_{1F} - P$ per period, and otherwise zero. Thus, under service-base competition the follower obtains $\tilde{\pi}_{1F}(P) = \max\{\pi_{1F} - P, 0\}$, while the leader's profits are:

$$\tilde{\pi}_{1L}(P) = \begin{cases} \pi_{1L} + P & \text{if} \quad P \leq \pi_{1F} \\ \pi_{1M} & \text{if} \quad P > \pi_{1F} \end{cases}, \tag{1}$$

where π_{1M} is the monopoly profit. We assume:

$$\pi_{1F} \geq 0, \tag{2}$$

$$\pi_{1M} \geq \pi_{1L} + \pi_{1F}. \tag{3}$$

Since profits do not depend on P if $P > \pi_{1F}$, the relevant range for P is the interval $[0, \pi_{1F}]$, which is not empty by assumption (2). It follows that $\tilde{\pi}_{1L}(P) \leq \pi_{1M}$.

When both firms have invested, the leader's flow profit is π_{2L} and the follower's is π_{2F}, with:

$$\Delta_2 = \pi_{2L} - \pi_{2F} \geq 0. \tag{4}$$

Investment cost

Each infrastructure is built at a single moment, and the investment cost is decreasing over time due to technological progress. We also assume that firms hold on to the technology indefinitely once they have invested, and that the infrastructure does not deteriorate over time. This allows us to avoid the issue of re-investment. Current investment cost at time T is $C(T)$, which we assume to be a positive, decreasing and convex, and twice continuously differentiable function:[1]

$$C(T) > 0,\ C'(T) < 0,\ C''(T) > 0 \quad \forall T \in \mathbb{R}. \tag{5}$$

This implies that $\lim_{T\to\infty} C(T) = \underline{C} \geq 0$ and $\lim_{T\to\infty} C'(T) = 0$. Let the discount rate be $\delta > 0$. We assume that both the leader and the follower would want to invest in finite time. There are decreasing returns to investment, in the sense that the increase in the leader's flow profits exceeds the follower's:

$$\pi_{1L} - \pi_0 > \pi_{2F} - \pi_{1F} > \delta\underline{C}. \tag{6}$$

Later, when we analyze a context where a bypass investment is may not be desirable, we allow $\underline{C}$ to be higher. Investment cost discounted to time zero is $A(T) = C(T)e^{-\delta T}$, which is decreasing in T and converges to zero.

To rule out immediate investment, we assume that investment at time zero leads to losses:

$$\delta C(0) > \max\{\pi_{1M}, \pi_{2L}\}. \tag{7}$$

Since $A'(0) = C'(0) - \delta C(0)$ and $A(0) = C(0)$, we have $-A'(0) > \delta A(0)$.

Firms' strategies

[1] We extend the definition of investment cost to dates before zero in order to simplify the exposition below.

Each firm plays a Markov strategy that is a function of time T, the access tariff P, and whether its rival has already invested or not. For each firm, the only decision to be made is when to make a unique investment.

Since time is continuous in this model we need to take care of the coordination problem identified by Simon and Stinchcombe (1989), i.e. the possibility of having both firms adopt at the same time but regretting this action afterwards. We follow the literature by assuming that firms move alternatingly on a fine discrete time grid, and consider the equilibria as grid size goes to zero. As a result, only one firm invests at any point in time.[2]

3 Investment Timing

Let us start to examine what happens when one of the firms, say firm i, has invested at some time T_i. In this case we need to solve the follower's investment problem in the continuation game.

Given the leader's investment at T_i and the access tariff, the discounted payoff of the follower investing at $T_j \geq T_i$ is:

$$\begin{aligned} \tilde{F}(T_i, T_j, P) &= \int_0^{T_i} \pi_0 e^{-\delta t} dt + \int_{T_i}^{T_j} \tilde{\pi}_{1F}(P) e^{-\delta t} dt + \int_{T_j}^{\infty} \pi_{2F} e^{-\delta t} dt - A(T_j) \quad (8) \\ &= \frac{1-e^{-\delta T_i}}{\delta}\pi_0 + \frac{e^{-\delta T_i} - e^{-\delta T_j}}{\delta}\tilde{\pi}_{1F}(P) + \frac{e^{-\delta T_j}}{\delta}\pi_{2F} - A(T_j). \end{aligned}$$

Before T_i no firm has invested, and profits are π_0. Between T_i and T_j, there is a period of service-based competition. After duplication, both firms offer their services through their own infrastructure, and we end up in facility-based competition.

Now we can determine the follower's optimal investment date. First define, for all $T \in \mathbb{R}$,

$$Z(T) = -A'(T)e^{\delta T} = \delta C(T) - C'(T). \quad (9)$$

This is a continuously differentiable and strictly decreasing function, with $\lim_{T \to -\infty} Z(T) = +\infty$ and $\lim_{T \to +\infty} Z(T) = \delta \underline{C}$.

The only incentive for investment that influences the follower's decision is the stand-alone incentive. He weighs the benefit of higher payoffs of investing

[2]Fudenberg and Tirole (1989) note there may exist equilibria involving a positive probability of coordination failure in discrete-time games. Hence one needs to make an assumption that excludes this possibility. There are several other alternatives, such as a randomization device as in Katz and Shapiro (1997).

today against the cost savings of delaying investment. There is no preemption motive since its rival has already invested.

Proposition 1 *Given the access price P and the leader's investment date $T_i \geq 0$, the follower invests at:*

$$T^F(T_i, P) = \max\left\{T^{F1}(P), T_i\right\}, \tag{10}$$

where $T^{F1}(P) = Z^{-1}(\pi_{2F} - \tilde{\pi}_{1F}(P)) > 0$.

Proof. The follower solves

$$\max_{T_j \geq T_i} \left\{ \frac{\pi_{2F} - \tilde{\pi}_{1F}(P)}{\delta} e^{-\delta T_j} - A(T_j) \right\},$$

with first-order condition:

$$\pi_{2F} - \tilde{\pi}_{1F}(P) = -A'(T_j)\, e^{\delta T_j} = Z(T_j).$$

By assumption (6) the left-hand side is larger than $\delta \underline{C}$, and by assumptions (4) and (7) we have:

$$\pi_{2F} - \tilde{\pi}_{1F}(P) \leq \pi_{2L} < -A'(0) = Z(0).$$

Thus $T^{F1}(P) = Z^{-1}(\pi_{2F} - \tilde{\pi}_{1F}(P))$ is well-defined, unique and positive. The second derivative of profits is[3]

$$\begin{aligned} \frac{\partial^2 \tilde{F}\left(T_i, T^{F1}, P\right)}{\partial T_j^2} &= \delta\left(\pi_2 - \tilde{\pi}_{1F}(P)\right) e^{-\delta T^{F1}} - A''\left(T^{F1}\right) \\ &= Z'\left(T^{F1}\right) e^{-\delta T^{F1}} < 0, \end{aligned}$$

hence we have a maximum. If $T^{F1}(P) \leq T_i$ then the optimal choice is to invest at $T_j = T_i$, otherwise it is at $T_j = T^{F1}(P) > T_i$. ■

Denote the follower's profits at its optimal investment date as $F(T_i, P) = \tilde{F}\left(T_i, T^F(T_i, P), P\right)$. Note that $T^{F1}(P)$, $T^F(T_i, P)$ and $F(T_i, P)$ are continuous functions, and that $F(T_i, P)$ is positive for all $T_i \geq 0$ and $P \in [0, \pi_{1F}]$. Note also that for all $T_i \in \left[0, T^{F1}(P)\right]$, $F(T_i, P)$ is increasing in T_i if $\pi_0 > \tilde{\pi}_{1F}(P)$ and decreasing otherwise. Since in this case the follower's investment date does not depend on T_i, if the follower's flow profit decreases

[3]Below we omit second-order conditions since they hold and are similar to the present one.

after the leader's investment its discounted payoff increases if the leader invests later.

Now that we have determined the follower's choice in the continuation game, we can define the discounted payoff of a leader investing at T_i as $L(T_i, P) = \tilde{L}\left(T_i, T^F(T_i, P), P\right)$, where

$$\tilde{L}(T_i, T_j, P) = \frac{1 - e^{-\delta T_i}}{\delta}\pi_0 + \frac{e^{-\delta T_i} - e^{-\delta T_j}}{\delta}\tilde{\pi}_{1L}(P) + \frac{e^{-\delta T_j}}{\delta}\pi_{2L} - A(T_i). \tag{11}$$

We first determine the leader's stand-alone investment date $T^S(P)$. Given that one firm must be the leader, the first investment will not occur after this date. Preemption before this date will occur depending on whether there is a first- or a second-mover advantage. We will see that there is a second-mover advantage if the follower's discounted payoff is higher than the leader's at $T^S(P)$.

Proposition 2 *Given the access price P, the leader's stand-alone investment date $T^S(P)$ is at $T^{S1}(P)$ if $\pi_{2L} \geq \pi_0 + \pi_{2F} - \tilde{\pi}_{1F}(P)$, while otherwise it is at either $T^{S1}(P)$ or $T^{S2} > T^{F1}(P)$, with*

$$\begin{aligned} T^{S1}(P) &= Z^{-1}(\tilde{\pi}_{1L}(P) - \pi_0) \in \left(0, T^{F1}(P)\right), \\ T^{S2} &= Z^{-1}(\pi_{2L} - \pi_0). \end{aligned}$$

Proof. See Appendix A. ■

There may exist two local maxima in the leader's discounted payoff, as has already been pointed out in Fudenberg and Tirole (1985) in a similar context. The first one, $T^{S1}(P)$, and which always exists, occurs before the follower's investment date $T^{F1}(P)$, and thus leads to a period of service-based competition. The second local maximum at T^{S2} only arises when either π_{2L} is low or P is high, and leads to immediate bypass by the follower. In this case, there is no period of service-based competition. In both cases $L\left(T^S(P), P\right)$ is positive, but when its second local maximum exists we cannot determine the location of its global maximum. [4]

[4] Fudenberg and Tirole (1985) show that any one of the two local maxima can be the global maximum. They argue that $L\left(T^{L1}\right) > L\left(T^{L2}\right)$ is typical of new markets, where the profit after the investment in the infrastructure increases strongly. The opposite case $L\left(T^{L1}\right) < L\left(T^{L2}\right)$ arises when the first investment simply transfers profit from the leader to the follower.

In equilibrium the leader may not invest at $T^S(P)$, since for high values of P the threat of preemption will induce investment at an earlier date. Indeed, whenever $L(T_i, P) > F(T_i, P)$ there is a first-mover advantage: The discounted payoffs of becoming a leader are strictly higher than the payoff of becoming a follower. In this case firms will compete to be leaders, each trying to invest slightly earlier that its rival. In equilibrium, one firm invests at the preemption date $T^R(P)$, which is the earliest date where that firms are indifferent between being a leader or a follower, and the other firm invests later. The following Proposition shows that the preemption date is well-defined:

Proposition 3 *Given the access price P, there is a unique date $T^R(P) \in \left(0, T^{F1}(P)\right]$ such that for all $T_i \in \left[0, T^{F1}(P)\right)$ we have $L(T_i, P) \lesseqgtr F(T_i, P)$ if $T_i \lesseqgtr T^R(P)$.*

Proof. See Appendix B. ■

Now we need to establish whether or not preemption will arise. The decisive factor is which of the two dates occurs earlier, the preemption or the stand-alone investment date. The following results are similar to Katz and Shapiro (1987), Riordan (1992) and Hoppe and Lehmann-Grube (2005).

Proposition 4 *For all $P \in [0, \pi_{1F}]$, in subgame-perfect equilibrium the follower invests at $\widetilde{T}^F(P) = T^{F1}(P)$, and the leader's investment $\widetilde{T}^L(P) < \widetilde{T}^F(P)$ falls into two cases:*

i) Preemption: If $T^R(P) < T^S(P)$, the leader invests at $\widetilde{T}^L(P) = T^R(P)$.

ii) Waiting: If $T^R(P) \geq T^S(P)$ the leader invests at $\widetilde{T}^L(P) = T^{S1}(P)$.

This outcome is unique up to relabeling of firms.

Proof. Similar to the proof of Theorem 1 in Hoppe and Lehmann-Grube (2005). Note that in our model $L(T_i, P) - F(T_i, P) = e^{-\delta T_i} \frac{\Delta_2}{\delta} \geq 0$ for all $T_i \geq T^{F1}(P)$, thus we do not need to restrict F to be non-increasing to obtain a unique outcome. Joint adoption equilibria, where both firms adopt at the same date $T > T^{F1}(P)$, are ruled out following the arguments in Riordan (1992). ■

We now plot the leader's and follower's payoffs as functions of the leader's investment date in order to explain the intuition of this result. We have two cases, depending on whether the follower's payoff is increasing (Figures 1 and 2) or decreasing (Figures 3 and 4) until $T^{F1}(P)$.[5]

[5] All these 4 figures are represented assuming that $\pi_{2L} > \pi_{2F}$. If $\pi_{2L} = \pi_{2F}$ we would have $L(T_i, P) = F(T_i, P)$ after $T^{F1}(P)$ in all 4 figures.

The follower's payoff $F(T_i, P)$ is (weakly) increasing in $T_i < T^{F1}(P)$ if $\pi_0 \geq \tilde{\pi}_{1F}(P)$, or $P \geq P_H = \pi_{1F} - \pi_0$, i.e. at the access price P the follower is worse off than before the leader's investment. In this case we have

$$L\left(T^{S1}(P)\right) > L\left(T^{F1}(P)\right) \geq F\left(T^{F1}(P)\right) \geq F\left(T^{S1}(P)\right), \qquad (12)$$

and there is a first-mover advantage. The equilibrium outcome is preemption at $T^R(P)$ because any attempt to wait with investment until some later date will be met with slightly earlier investment.

There are two sub-cases, depending on the leader's global maximum. In Figure 1 there is only one local maximum in the leader's payoff function, i.e. $P \leq P_H + \Delta_2$, while in Figure 2 we have $P > P_H + \Delta_2$ and a second local maximum. If one does not view the equilibria of the game as limits on a discrete time grid, then if the second maximum is high enough joint adoption equilibria just before T^{S2} may arise, see Fudenberg and Tirole (1985).

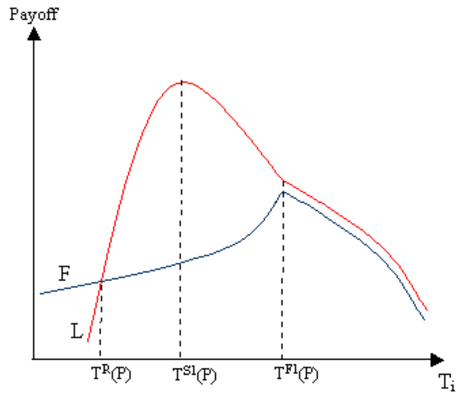

Figure 1

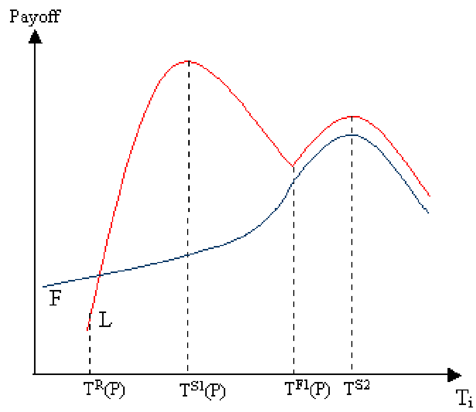

Figure 2

On the other hand, $F(T_i, P)$ is decreasing in $T_i < T^{F1}(P)$ if $P < P_H$. The leader's payoff has only one local maximum, but now the outcome may be waiting or preemption. If $L\left(T^{S1}(P)\right) > F\left(T^{S1}(P)\right)$, as in Figure 3, then again there is a first-mover advantage and the outcome is preemption. On the other hand, if $L\left(T^{S1}(P)\right) < F\left(T^{S1}(P)\right)$ as in Figure 4 then there is a second-mover advantage, and we have a waiting equilibrium.

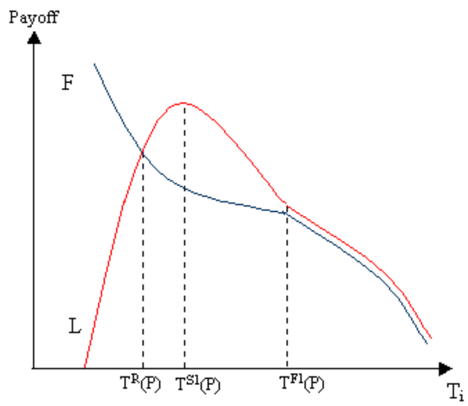

Figure 3

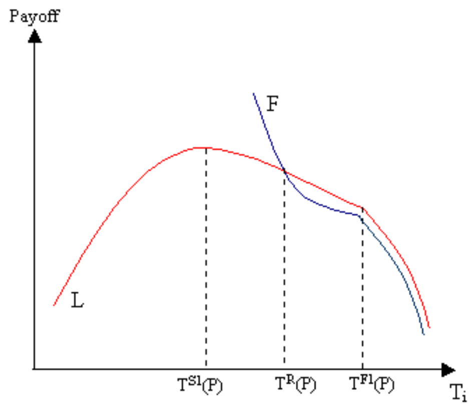

Figure 4

While being a known result in technology adoption games, the possibility of a waiting equilibrium is a novelty for models of access regulation. In fact, the existing literature generally obtains a simple preemption equilibrium.

4 Effects of the Access Tariff

We can now determine the effect of the access tariff on the leader's and follower's investment dates.

Proposition 5 *If the access charge $P < \pi_{1F}$ increases, the follower invests earlier.*

Proof. From Proposition 1, $\frac{\partial T^{F1}}{\partial P} = \left(Z^{-1}\right)' \left(\pi_{2F} - \pi_{1F} + P\right) < 0.$ ■

With a higher access tariff, the follower makes fewer profits prior to its investment and, as a result, it invests earlier. Since $P = \pi_{1F}$ leads to the same outcome as no access at all, mandatory access at $P < \pi_{1F}$ always delays the follower's investment as compared to the situation without access. As we will see below, similar to Riordan (1992) the effect of delay on welfare depends on the socially optimal second investment date.

With respect to the leader's decision, we need to analyze what happens when it waits or preempts.

Proposition 6 *In a waiting equilibrium, a higher access charge $P < \pi_{1F}$ makes the leader invest earlier. In the preemption equilibrium, with a higher access charge $P < \pi_{1F}$ the leader invests earlier (later) if $\left.\frac{\partial(L-F)}{\partial P}\right|_{T_i = T^R(P)} >$ $(<)\, 0$.*

Proof. From Proposition 2, $\frac{\partial T^{S1}}{\partial P} = \left(Z^{-1}\right)' (\pi_{1L} + P - \pi_0) < 0$.

The leader's preemption investment date is determined by the condition $L(T^R(P), P) = F(T^R(P), P)$ with L cutting F from below. Hence, we know that at $T^R(P)$ we have $\frac{\partial(L-F)}{\partial T_i} > 0$. By the Implicit Function Theorem, $\frac{dT^R(P)}{dP} = -\frac{\partial(L-F)}{\partial P} \Big/ \frac{\partial(L-F)}{\partial T_i}$. Therefore the stated result follows. ■

The result for the preemption equilibrium depends on whether an increase in the access price benefits or hurts the leader. In order to understand the effects involved, consider

$$\left.\frac{\partial(L-F)}{\partial P}\right|_{T_i=T^R(P)} = \frac{2}{\delta}\left(e^{-\delta T^R(P)} - e^{-\delta T^{F1}(P)}\right) + e^{-\delta T^{F1}(P)}\left(-\frac{dT^{F1}(P)}{dP}\right)\left[\pi_{2L} - \tilde{\pi}_{1L}(P)\right]. \tag{13}$$

The first term describes the direct effect on the difference in flow profits during service-based competition. A higher access price benefits the leader and hurts the follower, thus increasing the incentives for preemption. The second effect, however, an indirect effect caused by the anticipation of the follower's investment, may go both ways. If the leader's profits increase after duplication, i.e. $\pi_{2L} > \tilde{\pi}_{1L}(P)$, then earlier duplication again benefits the leader, and higher P indeed makes the leader invest earlier. On the other hand, if after duplication its profits decrease substantially, the total effect may become negative. As a result, the returns from the first investment decrease, and the leader delays investment.

We still need to determine for which values of P we have a waiting or preemption equilibrium. As we have seen, for $P \geq P_H$ we definitely have preemption, thus without the provision of access we would always obtain preemption. For $P < P_H$ we may have a preemption or waiting equilibrium, depending on whether $T^R(P)$ is smaller or larger than $T^{S1}(P)$. For our generic investment cost function, there may be none, one, or more than one $\hat{P} \in (0, P_H)$ with $T^R\left(\hat{P}\right) = T^{S1}\left(\hat{P}\right)$, which are the values of the access price for which we have transitions between both types of equilibria. As we will show in the next section, since the leader will only invest at the socially optimal date if the regulator induces a preemption equilibrium, this possible multiplicity of transitions between waiting and preemption equilibria poses no problem.

For completeness, we discuss briefly the possible cases. If there is no transition then we always have preemption. If there is one transition then we have a second-mover advantage when the access charge is low and a first-mover advantage for high P, i.e., there is a waiting equilibrium for $P \in \left[0, \hat{P}\right]$ and preemption for $\left(\hat{P}, \pi_{1F}\right]$. The leader's investment date is a continuous function of the access price:

$$\tilde{T}^L(P) = \begin{cases} T^{S1}(P) & if \quad 0 \leq P \leq \hat{P} \\ T^R(P) & if \quad \hat{P} < P \leq \pi_{1F} \end{cases}. \tag{14}$$

This function decreases on the first branch, but may be increasing for high $P > \pi_{2L} - \pi_{1L}$ on the second branch.

On the other hand, there may be more than one P such that $T^R(P) = T^{S1}(P)$. The reason is that both the stand-alone and preemption investment dates may decrease in parallel with a higher access price. In fact, if P increases we have a transition from a waiting to a preemption equilibrium if and only if $T^R(P)$ falls below $T^{S1}(P)$, i.e. if

$$\left.\frac{dT^{S1}(P)}{dP}\right|_{T^R=T^{S1}} - \left.\frac{dT^R(P)}{dP}\right|_{T^R=T^{S1}} > 0.$$

The first term is always negative, pointing towards a transition to waiting, while the second term can be either positive or negative. We can sign the whole expression unambiguously only in the case where a higher access charge delays preemptive investment, which forces a transition to a waiting equilibrium.

5 Socially Optimal Investment Timing

Social welfare is defined as the present value of the intertemporal stream of social benefits (profits and consumer surplus) minus discounted investment costs. Let S_0 be consumer surplus per period when neither firm has invested. S_1 is consumer surplus per period when one firm has invested in a new infrastructure, and the other has access to it. S_2 is consumer surplus per period when both firms have invested. Note that S_1 is independent of P since it is a lump-sum payment from the follower to the leader. We assume that consumer surplus does not decrease after the first investment:

$$S_1 \geq S_0. \tag{15}$$

Total surplus per period for each of the three cases is:

$$\begin{aligned} w_0 &= 2\pi_0 + S_0 \\ w_1 &= \pi_{1L} + \pi_{1F} + S_1 \\ w_2 &= \pi_{2L} + \pi_{2F} + S_2. \end{aligned} \tag{16}$$

We assume that total surplus (before investment cost) increases with both investments, and that both eventually are socially desirable, though only after date zero. Furthermore, we assume that total welfare increases more with the first investment than with the second one:

$$Z(0) > w_1 - w_0 > w_2 - w_1 > \delta \underline{C}. \tag{17}$$

Note that this assumption does not follow from the previous ones, because it also includes the possible reductions in payoffs by the firm which does not invest.

With investment dates $T_L \leq T_F$, net social welfare is given by:

$$\begin{aligned} W(T_L, T_F) = &\left(1 - e^{-\delta T_L}\right) \frac{w_0}{\delta} + \left(e^{-\delta T_L} - e^{-\delta T_F}\right) \frac{w_1}{\delta} \\ &+ e^{-\delta T_F} \frac{w_2}{\delta} - A(T_L) - A(T_F). \end{aligned} \tag{18}$$

The socially optimal investment dates are easily characterized:

Proposition 7 *Socially optimal investment occurs at dates $T_F^w > T_L^w > 0$, with*

$$T_F^w = Z^{-1}(w_2 - w_1), \quad T_L^w = Z^{-1}(w_1 - w_0). \tag{19}$$

Proof. The regulator maximizes W over $T_L \leq T_F$, with first-order conditions

$$\begin{aligned} w_1 - w_0 &= Z(T_L^w), \\ w_2 - w_1 &= Z(T_F^w). \end{aligned}$$

The left hand sides of both conditions are larger than $\delta \underline{C}$ by assumption (17). Thus $T_L^w = Z^{-1}(w_1 - w_0)$ and $T_F^w = Z^{-1}(w_2 - w_1)$ are well defined and unique. Assumption (17) also guarantees that $T_L^w > 0$ and $T_L^w < T_F^w$. ■

6 Optimal Regulation

Having determined the socially optimal investment dates, we now consider how a regulator can induce a socially optimal investment pattern using *ex ante* regulation.

For a start, we find the access charge such that each firm invests at the corresponding socially optimal date.

Proposition 8 *The follower invests at the socially optimal date with the access price $P_F^* \equiv S_2 - S_1 + \pi_{2L} - \pi_{1L}$ if $0 \leq P_F^* \leq \pi_{1F}$.*

Proof. Immediate from $T^{F1}(P_F^*) = T_F^w$. ■

When a follower invests, it changes its payoff but also consumer surplus and the leader's payoff. However, in its decision it does not take the latter into account. Hence, we need to make him internalize these effects through the access charge. Note that the higher are the consumer and leader's gains from duplication, the earlier is the socially optimal bypass investment date. On the other hand, if duplication reduces the leader's payoff then the follower should invest later than the mere consideration of consumer surplus would imply.

Proposition 9 *Let P_L^* be a solution of $T^R(P_L^*) = T_L^w$. If $0 \leq P_L^* \leq \pi_{1F}$, then the leader invests at the socially optimal date. This access charge results in preemption, while socially optimal investment by the leader cannot be achieved through a waiting equilibrium.*

Proof. Suppose P is such that we have a waiting equilibrium, which implies $P < P_H$. If $T_L^w \geq T^{S1}(P)$ then by definition of these two dates $P \geq P_H + S_1 - S_0$, which contradicts $P < P_H$ by (15). Therefore for this P we have $T_L^w < T^{S1}(P)$. In other words, if there is to be socially optimal investment by the leader it must be in a preemption equilibrium. ■

The leader always invests too late in waiting equilibria, because it considers only its private gains. As a result, the regulator needs to induce a preemption equilibrium, using an access price that is high enough, if he wants to achieve socially optimal investment by the leader.

If P is low enough then $T^R(P)$ is still decreasing in P, and higher gains in consumer surplus from investments make the regulator choose a higher access price. On the other hand, if P is already too high that any increase delays investment, then P should be lowered.

Now let us assume that both P_L^* and P_F^* belong to the interval $[0, \pi_{1F}]$, similar to Gans (2001), while we leave open which of the two is larger. Contrary to the latter paper, where a two-part tariff achieves socially optimal investment, in our model the regulator generically cannot achieve socially optimal investment by both firms using one access price. In fact, he only has one instrument and two objectives. Hence, the second-best constant access charge $P^{so} \in \arg\max_P W\left(T^R(P), T^{F1}(P)\right)$ is somewhere between P_L^* and P_F^*, with one firm investing too early and the other too late as compared to the first best.

A further problem is that this second-best access charge lacks time consistency. If the regulator does not commit to this price, and revises it after the leader's investment, he would change it to P_F^*. If the leader foresees this it would invest at $\tilde{T}^L(P_F^*)$, and *ex ante* welfare would be lower.

Given that in our model access is priced using a two-part tariff, if the regulator only aims for dynamic efficiency and ignores static efficiency, he can use the usage charge a as an instrument to induce to a first-best investment pattern with a time-consistent access charge P. He must choose $\widetilde{a}$ such that $P_L^*(\widetilde{a}) = P_F^*(\widetilde{a})$. Unfortunately, there is no simpler or explicit condition describing this level of usage charge.

According to De Bijl and Peitz (2004), with full participation and inelastic demand static welfare is independent of the usage charge. In this case, the increase in the usage charge is totally passed on to consumers by the follower, while the leader takes all the benefits from this increase. This implies that a regulator has some freedom to set the usage charge for dynamic objectives. However, for new services, we do not have full participation, and thus there will be a usage charge which maximizes static welfare. In this case, a regulator has to sacrifice static welfare if he wants to use the usage charge for dynamic objectives.

Hori and Mizuno (2004) show that if the regulator were to use explicit taxes and subsidies he could obtain the first best, because with these instruments he can further adjust both firms' payoffs. However, this option incurs the inefficiency costs associated with the use of subsidies and taxes.

We now suggest how the first best can be achieved through a time-variant access charge. This problem is not trivial, since the path of charges, which the regulator naturally must commit to, must be chosen such that forward-looking firms have the incentives to invest at the correct dates knowing that access prices will change.

In principle, the path of access charges could define a different value for each moment in time, resulting in an infinite number of instruments. On the other hand, contrary to what might be expected, we will show below that depending on the value of P_F^* only two levels of access charges may or may not be enough.

Define the path of access charges as a function $P(T)$ of time. Naturally, as before access charges will be paid only during the interval of service-based competition between the two investments.

Since the leader's stand-alone investment date $T^{S1}(P)$ does not change if the follower invests at T_F^w instead of $T^{F1}(P)$, the same argument as in Proposition 9 applies, and efficient investment can only be achieved in a preemption equilibrium.

Proposition 10 *Define* P_L^{**} *by* $\tilde{L}(T_L^w, T_F^w, P_L^{**}) = \tilde{F}(T_L^w, T_F^w, P_L^{**})$, *i.e.*

$$P_L^{**} = \frac{\delta\left(A\left(T_L^w\right) - A\left(T_F^w\right)\right) - \Delta_2 e^{-\delta T_F^w}}{2\left(e^{-\delta T_L^w} - e^{-\delta T_F^w}\right)} - \frac{\pi_{1L} - \pi_{1F}}{2}. \tag{20}$$

If $0 \leq P_L^{**} \leq P_F^*$, *a path of access charges such that both firms invest at their socially optimal dates is*

$$P(T) = \begin{cases} P_L^{**} & \text{if} \quad T < T_F^w \\ P_F^* & \text{if} \quad T \geq T_F^w \end{cases} \tag{21}$$

Proof. At time $T \geq T_L^w$ the follower solves:

$$\max_{T_j \geq T} \int_T^{T_j} \left(\pi_{1F} - P(t)\right) e^{-\delta t} dt + \frac{\pi_{2F}}{\delta} e^{-\delta T_j} - A(T_j).$$

Taking the first-order condition we obtain:

$$\begin{array}{r} \pi_{1F} - \pi_{2F} - P_L^{**} \; + Z(T_j) > 0 \text{ for } T_j < T_F^w \\ \pi_{1F} - \pi_{2F} - P_F^* \; + Z(T_j) < 0 \text{ for } T_j > T_F^w \end{array}$$

Hence, the follower invests at T_F^w, and since $P_L^{**} \leq P_F^* \leq \pi_{1F}$ the follower asks for access before T_F^w.

Since the leader receives P_L^{**} during the whole duration of service-based competition, the first investment will occur at the socially optimal preemption date T_L^w. ■

The access price P_L^{**} induces preemption at the optimal first investment date when firms know that the second investment will also occur optimally. Thus the difference between P_L^* and P_L^{**} is that the former supposes that the second investment is at the non-optimal date $T^{F1}(P_L^*)$.

Thus if $P_L^{**} \leq P_F^*$ the follower can be induced to invest at T_F^w simply by raising the access price to P_F^* or higher, or even end access to the leader's network, at the date when investment is meant to occur. This result is similar to Bourreau and Dogan (2003), where the regulator sets a time-variant access price in order to guarantee both static efficiency and optimal investment by the entrant. It also corresponds to the recommendation in Cave and Vogelsang (2003) of access pricing that are increasing over time.

Still, if $P_L^{**} > P_F^*$ then the above path of access charges does not lead to the first best: the follower will invest too early at $T^{F1}(P_L^{**})$. If the regulator wants the follower to invest at T_F^w he needs to set access charges below P_L^{**}.

However, a fixed charge at this level would not induce the leader to invest at T_L^w.

The solution to the seeming contradiction follows from the observation that, since investment cost decreases over time, the access price at which the follower is indifferent between investing or not decreases over time. Thus it is possible to set P above P_F^* without causing immediate investment, while at the same time giving the leader the return that is necessary for optimal investment. Higher payments right after T_L^w then compensate for lower payments closer to T_F^w. As before, at T_F^w the access charge can be set at P_F^*.

Let us formalize this idea. Given P, the follower invests at a date T such that $T = Z^{-1}(\pi_{2F} - \pi_{1F} + P)$. Hence, the follower is indifferent between investing or not if $P = Z(T) - \pi_{2F} + \pi_{1F}$, which is decreasing over time. We also need $P \leq \pi_{1F}$, so that the follower asks for access. Thus, the upper limit on the access charge at each $T < T_F^w$ is $\tilde{P}(T) = \min\{\pi_{1F}, Z(T) - \pi_{2F} + \pi_{1F}\}$, which is represented in Figure 5.

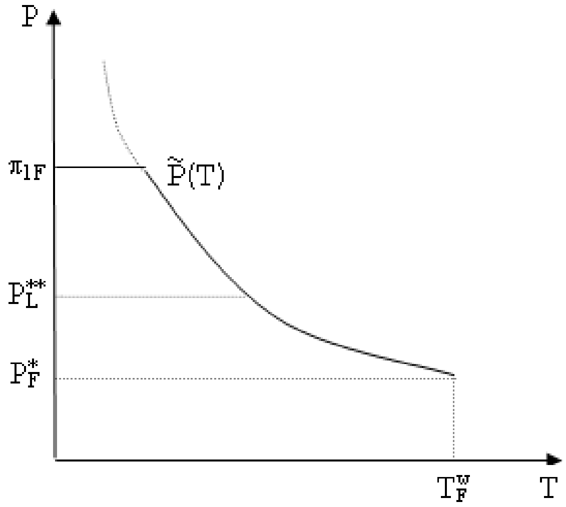

Figure 5

If the regulator wants to induce the leader to invest at the optimal date T_L^w, he needs to define a path of access charges $P(T) < \tilde{P}(T)$ on $T \in (T_L^w, T_F^w)$ such that at T_L^w the leader's and follower's payoffs coincide. This happens if and only if the average discounted access payment is equal to P_L^{**}, or

$$\frac{\delta}{e^{-\delta T_L^w} - e^{-\delta T_F^w}} \int_{T_L^w}^{T_F^w} P(t)\, e^{-\delta t} dt = P_L^{**}. \tag{22}$$

Thus achieving the first best is possible if either $P_L^{**} \leq P_F^*$, or

$$\int_{T_L^w}^{T_F^w} \tilde{P}(t)\, e^{-\delta t} dt > \frac{e^{-\delta T_L^w} - e^{-\delta T_F^w}}{\delta} P_L^{**}. \tag{23}$$

In both cases the access price paths are time consistent because the follower invests at the optimal date.

If condition (23) does not hold, then the access payments that are necessary to achieve preemption at the optimal date are so high that they induce the follower to invest too early. In this case not even an infinite number of instruments can achieve the first best. This case arises if the follower's payoffs increase very strongly after duplication, while total surplus increases little, i.e. the follower's gains are mainly due to business stealing.

7 Extensions

7.1 Undesirable bypass

Until now we have assumed that a bypass investment is desirable both for the follower and the regulator, see assumptions (6) and (17). In this section we change both assumptions.

Case 1: Socially desirable but privately undesirable bypass
This situation corresponds to the following assumption:

$$w_2 - w_1 > \delta \underline{C} > \pi_{2F} - \pi_{1F} \tag{24}$$

Here the regulator would like to encourage the follower to invest. This he can only achieve with a sufficiently high access charge:

$$P > \overline{P} = \delta \underline{C} - (\pi_{2F} - \pi_{1F}). \tag{25}$$

For $P > \overline{P}$ the follower duplicates at some $T < +\infty$, and for $P \leq \overline{P}$ the follower does not duplicate. By (24), we have:

$$P_F^* = (w_2 - w_1) - (\pi_{2F} - \pi_{1F}) > \overline{P}. \tag{26}$$

That is, the regulator cannot only induce the follower to invest at all, but even to invest at the optimal date. Therefore, both access price paths discussed in the previous section lead to a socially optimal investment pattern.

Case 2: Socially undesirable bypass

We continue to assume that the first investment is socially desirable, but that the second one is not:

$$w_1 - w_0 > \delta \underline{C} \geq w_2 - w_1. \tag{27}$$

Again, the stand-alone and optimal investment dates $T^{S1}(P)$ and T_L^w of the leader remain the same. Thus the regulator needs to induce investment in a preemption equilibrium, for example by choosing a constant access charge P_L^* such that $\tilde{L}(T_L^w, \infty, P_L^*) = \tilde{F}(T_L^w, \infty, P_L^*)$. This condition is equivalent to

$$P_L^* = \frac{1}{2}\left(\delta A(T_L^w) e^{\delta T_L^w} - \pi_{1L} + \pi_{1F}\right). \tag{28}$$

At this access charge the follower will not invest if $\pi_{2F} - \tilde{\pi}_{1F}(P_L^*) \leq \delta \underline{C}$, i.e. $P_L^* \leq \delta \underline{C} - \pi_{2F} + \pi_{1F}$. If P_L^* is larger than this value the regulator must adopt a path of access charges that decreases over time, as in the previous section.

7.2 Access holidays

"Access holidays" consists of a fixed time period after the leader's investment during which the leader is not subject to mandatory access, see e.g. Gans and King (2004). In our model the leader would earn the monopoly profit π_{1M} during this period. Since this is higher than $\tilde{\pi}_{1L}(P)$ for all P at which the follower asks for access, access holidays provide an additional means for the regulator to make investment for the leader more attractive.

We have seen in Section 6, and also the previous one, that there may exist an unresolvable conflict between the necessity of high access charges to make the leader invest optimally, and low access charges to keep the follower from investing too early, if the follower's incentives to invest largely surpass the social ones. Access holidays can help solve this problem, to some extent, by raising the leader's payoffs right after investment. This creates the possibility to set lower access charges later.

Naturally, since the follower receives zero profits without access, it would like to invest even earlier if the access holiday lasts too long. More precisely, it would invest at any T such that $\tilde{P}(T) \leq \pi_{1F}$, which is the access price at which its profits in service-based competition are zero, too. Thus the access holidays must end before the date $\left(\tilde{P}\right)^{-1}(\pi_{1F})$. This limits the additional profits that can be given to the leader.

There is an additional downside, however: The regulator is sacrificing static welfare in order to induce investments closer to the optimal dates. Thus the optimum would involve a trade-off between the two, and the first best cannot be achieved.

A second function for access holidays arises where investment by the leader is not privately desirable even under high access charges, but would be so under monopoly:

$$\pi_{1M} - \pi_0 > \delta \underline{C} > \pi_{1L} + \pi_{1F}.$$

If we assume that in this case a second investment will not occur, the regulator can increase the leader's returns from investment by either increasing the length of the access holidays or the value of the access charge. The former comes at the cost of lower consumer surplus, while the latter has no welfare cost with a two-part access tariff. The optimal outcome would then involve an access price at the upper limit π_{1F}, and an access holiday of the minimal length necessary to make the leader invest optimally.

8 Conclusions

This paper demonstrates how mandatory access influences the investment dates of two firms that want to build new infrastructures. As known from the literature on technology adoption, there are two types of equilibria. In the first type there is a first-mover advantage, and firms preempt each other. In the second type there is a second-mover advantage, leading to a waiting equilibrium. We show that in the context of access pricing, low access charges may lead to waiting, while high access charges lead to preemption.

While higher access charges make the follower invest earlier, and also the leader in a waiting equilibrium, its effects are ambiguous under preemption. If the stand-alone incentives for investment are strong enough then also under preemption the leader's investment will occur earlier. If on the other hand the reduction in payoffs caused by the anticipation of the follower's investment is the determinant factor, then the leader's investment will be delayed by a higher access charge.

Since the regulator needs to induce two firms to invest optimally, the first best cannot be achieved with a constant access charge. We show that, depending on the circumstances, an increasing path with only two values, or a decreasing path with possibly many more values, may lead to first-best investment. Still, even with a continuously changing access charge path the first best may not be achievable if the follower's private incentives are dominated by business-stealing. We show that the introduction of access holidays can alleviate this problem, apart from their more usual role of encouraging the leader's investment. Finally, no essentially new problems arise if bypass needs to be elicited by the regulator, or if no bypass investment occurs at all.

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Appendix A

Given the investment decision of the follower, the leader solves

$$\max_{T_i} \begin{cases} \frac{\tilde{\pi}_{1L}(P)-\pi_0}{\delta} e^{-\delta T_i} - A(T_i) + \left[\frac{\pi_0}{\delta} + \frac{\pi_{2L}-\tilde{\pi}_{1L}(P)}{\delta} e^{-\delta T^{F1}(P)}\right] & \text{if } \ 0 \leq T_i < T^{F1}(P) \\ \frac{\pi_{2L}-\pi_0}{\delta} e^{-\delta T_i} - A(T_i) + \frac{\pi_0}{\delta} & \text{if } \ \ T_i \geq T^{F1}(P) \end{cases}$$

Profits are continuous at $T_i = T^{F1}(P)$. On the branch $T_i < T^{F1}(P)$, the first-order condition for an interior maximum is $Z(T_i) = \tilde{\pi}_{1L}(P) - \pi_0$. By assumptions (3) and (6), the following inequalities hold:

$$\begin{aligned} P &\leq \pi_{1F}: \quad \pi_{1L} + P - \pi_0 > \pi_{2F} - (\pi_{1F} - P), \\ P &> \pi_{1F}: \quad \pi_{1M} - \pi_0 \geq \pi_{1L} + \pi_{1F} - \pi_0 > \pi_{2F}. \end{aligned}$$

Thus $\tilde{\pi}_{1L}(P) - \pi_0 > \pi_{2F} - \tilde{\pi}_{1F}(P)$ and $T^{S1}(P) = Z^{-1}(\tilde{\pi}_{1L}(P) - \pi_0) < T^{F1}(P)$. Furthermore $T^{S1}(P) > 0$ because by assumption (7) we have $\tilde{\pi}_{1L}(P) - \pi_0 < \pi_{1M} < Z(0)$. Therefore, on the first branch there is a unique interior maximum at $T^{S1}(P)$, and profits on the first branch are decreasing at $T_i = T^{F1}(P)$.

As concerns the second branch, the first-order condition for an interior maximum is $Z(T_i) = \pi_{2L} - \pi_0$, with solution $T^{S2} = Z^{-1}(\pi_{2L} - \pi_0)$. If $\pi_{2L} \geq \pi_0 + \pi_{2F} - \tilde{\pi}_{1F}(P)$ then $T^{S2} \leq T^{F1}(P)$, and the maximum on the second branch is at $T^{F1}(P)$, where it is dominated by $T^{S1}(P)$. If on the other hand $\pi_{2L} < \pi_0 + \pi_{2F} - \tilde{\pi}_{1F}(P)$ then $T^{S2} > T^{F1}(P)$, and we cannot decide whether the global maximum is at $T^{S1}(P)$ or T^{S2}. ■

Appendix B

We have

$$L(T_i,P)-F(T_i,P)=\left(e^{-\delta T_i}-e^{-\delta T^F(T_i,P)}\right)\frac{\tilde{\pi}_{1L}(P)-\tilde{\pi}_{1F}(P)}{\delta}$$
$$+e^{-\delta T^F(T_i,P)}\frac{\Delta_2}{\delta}-A(T_i)+A\left(T^{F(T_i,P)}\right),$$

which is continuous by continuity of $L(T_i,P)$ and $F(T_i,P)$. Since $T^{F\left(T^{F1}(P),P\right)}=T^{F1}(P)$,

$$L\left(T^{F1}(P),P\right)-F\left(T^{F1}(P),P\right)=e^{-\delta T^{F1}(P)}\frac{\Delta_2}{\delta}\geq 0,$$

by assumption (4). We also find that $L(0,P)<F(0,P)\ \forall P\in[0,\pi_{1F}]$ since $F(0,P)\geq 0$ and by assumption (7) $L(0,P)<0$. Thus there is a $T^R(P)\in\left(0,T^{F1}(P)\right]$ such that $L\left(T^R(P),P\right)=F\left(T^R(P),P\right)$. We will now show that there is at most one such date with $L(T_i,P)<F(T_i,P)$ for all $T_i\in\left[0,T^R(P)\right)$, and $L(T_i,P)>F(T_i,P)$ for all $T_i\in\left(T^R(P),T^{F1}(P)\right)$.

Maximizing or minimizing $L-F$ with respect to T_i in the interval $\left[0,T^{F1}(P)\right]$, we obtain the first-order condition

$$\frac{\partial(L-F)}{\partial T_i}=e^{-\delta T_i}\left(\tilde{\pi}_{1F}(P)-\tilde{\pi}_{1L}(P)\right)-A'(T_i)=0.$$

Whenever it holds,

$$\begin{aligned}\frac{\partial^2(L-F)}{\partial T_i^2} &= -\delta e^{-\delta T_i}\left(\tilde{\pi}_{1F}(P)-\tilde{\pi}_{1L}(P)\right)-A''(T_i)\\ &= -\delta A'(T_i)-A''(T_i)\\ &= Z'(T_i)\,e^{-\delta T_i}<0,\end{aligned}$$

so that $(L-F)$ is strictly quasi-concave on $\left[0,T^{F1}(P)\right]$. This implies that $L-F$ cuts the horizontal axis from below exactly once, and that any additional cut from above occurs only at $T^{F1}(P)$ and if $\pi_{2L}=\pi_{2F}$ (In this case we have $L=F$ also at $T^{F1}(P)$, but this does not upset the statement). ■