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

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ABSTRACT: The paper considers a market currently dominated by a dirty technology that imposes significant environmental costs. A clean technology, with zero environmental costs, is introduced after the maturity of the dirty technology's network. Adoption of the clean technology is not possible due to the network benefits in favour of the dirty technology. The paper considers two types of policy intervention to correct for the environmental externality. First, we find that the tax necessary to induce adoption of the clean technology is very high implying that a tax equal to the marginal environmental damage would not resolve the externality problem in many cases. Second, if tax revenues are earmarked towards subsidizing the clean technology, the tax is lower than in the previous case and can be set equal to the marginal external damage.

KEYWORDS: Environmental externalities, network effects, automobile market, fuel cell tegnology.

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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 significant 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 anthropogenic 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 which affect local air quality. In the U.S.A. these policies date back to 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] However, this is not the case for CO_2 emissions. Increases in fuel efficiency could reduce CO_2 emissions. However this reduction has been proven to be insufficient to offset the ever expanding use of automobiles.[5]

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

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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.

[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 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. Emissions of other pollutants is the result of low speed and idling engines that yield incomplete combustion, as well as of impurities in the fuels such as nitrogen.

[5] For example, in the EU, transportation is the only sector whose emission share has increased. The emission share increased by 3.1% over 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).

[6] Both short and long run demand for fuel has been found to be inelastic, with the short run elasticity being lower. P. Goodwin, J. Dargay and M. Hanly (2004) review a number of recent empirical studies that provide data on the effects of price changes on fuel consumption, traffic levels,

type of vehicle that does not use fossil fuels, and therefore does not contribute to either local or global pollution. For example, fuel cells in which hydrogen reacts with oxygen to produce electricity do not generate emissions. Although fuel cell vehicles are currently tested on the road, they are still not an economically viable alternative to conventional vehicles.[7]

Fuel cell vehicles have to overcome obstacles such as the relative price differential, the barrier that consumers are completely unfamiliar with the technology, and the nonexistence of generation, distribution, service, and refueling networks. There are two options in developing this type of clean technology's network. Hydrogen will either utilize the existing gasoline infrastructure or a totally new hydrogen infrastructure will be developed. The second option requires a new generation and distribution system as well as the conversion of existing refueling stations to store hydrogen. The degree of network compatibility is both a technical and an economic issue.[8] All existing studies estimate high costs for both options, which implies a low degree of compatibility.[9] To simplify the analysis we assume that the two networks are incompatible and that a new generation and distribution system is required to supply hydrogen. Thus, upon their introduction to the market, fuel cell vehicles will face a significant handicap related to network externalities.[10] 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 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.[11] Although part of this network, such as roads, could be utilized by fuel cell vehicles, there are substantial network effects that are technology specific.

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fuel efficiency and car ownership. See also the OECD (1997) study on taxation as an instrument to reduce fuel consumption.

[7] Other alternatives include the electric and hybrid electric vehicles.

[8] It has been suggested that the networks' incompatibility would be avoided by using a reformer that extracts hydrogen from gasoline, thus, making the two systems (backward) compatible (See Unruh (2002)). However, the Department of Energy (1999) study on the development of hydrogen infrastructure indicates that building a new network, although it requires greater up front investment, provides a better system-wide performance.

[9] For example, D'Angelo and Bilalis (2004) estimate the cost of converting just 10% of the 135,000 filling stations in the EU to hydrogen use, at 10-12 billion euros.

[10] Liebowitz and Margolis (1998a) have expressed their concern over the use of the term "network externalities", especially if the market participants have internalized these effects. They suggest using the term "network effects". In the rest of the paper we adopt this terminology.

[11] The underlying reasons behind the prevalence of the internal combustion over steam engined and electric vehicles during the late 1800s and early 1900s are discussed in Foray (1997), Foreman-Peck (1996) and Kirsch (2000).

In addition to the direct network effects on user's utility, there are also price effects. As the size of the network increases, both the price of the automobile and the service charge decreases due to the usual learning curve effects on production as well as the presence of economies of scale in the production and distribution of spare parts and fuel. Thus, the technology with the larger network also has a price advantage.

Both utility and price network effects favour the incumbent dirty technology. However, if the external costs associated with the emissions of the dirty technology exceed the private net benefits, there is a need for policy intervention to support the adoption of the clean technology. Despite the fact that the significance of network effects 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 such effects. This paper is a first attempt to fill this gap.

We develop a simple model of the automobile market in which significant network effects are present and which is currently dominated by a technology that generates an environmental externality in the form of emissions. Assuming that at some point in time an alternative zero-emission technology becomes available and that its adoption would be socially optimal, we address the following two questions. First, will the system exit the lock-in on its own and adopt the clean technology?[12] 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.[13] Second, if private incentives are not sufficient to induce the desired technological transition, what form should public intervention take?

We consider two alternative policies in promoting the adoption of the clean technology. We first consider a tax on the dirty technology assuming that the tax revenues are used to finance the government's general budget. We find that the tax necessary to induce adoption of the clean technology is very high in order to offset the installed base benefits and price differentials in favour of the dirty technology. However, we also find that adoption of the clean technology can be socially desirable even when marginal environmental damages are lower than the required tax needed to induce

[12] Our analysis 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, since both technologies share the same characteristics. The only market failure is due to the environmental damages of the dirty technology.

[13] This result is supported by the data on market penetration by alternative technology vehicles. Although in the last few years there has been an increase in the amount of alternative fuel vehicles (AFVs) due to government policy restrictions (i.e., see the 2003 Amendments to the California ZEV Regulation), the estimated number of AFVs on the road and gasoline/Diesel-Electric Hybrid Vehicles for 2001 is at 623,043. This represents a market penetration of only 0.26 percent (See Alternative Fuel Vehicles at the U.S. Energy Information Administration, accessible at www.eia.doe.gov and the Bureau of Transportation Statistics at ww.bts.gov for total number of vehicles in U.S. market). Cowan and Hulten (1996) also reach similar conclusions.

adoption. In essence, a tax equal to the marginal environmental damage would not resolve the externality problem in many cases. Second, we consider a combined policy instruments regime in which the government commits to use the revenues from a tax on the dirty technology to subsidize the clean technology, under a balanced budget constraint. We find that the tax-subsidy combination necessary to induce adoption of the clean technology involves a tax that is lower than in the previous case. Thus, under the combined policy instruments regime it is more likely that a tax equal to marginal environmental damage could induce adoption of the clean technology.

The paper builds upon the literature on network effects. In a series of papers, Brian Arthur examined the choice of technology in the presence of network effects. Arthur (1989) showed 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. Arthur (1988) surveyed dynamic systems of the self-reinforcing type that exists in many areas of economics. Liebowitz and Margolis, in a series of articles (1990, 1995a,b, 1998a,b), have argued that the presence of network effects and path dependency does not necessarily imply that market outcomes are inefficient. They proceed to propose three classes of path dependence. First-degree path dependence refers to the class of systems that are sensitive to initial conditions. Second-degree path dependence refers to the class of systems where the sensitivity of initial conditions leads to an inferior outcome. However, the inferiority of the outcome appears ex post. Lastly, third-degree path dependence refers to the class of systems where the sensitivity of initial conditions leads to an inferior outcome that is remediable. Thus, small accidental historical events alone do not imply that the outcome is inefficient. The class of systems that have sensitivity to initial conditions and are inferior ex post cannot be labelled inferior at the time of the choice since the state of knowledge is imperfect. Liebowitz and Margolis (1995a) stated that the third-degree path dependence, although it implies remediable inefficiency, is rare and if it occurred would be worthwhile analyzing. Foray (1997) argued that remediable lock-in is a self contradictory proposition since it would require the elimination of technological uncertainty.

Katz and Shapiro (1986a) examined the effects of network effects on technology adoption, while Katz and Shapiro (1985) and (1986b) analyzed the private and social incentives to achieve technical compatibility. Farrell and Saloner (1985) studied firms' incentives to exit from a lock-in when neither technology is proprietary. They found that the result depends on whether firms have complete information regarding other firms' actions. Farrell and Saloner (1986) showed that a new technology may not be adopted when the existing technology has already built 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 Farrell 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 environmental policy. 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 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. Therefore we ignore the possibility of switching technologies.[15] At time t, N users are in the market with $N(t) = \int_0^t n(s)ds$. 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 hence $N(t) = t$.

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. Basically the size of the network grows as follows $x(t) = N(t) = t$.

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 in-

[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 and assuming that the price of the clean technology is high enough, it will preclude these D-users switching to the new clean 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] This assumption, that the network benefits reach a maximum, eliminates one of the problems of network models presented by Liebowitz and Margolis (1998a). Liebowitz and Margolis argued that one of the driving forces behind the outcomes of network models is the assumption of linearly increasing, unbounded benefits.

dependent 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 that 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 the network's size. The assumption $x(t) = t$, yields, $p_{D_0}(1-zt)$.

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

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

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

The user adopting the dirty technology at time T, joins a network of size T and so the benefits in that period are $a+bT$, while the user 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 (i.e., $T > T_1$) we get that $\overline{D}(T_1) = \widetilde{D}(T_1)$.

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

The clean technology users' benefits are defined in a similar way. To focus on the environmental policy issue, we assume that both technologies share the same characteristics, that is, a, b, $p_{C_0} = p_{D_0}$, and z, are the respective parameters under the clean technology. We assume that the network of service stations supporting the clean technology reaches maturity at time T_2.[18] If all new users arriving at the market after time T^* adopt the clean technology, the present value of net benefits to the user entering the market at time T is:

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

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 *(i.e., $T > T_2 > T^*$)* 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 where all users adopt the clean technology after its introduction, and non-adoption, the case where no user adopts the clean technology.

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

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.[19] Adoption is the subgame-perfect Nash equilibrium. Adoption is a unique equilibrium if $\widetilde{C}(T^*) > \overline{D}(T^*)$, that is, if 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. The proof of Proposition 1 is delineated in the appendix.

Proposition 1 *Assuming the clean technology is introduced after the maturity of the dirty technology's network, the existence of network effects and/or the price differential in favor of the incumbent technology, 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 the two technologies share the same characteristics 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 on 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.

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

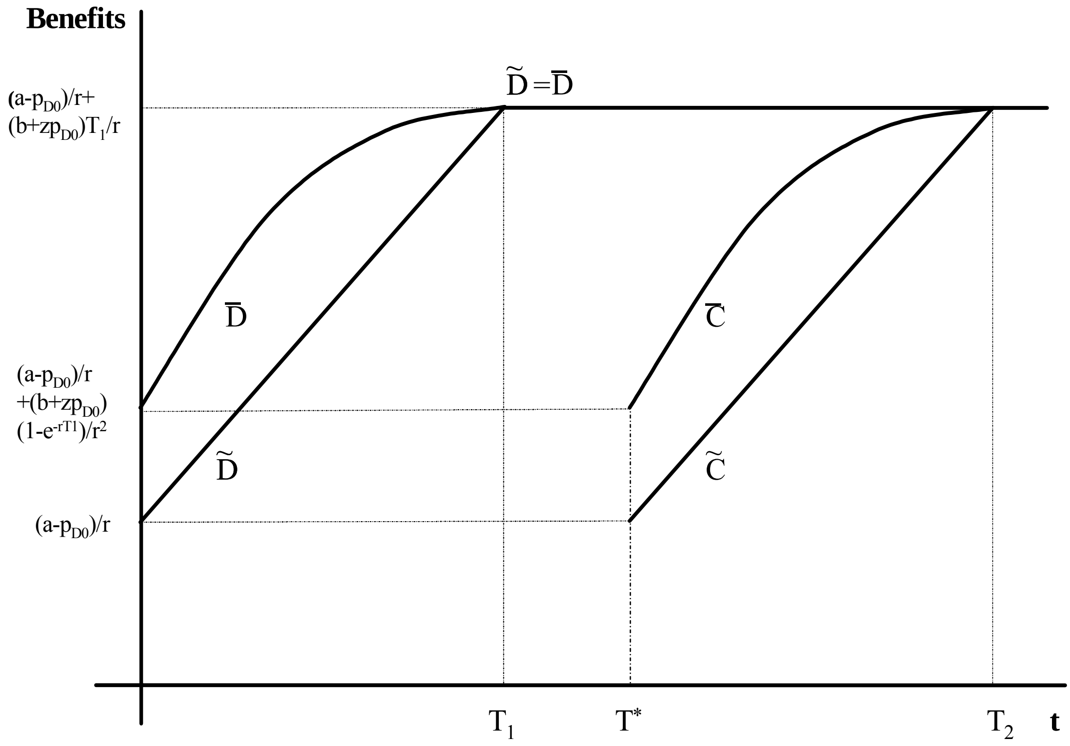

Figure 1: Private benefits derived from the dirty and the clean technology

4 Environmental externality and public policy

Assume now that the use of dirty technology automobiles imposes environmental damages on 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 (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 $t \in [T^*, T_2]$ and purchasing the

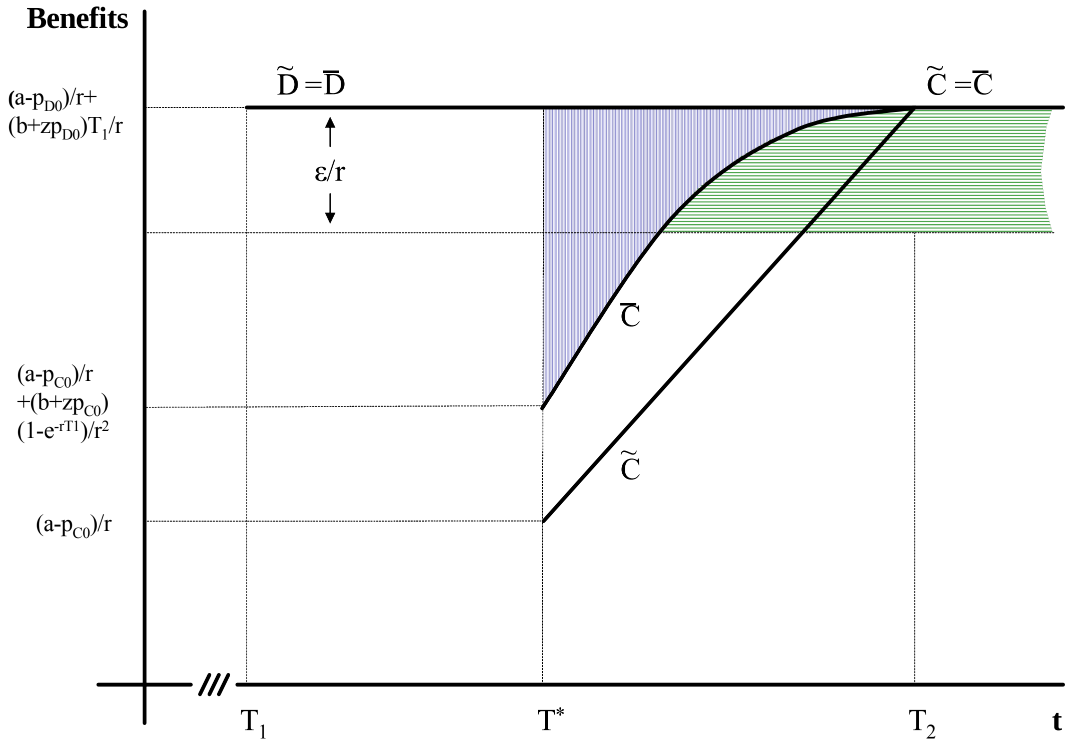

Figure 2: Welfare effects of the adoption of clean technology

clean technology, the policy maker has to compare their private loss, $\left(\overline{D}(t) - \overline{C}(t)\right)$, to the social benefits resulting from the reduced environmental damage. Figure 2 illustrates the situation. The vertically shaded area represents the reduced 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 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,

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

In what follows, we assume that the above condition holds and we consider the effectiveness of environmental policy intervention.

4.1 Tax policy

We examine first the case in which 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* $\tau_m = (b + zp_{D_0})T_1$.

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,

$$\tau_m = bT_1 + (p_{C_0} - p_{D_1}) = (b + zp_{D_0})T_1 \ . \tag{5}$$

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In order to induce adoption of the clean technology at time T^*, the tax needs to be greater than the sum of the difference between the service price of the two technologies, that is, $p_{C_0} - p_{D_1} = zp_{D_0}$, and the benefits of the installed base associated with the dirty technology, that is, bT_1. If the network 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 $(b + zp_{D_0})T_1 > \varepsilon$. Pigouvian taxation could induce adoption only if the environmental damages are such that $\frac{\epsilon}{r} > \overline{D}(T_1) - \widetilde{C}(T^*)$. Assuming that the dirty technology has accumulated substantial network benefits at time 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 existing consumers to respond to price changes, they do reflect the observation that moderate levels of taxation have minimal effects on emissions.[20]

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

4.2 Revenue neutral tax-subsidy policy[21]

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 a revenue neutral (balanced budget) policy in which the government earmarks environmental tax revenues to subsidize the the clean technology after time T^*. That is, the government levies a tax τ_s on the dirty technology from period T_τ, and commits to saving the revenues to subsidize the clean technology. We assume that the government returns the tax proceeds as a subsidy s to each user of the clean technology, every period from T^* until some time T_s after which subsidization of the clean technology is not required. Proposition 3 presents the characteristics of this policy.

Proposition 3 *(i) When the government commits to use the revenues from the tax on the dirty technology 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 $A > 0$.

Proof. (i) The present value of the net benefits that each user entering at time $T \geq T^*$ and adopting the clean 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 for adoption, 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 and utilizing equation (5) we can write,

$$\tau_m - \tau_s = (1 - e^{-r(T_s - T^*)})s \ . \tag{6}$$

Therefore, if $s \geq 0$, then $\tau_m \geq \tau_s$. Assuming a balanced budget policy, the government's intertemporal budget constraint evaluated at time T_τ is,

$$\begin{aligned} & \int_0^{T_\tau} \int_T^\infty \tau_s e^{-r(t-T)} dt dt + \int_{T_\tau}^{T^*} e^{-r(t-T_\tau)} \int_T^\infty \tau_s e^{-r(t-T)} dt dt \\ = \ & e^{-r(T^* - T_\tau)} \left[\int_{T^*}^{T_s} \left[\frac{s}{r}(1 - e^{-r(T_s - t)}) \right] e^{-r(t - T^*)} dt \right] \ . \end{aligned} \tag{7}$$

The first term on the left-hand side of equation (7) is the present value of the total tax revenue obtained from the existing users of the dirty technology. Since at T_τ there are

[21] We would like to thank an anonymous referee for pointing out the importance of subsidizing the clean technology.

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 any $T \geq T^*$ and adopting the clean technology receives a subsidy s per period of time and the present value of her total benefits at time T is $s\int_{T}^{T_s} e^{-r(t-T)}dt = \frac{s}{r}(1-e^{-r(T_s-T)})$. 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 (7). 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 (7) and solving for s yields

$$s = A\tau_s \ , \tag{8}$$

where $A = \frac{\left[(1+rT_\tau)e^{r(T^*-T_\tau)}-1\right]}{\left[1-(1+r(T_s-T^*))e^{-r(T_s-T^*)}\right]}$.[22] Thus, the government's balanced budget requirement imposes the restriction that the tax rate is proportional to the subsidy. Whether the tax is greater or smaller that the subsidy in any given period 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 (6) and (8) should hold. Solving the system of these two equations yields,

$$\tau_s = B(b + zp_{D_0})T_1 \ , \tag{9}$$

where $B = \frac{1}{\left[1+(1-e^{-r(T_s-T^*)})A\right]}$. Since $(1-e^{-r(T_s-T^*)})A > 0$, we get that $B < 1$ and therefore, $\tau_s > \tau_m$. The tax level sufficient to induce adoption of the clean technology is smaller when the generated revenues are used to subsidize the clean technology. ■

Proposition 3 states that if the government commits to use the environmental tax revenues to subsidize the clean technology from T^* to T_s, adoption of the clean technology could become the Nash equilibrium at a lower tax rate than in the absence of commitment. 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

[22] If taxes are imposed at $T_\tau = T^*$ and the subsidy is paid forever, equation (8) reduces to $s = rT^*\tau_s$. If taxes are imposed at $T_\tau = 0$, equation (8) reduces to $s = (e^{rT^*}-1)\tau_s$.

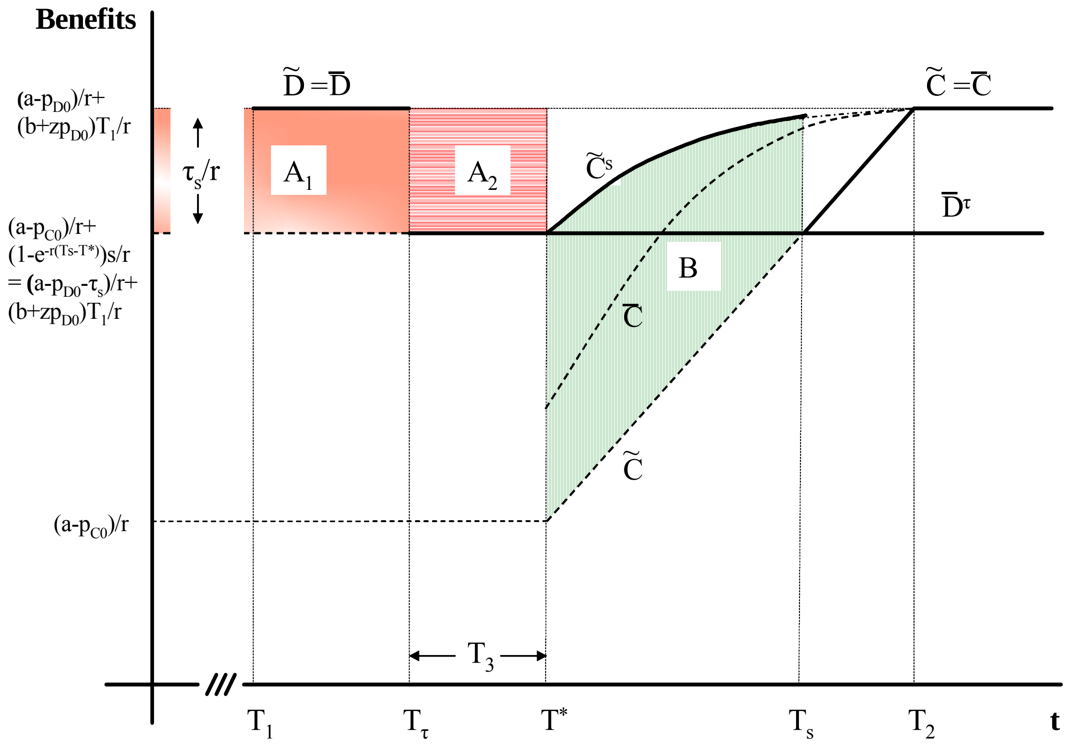

Figure 3: Pigouvian tax and subsidy sufficient to induce adoption, within a revenue neutral policy

of the model equals 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.

In order to make the policy more efficient, the government could choose to offer the subsidy for a limited amount of time. The minimum subsidization period is determined by the intersection of the $\overline{D}^\tau$ and the $\widetilde{C}$ curves, that is, $T_s^{\min} = \arg\{\overline{D}^\tau(T_1) = \widetilde{C}(T_s)\}$. The subsidy could be removed at time $T_s^{\min}$ 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 $T_s^{\min}$ exceed the benefits from adopting the old technology. $\overline{D}^\tau = \widetilde{C}(T_s)$ yields $T_s^{\min} = T^* + T_1(1-B)$. Since we have assumed that $T_1 = T_2 - T^*$ and we also 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 are derived as functions of 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 tax rate that equals the marginal external damage.

5 Conclusion

This paper examined the choice of technology in the automobile market in the presence of network effects 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 consumers making the same choice, since the number of service stations increase with the number of users of a particular technology. We considered two technologies: one that has developed a network of service stations and a second that is introduced after the maturity of the first technology's network. The use of the established technology imposes environmental damages on 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 assumed 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 a case there is need for corrective policy intervention. We first examined the case of a tax on the dirty technology. We found that the tax necessary to induce adoption of the clean technology is high and, in most cases, a Pigouvian tax will not be sufficient. However, adoption of the clean technology is welfare improving even at low levels of marginal environmental damage. To address these situations we examined the case in which the government commits to using the environmental tax revenues to subsidize the clean technology within a balanced budget. We find that in this case the tax rate required to induce adoption is lower relative to the case of no subsidization.

The results of this paper could apply to other cases where environmental externalities and excess inertia can be observed. For example, Cowan and Gunby (1996) provide two case studies to illustrate how the agricultural market can lock-in to the use of chemical controls for pests relative to the claimed superior method of integrated pest management (IPM). To the extent that such a claim is valid, taxing chemical controls and earmarking such taxes towards subsidizing superior methods such as IPM could tilt the market towards its adoption.

There are a number of directions in 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 introduced in the model. In such a case some of the consumers in each period could choose to not purchase the dirty technology. Within this new framework, optimal taxation could be examined that can result in the adoption of the cleaner technology. Another possible extension is to allow users the choice of scraping the old technology and switching to the clean technology. Assuming that the value of the automobile depreciates, alternative policies could be examined, such as subsidizing the cost of switching technology. Furthermore, the case of partially incompatible networks could be examined. As noted in the Introduction, although there is evidence of high degree of incompatibility, the possibility exists that existing gas stations could be transformed to hydrogen filling stations. If the transformation of stations is complete, for technical, security or legal issues, then the increase in the clean technology's network would imply a simultaneous decrease in the dirty technology's network. This would definitely accelerate the rate at which consumers switch technology.

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7 Appendix (Proof of Proposition 1)

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,

$$\widetilde{D}(T_1) - \overline{C}(T^*) = \frac{b + p_{D_0} z}{r} \left[T_1 - \frac{1}{r} \left(1 - e^{-r(T_2 - T^*)} \right) \right] > 0 \quad . \tag{10}$$

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 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

[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.

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,

$$
\begin{aligned}
\Delta W &= \int_{T^*}^{T_2} \left[\overline{D}(t) - \overline{C}(t)\right] e^{-r(t-T^*)} dt \\
&= \frac{b + p_{D_0} z}{r} \int_{T^*}^{T_2} \left[(T_1 + T^* - t) - \frac{1}{r}\left(1 - e^{-r(T_2 - t)}\right)\right] e^{-r(t-T^*)} dt \qquad (11) \\
&= \frac{b + p_{D_0} z}{r^2} \left[\left(T_1 - \frac{1}{r}\left(1 - e^{-rT_1}\right)\right) + \left(e^{-rT_1} T_1 - \frac{1}{r}\left(1 - e^{-rT_1}\right)\right)\right] \quad .
\end{aligned}
$$

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. ∎

[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.