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Network Externalities: Adoption of Low Emission Technologies in the Automobile Market

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RESUMEN

Este trabajo presenta un modelo sencillo del mercado de automóviles, en que existen importantes externalidades de red y de tipo ambiental y estudia la elección de tecnología por parte de los consumidores. Hay dos tipos de tecnología: una que actualmente domina el mercado pero impone importantes costes ambientales, y otra nueva que se puede introducir sin ningún impacto ambiental. Mostramos que, en ausencia de intervención política, los beneficios de la tecnología ya instalada y los diferenciales de precios en favor de la misma desincentivarán la adopción de la tecnología limpia. Consideramos distintas políticas tributarias que podrían inducir a los consumidores a adoptar la tecnología limpia si ello es conveniente desde el punto de vista del bienestar social. En primer lugar, un impuesto sobre la tecnología sucia utilizando la recaudación del impuesto para fines generales. En este caso, el tipo impositivo necesario debe ser mayor que el daño marginal ambiental. En segundo lugar, consideramos la posibilidad de emplear la recaudación del impuesto para subvencionar la adopción de la tecnología limpia. En este caso, le prueba que el tipo impositivo necesario es menor que en el primer caso y, más interesante aún, que el tipo impositivo se puede fijar exactamente igual al daño marginal. Finalmente, se estudia el caso en que el gobierno se compromete creíblemente a establecer una política de impuestos y subvenciones recaudatoriamente neutral antes de la introducción de la nueva tecnología y mostramos que el impuesto y la subvención podrían ser menores que en el caso sin compromiso previo.

ABSTRACT

This paper develops a simple model of the automobile market, in which significant network and environmental externalities are present, and examines consumers' choice of technology. There are two types of technology: one that currently dominates the market but imposes significant environmental costs, and one that is expected to be introduced and has zero environmental costs. We find that, in the absence of policy intervention, the benefits of the installed base and the price diferentials in favour of the existing technology will deter new users from adopting the clean technology. We consider diferent tax policies that will induce adoption provided it is welfare warranted. First, we analyze a tax policy on the dirty technology with the tax revenues generated being used for general purposes.Under this case, we find that the tax, to induce adoption, will be greater than the marginal environmental damage. Second, we consider the tax revenue generated from the dirty technology to be earmarked towards a future subsidy to the clean technology. In this case, the tax is found to be lower than the case where revenues are used for general purposes and more interesting is the fact that the tax can be set equal to the marginal damage. Finally, we examine the case where the government credibly commits a revenue neutral tax/subsidy policy prior to the introduction of the clean technology and we find that the tax and the subsidy expenditures required could be lower relative to the case without precommitment.

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1 Introduction

The transportation sector contributes significantly to both local and global air pollution. At the local level, mobile-source pollutants are responsible for a great part of the main elements of urban air pollution, namely, carbon monoxide (CO), nitrogen oxides (NO_x) volatile organic compounds (VOSCs) and particulate matter (PM).[1] At the global level, mobile-source pollutants are responsible for a substantial part of the human-made releases of carbon dioxide (CO_2), the most important of the greenhouse gases responsible for global warming.[2]

Most of the existing policies targeting automotive air pollution focus on the low level pollutants affecting local air quality. In the U.S.A. these policies date back in the fifties for the state of California and the Motor Vehicle Air Pollution Act of 1965 at the federal level.[3] Similar policies have been adopted in most industrialized nations. The success of these policies relies on the fact that it is technically possible to reduce low level pollutants without replacing the conventional internal combustion engine.[4] Although these policies have produced sizable reductions in local air pollution in many regions, most of the urban areas in industrialized nations may require further reductions in emissions. In contrast to the urban air pollution, it is impossible to substantially decrease CO_2 emission of the conventional internal combustion engines. Increases in fuel efficiency could reduce CO_2 emissions, but this decrease has been proven to be far from enough to balance the ever expanding use of automobiles, leading to sharp increases in the sector's emission.[5]

In general, there are two policy approaches that could address the problem of

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[1] According to the Environmental Protection Agency (EPA), in 1996 automobiles accounted for roughly 60% of total emissions of CO, 31% of NO_x, 30% of VOCs and 8% of PM. See EPA (1998) and in particular pp. 82-86. Similar statistics appear in all developed countries.

[2] It has been estimated that motor vehicles contribute somewhere between one fifth to one third of total CO_2 emissions depending on the country. In the EU for example, the transportation sector accounted for 28% of CO_2 emissions in 1998, as reported in European Environmental Agency (2000).

[3] Tietenberg (1996) provides a brief review of the history and the structure of regulatory intervention in Chapter 17.

[4] If an engine is running efficiently, the products of combustion are mainly carbon dioxide (CO_2) and water. Emission of other pollutants is the result of low speeds and iddling engines that yield incomplete combustion, as well as of inpurities in the fuels such as nitrogen.

[5] For example, in the EU the only sector whose emission share increases is transportation, with an increase of 3.1% in the period 1990-98. This is due to the increased traffic, which grew by 14.7 % during the same period. See section 3.3. of the European Environmental Agency (2000).

automobile emissions. The first approach addresses the need to reduce driving by providing price incentives in the form of gasoline taxation. Gasoline taxation has been seriously considered over the last decade, usually as part of a broader package of carbon/energy taxes. Gasoline taxation in a variety of rates has already been applied in a number of countries with consistently minimal results due, in part, to the inelastic nature of the demand.[6] The second approach is to promote the adoption of totally new type of vehicles that do not use fossil fuels and therefore do not contribute neither to local nor to global pollution. For example, fuel cell engines in which hydrogen reacts with oxygen to produce electricity with water as the only residual are currently tested on the road. However, they are still far from being an economically viable alternative to conventional vehicles.[7]

Fuel cell vehicles have to overcome the relative price differential, the barrier that consumers are completely unfamiliar with the technology, and the nonexistence of service and refueling networks.[8] Thus, upon their introduction to the market, fuel cell vehicles will face a significant handicap related to network externalities.[9] Network effects exist when the utility consumers derive from the use of a good or service depends upon the number of users already using the same good or service. Automobiles are subject to network effects since the utility that consumers derive from

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[6] Both short run and long run price elasticities of demand for fuel consumption have been found to be inelastic with the short run elasticity being more inelastic. For a review of the literature on new empirical studies, published since 1990, on the effects of price on fuel consumption, traffic levels, fuel efficiency and car ownership see P. Goodwin, J. Dargay and M. Hanly (2004). See also the OECD (1997) study on taxation as an in instrument to reduce fuel consumoption.

[7] Other alternatives includes the electric and hydrib electric vehicles.

[8] Refueling network problems could be overcome by installing a reformer in the existing automobiles that extracts hydrogen from gasoline making the systems (backward) compatible (See Unruh (2002). However, the installation of a reformer, even though compatible to the current system, would add to the cost of a vehicle. Hence the benefits of the installed base and price differentials of the existing system will persist. An alternative approach that is incompatible to the existing refueling distribution system is to build a new distribution system to supply hydrogen directly (or could also be indirect through natural gas distribution systems) to vehicles. The Department of Energy 1999 blueprint for hydrogen infrastructure development study indicates that the later approach, although requires greater up front investment, provides a better system wide performance. This paper examines the likelyhood of the later (discountinous) approach being provided by the private sector with and without government policies.

[9] Liebowitz and Margolis (1998b) have expressed a definitional concern on the usage of the term "network externalities" especially if the market participants have internalized these effects. Liebowitz and Margolis prefer the term "network effects" recognizing that the owners of the network will internalize such effects, even though a consumer may not internalize the effects she has on the other members of the network.

the use of their vehicle is positively related to the services they can enjoy, which in turn are positively related to the number of consumers already using automobiles. Conventional technology vehicles dominated transportation only after the establishment of a network of gasoline stations, repair shops, paved roads, etc.[10] Although part of this network, such as roads, could be utilized by the fuel cell vehicles there are substantial network externalities that are technology specific. To the extend that there are positive welfare gains to reduce the transportation sector's air pollution, and especially CO_2 emissions, environmental policies promoting the adoption of fuel cell vehicles could be designed. Furthermore, these policies would have to address the fact that internal combustion vehicles enjoy a great network advantage over fuel cell vehicles. Despite the fact that the significance of network externalities in the automotive market has been recognized in the literature, to the best of our knowledge, there is no work addressing the issue of environmental policy in the presence of network externalities.

In this paper we develop a simple model of the automobile market in which significant network externalities are present and which is currently dominated by a technology which imposes an environmental damage to the society. Assuming that at some point in time an alternative zero-emission technology becomes available, we address the following two questions. First, will the system on its own exit the lock-in and adopt the clean technology?[11] We find that, in the absence of policy intervention, the benefits of the installed base and the price differentials in favour of the existing technology will deter new users from adopting the clean technology even if the environmental gains exceed the private losses.[12] Secondly, if private incentives are not sufficient for the desired technological transition to take place, what form

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[10] The underlying reasons behind the prevailance of the internal combustion over steam engined and electric vehicles during the late 1800s and early 1900s is discussed in great detail in Foray (1996), Foreman-Peck (1996) and Kirsch (1995).

[11] The analysis in this paper is based on the premise that in the absence of environmental externalities the current technology is efficient. There is no market failure due to network effects. This paper does not argue that the new technology is superior in performance relative to the existing technology. Market failure occurs due to the environmental damages of the existing technology.

[12] This theoretical results supports the findings of the U.S. Energy Information Administration. In the July 1999 issue of the Annual Energy Review accessed at www.eia.doe.gov the amount of alternative fuel vehicles entering the U.S. market for each million conventional vehicle were a mere 1250. This translates into a market penetration of 0.1 percent. Similar conclusions have been reached by Cowan and Hulten (1996).

should public intervention take? First, we consider a tax on the dirty technology, and assume that the tax revenues generated are used for general purposes, that would make adoption of the clean technology a Nash equilibrium. We find that the tax will be greater than the marginal environmental damage to induce adoption. In order to induce adoption of the clean technology individuals' have to be compensated for both the price differential as well as the benefits of having an established service network for the dirty technology. Second, we consider a tax on the dirty technology and earmark the tax revenues towards a future subsidy to the clean technology buyers, within a budget-balancing requirement. Within this framework we find the tax/subsidy combinations that can induce adoption of the clean technology and satisfy the budget contsraint. In this case, the tax is found to be lower than the case where revenues are used for general purposes and more interesting is the fact that the tax can be set equal to the marginal damage. Finally, we examine the case where the government credibly commits, at a time prior to the introduction of the clean technology, a revenue neutral policy consisting of a tax on the dirty technology (i.e., a tax at the time of the announcement of the commitment) and a subsidy to the clean technology from the time of its introduction until some time prior to its maturity, then the tax and the subsidy expenditures required to induce adoption of the clean technology could be lower relative to the case without pre-commitment.

The paper builds upon the literature on network externalities (effects). In a series of papers, Brian Arthur has examined the choice of technology in the presence of network effects. Arthur (1983) and (1989) shows how small accidental historical events can lock an economic system into an inferior technology due to the presence of network effects, lock-in and path dependency.[13] Arthur (1988) surveys and discusses dynamic

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[13] Liebowitz and Margolis in a series of articles (1990, 1994, 1998a) have argued that the presence of network effects and path dependency does not necessary imply that market outcomes are inefficient. They proceed to propose three classes of path dependence inefficiencies. First, the class of systems that are sensitive to initial conditions. Second, the class of systems where an inferior outcome exist but appear ex post. Third, the class of systems where inferiority exists and the outcome is remediable. In the first class of systems the outcome does not imply inefficiency. In the class of systems that have sensitivity to initial conditions and are inferior ex post cannot be labellled inferior at the time of the choice since the state of knowledge is imperfect. It is the sensitivity to inital conditions and ex ante ineffficiency that the error was avoidable. Liebowitz and Margolis (1994, pg 224) state that remediable inefficiency, if it occured, would be an interesting finding worthy of analysis. Foray (1997) argues that remediable lock-in is a self contradictory proposition since it would require the elimination of technological uncertainty.

systems of the self-reinforcing type that exists in many areas of economics. Katz and Shapiro (1986a) examine the effects of network effects on technology adoption, while Katz and Shapiro (1985) and (1986b) analyze the private and social incentives to achieve technical compatibility. Farell and Saloner (1985) study firms' incentives to exit from a lock-in when neither technology is proprietary. They find that the result depends on whether firms have complete information regarding other firms' actions. Farell and Saloner (1986) show that a new technology may not be adopted when the existing technology has already build a strong network. The benefits of the existing technology's installed base can result in a bias against superior technologies yielding "excess inertia". Our analysis is closely related to the approach developed in Farell and Saloner (1986). Our model is based on "excess inertia" and environmental externalities. [14]

The paper is organized as follows. In section 2 we present the model emphasizing the elements of individual decision making. In section 3 we examine the technology choice of individuals without taking into account environmental externalities. In section 4 we take into consideration the fact that the existing technology imposes environmental damages and we examine the effectiveness of the environmental policies The last section concludes the paper.

2 The model

Assume that there are two types of technology in the automobile industry: the currently available, denoted by D (dirty), and the new technology denoted by C (clean), which is introduced at some time $T^* > 0$. We assume that the service networks of the two technologies are incompatible. Users arrive at the market continuously over time with arrival rate $n(t)$ and they have inelastic demand for a single automobile. For simplicity we further assume that each consumer is infinitely-lived and that the product is also infinitely durable, so that users do not enter the automobile market at any other point in the future, that is, we ignore the possibility of switching technologies.[15] At time t, N users have arrived in the market with $N(t) = \int_0^t n(s)ds$.

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[14] In Farell and Saloner (1986) "excess inertia" was an exceptional case and environmental externalities were not present.

[15] Existing users have paid for the D-technology whether they use it or not and assuming that the price of the clean technology is high enough it will preclude these D-users switching to the new clean

We assume the simplest form of market growth, a linear growth with just one user arriving at the market per period of time, that is, $n(t) = 1$ and $N(t) = t$.

As the number of users of a given technology increases, so does the number of service stations for this particular technology. To avoid adding unnecessary notation, we assume that one service station opens up with every new user of the corresponding technology, that is, the size of the network that grows uninterrupted up to time t is, $x(t) = N(t) = t$.

We assume that automobile users receive benefits that are increasing in the network's size up to the maturity of the technology. After the network's maturity, users' network benefits are constant.[16] Prior to the maturity of the technology, each user that purchases the dirty (clean) technology enjoys a flow of benefits $D(x(t))$ $(C(x(t)))$ at time t, at which the network size is $x(t)$. For simplicity, we assume linear network benefits, that is, benefits at time t are $a + bx(t)$, where a denotes the benefits independent of the network's size, and b measures the strength of the network effect. Given that $x(t) = N(t) = t$, total benefits at time t are $a + bt$.

Users pay a purchasing price and a price for servicing their automobile, which includes the price of the fuel each technology uses as well as the price for servicing the automobile.[17] The service price of the automobile, inclusive of the purchase price, decreases as the size of service stations' network strengthens, because of the usual learning curve as well as the presence of economies of scale in the production and distribution of spare parts and fuel. The service price decreases up to the time that the network matures. The service price the user has to pay at time t is a decreasing function of the network size, that is, $p_{D_0}(1 - zx(t))$, where p_{D_0} is the price at the time that the dirty technology is introduced and z is a positive parameter denoting the sensitivity of price to network's strength. Given the assumption regarding the growth of the network, $p_{D_0}(1 - zt)$.

The present value of the flow of net benefits up to time of network's maturity T_1 to a user that purchases the old technology at time $T < T_1$, is $\int_T^{T_1} \left(a + bt - p_{D_0}\left(1 - zt\right)\right)$

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technology. This is a simplifying assumption that does not affect the conclusions of the model but affects the market size at any particular point in time.

[16] Assuming that the network benefits terminate beyond the maturity of the industry eliminates one of the problems of network models presented by Liebowitz and Margolis (1998). Liebowitz and Margolis argued that one of the driving forces behind the outcomes of network models is the assumptions of having linear unbounded increasing benefits to consumers as the network size increases.

[17] The purchase price can be considered part of the service price without a loss of generality.

$e^{-r(t-T)}dt$, where r denotes the constant discount rate. After the network's maturity and regardless of whether the network of the dirty technology keeps growing or not, each user receives a constant flow of benefits $a + bT_1$ and pays a constant service price per period $p_{D_1} = p_{D_0}(1 - zT_1) > 0$, which is the lowest service price possible. Thus, the value of the flow of benefits from time T_1 up to infinity, evaluated at time T at which the user enters the market, is $\left[\int_{T_1}^{\infty}(a + bT_1 - p_{D_1})\, e^{-r(t-T_1)}dt\right] e^{-r(T_1-T)}$. Therefore, the present value of the net benefits the user entering the market at time T gets is,

$$\overline{D}(T) = \int_{T}^{T_1} \left[a + bt - p_{D_0}(1 - zt)\right] e^{-r(t-T)}dt + (a + bT_1 - p_{D_1}) \int_{T_1}^{\infty} e^{-r(t-T)}dt$$

$$= \frac{a + bT - p_{D_0}(1 - zT)}{r} + \frac{b + p_{D_0}z}{r^2}\left(1 - e^{-r(T_1-T)}\right) \ . \qquad (1)$$

The user adopting the old technology at time T, joins a network of size T and so her benefits in that period are $a + bT$, while she pays a service price $p_{D_0}(1 - zT)$. The first term in equation (1) gives the discounted sum of the stream of net benefits from T to infinity, if the network does not grow any further, denoted by $\widetilde{D}(T)$. If the network continues to grow after T, at a rate of b, the user receives additional benefits $\frac{b}{r}$ from the use of the automobile, and benefits $\frac{p_{D_0}z}{r}$ from the service price reduction every period. Since the network ceases to grow after time T_1, the discounted value of these benefits is $\frac{b+p_{D_0}z}{r^2}\left(1 - e^{-r(T_1-T)}\right)$, which is the second term in equation (1). Thus, for any user entering the market after the maturity of the dirty technology's network, that is, $T > T_1$, we get that $\overline{D}(T_1) = \widetilde{D}(T_1)$.

The net present value of the benefits that a user adopting the clean technology gets are defined in a similar way. To focus on the environmental policy issue, we assume that the value of the parameters is the same under both technologies, that is, a, b, $p_{C_0} = p_{D_0}$, and z, are the respective parameters under the clean technology.[18] We assume that the network of service stations supporting the clean technology reaches maturity at time T_2.[19] If all new users arriving at the market after time T^* adopt the clean technology, the present value of net benefits the user entering the market at time T gets is,

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[18] This is a reasonable assumption if the new technology has similar performance characteristics on the road.

[19] For simplicity we assume that the required time for maturity is the same for both networks, that is, $T_2 - T^* = T_1$.

$$\begin{aligned}\overline{C}(T) = &\int_T^{T_2} \left[a + b\left(t - T^*\right) - p_{C_0}\left[1 - z\left(t - T^*\right)\right]\right] e^{-r(t-T)} dt \\ &+ \left[a + b\left(T_2 - T^*\right) - p_{C_1}\right] \int_{T_2}^{\infty} e^{-r(t-T)} dt \\ = &\frac{a + b\left(T - T^*\right) - p_{C_0}\left[1 - z\left(T - T^*\right)\right]}{r} + \frac{\left(b + p_{C_0} z\right)}{r^2}\left(1 - e^{-r(T_2 - T)}\right) \ . \end{aligned} \tag{2}$$

The interpretation of equation (2) is similar to that given for equation (1). If the user who adopts the clean technology at time T is the last user of the new technology, the present value of the flow of her net benefits is, $\widetilde{C}(T) = \frac{a+b(T-T^*)-p_{C_0}[1-z(T-T^*)]}{r}$. Thus, if the user enters the market after the maturity of the new technology's network, that is, $T > T_2 > T^*$, then, $\overline{C}(T_2) = \widetilde{C}(T_2)$.

3 Nash equilibrium adoption decisions by users

A user arriving at the market before the introduction of the new technology, that is, at time $t < T^*$, does not have any choice but to adopt the dirty technology. We assume that all users entering any time before T^* choose to purchase, that is, we assume that $a > p_{D_0}$. A user that enters the market after the introduction of the clean technology, that is, at time $t \geq T^*$, chooses between the dirty and the clean technology automobile, given the decision of all previous users. The Nash equilibrium is characterized by the network effect which has been termed in the literature either as the bandwagon or installed-base effect. Simply put, the more users continue to adopt the dirty technology after the introduction of the clean technology, the more difficult it becomes for the latter to ever be adopted. We examine the equilibrium decision of users after the introduction of the new technology. Two possible outcomes are considered: adoption, that is the case all users adopt the clean technology after its introduction, and non-adoption, the case that no user adopts the clean technology.

Adoption is a subgame-perfect Nash equilibrium if the user entering the market at time T^* purchases the clean technology automobile. This occurs if the user's discounted future benefits from C, assuming the network of clean technology keeps expanding, exceed those from D, assuming that the network of the dirty technology ceases to expand, that is, $\overline{C}(T^*) \geq \widetilde{D}(T^*)$. If the user at T^* finds it beneficial to adopt the clean technology, it is certain that all subsequent users will do the same.[20] Adoption is the subgame-perfect Nash equilibrium. Adoption is a unique equilibrium if $\widetilde{C}(T^*) > \overline{D}(T^*)$, that is, the net present value of the benefits from the clean technology to the user entering at time T^* are higher even if she is the only user of the clean technology. If instead, $\overline{D}(T^*) \geq \widetilde{C}(T^*)$, then all users will keep purchasing the dirty technology. In this case, non-adoption is the subgame-perfect Nash equilibrium. Non-adoption is a unique equilibrium if $\widetilde{D}(T^*) > \overline{C}(T^*)$. Proposition 1 summarizes the results in the case that no environmental concerns are raised.

Proposition 1 *Assuming the clean technology is introduced after the maturity of the dirty technology's network, the existence of network effects renders the introduction of the clean technology impossible. Non-adoption is a unique equilibrium and it is also efficient.*

Figure 1 illustrates the net benefits of the two technologies. The curve $\widetilde{D}$ ($\widetilde{C}$) presents the net present value of benefits a user enjoys if she is the last purchasing the dirty (clean) technology. These benefits are increasing over time at a constant rate of $b + z$. If the network continuous to grow, the net present value of benefits is presented by the $\overline{D}$ and $\overline{C}$ curves whose slope is increasing in a decreasing rate, i.e. $\partial\overline{D}/\partial T > 0$, $\partial\overline{C}/\partial T > 0$ and $\partial^2\overline{D}/\partial T^2 < 0$, $\partial^2\overline{C}/\partial T^2 < 0$, $\forall T,\ T \in [0, T_1)$. Since we have assumed that there is no difference between the two technologies' benefits and $T^* > T_1$, non-adoption is a unique equilibrium as shown in Figure 1.

In the case of an early introduction of the clean technology, that is, $T^* < T_1$, there could be multiple equilibria since part of the $\overline{C}$ curve could lie above the $\widetilde{D}$ curve. Alternatively, adoption could be the equilibrium if the new technology was introduced early and offered either superior network-independent or network related benefits. In this paper we focus in what we see as the most realistic scenario, which is also the worst possible case for adoption of the clean technology, namely the case in which the network of the dirty technology matures before the introduction of the clean technology.

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[20] Because users are infinitesimal, any deviation by a single user will not affect the choice of subsequent users. See Farrell and Saloner (1985).

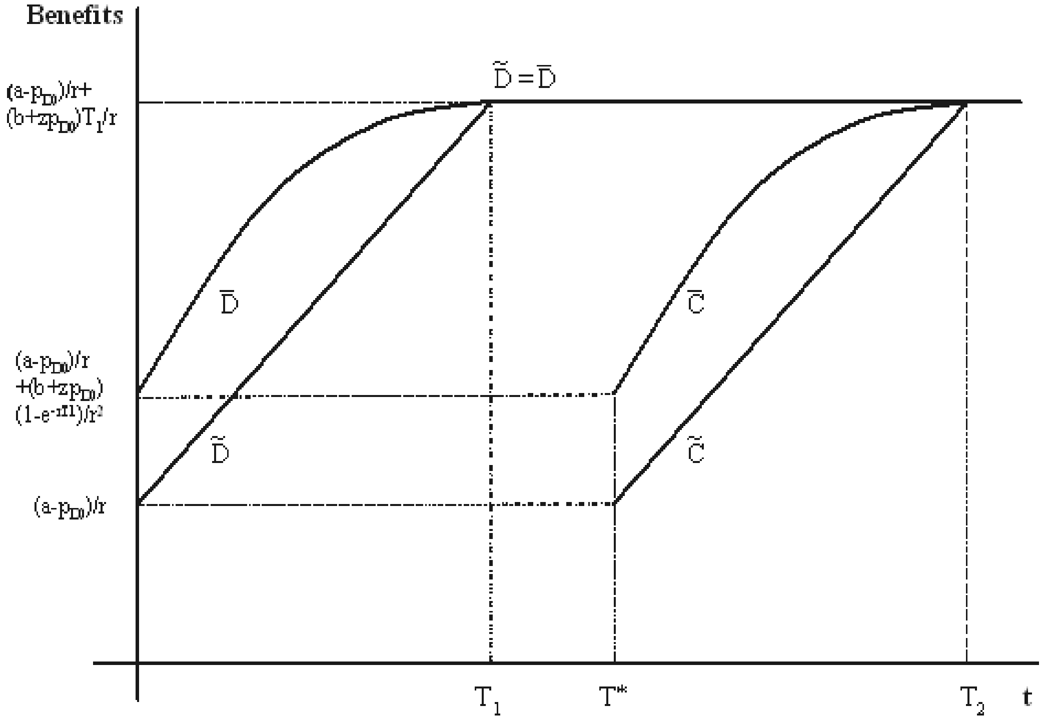

Figure 1: Private benefits derived from the dirty and the clean technology

4 Environmental externality and public policy

Assume now that the use of dirty technology automobiles imposes environmental damages to the society. We assume that the environmental damage, ε, that each user generates is constant per period of time and the same for all users. Therefore, the total environmental damage that a user entering the market at time T imposes upon the society is,

$$\int_{T}^{\infty} \varepsilon e^{-r(t-T)} dt \ . \tag{3}$$

Since we assume that all users purchase an automobile upon arriving at the market (full market coverage), and further that there is no variation in the driving activity among users, the per period environmental damage is the same for all users.

For simplicity we assume that the clean technology automobile has zero environmental impact. Thus, the private benefits of the C technology equal the social benefits. From the previous section we know that $\overline{D}(T) > \overline{C}(T)$, $\forall\ T_2 > T > T^*$ and $\overline{D}(T_1) = \overline{C}(T_2)$, $\forall\ T > T_2$. For users arriving at time $t \in [T^*, T_2]$, the policy maker has to compare their private loss, $\left(\overline{D}(t) - \overline{C}(t)\right)$, from choosing the clean technology, to the social benefits resulting from the reduced environmental damage. Figure 2 illustrates the situation. The vertically shaded area represents the (non discounted) loss in private benefits for all users arriving during the time period $t \in [T^*, T_2]$, if the clean technology is adopted at time T^*. The horizontally shaded area represents the (non discounted) environmental damage that all users entering the market after time T^* would impose on the society if they adopt the dirty technology. Since the losses in private benefits from the adoption of the clean technology shrink as the installed base of the new technology increases, there could exist a large enough value of ε that could make adoption of the new technology, at the time of its introduction, welfare superior.However, from the previous section we know that the clean technology will never be adopted based on private incentives. Therefore, policy intervention is warranted under the following condition,

$$\Delta W_{T^*} = \int_{T^*}^{T_2} \left[\overline{C}\,(t) - \overline{D}\,(t)\right] e^{-r(t-T^*)} dt + \int_{T^*}^{\infty} \frac{\varepsilon}{r} e^{-r(t-T^*)} dt > 0 \ . \tag{4}$$

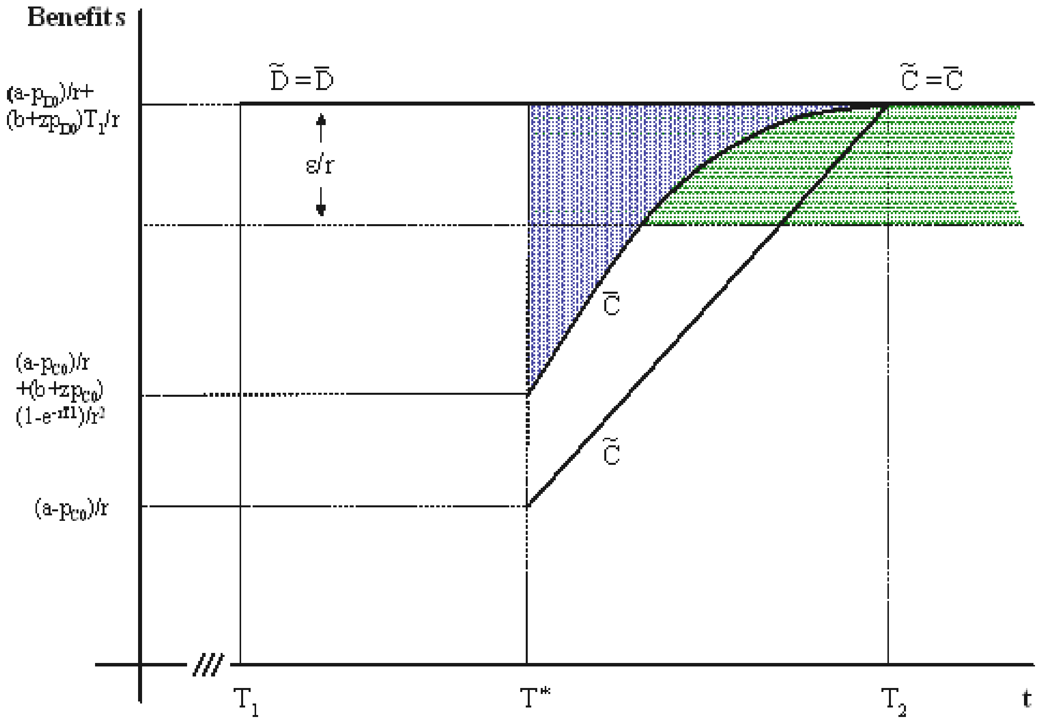

Figure 2: Welfare effects of the adoption of clean technology

4.1 Tax policy

Assume that the above condition holds and the government decides to impose a tax τ on the dirty technology. The tax is imposed on the service price of the dirty technology and paid each period of time. We assume that the government imposes the tax effective at some period T_τ, where $T_1 < T_\tau \leq T^*$. Proposition 2 presents the level of tax sufficient to induce adoption of the clean technology as the Nash equilibria.

Proposition 2 *The level of tax sufficient to induce adoption of the clean technology as the Nash equilibria is* $\tau_m = (b + zp_{D_0})T_1$.

The tax has to compensate for the difference between the service prices of the clean and dirty technology, since $p_{C_0} > p_{D_1}$ at time T^*, as well as for the benefits of the installed base associated with the dirty technology at time T^*. If the benefits of using the dirty technology are large, then the tax required to induce adoption will exceed the standard Pigouvian taxation, $\tau = \varepsilon$. Formally, $\tau_m > \tau$ if $(b + zp_{D_0})T_1 > \varepsilon$. As shown in Figure 2, the Pigouvian taxation could induce adoption only if $\frac{\epsilon}{r} > \overline{D}(T_1) - \widetilde{C}(T^*)$. All but a very high tax will be ineffective and will only raise government revenue. Although the assumptions of the model are very restrictive, not allowing consumers to respond to price changes, they do reflect the observation that moderate levels of taxation have minimal effects on emissions.[21]

4.2 Revenue neutral tax-subsidy policy

However, from equation (4) we know that adoption of the clean technology could be socially desirable even at moderate levels of environmental damages. Thus, assuming $(b + zp_{D_0})T_1 > \varepsilon$, we consider alternative policies that could induce adoption of the clean technology at a lower tax rate. Following the above discussion we consider a revenue neutral (balanced budget) policy in which the government earmarks environmental tax revenues to be used as subsidies to the users adopting the clean technology after time T^*. Assume that, in addition to a tax τ_s levied on the dirty technology from period T_τ, a subsidy s is given to each user of the clean technology, every period until a time T_s. Proposition 3 presents the characteristics of this policy.

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[21] Users are assumed homogeneous, all using their automobiles with the same, inelastic intensity and therefore, generate the same amount of emission regardless of price.

Proposition 3 *(i) When the revenues from the tax on the dirty technology are used to subsidize the clean technology within a revenue neutral policy, the required tax to induce adoption of the clean technology is lower relative to the case in which tax revenues were used elsewhere in the economy. That is,* $\tau_s < \tau_m$.
(ii) The rates of the tax-subsidy policy are $\tau_s = B(b + zp_{D_0})T_1$ *and* $s = A\tau_s$*, where* $B < 1$ *and* $A > 0$.

Proposition 3 states that if the government uses the environmental tax revenues to subsidize the clean technology from the time of its introduction until time T_s, adoption of the clean technology could become the Nash equilibrium. Figure 3 illustrates the case in which the required tax to induce adoption of the clean technology within a revenue neutral policy equals the, exogenously given, environmental damage, that is, $\tau_s = \tau = \varepsilon$.

The imposition of τ_s on the dirty good shifts the $\overline{D}$ curve downwards to $\overline{D}^{\tau}$ from time T_τ onwards. The subsidy on the clean technology moves the $\widetilde{C}$ upwards to $\widetilde{C}^{s}$ from time T^* until T_s. Notice that $\widetilde{C}^{s}$ is not linear, because the net present value of the subsidy that the user receives depends on time. Area A_1 presents the tax revenue received from all users of the dirty technology at time T_τ, which by the assumption of the model are T_τ. Area A_2 is the (non discounted to period T_τ) present value of the tax revenue that will be received from all users entering from T_τ to T^*. Area B is the (non discounted to period T_τ) present value of the subsidy expenses to all users entering from T^* to T_s. The minimum subsidization period is defined by the intersection of the $\overline{D}^{\tau}$ and the $\widetilde{C}$ curves to guarantee that adoption of the clean technology remains always the unique equilibrium even after the removal of the subsidy. Thus, the subsidy could be removed at time T_s since after that time the clean technology's network has grown enough to guaranty that even without the subsidy the benefits to the users entering after T_s exceed the benefits from adopting the old technology.

For the construction of Figure 3 it is assumed that the parameters of the model (a, b, z, p_{C0}, p_{D0}, T_1 and T^*) are such that $\tau_s = B(b + zp_{D_0})T_1 = \varepsilon$. In Figure 3 we have also assumed that the government provides the subsidy for just the minimum time period required, that is, $T_s = \arg\{\overline{D}^{\tau}(T_1) = \widetilde{C}(T_s)\}$. In such case, the government can

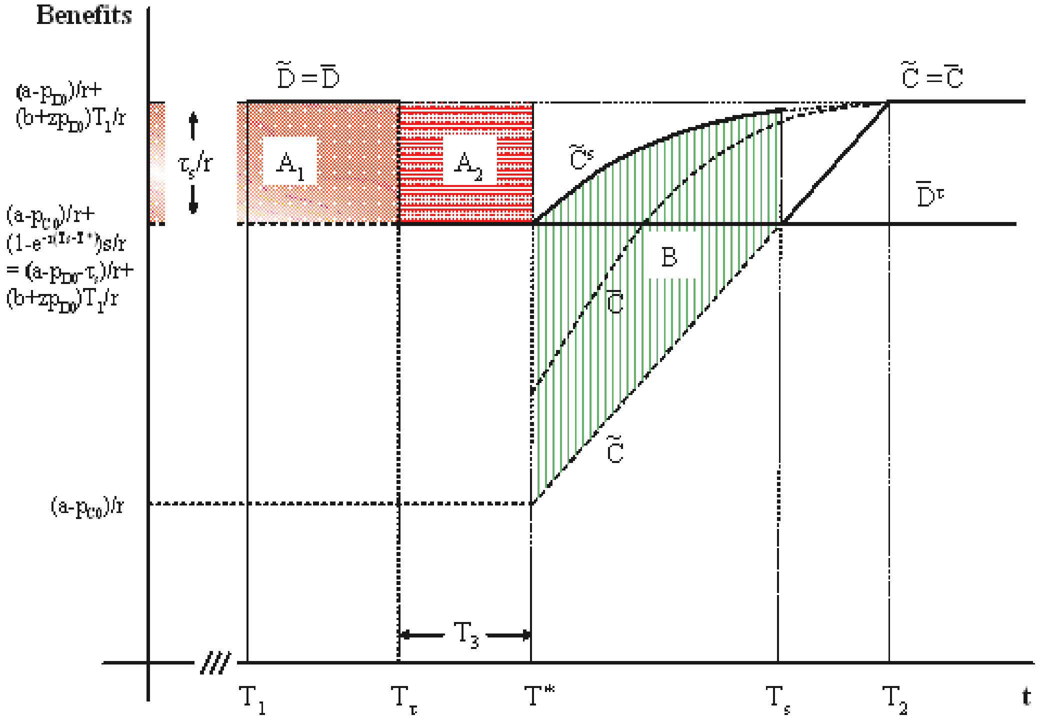

Figure 3: Pigouvian tax and subsidy sufficient to induce adoption, within a revenue neutral policy

choose only the time of the introduction of the tax. As it is shown in the Appendix, $\frac{\partial \tau_s}{\partial T_\tau} > 0$, which implies that the earlier the government imposes the tax, the lower is the required tax rate.

4.3 Precommitment to the tax-subsidy policy

The combined instruments environmental policy examined in the previous Section could become more effective if the government, at some time $T^* - T_3$, where $T_3 > 0$ levies a tax τ_a on the dirty technology and credibly commits on subsidizing the clean technology from time T^* to T_s.[22] Although at tine $T^* - T_3$ the new technology is not available, new users entering at this time could rationally decide to postpone their purchase for T_3 periods. Their decision is based on the values of the net benefits from each technology including the tax and subsidy rates. If all users entering at time $t \in [T^* - T_3, T^*]$ choose to wait for the introduction of the clean technology instead of purchasing the currently available dirty technology, the size of the clean technology's network at time T^* will be T_3.

To keep consistent with the previous Section, we assume that the announcement is made at the time that the tax is levied, that is, $T_\tau = T^* - T_3$. The user entering at T_τ expects potential benefits of $\widetilde{C}^a(T_\tau)$, which she will enjoy at time T^* when she will start using her automobile. If she chooses to wait for the introduction of the clean technology automobile, all users entering the market subsequently will make the same choice, and thus, the clean technology's network will grow to T_3 by the time T^*. Therefore, the present value of the benefits that the clean technology user entering at time T_τ will receive at T^*, equals the discounted sum of the benefits corresponding to a network size $T^* + T_3$ plus the subsidy whose present value at time T^* is $\frac{s}{r}(1 - e^{-r(T_s - T^*)})$, that is, $\widetilde{C}^a(T_\tau) = \left[\widetilde{C}(T^* + T_3) + \frac{s}{r}(1 - e^{-r(T_s - T^*)})\right] e^{-rT_3}$. Alternatively, she could choose to purchase the dirty technology automobile and enjoy benefits $\overline{D}^a(T_1)$. Thus, adoption of the clean technology is a Nash equilibrium if $\overline{D}^a(T_1) < \widetilde{C}^a(T_\tau)$. Proposition 4 shows that the government could achieve adoption of the clean technology with lower tax and subsidy rates, if it precommits on the combined instruments policy.

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[22] Earmarking the tax revenue towards the clean sector and placing such revenue in a special fund would add credibility to the government's action.

Proposition 4 *If the government credibly commits at time* $T_\tau = T^* - T_3$ *to a revenue neutral policy consisting of a tax* τ_a *on the dirty technology from time* T_τ *to infinity and a subsidy* s_a *to the clean technology from time* T^* *to* T_s*, then the tax and the subsidy rates required to induce adoption of the clean technology could be lower relative to the case without precommitment.*

Figure 4 illustrates the effect of early commitment on the tax-subsidy policy. Line $\overline{D}^a$ illustrates the benefits that a user receives from purchasing the dirty technology after its network maturity. Notice that $\overline{D}^a$ lies above the $\overline{D}^\tau$ curve indicating that $\tau_a < \tau_s$. The curve $\widetilde{C}^a(T)$ illustrates the present value of benefits, including a subsidy s_a, a user enjoys if she is the last to purchase the clean technology. Notice that the upward move of this curve relative to $\widetilde{C}(T)$ is smaller compared to the one in Figure 3, reflecting the fact that $s_a < s$. The curve $\widetilde{C}^a(T)$ is not linear for the same reasons that the $\widetilde{C}^s$ curve in Figure 3 is not linear. The curve $\widetilde{C}^a(T + T_3)$ illustrates the present value of the clean technology's benefits if users entering from time T_τ to T^* postpone their consumption, in which case at time T^* the clean technology's network has grown by T_3. Therefore, the $\widetilde{C}^a(T + T_3)$ curve is the leftward shift of the $\widetilde{C}^a(T)$ curve by T_3 periods.

Given the credible commitment of the government on all its policy elements (τ_a, s_a, T_τ and T_s) the user entering at time T_τ expects to receive, at time T^*, benefits equal to $\widetilde{C}^a(T^* + T_3)$, if she postpones her consumption to that time and purchases the new technology. All users entering subsequently up to time T^* expect the same benefits, but their discounted value is increasing the less time they have to wait. These benefits are represented by the dashed line connecting point $\widetilde{C}^a(T^* + T_3)e^{-rT_3}$ to the $\widetilde{C}^a(T + T_3)$ curve. Therefore, from time T^* to T_s, the clean technology's benefits are presented by the $\widetilde{C}^a(T + T_3)$ curve. The benefits of the users entering after time T_s are presented by the $\widetilde{C}(T + T_3)$ curve which is the leftward shift of the original $\widetilde{C}(T)$ curve. The subsidy should be given at least up to the time T in which the clean technology's network has grown sufficiently, so that its benefits even without the subsidy, $\widetilde{C}(T + T_3)$ exceed the dirty technology's benefits which are fixed at $\overline{D}^a$. Since at T^* the clean technology's network is already T_3, the clean technology's network matures at time $T_2 - T_3$.

As shown in the Appendix, there exist combinations of tax and subsidy that can induce adoption of the clean technology, and the rates of tax and subsidy are lower when the government commits on this policy at some time T_τ. This case is illustrated in Figure 4, where $\widetilde{C}^a(T^* + T_3)e^{-rT_3} > \overline{D}^a$, that is, all users entering from the time of the policy's announcement until T^* choose to wait for the introduction of the clean technology. If the early commitment on the tax-subsidy policy is effective, the government's tax revenues are reduced by the present value of the amount that the users entering at $t \in [T_\tau, T^*]$ would pay, an amount approximated by the area A_2 in Figure 3. Furthermore, since $\tau_a < \tau_s$, the revenue from all users up to T_τ is smaller than without precommitment. However, the subsidy expenditure is also reduced since the required subsidy rate is lower in the case of precommitment. Since $\widetilde{C}^a(T^*) < \widetilde{C}^s(T^*)$ and the minimum period of subsidization is smaller in the case of precommitment, the subsidy expenditure on the $[T^*, T_s]$ users is smaller than without the preannouncement, that is area B_2 is smaller than area B in Figure 3. Therefore, in the case of precommitment, government's budget will be balanced at tax and subsidy rates lower than in the case without precommitment, if the sum of areas B_1 in Figure 4 and A_2 in Figure 3, is smaller than the difference between area B in Figure 3 and B_2 in Figure 4. Under this condition, the government can induce adoption of the clean technology applying lower rates of the policy instruments if it makes an early commitment on this policy.

5 Conclusion

The present paper examines the technology choice in the automobile market in the presence of network externalities and environmental externalities. New users arrive at the market every period, each purchasing one automobile. The benefits that consumers derive depend on the number of additional consumers making the same choice, since with the number of users of a particular technology, the number of service stations increases as well. We consider two technologies: one that has developed a network of service stations and one that will be introduced sometime in the future. The use of the established technology imposes an environmental damage to the society while the new technology does not impose any environmental cost. When the clean technology is introduced, the dirty technology is offered at a lower price and has reached the maximum possible service network. We assume that the clean technology network builds solely upon new users.

In the absence of any regulatory intervention, we find that the clean technology will not be adopted. This is due to the fact that the first users of the clean technology bear an excessively high share of the costs and thus, they choose to purchase the dirty technology. The private decision is welfare superior when environmental externalities are not present. Accounting for the environmental cost of the dirty technology, the non-adoption equilibrium may become socially inefficient. In such case there is need for corrective policy intervention. We first examine the case of a tax on the dirty technology. We find that a Pigouvian tax will not be sufficient to induce adoption of the clean technology. Furthermore, the tax rate required to induce adoption decreases if the government uses the tax revenues to subsidize the clean technology within a balanced budget. Finally, we show that the value of both elements of the policy can be reduced if the government commits on the tax and subsidy rates at an early time.

There is a number of directions towards which the present analysis can be extended. In order to allow for partial response to environmental taxation, the case of many heterogeneous agents entering each period could be examined. In such case, some of the consumers in each period could choose not to purchase, for a sufficiently high level of taxation. Another possible extension is to allow users the choice of scraping their dirty technology and switch to the clean technology. Assuming that the value of automobiles depreciate, alternative policies could be examined, such as subsidizing the cost of switching technology.

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7 Appendix

7.1 Proof of Proposition 1

Proof. Proof. Non-adoption is an equilibrium if $\overline{D}(T^*) \geq \widetilde{C}(T^*)$, and a unique equilibrium if $\widetilde{D}(T^*) > \overline{C}(T^*)$. Since we focus on the case in which $T^* > T_1$, then, $\overline{D}(T^*) = \widetilde{D}(T^*) = \widetilde{D}(T_1)$. Therefore, non-adoption is a unique equilibrium if,

$$\widetilde{D}(T_1) - \overline{C}(T^*) = \frac{b + p_{D_0} z}{r} \left[T_1 - \frac{1}{r} \left(1 - e^{-r(T_2 - T^*)} \right) \right] > 0 \quad . \tag{5}$$

■

Non-adoption is a unique equilibrium if $T_1 > \frac{1}{r}\left(1 - e^{-r(T_2 - T^*)}\right)$. Since $T_2 - T^* = T_1$ this inequality is written as $rT_1 + e^{-rT_1} > 1$, which holds for all positive values of r. [23] In terms of Figure 1, this proves that $\overline{C}(T^*)$ cannot lie above the horizontal line $\widetilde{D}(T_1)$.

The welfare difference between adoption and non-adoption is given by the net present value of the difference $\overline{D}(t) - \overline{C}(t)$, $\forall t, t \in [T^*, \infty)$, that is, for all users entering

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[23] To simplify the exposition, denote by $\theta = rT_1$. Thus, we want to prove that $\theta + e^{-\theta} > 1$. It sufices to show that the minimum value that the expression $\theta + e^{-\theta}$ admits is greater than 1. The first derivative of the expression with respect to θ is, $1 - e^{-\theta}$, which becomes zero for $\theta = 0$. Therefore, for $\theta = 0$ the expression reaches its minimum value which is 1 . Since both r and T_1 are strictly positive, then $\theta > 0$, and the value of the expression is strictly greater than 1.

after the introduction of the clean technology. Note that since we are interested in the case in which $T^* > T_1$, then $t > T_1$ and thus, $\overline{D}(t) = \widetilde{D}(t) = \widetilde{D}(T_1)$. Given the symmetry in benefits and cost, it is apparent that after the maturity of the clean technology's network, the welfare difference is zero. Thus, we are concerned with users entering the market at time $t \in [T^*, T_2)$. The welfare difference is,

$$\begin{aligned}
\Delta W &= \int_{T^*}^{T_2} \left[\overline{D}(t) - \overline{C}(t)\right] e^{-r(t-T^*)} dt \\
&= \frac{b + p_{D_0} z}{r} \int_{T^*}^{T_2} \left[(T_1 + T^* - t) - \frac{1}{r}\left(1 - e^{-r(T_2 - t)}\right)\right] e^{-r(t-T^*)} dt \qquad (6) \\
&= \frac{b + p_{D_0} z}{r^2} \left[\left(T_1 - \frac{1}{r}\left(1 - e^{-rT_1}\right)\right) + \left(e^{-rT_1} T_1 - \frac{1}{r}\left(1 - e^{-rT_1}\right)\right)\right] \quad .
\end{aligned}$$

The term in the brackets is positive and thus, non-adoption is efficient.[24] Therefore, non-adoption is a unique and efficient equilibrium if there are no external costs imposed by the dirty technology. ■

7.2 Proof of Proposition 2

Proof. In order to induce new users to adopt the clean technology, the tax has to be such that adoption becomes a unique equilibrium, that is $\overline{D}^{\tau}(T^*) < \widetilde{C}(T^*)$. Since $T^* \geqq T_{\tau} > T_1$, then $\overline{D}^{\tau}(T_1) = \overline{D}^{\tau}(T^*)$. Thus, the minimum tax sufficient to induce adoption of the clean technology is obtained by setting $\overline{D}^{\tau}(T_1) = \widetilde{C}(T^*)$. A user of the dirty technology entering at time $T \geqq T_{\tau}$ receives net benefits whose present value is, $\overline{D}^{\tau}(T_1) = \widetilde{D}(T) = (a + bT_1 - (p_{D_1} + \tau)) \int_T^{\infty} e^{-r(t-T)} dt = \frac{a + bT_1 - p_{D_1} - \tau}{r}$. The benefits of the last user of the clean technology is $\widetilde{C}(T^*) = \frac{a - p_{C_0}}{r}$. Therefore, the tax level sufficient to induce adoption of the clean technology is,

$$\tau_m = bT_1 + (p_{C_0} - p_{D_1}) = (b + z p_{D_0}) T_1 \qquad (7)$$

■

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[24] To prove that the term in brackets is positive, we follow the same line of thought as in the previous footnote. Denote by $\theta = rT_1$. The expression in brackets reaches its minimum value of 0 for $\theta = 0$. Since neither r nor T_1 can be zero, then $\theta > 0$, and the value of the expression is strictly positive.

7.3 Proof of Proposition 3

Proof. (i) The present value of the net benefits that each user entering at time $T \geq T^*$ and adopting the new technology receives is $\widetilde{C}^s(T^*) = \widetilde{C}(T^*) + s\int_T^{T_s} e^{-r(t-T)}dt = \frac{a - p_{C_0} + s\left[1 - e^{-r(T_s - T)}\right]}{r}$. Substituting this into the condition sufficient to induce adoption of the clean technology as the Nash equilibria, that is, $\widetilde{C}^s(T^*) \geq \overline{D}^{\tau}$, yields the following relation between the tax and the subsidy, $\tau_s \geq (b + zp_{D_0})T_1 - (1 - e^{-r(T_s - T^*)})s$. Assuming the condition holds with equality we can write,

$$\tau_m - \tau_s = (1 - e^{-r(T_s - T^*)})s. \tag{8}$$

Therefore, $\tau_m > \tau_s$ assuming $s > 0$.

Assuming a balanced budget, the government's intertemporal budget constraint evaluated at time T_τ is

$$\begin{aligned} & \int_0^{T_\tau} \int_T^{\infty} \tau_s e^{-r(t-T)} dt dt + \int_{T_\tau}^{T^*} e^{-r(t-T_\tau)} \int_T^{\infty} \tau_s e^{-r(t-T)} dt dt \\ = \; & e^{-r(T^* - T_\tau)} \left[\int_{T^*}^{T_s} \left[\frac{s}{r}(1 - e^{-r(T_s - t)}) \right] e^{-r(t - T^*)} dt \right] \end{aligned} \tag{9}$$

The first term on the left-hand side of equation (9) presents the present value of the total tax revenue obtained from the existing users of the dirty technology. Since at T_τ there are by assumption T_τ users of the dirty technology and each of them pays a total of $\frac{\tau_s}{r}$, the value of the first term is $\frac{\tau_s}{r} T_\tau$. The second term is the tax revenue collected from new users of the dirty technology from T_τ to T^* discounted to the time of government's decision T_τ, that is, $\frac{\tau_s}{r}\int_{T_\tau}^{T^*} e^{-r(t-T_\tau)}dt = \frac{\tau_s}{r^2}(1 - e^{-r(T^* - T_\tau)})$. Each user entering at $T \geq T^*$ receives a subsidy s per period of time and the present value of her total benefits at time T are $s\int_T^{T_s} e^{-r(t-T)}dt = \frac{s}{r}(1 - e^{-r(T_s - T)})$. Summing up the benefits of all the clean technology users entering from time T^* until T_s, discounted to time T^*, and then discounting this sum to the time of government's decision T_τ, yields the right-hand side of equation (9). The subsidy expenditure is $e^{-r(T^* - T_\tau)}\left[1 - (1 + r(T_s - T^*))\, e^{-r(T_s - T^*)}\right] \frac{s}{r^2} < \frac{s}{r^2}$, since both $e^{-r(T^* - T_\tau)}$ and the term in brackets are less than unity. Substituting the above components into (9) and solving for s yields

$$A\tau_s = s \tag{10}$$

where $A = \frac{\left[(1+rT_\tau)e^{r(T^*-T_\tau)}-1\right]}{\left[1-(1+r(T_s-T^*))e^{-r(T_s-T^*)}\right]}$.[25] Thus, the government's balanced budget requirement imposes the restriction that the tax expenditure per period per user is proportional to the subsidy per period per user. Whether the tax is greater or smaller that the subsidy depends on the policy's timing and the rate of interest.

For the tax-subsidy policy to be revenue neutral and induce adoption of the clean technology, equations (8) and (10) should hold. Solving the system of these two equations yields,

$$\tau_s = B(b + zp_{D_0})T_1$$

where $B = \frac{1}{\left[1+(1-e^{-r(T_s-T^*)})A\right]}$. The tax level sufficient to induce adoption of the clean technology is smaller when accompanied by a subsidy within a revenue neutral policy. That is, $\tau_s > \tau_m$ since $(1 - e^{-r(T_s-T^*)})A > 0$ implies $B < 1$.

The minimum time period during which the subsidy to the clean technology should be given is determined by the intersection of the $\overline{D}^\tau$ and the $\widetilde{C}$ curves. $\overline{D}^\tau = \widetilde{C}(T_s)$ yields $T_s = T^* + T_1(1-B)$. Since we have assumed that $T_1 = T_2 - T^*$ and from above we know that $0 < B < 1$ it is clear that the government can eliminate the subsidy before the maturity of the clean technology's network. If the government decides to provide the subsidy for the minimum amount of time, then by substituting $T_s(\min)$ into the values of B and A, the policy variables τ_s and s depend only on the time of the tax introduction, T_τ.

Since $\tau_s = B(b + zp_{D_0})T_1$, the $sign\left[\frac{\partial\tau_s}{\partial T_\tau}\right] = sign\left[\frac{\partial B}{\partial T_\tau}\right] = -sign\left[\frac{\partial A}{\partial T_\tau}\right]$. From the definition of A we derive, $\frac{\partial A}{\partial T_\tau} = -r^2 T_\tau e^{r(T_s-T^*)} < 0$ which then yields $\frac{\partial\tau_s}{\partial T_\tau} > 0$. Thus, the minimum required tax is lower the earlier is levied. Therefore, the government could adjust the time of policy intervention, T_τ such that the combination of tax and subsidy required to induce adoption of the new technology involves a lower tax rate. ■

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[25] If taxes are imposed at time $T_\tau = T^*$ and the subsidy paid forever, equation (10) reduces to $rT^*\tau_\nu = s$. If taxes are imposed at $T_\tau = 0$ and subsisdies are provided forever $T_2 \rightarrow \infty$, equation (10) reduces to $(e^{rT^*} - 1)\tau_\nu = s$.

7.4 Proof of Proposition 4

Proof. Adoption of the clean technology is a Nash equilibrium if

$$\overline{D}^a(T_\tau) < \widetilde{C}^a\left(T_\tau\right)$$

Notice that, $\overline{D}^a(T_1) = \overline{D}^a(T_1) = \overline{D}(T_1) - \frac{\tau_a}{r}$, and $\widetilde{C}^a\left(T_\tau\right) = \widetilde{C}^a\left(T^* + T_3\right)e^{-rT_3} = \left[\widetilde{C}\left(T^* + T_3\right) + \frac{s}{r}(1 - e^{-r(T_s - T^*)})\right]e^{-rT_3}$. Thus the necessary condition for adoption is, $\overline{D}(T_1) - \frac{\tau_a}{r} < \left[\widetilde{C}\left(T^* + T_3\right) + \frac{s}{r}(1 - e^{-r(T_s - T^*)})\right]e^{-rT_3}$. Setting this condition with equality yields the minimum tax necessary to adopt the clean technology for a user entering at time $T_\tau = T^* - T_3$,

$$\tau_a = r\left[\overline{D}(T_1) - \left[\widetilde{C}\left(T^* + T_3\right) + \frac{s_a}{r}(1 - e^{-r(T_s - T^*)})\right]e^{-rT_3}\right]$$

Simplifying yields:

$$\tau_a = (b + zp_{D_0})T_1 + r\left[\widetilde{C}(T^*) - \widetilde{C}(T^* + T_3)e^{-rT_3}\right] - (1 - e^{-r(T_s - T^*)})e^{-rT_3}s_a$$

From the proof of Proposition 3 we know that, in the absence of precommitment, the minimum tax required for adoption is, $\tau_s = (b + zp_{D_0})T_1 - (1 - e^{-r(T_s - T^*)})s$. Therefore,

$$\tau_a - \tau_s = r\left[\widetilde{C}(T^*) - \widetilde{C}(T^* + T_3)e^{-rT_3}\right] - (1 - e^{-r(T_s - T^*)})(e^{-rT_3}s_a - s) \tag{11}$$

The balanced budget constraint facing the government at time T_τ given the adoption of the clean technology is,

$$\begin{aligned} & \int_0^{T_\tau}\int_T^\infty \tau_s e^{-r(t-T)}dtdt \\ = \ & e^{-rT_3}\frac{s_a}{r}(1 - e^{-r(T_s - T^*)})T_3 + \left[\int_{T^*}^{T_s}\frac{s_a}{r}\left[1 - e^{-r(T_s - t)}\right]e^{-r(t - T^*)}dt\right]e^{-rT_3} \end{aligned}$$

The first term is the revenue the government generated from the existing T_τ users of the dirty technology and equals $\frac{\tau_a}{r}T_\tau$. The subsidy is composed of two elements. The first presents the value of the subsidy given, from time T^* to T_s, to users that choose to wait for the introduction of the clean technology, that is, T_3 users, discounted from period T^* to T_τ. The second element presents the value of the subsidy given to all users entering from time $T^*$to time T_s, discounted from period T^* to T_τ.

The balanced budget condition simplifies to the following condition,

$$A^a \tau_a = s_a$$

where, $A^a = \frac{rT_\tau e^{rT_3}}{\left[1-e^{-r(T_s-T^*)}-r(T_s-T^*)e^{-r(T_s-T^*)}+(1-e^{-r(T_s-T^*)})rT_3\right]}$. Therefore, as in the case without precommitment, tax expenditure per period per user is proportional to the subsidy per period per user. Comparison of the proportionality factors in the two cases yields, $A^a < A$. Thus, for $\tau_a < \tau$, it is required that $\frac{s_a}{s} < \frac{A^a}{A} < 1$.

Return now to equation (11). Assuming that the network effects are strong and the discount rate not very high, we have that $\widetilde{C}(T^*) < \widetilde{C}(T^* + T_3)e^{-rT_3}$. Thus, $\widetilde{C}(T^*) - \widetilde{C}(T^* + T_3)e^{-rT_3} < 0$. We also know that $1 > 1 - e^{-r(T_s-T^*)} > 0$. However, since $s_a < s$, and $e^{-rT_3} < 1$, then $e^{-rT_3}s_a - s < 0$. Therefore, $\tau_a < \tau$, if $\frac{r}{(1-e^{-r(T_s-T^*)})} > \frac{(s-e^{-rT_3}s_a)}{\left[\widetilde{C}(T^*+T_3)e^{-rT_3}-\widetilde{C}(T^*)\right]}$. Intuitively, the difference between the clean technology's benefits when its network has grown to T_3 discounted by T_3 periods and when there is no network at all, should be large enough relative to the difference between the subsidy rate in the two cases. This condition depends on the parameters b and z, indicating the network benefits, the time periods T_3 and $T_s - T^*$ and the discount rate r. ■