# The Taxation of Spectrum Rights: Tools for Efficiency and Distribution


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**Abstract**

This paper examines the usual equity arguments for spectrum fees and notes where they may not necessarily achieve their ostensible distributional goals. It highlights the difference between establishing transfers from commercial users to taxpayers and generating net social benefits. The paper reviews the efficiency enhancing potential of fees in a second best context. In particular, it shows how fees could make the private opportunity costs of holding spectrum rights more closely resemble the social opportunity costs in a regulatory environment of substantial transactions costs to subdividing and transferring spectrum assets to higher and better uses. Finally, it reviews instances in which spectrum fees could provide substantial efficiency gains if they replace more distortionary command and control requirements, such as build-out requirements that specify the timing and scope of wireless service deployment. An optimal timing model shows that an ad valorem spectrum tax would unambiguously accelerate the time to build-out.

## 1. Introduction

Spectrum license fees raise revenue from spectrum rights holders and increase the opportunity cost of holding on to those rights. Currently, the FCC has the statutory authority only to collect application processing fees and annual regulatory fees to recover the annual costs of its enforcement, policy and rulemaking, user information, and international activities.[1]

The Bush Administration and others have offered proposals for expanding the FCC's fee authority beyond cost recovery. For example, the Bush Administration has offered a bill that would allow the FCC to impose such fees on holders of spectrum that the FCC did not auction:

> "For licenses or construction permits which are not granted through the use of competitive bidding as set forth in subsection (j), the Commission is authorized to establish, assess, and collect annual user fees on holders of spectrum licenses or construction permits, including their successors or assignees, in order to promote efficient and effective use of the electromagnetic spectrum." [2]

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[1] The FCC website explains the structure and function of these administrative fees. See http://www.fcc.gov/fees/

[2] Transmitted with a letter dated June 30, 2006, from John J. Sullivan, General Counsel of the U.S. Department of Commerce to Chairman Ted Stevens and Co-Chairman Daniel Inouye of the Senate Committee on Commerce, Science, and Transportation, and Chairman Joe Barton and Rep. John Dingell of the House Energy and Commerce Committee: http://www.ogc.doc.gov/ogc/legreg/letters/109/telecombillJun3006.htm

This paper reviews the economic arguments for imposing spectrum fees, examines their efficiency and distributional effects, and assesses the degree to which, in the absence of a complete market for spectrum rights, annual spectrum fees can replace inefficient and arbitrary build out requirements.

Spectrum fees have received much less attention than spectrum auctions in the economic literature. A memorandum by the U.S. Congressional Budget Office (1998) reviews the efficiency and equity issues surrounding spectrum fees, with particular attention to two legislative proposals considered by the 105th Congress: broad fees on all private license holders and more narrow fees imposed only on select wireless service providers.[3]

## 2. Why tax spectrum rights?

### 2.1. Cost recovery

An annual or otherwise periodic fee to spectrum license holders essentially amounts to a property tax on spectrum rights, although the rights may not technically be "property" in a strict legal sense. Policymakers may justify such taxes on the grounds of fairness or economic efficiency.[4] Current FCC fees cover the FCC's expenses for managing and enforcing spectrum rights. Current application fees cover the government's costs of license processing. Regulatory fees cover the budget for FCC's enforcement, policymaking, rulemaking, international, and user information activities. As CBO (1998) notes, both kinds of fees are imposed under the rationale that the recipients of government services should pay for them. This and related equity arguments deserve a slight quibble since the ultimate incidence of the fees depends on the extent to which licensees pass along their costs to suppliers and consumers, which may not be in exact proportion to the surpluses that accrue to each segment of the supply chain. In addition to the usual efficiency question of whether such fees distort production or consumption decisions, user fees raise at least two political economy considerations: the alternative funding source one compares fees to and the effect of user-fee financing on the substance and process of government policy. The existing application and regulatory fee structure is largely lump sum (that is, not a function of the output decisions by licensees), so is unlikely to distort output markets. The fees could be efficiency-enhancing if they cost effectively speed necessary administrative activities, or the fees could be distortionary if they result in greater (inefficient) regulatory effort relative to a world in which such activities are financed by general funds.

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[3] Congressional Budget Office, "Two Approaches for Increasing Spectrum Fees," November 1998. Primary authors: Coleman Bazelon and David Moore. Available at http://www.cbo.gov/showdoc.cfm?index=1047&sequence=0

[4] This section echoes and extends the economic logic in CBO (1998).

## 2.2. Rent recovery

One common equity argument for imposing spectrum fees above cost recovery levels is that some spectrum rights were distributed by the federal government free to applicants through lotteries or comparative hearings, so the public has never been compensated by commercial users for access to valuable public resources. Some observers believe that regardless of the initial license allocation process, the public deserves an ongoing stream of rents as compensation for continued private access to public airwaves, analogous to the royalties the federal government receives for offshore mineral resources or the rents it receives for grazing on federal land. One might justify the fee as compensation to the public for extra-normal profits in a regulated industry, but that logic would not apply to the vigorously competed mobile radio market.[5]

Spectrum fees create a transfer from whoever bears the final incidence of the fees to the general taxpayer (to the extent that the fees go into the general treasury rather than earmarked accounts). However, such transfers should not be construed as the source of the net social benefits from the resource. The social benefit from spectrum derives from the exploitation of the resource for productive purposes and the consumer and producer surpluses that emerge. Indeed, the consumer benefits from wireless communications will always be vastly greater than any potential decrement in the deadweight loss of the fiscal system by substituting spectrum fees for, say, income tax revenue.

Although taxing commercial users on the benefits they receive from public resources may seem intuitively fair, let us look a little deeper. Suppose our equity concern is that some commercial users never paid for the resource rights, and we think they should be taxed now. Certainly spectrum fees will capture net rents for the general taxpayer.[6] And the government can limit spectrum fees to licenses that were not competitively allocated.[7] The incidence of fees imposed now, however, may not fall on those who originally benefited from gratis rights. In particular, many current holders of spectrum rights bought those rights in a secondary market by buying licenses or whole companies for full market value. Any benefits of free allocations of spectrum accrued to the

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[5] In its 2005 "Annual Report and Analysis of Competitive Market Conditions With Respect to Commercial Mobile Services," the FCC concludes there is effective competition in the CMRS marketplace and notes that "97 percent of the total U.S. population lives in counties with access to three or more different operators offering mobile telephone service." http://wireless.fcc.gov/cgi-bin/wtb-document-index.pl?t=4&y=5&m=9

[6] The net gain to the fisc could be offset in part by a reduction in tax revenue on the lower corporate profits of licensees and those to whom they pass their costs.

[7] The Administration bill referenced above limits FCC authority to collect fees to "licenses or construction permits which are not granted through the use of competitive bidding."

original licensee and those with whom they shared the benefits, for example through better service or content. Even in cases where the current licensed entity was the recipient of free spectrum rights, the incidence of new fees may not fall on the same *individuals* who originally benefited. Most gratis licensing occurred decades ago (e.g., to broadcasters), so current stockholders may not be the same individuals as the stockholders at the time the resource rights were granted.

Regardless of the initial allocation system for the licenses, current licensees would bear the greatest burden of the fees because the future fees that producers cannot pass along will be capitalized into the secondary market value of licenses. In other words, not only will current licensees pay fees while they hold the license, their capital assets will depreciate by the present discounted value of the licensees' share of the tax burden.

Of course, if the equity objective is primarily to raise federal revenue without regard to whether it comes from those who benefited from free spectrum, then spectrum fees on current license holders will serve that purpose. So would fees on any kind of government license holders.

### 2.3. Efficiency gains

The economic efficiency arguments for spectrum fees assert that price signals can address imperfections in the current regulated environment or replace more inefficient policies. This section and Section 2.4 examines those ideas in general, and Section 3 looks in more detail at specific potential reforms. Most agree that the existing rigid policy framework limits the private opportunity costs of holding spectrum idle and generally creates substantial efficiency losses. Thus, the social opportunity costs of idle or underutilized spectrum (which include the forgone consumer surplus) are inefficiently higher than the private opportunity costs. A first best policy approach would seek to improve the spectrum rights regime to better expose license holders to the "real" opportunity cost of unused spectrum rights and create more efficient incentives to provide spectrum-dependent services or sell the rights to someone who will. The first best approach allows potentially enormous efficiency gains by giving licensees greater flexibility in the choice of services they could provide, as well as efficient incentives to build out, subdivide, or transfer their rights.

Part and parcel of the first best approach would be policy reforms that cost effectively reduce transactions costs for subdividing, aggregating, and transferring spectrum rights. For example, the FCC has introduced measures designed to streamline secondary market transactions. Transactions costs, however, include the private sector costs of contracting, attorneys, and related managerial attention. Policymakers can assist private efforts to reduce these costs by cost effectively supporting data systems and regulatory processes that allow the private sector (including third party brokers) to standardize and automate secondary market transactions.

In the absence of a full deployment of the first best approach, fees on spectrum licenses would increase the private opportunity cost of holding spectrum rights, potentially better reflecting the social opportunity costs.  Price signals can in theory induce more efficient timing or scope in the deployment of highly regulated licensed services, and the rest of this paper explores this potential.  Although this paper examines the efficiency-enhancing potential of spectrum fees, fees remain a poor substitute for the first best approach of pursuing a system of flexible exclusive exhaustive spectrum rights in the licensed space.

### 2.4. Optimal spectrum taxes

The optimal design of a spectrum tax to offset existing regulatory distortions in opportunity costs is tricky.  To have any effect, the tax must be higher than the transactions costs associated with a more efficient reallocation of the resource, but it should not be so high as to induce firms to undertake transactions that would not be Pareto improving in a more efficient policy context.  Although social opportunity costs of idle spectrum may be higher than private costs in the current regulated setting, it may be fully efficient for some rights holders to leave certain spectrum idle or "underutilized," neither building out a business nor devolving those rights to other parties who would.  Technology and other factors evolve rapidly, so building out a spectrum-dependent business is risky.  In addition, the physical capital (such as transmitters and towers) and the labor involved in first establishing wireless services are quickly sunk upon deployment, especially if the equipment has a low scrap value. The dual presence of uncertainty and sunk costs creates an option value to waiting to invest, making it worthwhile (up to a point) to forgo a revenue stream temporarily to resolve uncertainty and obtain more information about alternative investment returns.

Another reason that some idle spectrum can be efficient is that a license can include spectrum rights that are lumpy and heterogeneous in value, for example by covering broad geographic areas.  The licensee may find it profitable to build out in some areas but not others, essentially leaving some spectrum rights (a subset of the total geography) idle.  Although the economics may simply not work for anyone to build out service in some areas, other areas could be served by niche firms, for example that specialize in rural service.  Thus efficient fees would optimally induce the primary licensee to undertake subdividing and transferring unused rights when the transactions costs are lower than the incremental social benefits from the transaction.

Another reason the most efficient tax is complex is that it would equal the difference between the current private opportunity costs and the optimal social opportunity costs of the rights, which is not a simple formula. Such a tax may or may not be a function of objective features of the license. In contrast to some legislative proposals, an efficiency-enhancing tax would not be a function of how the license was originally allocated (for example auctioned or gratis), since the private opportunity costs at issue are strictly forward-looking. Thus there could be a conflict between equity goals and efficient pricing.

For fees to provide an efficient incentive, of course, the algorithm for computing fees must be sufficiently detailed so that firms can indeed reduce their tax bills by transferring subsets of their spectrum assets.

## 3. Fees as cost effective alternatives to inefficient distributional policies

This section explores ways in which spectrum fees may substitute for command and control requirements. Section 3.1 looks at using spectrum fees as a more equitable approach to capturing rents from broadcasters than public interest obligations. Section 3.2 asks whether spectrum fees that spur faster service deployment could substitute for build out requirements.

### 3.1. Spectrum fees as alternatives for public interest broadcasting

Some have proposed spectrum fees specifically for broadcasters that would replace their public interest obligations. For example, Geller and Watts (2002) argue that the benefits to society of current compliance with rules mandating children's programming, local affairs content, and electoral coverage are much smaller than the benefits broadcasters receive from free spectrum use.[8] Thus in their view, society has struck a poor bargain. Consistent with the discussion above, they also cite the high social opportunity cost of broadcast spectrum relative to the private opportunity costs. Their recommended approach would be a five percent tax on gross advertising revenues, which would be earmarked for directly subsidizing children's programming and other socially beneficial broadcast-related purposes.

### 3.2. Spectrum fees as alternatives to build-out requirements

This section explores what could be the most important economic potential of spectrum fees: replacing inefficient, onerous, and arbitrary build out requirements. Section 309 (j)(4)(B) of Title 47 in the U.S. Code lays out the FCC's authority to require license holders to build out a business model within a certain time frame and/or within

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[8] Henry Geller and Tim Watts, "The Five Percent Solution: A Spectrum Fee to Replace the 'Public Interest Obligations' of Broadcasters," New America Foundation, Spectrum Series Working Paper #3, May 2002. http://www.newamerica.net/Download_Docs/pdfs/Pub_File_844_1.pdf

specified geographic areas. These license provisions are called "performance requirements" or "construction requirements." Section 309 states that auctioned licenses "shall" include performance requirements to:

- "ensure prompt delivery of service to rural areas,
- prevent stockpiling or warehousing of spectrum by licensees or permitees; and
- promote investment in and rapid deployment of new technologies and services."[9]

Rather than relying on market forces to promote efficient levels of deployment and innovation, the FCC has chosen to interpret the statutory objectives literally and issue command and control benchmarks. The FCC requires most wireless service providers to provide "substantial service," meaning service that is "sound, favorable, and substantially above a level of mediocre service which just might minimally warrant renewal. Failure by any licensee to meet this requirement will result in forfeiture of the license and the licensee will be ineligible to regain it."[10] The social objectives imbedded in performance requirements (such as deploying services in rural areas) are distributional goals and do not involve market failures. Build out requirements constitute transfers to those who would not otherwise be in coverage areas from individuals in more profitable areas. To the extent that such transfer costs are borne by the licensee, they also reduce the licensee auction revenues to the general treasury by devaluing the spectrum rights accordingly.

In rules for specific services, the FCC provides safe harbor examples of substantial service. For example, "regional narrowband PCS licensees shall construct base stations that provide coverage to a composite area of 150,000 square kilometers or serve 37.5 percent of the population of the service area within five years of initial license grant date; and, shall construct base stations that provide coverage to a composite area of 300,000 square kilometers or serve 75 percent of the service area population within ten years of initial license grant date." [11] Why 150,000 square kilometers? Why 37.5 percent of the population? Why five years? The FCC provides no economic justification for such arbitrary values.[12] Rather, the scope and timing of build out requirements seem primarily driven by social or political concerns about ensuring services for rural residents and preventing spectrum "stockpiling."

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[9] http://www.law.cornell.edu/uscode/html/uscode47/usc_sec_47_00000309----000-.html
[10] 47 CFR 27.14 (a)
[11] 47 CFR 24.103. Available at http://a257.g.akamaitech.net/7/257/2422/09nov20051500/edocket.access.gpo.gov/cfr_2005/octqtr/47cfr24.103.htm.
[12] As an independent agency, the FCC is not subject to the rigors of Executive Order 12866, which among other things instructs agencies to analyze the costs and benefits of regulatory alternatives and choose the approaches that maximize net benefits. See http://www.whitehouse.gov/OMB/inforeg/eo12866.pdf#search=%22e.o.%2012866%22.

Not only are build out requirements within a license economically arbitrary, there appears to be little consistency in the rules for otherwise comparable licenses. For example, 47 C.F.R. Section 24.203 governs the construction requirements for broadband PCS licenses.[13] It requires licensees of 30 MHz blocks to serve with a signal level to cover at least one-third of the population in their licensed area within five years of being licensed and two-thirds of the population in their licensed area within ten years of licensure. However, the same rule requires licensees of certain 10 MHz blocks to cover only one-quarter of the population in their licensed area within five years of being licensed. The same section is silent about 10 year milestones for 10 MHz blocks. Even if one believed that coverage milestones were appropriate, there seems to be no particular logic or boundaries driving them. Thus we see that the social objectives, however rigidly implemented for a particular licensee, are not consistently applied across a given industry.

The efficiency costs of current command and control requirements on the scope and timing of service deployment are uncertain, but they could be significant, and they could even work at cross purposes to the objectives of the statute. Construction requirements distort production incentives, for example by constraining firms' efficient recognition of the significant option value to waiting to make large quickly-sunk capital investments in an uncertain and evolving market. Likewise, performance requirements may inadvertently prevent firms from deploying the most efficient equipment or new technologies by mandating the timing and scope of that deployment. Finally, they distort resource allocations to uneconomic areas away from more cost effective areas.

These economic inefficiencies raise the question of whether such policies are cost effective and whether more cost effective means to meet distributional goals exist. Given the proper authority, the FCC could impose spectrum fees that increase the opportunity cost of holding spectrum idle and change the net returns to subdividing rights to others who will provide services in less attractive areas. Properly designed spectrum fees would accelerate the time to build-out, but would allow firms the flexibility to make tradeoffs across temporal, spatial, and technical options. Clearly, if the potential profit from build-out is high enough, spectrum fees would have no accelerating effect.

Appendix A adapts a model of land development in Shoup (1970) to the decision by spectrum license holders to deploy a physical-capital intensive service. It shows that in the relevant range, ad valorem spectrum taxes unambiguously reduce the optimal

[13] Available at http://a257.g.akamaitech.net/7/257/2422/09nov20051500/edocket.access.gpo.gov/cfr_2005/octqtr/47cfr24.203.htm

waiting period to build-out. An ad valorem approach would determine tax liability by establishing an "assessment" as the basis to which the tax rates are applied and multiplying it by a tax rate. The proportion of actual market value that a taxing authority uses as the property tax basis is known as the "assessment ratio."

## 4. Conclusion

This paper examines the usual equity arguments for spectrum fees and notes where they may not necessarily achieve their ostensible distributional goals. It highlights the difference between establishing transfers from commercial users to taxpayers and generating net social benefits. The paper reviews the efficiency enhancing potential of fees in a second best context. In particular, it shows how fees could make the private opportunity costs of holding spectrum rights more closely resemble the social opportunity costs in a regulatory environment of substantial transactions costs to subdividing and transferring spectrum assets to higher and better uses. Finally, it reviews instances in which spectrum fees could provide substantial efficiency gains if they replace more distortionary command and control requirements, such as build-out requirements that specify the timing and scope of wireless service deployment. An optimal timing model shows that an ad valorem spectrum tax would unambiguously accelerate the time to build-out.

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**Appendix A**
**Theoretical Framework**

## A.1. The theoretical model

In this Appendix, I develop an optimal timing model for spectrum build-out and compare two different versions of the model: one with no taxes and one with ad valorem spectrum fees. The spectrum rights holder chooses the time to convert from low-intensity (or idle) use to a "highest and best" [14] use that requires a lumpy investment in physical capital. I show that the optimal build-out time is unambiguously decreasing in the value of the tax rate. The model draws from Morris (1999), which developed the models in Anderson (1986). The geographic scope of the build-out does not appear explicitly. However, the model could be extended to look at spatial variations as well as timing.

## A.2. No-tax regime

In this model, an owner of spectrum receives a net income stream *f(t)* from low-intensity spectrum use. This low intensity use could mean leaving the spectrum idle, providing relatively low-valued services, or leasing the spectrum to other users. These low intensity returns accrue in the time period before the licensee builds out a business model that requires substantial physical capital.

The function *V(t,D)* is the economic value of the spectrum at time *t*, calculated as the present discounted value of the stream of net revenues from time *t* forward. The licensee's objective is to choose *D*, the build-out time, to maximize the value of the spectrum at time zero: *V(0,D)*. This model assumes perfect foresight, so at time zero the landowner knows perfectly all potential alternative returns and can choose the optimal time *D* when the spectrum will be developed.[15] The post-build-out returns depend on the time at which build-out occurs because the nature of the optimal build-out project changes, along with technology, capital costs, market conditions, and other factors. After the spectrum-dependent business is built-out, the spectrum owner receives a post-build-out net income stream *h(t,D)*, where $t > D$. Although this model does not formally account for the option value of waiting to invest, the changing options for build-out models over time are imbedded in *h(t,D)*. The function *h(t,D)* also

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[14] This expression is used in property tax legislation to indicate the resource use with maximum net economic returns.

[15] This simple deterministic model conveys the basic intuition of the effect of spectrum fees on build out timing. A stochastic dynamic model would more explicitly include the option value of waiting to invest and would be more appropriate for analyzing market and regulatory uncertainties.

includes amortized costs of the build-out and all taxes except spectrum fees, which will enter into the model explicitly in the next section.

We discount the net income streams by a constant rate *r*, which is also the alternative rate of return the spectrum rights holder could earn if he or she sold those rights and invested the money. Thus we can write the value of the spectrum at *t*, any time prior to build-out, as:

$$V(t,D)=\int_t^D [f(u)]e^{-r(u-t)}du+\int_D^{\infty}[h(u,D)]e^{-r(u-t)}du. \qquad \text{[A.1]}$$

The first integral represents the discounted net returns from time *t* to time *D*, when build-out occurs. The second term represents the post-build-out returns, discounted to time *t*.

### A.3. Ad valorem tax regime

We now assume spectrum is subject to an ad valorem fee $\tau$.[16] We assume the tax basis for the spectrum fee is the marketable value of the spectrum rights contained in the license. The tax basis is strictly the value of the spectrum rights, not the value of the business that provides the spectrum-dependent services (which includes the scrap value of the physical capital, intangibles, and other factors).[17] This model assumes that regulators set a tax basis through explicit assessments and then apply a nominal tax rate to the basis to determine the tax liability. However, the results generalize to any fee formula that rises in direct proportion to the market value of the spectrum (for example by applying a multiplier to a function of band, bandwidth, service area, and other parameters).

Elaborating equation A.1, the value of the spectrum at *t*, any time prior to build-out, is:

$$\mathrm{V(t,D)}=\int_{\mathrm{t}}^{\mathrm{D}}[\mathrm{f(u)}-\tau\mathrm{V(u,D)}]\mathrm{e}^{-\mathrm{r(u-t)}}\mathrm{du}+\int_{\mathrm{D}}^{\infty}[\mathrm{h(u,D)}-\tau\mathrm{V(u,D)}]\mathrm{e}^{-\mathrm{r(u-t)}}\mathrm{du}. \qquad \text{[A.2]}$$

The first integral represents the discounted low-intensity returns before build-out at time *D*, adjusted for ad valorem fees. The second term represents the post-build-out returns, discounted to time *t* and adjusted for the same tax treatment.

Anderson (1986) determines a non-recursive expression for the second integral and shows that the value function in Equation A.2 can be written:

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[16] For the purposes of this paper, I assume the same nominal tax rate before and after build-out. Regulators could choose fee structures that place higher ad valorem tax rates on the spectrum resources used by different kinds of service providers.

[17] This approach could apply even in a regulatory environment in which the spectrum rights are encumbered by specific service rules.

$$V(t,D) = \int_t^D f(u)e^{-(r+\tau)(u-t)}du + e^{-(r+\tau)(D-t)}H(D),$$

[A.2′]

where, for notational convenience, we define a function H(D) such that

$$\mathrm{H(D)} = \int_{\mathrm{D}}^{\infty} \mathrm{h(u,D)e^{-(r+\tau)(u-D)}du} \qquad \text{[A.3]}$$

and let

$$H'(D) = \frac{d}{dD}H(D). \qquad \text{[A.4]}$$

*H(D)* represents the value of the spectrum upon build-out , i.e. the net (after tax) present value at time *D* of returns from the highest and best use. Then *H′(D)* is the change in spectrum value with respect to the build-out time.[18] While an increase in D reduces the range of integration, *H(D)* may increase in *D* if, for example, capital costs are falling or technology is improving. Thus *H′(D)* can be positive or negative.

To determine the optimal time to build out, we need a first order condition (which equates the marginal cost of waiting to the marginal benefit of waiting) and a second order necessary condition, under which the marginal benefit of waiting is declining at the optimum development time. Anderson derives the first order condition implied by optimizing *V(0,D*) with respect to *D* for ad valorem taxation. This condition can be written:

$$\frac{H'(D)}{H(D)} + \frac{f(D)}{H(D)} = r + \tau\ . \qquad \text{[A.5]}$$

The left hand side is the marginal value of waiting to build-out. It is composed of two parts: the rate of change in the value of the spectrum (capital gain or loss) as a function of development time and the interim returns from low intensity use (dividend yield). The right hand side is the marginal opportunity cost of holding the spectrum idle or otherwise in low intensity use, i.e. the sum of the alternative rate of return on the value of the spectrum rights ( i.e., the discount rate) and the tax rate.

Now consider the second order necessary condition:

$$\mathrm{H''(D) - (r+\tau)H'(D) + f'(D) \le 0.} \qquad \text{[A.6]}$$

Substituting the first order condition into the second order condition (for r + τ) and rearranging:

$$\frac{H''(D)H(D) - [H'(D)]^2 + f(D)H'(D) - f'(D)H(D)}{[H(D)]^2} \le 0. \qquad \text{[A.7]}$$

This is equivalent to

[18] Note that this assumption of differentiability excludes jumps in post-build-out returns that may actually be quite possible.

$$\frac{d}{dD}\left[\frac{H'(D)}{H(D)} + \frac{f(D)}{H(D)}\right] \leq 0,$$

[A.8]

i.e., the marginal benefit to waiting to develop is declining in $D$ at the optimum. There may be multiple values for $D$ that satisfy conditions A.5 and A.8. The licensee will be indifferent between the ones that maximize the net present value of the returns from the resource.

A graph of these equations illustrates that the imposition of taxes unambiguously reduces the optimal time to build out in this model. First see Figure A.1 below. Without spectrum fees, the marginal cost of holding spectrum relatively idle and waiting to build out is constant over time at $r$. The marginal benefit of waiting to develop is represented by the curve in Figure A.1. Two local optima are designated as $D_1$ and $D_2$ for the no-tax world. The licensee will choose build-out time $D_2$ over time $D_1$ if area A (the total cost of waiting from $D_1$ to $D_2$) is smaller than area B (the total benefit of waiting from $D_1$ to $D_2$).

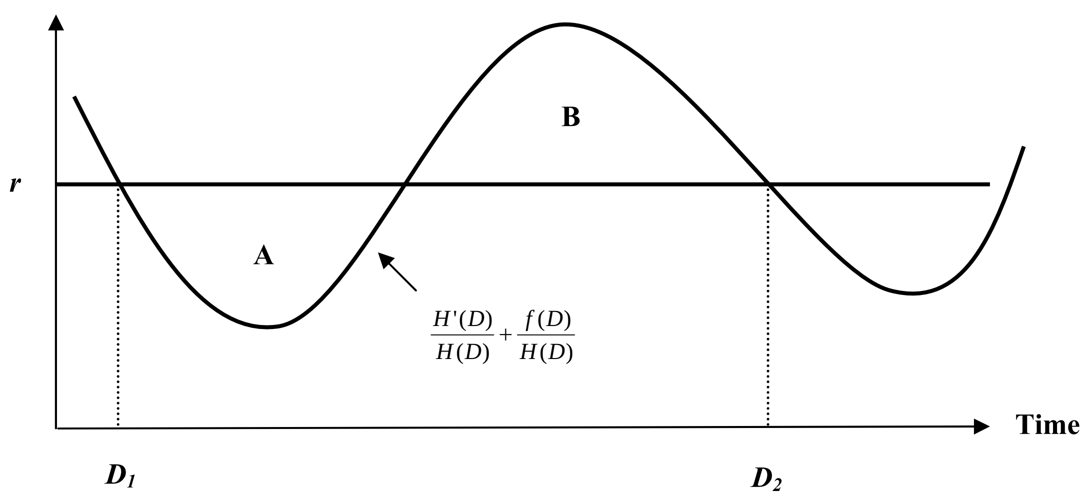


**Figure A.1. Optimal build-out timing in a no-fee world**

Figure A.2 below shows the effect of imposing an valorem tax $\tau$. It shifts up the horizontal marginal cost of waiting to develop to $r + \tau$ for all $D$. The development times $D_1$ and $D_2$ that met the first and second order conditions in the no-tax world shift back to $D_1$' and $D_2$', both unambiguously earlier. In addition, we see that the area A (the cost of waiting from a local optimum to a later local optimum) is increased, and the area B (the benefit of waiting from a local optimum to a later local optimum) is decreased, introducing the possibility that spectrum fees would shift the global optimal time to develop even more, from $D_2$ to $D_1$'. Intuitively, this means that because spectrum fees add to the carrying cost of spectrum, a firm that would have otherwise waited for new technology to deploy would not.

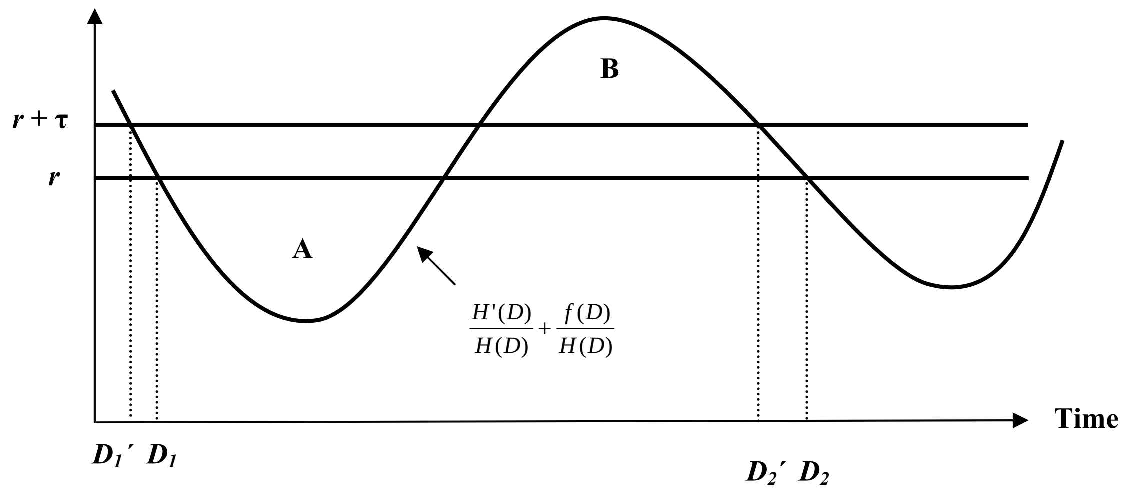


**Figure A.2. Spectrum fees accelerate build-out timing**