Product Differentiation in the Presence of Environmental Concern, Network Effects, Installed Base and Compatibility: The Automobile Market

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Abstract

The paper addresses the problem of entry barriers for a new technology – hydrogen powered cars or cars with fuel cell engines – if the network of its filling stations is missing or thin. We use Hotelling's model of product differentiation to characterize a situation where an incumbent firm produces the old technology, compatible with the existing network of filling stations, and an entrant with a new technology, who cannot use this network for its products.

The objective of our approach is to develop a model which captures horizontal product differentiation under environmental awareness, product innovation under network effects, and price competition whereby environmentally friendly engines are costlier to produce than the conventional gasoline powered engine. The network of petrol stations provide the complementary good. In the first part of the paper we characterize the possibility of a fulfilled expectation equilibrium. Such an equilibrium could be one with either the firm offering the conventional engine as the only producer, or one with the firm offering the new technology as the only producer, or one where both firms share the market. Which equilibrium will emerge depends on the cost of producing energy efficient engines and on environmental awareness of the consumers. Due to the latter aspect the innovative firm has a chance to enter the market. We use a two stage game in prices and characteristics to analyse the respective market structure. We show that if environmental awareness is strong, the firm with the conventional technology will improve energy efficiency of its product. If the network effect is weak, both firms will be in the market. Prices and profits will decline if the role of the network effect becomes important.

In the second part of the paper we assume that the entrant has to invest in remodeling existing filling stations for making them compatible. This, however, raises his costs. In the intertemporal setting of our model, the Hotelling pricing rule for exhaustible resources encourages the entrant to invest in compatibility because the price of gasoline will rise in the long run to the price of the backstop technology - fuel cells. Depending on the cost of compatibility, our model indicates three possible outcomes. Either the costs of compatibility are too high and governmental support is required. Or the incumbent bears losses in initial periods by waiting for profits in later periods when full compatibility of the network is reached. Or the entrant benefits from the fact that the price of oil reaches the price of the backstop technology (full cells) rather soon.

Keywords: Network effects, compatibility, environmental concern, price competition, lock-in effect, automobiles.

JEL classification: L 11, L 15, L 62, Q 42.

1. Introduction*

There are many goods for which the utility that a user derives from consumption of the good depends upon the number of other agents buying the good. Industries which are characterized by the existence of those network externalities include the computer industry, the telecommunications industry, the consumer electronics industry (video cassette recorders, compact disc players, etc.) or the automobile industry (repair and gas stations). For products of these industries the value of consuming a particular good increases in the number of consumers (the installed base) who have already purchased the good. Networks exhibit positive consumption and production externalities. A positive consumption externality (or network externality) signifies the fact that the utility of consuming a good (e.g. a car engine driven by hydrogen) increases with the (expected) number of other consumers of the good (other car owners). Depending on the network, the externality may be direct or indirect. The source of a positive consumption externality could be a direct physical effect (e.g. the telephone or fax network) or may be generated through indirect effects (e.g., the number of personal computers and the amount and variety of the complementary good software)[1]. For a durable good like an automobile, for example, consumption externalities arise when the availability of postpurchase service for the good depends on the size of the service network. Network externalities arise out of the complementarity of different network pieces. In our paper car owners value being part of a large network, i.e. using a technology that many other car owners also use (the direct network effect). Car owners also value a technology for which there is a wide variety of gasoline stations available, and more gasoline stations associate with a technology if more owners use it (the indirect network effect).

Our example throughout the paper will be the market for natural gas powered cars or hydrogen powered cars. Sales will be initially retarded or blocked by consumers' awareness of the thin network of service stations offering natural gas. The scope of the relevant network that gives rise to the consumption externality is identical to the number of already existing petrol stations. The feature of this market is that cars with different engines may use the same network. However, the owner of a natural gas powered car will find a very thin service system since only a few petrol stations are

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[1] See Katz and Shapiro (1985, 1992) and Economides (1996) for more examples.

equipped with natural gas pump posts. This small network will reduce his initial willingness to pay for such a motor vehicle. An entrant could extend its size of the network year by year (the installed base). He is confronted with the problem that on account of a former decision a development is continued although another direction could lead to a better equilibrium (the lock-in effect).

The interest in a new kind of fuel (natural gas, hydrogen) for cars or in a new technology (fuel cells) arises from the concern about global warming and the scarcity of fossil fuel. CO_2 emissions could be (partly drastically) reduced by gas-driven cars (natural gas, methane, compressed natural gas (CNG)), by hydrogen powered cars or by a fuel-cell engine system. The fuel-cells are the technology for the distant future. They convert natural gas, methanol or hydrogen fuel into electricity without combustion. When the fuel is hydrogen, then water vapour is the only by-product from the fuel cell itself.[2] It will take about eight years before fuel-cell powered cars are available commercially, and maybe another eight years before they become affordable due to mass production. The true time period will depend, however, on the consumption externality in terms of the network of service and filling stations.[3] To overcome the network problem, most car manufacturers produce bi-fuel powered cars. The disadvantage of these cars is the reduction of space for the backseats and for luggage, which is needed for the two tank fillings.

Hydrogen powered cars are even more environmentally friendly than gas powered cars, but driving with hydrogen is more expensive than with gasoline, given the current price of gasoline. Research institutes, governments and the European Union have started an initiative to develop hydrogen powered cars which are supposed to replace the gasoline powered cars by 2025. The background of this initiative is the assumption that the price of oil will increase due to higher costs of exploration of the scarcer becoming exhaustible resource. Besides the expected price increase of oil,

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[2] But one must consider how the hydrogen gets produced. If it is produced from natural gas (as most hydrogen is) then carbon dioxide is released to the atmosphere in the production of the hydrogen.

[3] One advantage of gas powered cars versus gasoline powered ones is their environmental record and energy bill. From burning methane, emissions of all air pollutants will be lower; CO_2 emissions by 25 percent and the summer smog causing reactive carbon-hydrate are down up to 80 percent. The milage of 25 kilogram methane is 360 km and the costs for that distance € 15 (61 cents per kilogram, tax reduced till 2009). For a gasoline driven car the cost for this distance is about twice as high. However, the price of a gas powered car is about € 2000 higher than for its gasoline power version.

the other reason for a switch to hydrogen is global warming.[4] Like in the case of the gas powered engine, the technique is not the problem, the problem is the network.[5]

The objective of the paper is to investigate a market for cars with conventional engines versus cars powered by natural gas or hydrogen. These technologies are subject to indirect network externalities generated by the availability of filling stations that carry the appropriate type of fuel. Two competing firms choose simultaneously and independently from each other their technology, that is their locations in a horizontal product differentiation dimension on the unit interval. This location also corresponds to how environmentally friendly a product is. Consumers differ in their preferences for the product attributes but they all share the same preference concerning the environmental aspect of the product.

In order to relate our findings to the existing literature, we should point out that there are two types of product differentiation – horizontal product differentiation within the same quality group and vertical product differentiation in terms of different quality levels. Horizontal product differentiation emphasizes the fact that the supply of a product variant (within this quality group) does not satisfy completely some or many consumers. It could therefore be a profit maximizing strategy to offer modifications of a standard product which is closer to the preferences of some customers. Under vertical product differentiation firms choose a high or low quality class in the product space.[6] There is a price-quality competition with a trade-off in higher prices for better quality or a lower price for the lower quality. In either of these product differentiation models the firms will choose distinct characteristics or qualities because as those become close, price competition between the increasingly similar products reduces the firms' profit. In vertical product differentiation models with environmental background, the focus of environmental policy is often on minimum quality standards (see, e.g. Crampes and Hollander, 1995; Ronnen, 1991; Motta and Thisse (1999)).[7]

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[4] Hydrogen is produced from renewable or non-exhaustible resources like biomass, wind or solar energy. Whereas a gasoline powered car emits 160 gr. CO_2 per km, a hydrogen driven car would emit only 35 gr. CO_2 per km if hydrogen is produced from a non-exhaustible resource.

[5] Hydrogen is filled as a liquid at a temperature of –253° C in a special tank.

[6] See Gabszewicz and Thisse (1979) or Shaked and Sutton (1982) for typical models of vertical product differentiation.

[7] Environmentally orientated papers dealing with aspects of vertical or horizontal product differentiation are Arora and Gangopadhyay (1995), Grilo, Shy and Thisse (2001), Lombardini-Riipinen (2003), Cremer and Thisse (1999), Moraga-Gonzales and Padron-Fumero (2002), Bandol and Gangopadhyay (2003), or Greaker (2003).

There is a substantial amount of literature on network externalities, see for example Katz and Shapiro (1985, 1986, 1992, 1994), Farrell and Saloner (1985, 1986), Matutes and Régibeau (1996), and especially the book by Shy (2001) devoted to this topic. These authors do not use, however, the models of horizontal or vertical product differentiation. Katz and Shapiro (1985) consider a model of static oligopolistic competition with network externalities. Consumers form exogenous expectations on the network size of the competing firms on the market (as they will do in our model). Then firms determine their prices on which consumers base their purchase decision. The structure of the equilibria confirms the importance of consumers' expectations in markets where network externalities are present. Farrell and Saloner (1986) analyze the incentives for adopting a new technology that is incompatible with the installed base. In an equilibrium, the outcome depends on the size of the installed base when the new technology is introduced, it depends on how quickly the network benefits of the new technology are realized, and on the relative superiority of the new technology.[8] Their model is dynamic as is our second model which is an extension of our first one, a model with fulfilled expectations on the network size.[9]

The paper is organized as follows. In Section 2 we present a static duopoly model and in section 3 a dynamic model when network effects are present. Section 2.2 characterizes the conditions for possible market structures and section 2.3 compares the private decision on the type of engine with the decision of a welfare maximizing regulator. In section 3 we extend our model by assuming that the entrant has to invest in achieving compatibility to the existing network. In section 3.1 we present the model and in section 3.2 the dynamic structure of the game. In section 3.3 we characterize a steady state situation where the entrant has no incentive anymore to invest in compatibility. Some or all petrol stations have been remodeled and cars can refuel either gasoline or hydrogen at those stations. Section 4 concludes the paper.

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[8] A model on the automobile market based on the approach by Farell and Saloner (1986) has been outlined by Sartzetakis and Tsigaris (2000).

[9] Another strand of the literature on network economics utilizes an approach sometimes referred to as the supporting services approach. Software packages, for example, are regarded as supporting services for the hardware. The literature utilizing the supporting services approach includes Chou and Shy (1990, 1993) and Church and Gandal (1992 a, b, 1993 and 1996). Like in our car engine case, in many instances supporting services are incompatible across brands. Since a hydrogen powered car must be gasstation compatible, we can not utilizes these models for our case because they compare equilibrium profits and welfare under compatibility and under incompatibility.

2. A static fulfilled expectation equilibrium

In this section we consider a non-cooperative game in two stages: In the first stage the firms simultaneously choose their respective characteristics. In the second stage firms compete in prices taking into account the degree of product differentiation. Firm G (G for gasoline) decides to produce the conventional gasoline powered engine whereas firm H intends to produce a hydrogen powered engine, i.e., we assume that the product embodying technology G is already in use when our analysis begins at time zero. In contrast, the "sponsor"[10] of technology H, firm H, chooses time zero to introduce its new product to the market. We assume that it is possible for firm G to bring out improved versions of its technology, and that firm H can introduce only a single version of its technology. Firm H is convinced that environmental concern and the prospect of running out of oil in the near future is a good reason to offer cars with this new technology. Therefore firm H will produce the characteristic at the upper end of the zero-one characteristic line. Firm G adheres to the conventional technology but will use its option to vary its technology in terms of gasoline efficiency. Depending on environmental concern and cost aspects, it will choose characteristics within the [0, 1] interval. Both firms include installed base considerations. In our first model, the network of gasoline stations is exogenous to the firms and they know about consumers' awareness of the compatibility of an engine with a filling station. Our model differs from standard models of product differentiation because of the introduction of a network externality (lock-in) and of consumers' awareness of a negative (environmental) externality. As a natural gas powered car is not compatible with the existing network of gasoline stations, we exclude compatibility efforts of firm H with the installed base of firm G.[11]

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[10] Katz and Shapiro (1986) call a firm a sponsor of a technology if it controls the property rights to a given technology. In that case the firm will be willing to invest into the network or in the form of penetration pricing to establish the technology because then there is the prospect of profits in later periods.

[11] We also exclude the strategy to produce cars with bi-fuel engines, having two tanks. This strategy, observable in reality, is a way to become compatible with the installed base. Although it would eliminate the advantage of the installed base of the competitor it raises the cost of production and in addition reduces the capacity of the trunk compartment. Instead of adding another stage to the game where firms simultaneously decide upon the compatibility of their products, then on quality and finally on prices, we could interpret a car close to the right end of the product line to be equivalent to a bifuel car. For the consumer, partial compatibility is offset by the reduced space of the trunk compartment.

2.1 The model

Consumers base their purchase decision on prices, product differentiation (gasoline consumption and environmental characteristics), and on the network effect. Consumers' awareness comes from the negative externality caused by traffic such as air pollution from CO_2 and NO_X emissions. As a characteristic q of the good, which affects the willingness to pay of a potential customer, we consider different types of engines within a quality class of motor vehicles. The characteristic of the consumer, described by $\theta \in [0,1]$, is the interest in energy related attributes of a car, which is the reason for the different willingness to pay. Some consider gas-guzzlers as a comfortable car although they are extremely environmentally unfriendly, while others care about an environmentally friendly technology like fuel cells although they have asymmetric information with respect to the property and reliability of this technology. There is a continuum of consumers uniformly distributed over Hotelling's [0, 1] interval. Each consumer buys one unit of the product. Products localized to the left are characterized by aspects linked to fuel inefficiency like horse power and driving dynamics, and products to the right by stillness in running, by a low noise gauge of the engine and by a jerk-free start and a more comfortable stop and go driving. In such a model of horizontal product differentiation we do not assume that if $q_H > q_G$ and prices are equal, all consumers purchase the environmentally more friendly car with q_H. Some consumers prefer automatic transmission (which needs more fuel), a better initial velocity, they enjoy the noise of the engine and its driving dynamics. That is, we assume that the difference in the willingness to pay if product characteristics q_G and q_H differ, is positive for some consumers and negative for others. The net-utility of consumer $\theta \in [0,1]$ for a unit of the good of quality q_G is defined by

$$(1) \qquad v(q_G,\theta) = u - \tau \cdot (q_G - \theta)^2 - d\,(1 - q_G) - p_G + \gamma \cdot n_G(\sigma)$$

in which *u* stands for the gross, intrinsic utility a consumer derives from consuming one unit of the product.[12] The term $\tau\left(q_G-\theta\right)^2$ represents the costs a consumer, located at $\theta\in\left[0,1\right]$, he bears if he does not get his preferred characteristic because he buys from firm G selling characteristic q_G. His ideal car within the class of middle sized family cars is θ but firm G offers q_G. The parameter τ expresses the strength of personal preferences. It can be normalized to 1 in the gross utility term (the term without the price) without loss of generality. With $d\cdot\left(1-q_G\right)$ we express the awareness of a negative externality caused by the product, i.e. environmental concern. It is modelled as a bad conscious of not having purchased the most energy efficient and hence environmentally friendly product at the end of the quality line [0, 1]. We therefore incorporate environmental concern directly into individual preferences.[13] The term $d\left(1-q_G\right)$ is a money-metric measure of the cost of negative externalities from fuel consumption. When $q_G=0$, then *d* represents the highest money-metric disutility from emissions (environmental damage) including excessive fuel consumption. When $q_G=1$, there is no money-metric disutility because the consumer has decided in favour of the most environmentally friendly and efficient technology. The fuel bill is taken into account by defining *u* as a net intrinsic utility adjusted for fuel costs. The difference in fuel consumption is captured by $d\left(1-q_G\right)$.

The price of firm G is p_G and the term $\gamma\cdot n_G\left(\sigma\right)$ is the network benefit for good G where σ is the expected market share of firm H, i.e. $n_G\left(0\right)=n$ at the beginning with *n* as the total number of customers. Network benefits enter consumers' utility and they are willing to pay for that. The size of the network benefit is modelled as a product of the strength of the network effect γ and its size $n_G(\sigma)$. The higher γ, the more important is the network. Since $n_G+n_H=n$, $n_H\left(\sigma\right)$ are the

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[12] In the tradition of spatial models of product differentiation, it is assumed that *u* is sufficiently large to ensure that all consumers prefer buying rather than dropping out of the market.

[13] See Conrad (2002) for a model with care for the environment. In such a model θ is no longer "the bliss point" of the consumer, as in conventional horizontal product differentiation models. The FOC of (1) with respect to q_G yields $\theta+\dfrac{d}{2\,\tau}$ as the bliss point.

customers of firm H $\left(n_H\left(0\right)=0\right)$. The network benefit for firm G decreases, i.e. will become less important when the number of consumers $n_H\left(\sigma\right)$, connected to the competing network of good H, increases. All *n* consumers have bought the product of firm G in the past. Its characteristic could have been $q_G=0$ whereas firm H considers to produce only the new, energy efficient product, i.e. $q_H=1$. This maximal horizontal product differentiation at the $0-1$ end points of the Hotelling line is the outcome of the standard Hotelling model without environmental concern and network effects. Later on we will derive the parameter constellations under which maximal horizontal differentiation is a Nash equilibrium, and under which one $q_G>0,\ q_H=1$ is an equilibrium of the two stage game in price and quality competition.

The net-utility of a customer when buying a unit from firm H is:

$$v\left(q_H,\theta\right)=u-\tau\cdot\left(q_H-\theta\right)^2-d\left(1-q_H\right)-p_H+\gamma\, n_H\left(\sigma\right). \tag{2}$$

Even if the attribute is highly esteemed (e.g. $q_H=1$) and the good not expensive, the innovative firm might be unsuccessful because the installed base does not exist. As $n_H\left(0\right)$ is zero or very small at the beginning, the network benefit term represents the aspect that when introducing a new technology, the first question that comes to mind is whether the new technology will be adopted given the large installed base (i.e. $n-n_H$) of the existing technology. In addition, firm G can defend its market share by improving fuel efficiency of a G-car in raising q_G from $q_G=0$ (10 ltr./100 km) to $q_G=0.5$ (6 ltr./100 km) or finally towards $q_G=1$ (3 ltr./100 km). In the case of $q_G=1$, households are indifferent in terms of the property of fuel efficiency of cars.

The difference of the net-utilities in (1) and (2) shows the possibilities, firms have for attracting customers:

$$v\left(q_G,\theta\right)-v\left(q_H,\theta\right)=\underbrace{p_H-p_G}_{\text{price effect}}-\underbrace{\tau\left[\left(q_G-\theta\right)^2-\left(q_H-\theta\right)^2\right]}_{\text{horizontal product differentation}}\underbrace{-d\cdot\left(q_H-q_G\right)}_{\text{image concern}}+\underbrace{\gamma\left(n_G(\sigma)-n_H(\sigma)\right)}_{\text{network effect}} \tag{3}$$

Firm G can increase or keep its market share by a price advantage, by product differentiation, by taking into account environmental concern of consumers, and by the difference of the size of the network. Whereas firms can determine price and quality, they can not influence the network advantage which comes from the installed base in the past and from expectations on demand and on compatibility.

The network situation at the beginning is characterized by the fact that the network of G-cars (gasoline station, repair shops) is sufficient, but there is no network for H-cars. The situation is characterized by non-compatibility between products in the sense that each firm continues to produce according to its own technology, but the products (cars) of the two firms can not use the same service installation. For products with network effects, expectations play a central role because the vigour of the network depends on the expected future market share and on the market share in the past. In order to determine the expected market share, we assume that consumers have rational expectations; i.e. they expect the market share which will result at the end of the competitive process. [14] In such a fulfilled expectation equilibrium it is:

$$n_G\left(1-\hat{\theta}\right)=n\cdot\hat{\theta} \qquad\qquad n_H\left(1-\hat{\theta}\right)=n\cdot\left[1-\hat{\theta}\right], \tag{4}$$

where $\hat{\sigma}=\left(1-\hat{\theta}\right)$ is the expected market share of firm H (consumers to the right of $\hat{\theta}$) and $\hat{\theta}$ is the expected market share of firm G (consumers to the left of $\hat{\theta}$) and by $\hat{\theta}$ we denote the critical consumer who is indifferent between consuming q_G or q_H.

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[14] When network externalities exist, consumers must form expectations regarding the size of (competing) networks. Katz and Shapiro (1985) use a notion of fulfilled expectation equilibrium. For some set of expectations only one firm will produce output, while for other sets of expectations there will be both firms in the market. At a market equilibrium of the simple single-period world, expectations are fulfilled $\left(n=n^e\right)$.

We are interested in finding a consumer $\hat{\theta} \in (0,1)$ who is indifferent at prices p_G, p_H to purchase from producer G (to the left of $\hat{\theta}$) or from producer H (to the right of $\hat{\theta}$). From $v(q_G, \hat{\theta}) = v(q_H, \hat{\theta})$ and the condition, that the networks, expected by the consumer, are the actual networks, i.e. (4), we can solve for $\hat{\theta}$ to get firm G's specific demand function $D_G(p_G, p_H) = \hat{\theta}$:

(5) $$D_G(p_G, p_H) = \hat{\theta} = \frac{p_H - p_G + (q_H - q_G)[q_G + q_H - d] - \gamma \cdot n}{2(q_H - q_G) - 2\gamma n}$$

where τ has been set equal to 1. In this comparative static analysis we assume that an equilibrium emerges after a certain period of time. We do not describe the market process which might lead to the following three types of equilibrium market structure:

a) $\hat{\theta} = 1$, $1 - \hat{\theta} = 0$ (market exit of firm H)

b) $\hat{\theta} = 0$, $1 - \hat{\theta} = 1$ (market exit of firm G)

c) $0 < \hat{\theta} < 1$, $1 > 1 - \hat{\theta} > 0$ (both firms share the market) .

Our objective is to characterize the quality choices and pricing policies which would be consistent with these three types of market structure. Case a) characterizes a market structure where firm G has defended its leading position. All customers still buy the G-car at energy efficiency q_G^*. Case b) describes the situation where firm G has been driven out of the market and firm H serves the whole market. Case c) characterizes a market structure where firm H has captured $100 \cdot (1 - \hat{\theta}) > 0$ percent of the total market.

The demand function for firm H is

(6) $$D_H(p_G, p_H) = 1 - \hat{\theta} = \frac{p_G - p_H + (q_H - q_G)[2 + d - q_G - q_H] - \gamma n}{2(q_H - q_G) - 2\gamma n}.$$

We observe that the price response of market demand is higher if there is a network effect. A marginal decrease of firm G's price raises its demand by $1/2\left(q_H - q_G\right)$ if $\gamma = 0$, but by the higher factor $1/\left[2\left(q_H - q_G\right) - 2\,\gamma\, n\right]$ under network effects. Demand is raised by the non-network term which raises expectations of a higher market share. This in turn raises demand beyond the factor $1/2\left(q_H - q_G\right)$.

In producing the two characteristics we assume that costs increase in q. The costs of production are higher for a producer of family-sized middle class cars if he offers an engine with about the same horsepower but with a better fuel efficiency. By backward induction, firms maximize profit with respect to price:

(7) $$\pi_G = p_G\, n_G - c\, q_G\, n_G = n\left(p_G - c\, q_G\right)\cdot \hat{\theta}\left(p_G, p_H\right)$$

(8) $$\pi_H = p_H\, n_H - c\, q_H\, n_H = n\left(p_H - c\, q_H\right)\cdot\left(1 - \hat{\theta}\left(p_G, p_H\right)\right).$$

The Nash-equilibrium in prices $\left(p_G^*, p_H^*\right)$ is:

(9) $$p_G^* = \frac{1}{3}\left[\left(q_H - q_G\right)\left[2 + q_G + q_H - d\right] - 3\,\gamma\, n + c\left(q_H + 2\, q_G\right)\right]$$

(10) $$p_H^* = \frac{1}{3}\left[\left(q_H - q_G\right)\left[4 - q_G - q_H + d\right] - 3\,\gamma\, n + c\left(q_G + 2\, q_H\right)\right]$$

Under price competition, the network effect lowers the equilibrium prices of both firms. The benefit of the network shifts the positively sloped reaction functions of both firms outwards and hence increases price competition.

Finally, the equilibrium market share follows from (5) by inserting p_G^*, p_H^* from (9) and (10):

(11) $$\theta^{*}\left(q_G,q_H\right)=\frac{\left(q_H-q_G\right)\left[2+q_G+q_H-d\right]-3\,\gamma\,n+c\left(q_H-q_G\right)}{6\left[\left(q_H-q_G\right)-\gamma\,n\right]}.$$

Similarly, from (6):

(12) $$1-\theta^{*}\left(q_G,q_H\right)=\frac{\left(q_H-q_G\right)\left[4-\left(q_G+q_H-d\right)\right]-3\,\gamma\,n-c\left(q_H-q_G\right)}{6\left[\left(q_H-q_G\right)-\gamma\,n\right]}.$$

The second order condition of the profit maximization problem in (7) postulates that the denominator in (11) must be positive.

Before we interpret prices and market shares for our three cases a) - c), we analyse the quality game at the first stage of our two-stage game. As mentioned at the beginning, we want a situation where firm H has committed to $q_H=1$, i.e. either it produces H-cars or it does not produce at all. Only firm G has the option to vary q_G in terms of fuel efficiency. In order to get a subgame perfect equilibrium in the quality choices q_G and $q_H=1$, we let firm H choose its optimal response to q_G. With a Nash equilibrium in qualities, we will set cost and environmental aspects (i.e. c and d) such that $q_H=1$.

The problem of firm G is:

(13) $$\max_{q_G}\quad \pi_1\left(q_G,q_H\right)=\left[\,p_G^{*}\left(q_G,q_H\right)-c\,q_G\right]n\cdot\theta^{*}\left(q_G,q_H\right)$$

If an interior solution exists, then q_G^{*} follows from $\frac{\partial\,\pi_G}{\partial\,q_G}=0$. The FOC is

(14) $$3\,q_G^{*2}+q_G^{*}\left(-4\,q_H+2-\left(d-c\right)+4\,\gamma\,n\right)+q_H^{2}-q_H\left(2-d-c\right)+2\,\gamma\,n\left(1-\left(d-c\right)\right)-\gamma\,n=0$$

Hence we have to solve a quadratic equation in q_G^*.

Similarly, the problem of firm H is:

(15) $$\max_{q_H} \quad \pi_H\left(q_G, q_H\right) = \left[p_H^*\left(q_G, q_H\right) - c\, q_H\right] \cdot n \cdot \left(1 - \theta^*\left(q_G, q_H\right)\right).$$

Again, if an interior solution exists, then q_H^* follows from $\frac{\partial \pi_H}{\partial q_H} = 0$. The FOC is

(16) $$-3\, q_H^{*2} + q_H^*\left(4\, q_G + 4 + d - c + 4\,\gamma\, n\right) - q_G^2 - q_G\left(4 + d - c\right) - 2\,\gamma\, n\left(3 + d - c\right) + 2\,\gamma\, n = 0.$$

By adding up equations (14) and (16), it is possible to find the following Nash-equilibrium in qualities:[15]

(17) $$q_G^* = -\frac{1}{4} + \frac{d-c}{2} \quad , \qquad q_H^* = \frac{5}{4} + \frac{d-c}{2}.$$

For an interior solution $q_G^* \geq 0$ and $q_H^* \leq 1$, $d - c$ should be $\geq 1/2$ and $\leq -1/2$. There is therefore no interior solution. Since we wish that firm H offers only energy efficiency $q_H^* = 1$, this assumption is consistent with the assumption $d - c \geq -1/2$. If even $d - c \geq 1/2$, then $q_H^* = 1$ in addition with $q_G^* \geq 0$ is an interior solution. We notice that $d - c$ must be large enough (at least $-1/2$) that there is a sponsor who is willing to offer the new technology. In case the government wishes to prevent this kind of market failure, it has to raise environmental concern *d* in the population or it has to subsidize the cost of production, *c*.

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[15] Several other pairs of solution did not satisfy either the restriction $\gamma > 0$, or the denominator in θ^* became zero for the q_G, q_H pair. Such a solution was $q_G = \frac{1}{2} + \frac{d-c}{2} - \frac{\gamma\, n}{2}$ and $q_H = \frac{1}{2} + \frac{d-c}{2} + \frac{\gamma\, n}{2}$.

2.2 Three types of market structure in an equilibrium

We consider two cases of $d-c$. One where the difference is less than $1/2$ and one where it is greater than $1/2$. The case $d-c\in\left[-1/2\,,1/2\right]$ we call weak environmental concern and it implies that we have a corner solution for $q_i\left(q_G^*=0,q_H^*=1\right)$. The formula for the market share θ^* is then as presented in Table 1.

Table 1: Weak environmental concern: $d-c\in\left[-\frac{1}{2},\frac{1}{2}\right]$

$$q_G^*=0\,,\quad q_H^*=1\,,\quad \theta^*=\frac{1}{2}-\frac{d-c}{6\left(1-\gamma\,n\right)}$$

	$d-c=-1/2$	$d-c\in\left(-1/2,0\right)$	$d-c=0$	$d-c\in\left(0,1/2\right)$	$d-c=1/2$
	values of θ^*				
$\gamma\,n=\frac{5}{6}$ [1)]	1	$\frac{\partial\,\theta^*}{\partial\left(d-c\right)}<0$	$\frac{1}{2}$	$\frac{\partial\,\theta^*}{\partial\left(d-c\right)}<0$	0
$\gamma\,n=0$	$\frac{7}{12}$	$\frac{\partial\,\theta^*}{\partial\,\gamma\,n}>0$	$\frac{1}{2}$	$\frac{\partial\,\theta^*}{\partial\,\gamma\,n}<0$	$\frac{5}{12}$

$$p_G=1-\frac{d-c}{3}-\gamma\,n\quad,\qquad p_H=1+\frac{d-c}{3}+c-\gamma\,n$$

[1)] The SOC of (7), i.e. $2\left(q_H^*-q_G^*\right)-2\,\gamma\,n>0$ implies $\gamma\,n<1$.

If the environmental concern is very weak $\left(d-c=-1/2\right)$, the market share θ^* of firm 1 will be above $1/2$ irrespective of the network effect (column 2 in Tab.1). It can even be 1 if in addition the network effect is strong $\left(\gamma\,n=5/6\right)$. Then firm G will remain a monopoly producing energy inefficient $\left(q_G^*=0\right)$ products at low costs $\left(q_G^*\,c=0\right)$, i.e. without investment costs for improved energy efficiency. If the supporting network effect is weak, the market share declines towards $7/12$

and firm H can reach a market share up to $5/12$. Its products are costly $\left(q_H^* \; c = c\right)$, but environmentally concerned consumers find them attractive and the network is not an obstacle to buy them. We notice that in general a higher network effect favours that firm which had achieved a market share above $1/2$ even without such an effect. Network effects will strengthen the dominance of the successful firm. The more the *d*-effect dominates the *c*-effect, the smaller becomes the market share of firm G (column 3).

In case, the *d*-effect balances the *c*-effect (i.e. $d - c = 0$), then the two firms will share the market irrespective of the network effect (column 4). Consumers are indifferent between paying $p_G = 1 - \gamma \, n$ for the cheaper, energy inefficient product or $p_H = 1 + c - \gamma \, n$ for the more expensive but energy efficient one.

If the *d*-effect dominates the *c*-effect (i.e. $d - c = 1/2$), then the market share of firm G will be below $1/2$, irrespective of the network effect (column 6). The dominating *d*-effect operates in favour of firm H. It is supported by the network effect because market shares beyond $1/2$ raise the benefit of a network. If the network effect is high $\left(\gamma \, n = 5/6\right)$, firm G will be driven out of the market because competition forced it to charge a price $p_G^* = 0$ (for firm H it is $p_H^* = c + 1/3$). As the partial derivatives indicate, the market share θ^* decreases in $d - c$ (column 5). If environmental concern dominates the cost aspect $\left(d - c > 0\right)$, then the market share of firm G (it is less than $1/2$) declines with the network effect (column 5), but increases in it (the market share is greater than $1/2$), when environmental concern is very weak (column 3).

Table 2: Prices and profits under weak environmental concern

	$d-c=-\frac{1}{2}$	$d-c=0$	$d-c=\frac{1}{2}$
$\gamma \cdot n=\frac{5}{6}$	$p_G=\frac{1}{3},\ \pi_G=\frac{1}{3}n$ $p_H=c,\ \pi_H=0$	$p_G=\frac{1}{6},\quad \pi_G=\frac{1}{12}n$ $p_H=\frac{1}{6}+c,\ \pi_H=\frac{1}{12}n$	$p_G=0,\quad \pi_G=0$ $p_H=\frac{1}{3}+c,\ \pi_H=\frac{1}{3}n$

$$\frac{\partial\, p_i}{\partial(\gamma\, n)}<0,\quad \frac{\partial\, \pi_i}{\partial(\gamma\, n)}<0,\quad \frac{\partial\, p_G}{\partial(d-c)}<0,\quad \frac{\partial\, \pi_G}{\partial(d-c)}<0,\quad \frac{\partial\, p_H}{\partial(d-c)}>0,\quad \frac{\partial\, \pi_H}{\partial(d-c)}>0$$

In Table 2 we present the price and profit situation under the different environmental concerns and a network impact of $\gamma \cdot n = 5/6$ as discussed in Table 1. As we know from (9) and (10), a well developed network enforces price competition. Prices are highest if there is no network required $(\gamma=0)$. For each $d-c$, profits of both firms increase if the network effect becomes weaker ($\partial\, \pi_i/\partial(\gamma\, n)<0$). The worst case for firm G is a strong network effect ($\gamma\, n=5/6$) and environmental concern, dominating the cost aspect $(d-c=1/2)$. The intuition behind this result is that firm G has problems to attract customers for its less environmentally friendly product and hence does not have a high market share to get support from a strong network effect (its share is zero according to Tab. 1). The worst case for firm H is also a strong network effect in addition with a cost aspect that dominates environmental concern $(d-c=-1/2)$. The reason is that the high-cost firm H with the environmentally friendly product has problems to get support from the network effect if customers do not care much about the environment (now its market share is zero according to Tab. 1). If environmental concern increases, firm G lowers its price to prevent a decline in its market share ($\partial\, p_G/\partial(d-c)<0$), but firm H can increase its price because its product becomes more attractive ($\partial\, p_H/\partial(d-c)>0$).

Table 3: Strong environmental concern: $d-c\in\left[1/2\,,5/2\right]$				
$q_G^* = -\frac{1}{4} + \frac{d-c}{2}\,,\quad q_H^* = 1$				
	$d-c=1$	$d-c=2$	$d-c=5/2$	$d-c\in\left(1/2,5/2\right)$
	$q_G^* = 1/4$	$q_G^* = 3/4$	$q_G^* = 1$	$q_G^* \in \left(0,1\right)$
	values of θ^*			
$\gamma\, n = 9/16$	0	- [a]	$1/2$	$\frac{\partial\,\theta^*}{\partial\left(d-c\right)} < 0$ $\frac{\partial\,\theta^*}{\partial\left(\gamma\, n\right)} < 0$
$\gamma\, n = 0$	0.375	0.29	$1/2$	
[a] The SOC of (7) implies $\gamma\, n < 1/4$ for this case				

Table 3 presents the change in the market structure and in environmental quality when environmental concern becomes stronger. As in this case firm G's market share drops below $1/2$, it raises its environmental quality q_G^* and it even could match with $q_H^* = 1$ when $d-c \geq 5/2$. If environmental concern increases from $d-c = 1/2$ to $d-c=1$, firm G raises its quality q_G^* from 0 to $q_G^* = 1/4$ but will not gain a market share θ^* beyond $1/2$ (column 2 in Tab. 3).[16] If $\gamma\, n = 9/16$ and $d-c=1$, then $p_G^* = c/4 = c\, q_G^*$, i.e. price is equal to average cost. As $p_H^* > c = c\, q_H^*$ in that case, $\theta^* = 0$ is the final market structure. Since the market share does not exceed 0.375, a strong network effect finally leads to market exist of firm G. We again observe that a strong network effect works in favour of the dominant firm; this time it is firm H which has a market share above ½. Similarly, when $d-c=2$, firm G will raise its quality further (from $q_G^* = 1/4$ to $q_G^* = 3/4$), but will not gain a market share θ^* beyond 0.29 (column 3).[17] If $\gamma\, n$ increases, the market share will soon approach zero. We observe

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[16] Its market share would be larger than $1/2$ if $\gamma\, n > 3/4$, but the SOC of (7), $2\left(q_H^* - q_G^*\right) - 2\,\gamma\, n > 0$, implies $\gamma\, n < 3/4$.

[17] Its market share would be larger than $1/4$ if $\gamma\, n > 1/4$, but this violates the SOC of (7) which implies $\gamma\, n < 1/4$.

that when environmental concern increases, i.e. $d-c$, firm G raises its quality q_G^* but nevertheless loses market shares (i.e. $\frac{\partial\,\theta^*}{\partial\left(d-c\right)}<0$). Finally, the case presented in the 4th column of Table 3 implies that both firms choose $q_G^* = q_H^* = 1$. This would imply that they share the market and charge a price $p_G^* = p_H^* = c - \gamma\, n$ below unit cost. This market structure does not occur because both firms make a loss.[18]

Table 4: ***Prices and profits under strong environmental concern***			
	$d-c=1$	$d-c=\frac{5}{2}$	$d-c\in\left(\frac{1}{2},\frac{5}{2}\right)$
$\gamma\cdot n=\frac{9}{16}$	$p_G=\frac{c}{4}, \quad \pi_G=0$ $p_H=\frac{3}{8}+c, \pi_H=0{,}375n$	$p_i=c-\gamma\cdot n$ $\pi_i<0$ *SOC not fullfilled*	$\frac{\partial\,p_G}{\partial\left(d-c\right)}?$ $\quad \frac{\partial\,p_i}{\partial\left(\gamma\,n\right)}<0$ $\frac{\partial\,p_H}{\partial\left(d-c\right)}<0$ $\quad \frac{\partial\,\pi_i}{\partial\left(\gamma\,n\right)}<0$ $\frac{\partial\,\pi_i}{\partial\left(d-c\right)}<0$

Table 4 presents the price and profit situation which corresponds to the cases analysed in Table 3. As in Table 2, the profit situation for both firms improves if the network effect becomes less important because in that case price competition is weak and prices are high. Firm G responds to an increasing environmental concern by increasing its quality and hence has to raise its price. On the other side, the products become less heterogeneous and price competition will result in lower prices. If the cost effect of producing a higher q_G dominates the stronger price competition effect, then firm G might increase its price (see the last column in Tab. 4). As under weak environmental concern firm G sticks to $q_G^* = 0$, more environmental concern permits firm H to raise its price (see Table 2). The opposite is the case when firm G responds by increasing its quality q_G^*.

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[18] The SOC of (7) and (8), i.e. $2\left(q_H^* - q_G^*\right) - 2\,\gamma\,n > 0$, cannot be satisfied because of the restriction $\gamma \geq 0$.

2.3 Socially optimal position of environmentally friendly engines

We finally control whether the private choice of the characteristics q_G^* and q_H^* coincides with the socially optimal ones, preferred by an environmental authority. For that purpose we define social welfare as a function of q_G and q_H. It is equal to the aggregate willingness to pay minus cost of production. However, the authority's environmental concern, $\bar{d}$, may differ from the private damage parameter, *d*, which will be replaced by $\bar{d}$ in the welfare function. Therefore,

$$\begin{aligned} W(q_G,q_H) &= \int_0^{\bar{\theta}} \left[u-(q_G-\theta)^2-\bar{d}\cdot(1-q_G)+\gamma\cdot n\,\theta-c\,q_G\right]d\,\theta \\ &\quad+\int_{\bar{\theta}}^{1} \left[u-(q_H-\theta)^2-\bar{d}\cdot(1-q_H)+\gamma\cdot n\,\theta-c\,q_H\right]d\,\theta. \end{aligned} \tag{18}$$

The market share $\bar{\theta}$ separates the consumers with higher welfare from q_G from those with higher welfare from q_H:

$$u-\left(q_G-\bar{\theta}\right)^2-\bar{d}\,(1-q_G)+\gamma\,n\,\bar{\theta}-c\,q_G=u-\left(q_H-\bar{\theta}\right)^2-\bar{d}\,(1-q_H)+\gamma\,n\,\bar{\theta}-c\,q_H\,.$$

This condition yields

$$\bar{\theta}=\frac{1}{2}\left(q_G+q_H-d+c\right). \tag{19}$$

For maximizing welfare in (18) with respect to q_G and q_H, we first integrate *W* with respect to θ, and then we set the partial derivatives of $W(q_G,q_H)$ equal to zero. Solving the two FOCs for q_G and q_H yields the characteristics which maximize social welfare:[19]

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[19] The proof will be sent on request to the interested reader by mail or e-mail.

(20) $$\hat{q}_G = \frac{\bar{d}-d}{2} + \frac{d-c}{2} + \frac{1}{4} \quad , \qquad \hat{q}_H = \frac{\bar{d}-d}{2} + \frac{d-c}{2} + \frac{3}{4} .$$

The optimal characteristics consist of two terms. The first term suggests a bias towards the environmentally more friendly engine if social environmental concern exceeds private environmental concern (i.e. $\bar{d}-d>0$). The second term takes into account costs and private environmental awareness and adjusts the position of the socially optimal characteristics $1/4$ and $3/4$, obtained in the standard model ($\bar{d}=d=c=0$).[20]

Our next step is to compare the Nash-equilibrium in characteristics, q_i^* in (17), with the socially optimal ones, $\hat{q}_i$ in (20). Since we found out that firm H will only stick to $q_H^*=1$ if $d-c \geq -1/2$, we will assume that the authority is also interested that firm H chooses $q_H^*=1$; that is we assume $\bar{d}-d \geq 1$ for the case of weak environmental concern, i.e. for $d-c \in [-1/2, 1/2]$. Therefore $q_H^* = \hat{q}_H = 1$ under weak environmental concern by the consumers but strong environmental concern by the regulator $(\bar{d}-d \geq 1)$. In that case it is $q_G^*=0$ but $\hat{q}_G>0$. In order to achieve that q_G^* is equal to $\hat{q}_G$, we have to introduce a policy parameter as an incentive for firm G to produce $\hat{q}_G$. One possibility is to set $\bar{c}=c-s$ where s could be a subsidy $(s>0)$ or a tax $(s<0)$ on the unit cost of production. We are interested in finding a value of s such that $q_s^*(s)=\hat{q}_G$, i.e.

(21) $$q_G^*(s) = -\frac{1}{4} + \frac{d-(c-s)}{2} = \frac{\bar{d}-d}{2} + \frac{d-c}{2} + \frac{1}{4} = \hat{q}_G .$$

This condition is satisfied for

(22) $$s = \bar{d} - d + 1$$

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[20] Inserting $\hat{q}_i$ in (20) into $\bar{\theta}$ in (19) yields $\bar{\theta}=1/2$ for the location of the indifferent consumer.

i.e. *s* is positive and a subsidy for the firm if it raises the energy efficiency of its engines from $q_G^* = 0$ to $q_G^*(s) = \hat{q}_G > 0$. The subsidy has two effects; it corrects environmental misperception (the $\bar{d} - d$ term) and market imperfection (the second term). Firm H benefits from this policy too because it also gets the subsidy but produces already the hydrogen powered engine.

An alternative policy to raise q_G^* could be a campaign to enhance environmental awareness, *d*, of the consumers by δ (advertising, TV spots, etc.). The equivalent condition to (21) is

$$q_G^*(\delta) = -\frac{1}{4} + \frac{d + \delta - c}{2} = \bar{d} - d + \frac{d - c}{2} + \frac{1}{4} = \hat{q}_G .$$

The size of the required impact on environmental awareness is a δ which is equal to *s* in (22).

Let us finally consider the case of strong environmental concern, i.e. $d - c \in [1/2, 5/2]$. Since the authority is interested in hydrogen powered engines, i.e. $\hat{q}_H = 1$, it is $\hat{q}_H = 1$ in (20) if $\bar{d} - d \geq 1/2 - (d - c)$; i.e. $\bar{d} - d \geq -2$. From q_G^* in (17) and $\hat{q}_G$ in (20) it is easy to see that

$$\begin{array}{lll} q_G^* = \hat{q}_G & \text{if} & \bar{d} - d = -1 \\ q_G^* < \hat{q}_G & \text{if} & \bar{d} - d > -1 \\ q_G^* > \hat{q}_G & \text{if} & \bar{d} - d < -1. \end{array}$$

Therefore in the first case no policy parameter is required to adjust the private decision with respect to q_G and q_H. In the second case a subsidy is required to raise q_G^*, because $s = \bar{d} - d + 1$ in (22) is positive as $\bar{d} - d > -1$. In the third case *s* is negative and a tax as $d - c < -1$. We conclude that it is possible for the regulator to give incentives such that the private choice of the type of engine coincides with the regulator's goal.

3. A dynamic model with investment in compatibility

In this section we continue to investigate the relationship between an incumbent firm and an entrant and focus now on the non-compatibility of filling stations to the new technology. The two competing firms have chosen already simultaneously and independently from each other their technology and we assume that their locations are at either end on the unit interval. We model a repeated two stage game where in a first stage firm *H* invests in the network while firm *G* does not need to invest into the existing network as it already is compatible. In a second stage both firms compete in prices. In this dynamic setting the prices are the control variables and the size of the network is the stock variable. We are interested to see whether the entrant can overcome the look-in effect and can conquer market shares.

Papers focusing also on compatibility decisions of oligopolistic firms where network externality interact with other quality dimensions, which the firms can control, are Belleflamme (1998), Bental and Spiegel (1995), de Palma and Leruth (1996) and Baake and Boom (2001). The example, given in papers for network externality and incompatibility are personal computers with different qualities using the same operating system and having the same network externality from sharing the same pool of available software products. Compatibility can be achieved by an adapter. With an adapter, the network size comprises the consumers of both products. The endogenous adapter decision is similar to our network of gasoline stations where after their remodeling (adapter), the network can be used by both engines.

3.1 Network effect and compatibility

In the first stage of our non-cooperative repeated game the incumbent trusts on the lock-in effect and on his well-extended network whereas the sponsor has to invest in compatibility to remodel the gas-stations. Since this increases the entrant's cost, he needs support for his costly investment by environmental concern in the society and by a steadily raising gasoline price. In the second stage of the game firms compete in prices taking into account the size of their installed base. Compatibility of the new product with the installed base of the incumbent is not a meaningful strategy for the producer of an engine as it is for a PC producer offering IBM compatible PCs which can use the standard software.[21] In our model the entrant has to invest money in remodeling the existing network to make it compatible to hydrogen powered cars.

The net-utility of consumer θ, who buys a unit of good *G* in period *t*, indexed in five-year intervals, is:[22]

$$v_G(\theta) = u - \tau \cdot \theta^2 - p_G + \gamma\, n_G - \alpha_G\, f_G \,. \tag{23}$$

The net-utility of consumer θ, who buys a unit of good *H* in period *t* is:

$$v_H(\theta) = u - \tau(1-\theta)^2 - p_H + \gamma\, n_H - \alpha_H\, f_H \,. \tag{24}$$

By assumption, firm *G* produces at zero on the 0–1 Hotelling line, and firm *H* at one. The locations are fixed, i.e. the firms produce either gasoline powered cars or hydrogen powered cars (no bi-fuel engine). The meaning of the variables is $\tau \cdot \theta^2$ for transportation costs, n_i for the size of network *i*, $i = G, H$, f_G for the current gasoline price (*f* for fuel), f_H for the price for hydrogen fuel (backstop technology), and α_G, α_H are consumption coefficients, expressing quantity aspects and environmental concern $(\alpha_G > \alpha_H)$. The main characteristic of the consumer is environmental concern, which is the reason for the different willingness to pay. Some consumers consider gasoline powered cars as environmentally unfriendly, while others do not care about an environmentally friendly technology like fuel cells. The difference of the net-utilities in (23) and (24) shows the possibilities, firms have to attract customers:

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[21] See Pfähler and Wiese (1998) for a game in the degrees of compatibility. For a survey on compatibility and network effects see Wiese (1997).

[22] We consider only those consumers who buy a car every five years. This is the target group for the automobile producers. We assume that owners of cars older than five years will buy used cars older than five years when replacing their cars.

$$\underbrace{v_G(\theta)-v_H(\theta)}_{\text{difference in utility}} = \underbrace{p_H - p_G}_{\text{price effect}} + \underbrace{2\,\tau\left(1/2-\theta\right)}_{\text{product differentiation}} + \underbrace{\gamma\left(n_G - n_H\right)}_{\text{network effect}} + \underbrace{\alpha_H\; f_H - \alpha_G\; f_G}_{\text{fuel price and environmental concern}}$$

Favorable for the incumbent is a higher price of the entrant, its product differentiation in terms of attracting consumers to the left of $1/2$ on the [0,1] line, a larger network effect, and a relatively high price for hydrogen and a relatively low environmental concern (α_H relative to α_G).[23]

Next, we define the size of the network in its general form in terms of a share as:

$$(25) \qquad \underbrace{n_i = \theta_i^e}_{\text{direct}} \quad + \quad \underbrace{\frac{IB_i}{IB_G + IB_H}}_{\text{indirect}} \quad + \quad \underbrace{s_i\left(IB_i\right)\left(\theta_j^e + \frac{IB_j}{IB_G + IB_H}\right)}_{\text{compatibility}}$$

where θ_i^e is the expected market share of cars of type *i*, IB_i is the installed base and $s_i\left(IB_i\right)$ is the degree of compatibility of network $j \neq i$ for network *i*. The higher s_i, the more enforces the network size of firm *j* the network size of firm *i*. IB_G are the gas stations with gasoline pumps only, IB_H are the remodeled gasoline stations, i.e. those with pumps for gasoline as well as for hydrogen (natural gas, etc.). The sum of the gas stations, $SIB = IB_G + IB_H$, is constant, i.e. new gas stations will not be built, only existing gas stations IB_G will be remodeled to become compatible.

We will simplify (25) by first neglecting the direct effect, i.e. the expected market share of cars. Consumers will not expect a better network for *H*-cars because they see more *H*-cars on the road, i.e. $\theta_i^e = 0, i = G, H$. Since firm *G* does not need any gas stations that have been remodeled to also sell hydrogen, the degree of compatibility of the *H*-stations for its network equals one, i.e. $s_G\left(IB_G\right) = 1$. From the point of view of firm *G* the total network *SIB* is compatible for gasoline cars, that is, the entire installed base contributes to firm *G*'s network size, regardless whether the gas

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[23] Horizontal product differentiation implies that the difference in utility should be negative for consumer θ close to 1 and positive for consumer θ close to zero if $p_H = p_G$. This property requires $\gamma\left(n_G - n_H\right) + \alpha_H\; f_H - \alpha_G\; f_G < \tau$.

stations sell gasoline only or gasoline as well as hydrogen. Therefore, (25) simplifies to $n_G = 1$. For firm *H*, the portion of the installed base in the network size in (25) is the portion of gas stations remodeled in the past to also sell hydrogen. (2. term in (25)). Firm *H* invests in the installed base IB_H in order to increase the compatibility of gas stations with hydrogen; i.e. $s_H\left(IB_H\right) > 0$ and $s'_H > 0$. A higher s_H means that a higher portion of former non-compatible *G*-stations can now be made compatible. Therefore, if we normalize *SIB* to one for convenience, (25) will become:

(26) $$n_H = IB_H + s_H\left(IB_H\right) \cdot IB_G .$$

If $s_H = 1$, then follows $n_H = 1$ analogously to $n_G = 1$.[24] A degree of compatibility of $s_H = 1$ means that all former *G*-stations ($IB_G\left(0\right)$ at the beginning) have been remodeled as $G + H$ stations.[25]

From $v_G\left(\theta\right) = v_H\left(1-\theta\right)$, we can solve for the indifferent consumer, $\tilde{\theta}$:

(27) $$\tilde{\theta} = \frac{1}{2\,\tau}\left[\tau + p_H - p_G - \gamma\left(-1 + IB_H + s_H\ IB_G\right) - \alpha_G\ f_G + \alpha_H\ f_H\right].$$

Since all consumers θ with $\theta < \tilde{\theta}$ buy good *G*, the demand function of firm *G* is $x_G\left(p_G, p_H, IB_G, IB_H\right) = \tilde{\theta}$. Because of $x_G + x_H = 1$, the demand function of firm *H* is

(28) $$x_H\left(p_G, p_H, IB_G, IB_H\right) = \frac{1}{2\,\tau}\left[\tau + p_G - p_H + \gamma\left(-1 + IB_H + s_H\ IB_G\right) + \alpha_G\ f_G - \alpha_H\ f_H\right]$$

Firm *G* maximizes profit with respect to price:

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[24] One should consider that the number of $IB_G{}'s$, the gas stations not yet remodeled, declines over time when IB_H increases. If all $IB_G{}'s$ have been remodeled, it is $IB_G = 0$ and $n_H = IB_H$.

[25] A specification for $s_H\left(IB_H\right)$ could be $s_H\left(IB_H\right) = IB_H$ or $s_H\left(IB_H\right) = a \cdot IB_H + \left(1-a\right)IB_H^2$. In both cases is $s_H = 0$ for $IB_H = 0$ and $s_H = 1$ for $IB_H = SIB = 1$.

$$\max_{p_G} \ \pi_G = \left(p_G - c_G\right) \cdot x_G \left(p_G, p_H, IB_G, IB_H\right).$$

Since firm *G* does not need to invest in compatibility, its maximization problem is not an intertemporal one but is the same in each period, given price p_H and its installed base SIB. Firm *H* maximizes profit with respect to price and to investment in compatibility:

$$\max_{p_H, I_H} \quad \pi_H = \int_0^T e^{-rt} \left\{ \left(p_H - c_H\right) \cdot x_H \left(p_G, p_H, IB_G, IB_H\right) - C\left(I_H\right) \right\} dt$$

s.t. $\dot{IB}_H = I_H$ with $IB_G = 1 - IB_H$ and *r* as the discount rate. We assume that the remodeling department operates under decreasing returns to scale.[26] This is a realistic assumption because firm *H* needs special equipment and specially trained workers which it can not use anymore after remodeling is finished.

Next we simplify (27) and (28) by defining:

(29) $$\Delta n^{IB} := 1 - IB_H - s_H \ IB_G$$

(30) $$\Delta f := \frac{\left(\alpha_H \ f_H - \alpha_G \ f_G\right)}{\gamma}.$$

Then the market shares are[27]:

(27') $$x_G = \frac{1}{2} + \frac{1}{2\tau} \left[p_H - p_G + \gamma \left(\Delta n^{IB} + \Delta f \right) \right]$$

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[26] If e.g. $C\left(I_H\right) = \delta \ I_H^2$, this implies that marginal investment costs increases with the number of investment projects, I_H, of remodeling existing gasoline stations.

[27] See Pfähler and Wiese (1998) for a model with network effects, installed bases and competition in prices and degrees of compatibilities (Chapter L).

(28’) $$x_H = \frac{1}{2} - \frac{1}{2\tau}\left[p_H - p_G + \gamma\left(\Delta n^{IB} + \Delta f \right)\right].$$

The firm has a “natural share of customers” of $1/2$. If prices are identical and there is no network effect, then demand is equal to this natural share of customers. If $p_G < p_H$, then more customers purchase good *G* not because of the nearness to their preferences but because of the favorable price.

Under profit maximization, the FOCs with respect to p_G and p_H lead to a Nash equilibrium of the simultaneous price competition in every period *t*:

(31) $$p_G^N(t) = \frac{1}{3}\left[c_H + 2\,c_G + 3\tau + \gamma\left(\Delta n^{IB}(t) + \Delta f(t)\right)\right]$$

(32) $$p_H^N(t) = \frac{1}{3}\left[c_G + 2\,c_H + 3\tau - \gamma\left(\Delta n^{IB}(t) + \Delta f(t)\right)\right].$$

Inserting (31) and (32) in (27’) and (28’) results in the market shares $x_G^N\left(IB_H, f_H, f_G\right)$ and $1 - x_G^N = x_H^N$:

(33) $$x_G^N(t) = \frac{1}{2} + \frac{1}{6\,\tau}\left[c_H - c_G + \gamma\left(\Delta n^{IB}(t) + \Delta f(t)\right)\right]$$

(34) $$x_H^N(t) = \frac{1}{2} - \frac{1}{6\,\tau}\left[c_H - c_G + \gamma\left(\Delta n^{IB}(t) + \Delta f(t)\right)\right].$$

There is a sequence of Nash equilibria over time which firm *H* can influence in its favor by investing in compatibility, $I_H(t)$, to raise its installed base, $IB_H(t)$. The main motivation for the sponsor is its perfect information on the increasing price path $f_G(t)$ of gasoline. We assume that it increases over time according to the Hotelling price rule of a resource, i.e. $f_G(0)\, e^{rt}$ where *r* is the discount rate. It means that for an oil company to be indifferent between extracting the resource in the current period and a future period, the price must rise at the discount rate. An optimal exploitation path for crude oil is based on this Hotelling price rule.

Profit for firm *H* is:

$$\pi_H\left(I_H, IB_H, \Delta\, f\right) = \left[\, p_H^N\left(IB_H\left(t\right), \Delta\, f\left(t\right)\right) - c_H \,\right] \cdot x_H^N\left(t\right) - C\left(I_H\left(t\right)\right)$$

where $IB_G\left(t\right)$ has been replaced by $IB_G\left(t\right) = 1 - IB_H\left(t\right)$. With a fixed price of the backstop technology, f_H, the difference in the cost of the two complementary fuels declines over time according to (30).

The intertemporal problem of firm *H* is then to control the outcome on the path of Nash equilibria by choosing an optimal investment path $IH\left(t\right)$:

(35) $$\max_{I_H} \int_0^T e^{-rt}\, \pi_H\left(I_H, IB_H, \Delta\, f\right) dt \qquad \text{s.t. } \dot{IB}_H = I_H\,.$$

The Hamilton function for (35) is $H = \pi_H(\quad) + \mu \cdot I_H$ and the maximum principle yields

(36) $$H_{I_H} = \frac{\partial\, \pi_H}{\partial\, I_H} + \mu = 0\,.$$

The portfolio balance condition for μ is:

(37) $$\dot{\mu} = r\mu - H_{IB_H} = r\mu - \pi_{IB_H}\,.$$

I_H is the control variable, IB_H the state variable and μ is the co-state variable or shadow value of the installed base.

3.2 The price path of oil, the price of the backstop technology, and the exhaustion of oil

If the oil resource is exhausted in *T*, $f_G(T)$ must be equal to the price of the backstop-technology hydrogen, i.e. $f_H = f_G\left(0\right)e^{rT} = f_G\left(T\right)$, and no consumer buys from firm *G* anymore. In that case, x_G should be zero and there are only cars run by hydrogen; investment in IB_H should be finished by then. For such a steady state in *T* it is $\dot{IB}_H = 0$, i.e. $I_H(T) = 0$, and $\dot{\mu} = 0$, i.e. $\mu(T) = \frac{1}{r}\pi_{IB_H}$. Prior to *T*, the time path of the solutions $I_H\ (t)$ and $IB_H\ (t)$ are functions of f_H and $f_G\ (t)$,

$$(38) \qquad I_H\left(t\right) = I_H\left(f_H, f_G(t)\right) \quad , \qquad IB_H\left(t\right) = IB_H\left(f_H, f_G(t)\right).$$

The firms need to know the values of f_H, $f_G\left(0\right)$ and *T*. The price f_H of the backstop technology is defined such that the market share of the old technology is zero when the price of its complementary good gasoline, $f_G\ (T)$, reaches f_H, i.e. $x_G\left(f_H, f_G\left(0\right)e^{rT}\right) = 0$. That means that firm *H* must know the price path of gasoline, $f_G(t)$. Under complete information, however, it knows the strategy of the oil industry, which, under profit maximizing behavior, will have exploited its oil field exactly then, when the market share for cars run by gas has reached zero. That means that at time *T*, the oil price must have reached the level f_H, meaning the highest possible price when the oil field is exploited afterwards. Therefore, $f_G(T)$ at $x_G = 0$ must be equal to the price of the backstop technology,

$$(39) \qquad f_H = f_G\left(0\right)e^{rT} = f_G\left(T\right).$$

Once we have derived $f_G(T)$ from the condition $x_G\left(f_H, f_G(0)e^{rT}\right)=0$, assuming $f_G(T)=f_H$, its solution $f_G(T)=f\left(c_H, c_G, \alpha_H, \alpha_G\right)$ defines by (39) the price of the backstop technology.

3.3 The dynamic structure of the game

In every period there is a compatibility decision by means of I_H, where we have assumed that firm *G* need not to invest in compatibility, because the sponsor (firm *H*) has to remodel the existing installed base which is compatible for gasoline powered cars anyhow. Knowing the Nash price equilibria, depending on IH_H and IB_H, firm *H* can determine an optimal path for its compatibility decision. Before we prove our results, we characterize in Table 5 three points in time with their corresponding values of the variables. Depending on the price of the backstop technology, a steady state could be reached at a time T^*, prior to *T*, with all gasoline stations remodeled[28] and the firms share the market. The middle part of Table 5 characterizes this situation. After a while (at *T*), the gasoline price has reached the price of the backstop technology and environmentally friendly hydrogen powered cars become more attractive to the consumers. This outcome is characterized in the lower part of Table 5.

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[28] We will prove in the next section, that in a steady state $IB_G=0$, i.e. there are no gas-stations anymore which serve only gasoline.

$t < T^*$: firm *H* invests in compatibility				
$IB_G(t) > 0$:	$s_G = 1$	$I_G = 0$	$p_G(t)$	$\pi_G > 0$
$IB_H(t) > 0$:	$s_H\left(IB_H\right) > 0$	$I_H(t) > 0$	$p_H(t)$	π_H ?
$f_G(t) < f_H$		$\swarrow \quad \searrow$	$x_G(t) > 0$,	$x_H(t) > 0$
	$s_H\left(IB_H\left(t+1\right)\right)$	$\dot{IB}_H\left(t+1\right)$		
$t = T^*$: full compatibility; both firms share the market				
$IB_G(T^*) = 0$:	$s_G = 1$	$I_G = 0$	$p_G(T^*) > c_G$	$\pi_G > 0$
$IB_H(T^*) = SIB = 1$	$s_H\left(SIB\right) = 1$	$I_H(T^*) = 0$	$p_H(T^*) > c_H$	$\pi_H > 0$
$f_G(T^*) < f_H$			$x_G(T^*) > 0$,	$x_H(T^*) > 0$
$t = T > T^*$: oil price reaches the price q_H; market exit of firm *G*				
$IB_G(T) = 0$:	$s_G = 1$	$I_G = 0$	$p_G(T) = c_G$	$\pi_G = 0$
$IB_H(T) = SIB = 1$	$s_H\left(SIB\right) = 1$	$I_H(T) = 0$	$p_H(T) > c_H$	$\pi_H > 0$
$f_G(T) = f_H$			$x_G(T) = 0$,	$x_H(T) = 1$

Table 5: Steady state periods with crude oil $\left(T\right)$ and without $\left(T^*\right)$.

We continue by examining the point in time *T* where the oil resource is exhausted. For that purpose we (i) need a resource constraint, (ii) a price of gasoline $f_G(0)\,e^{rT}$ where $x_G = 0$, and (iii) the Hotelling path satisfying $f_H = f_G\left(0\right)e^{rT}$. These three conditions permit us to determine T, f_H, and $f_G\left(0\right)$. If a steady state occurs in *T*, it is $I_H(T) = 0$ and therefore $C\left(I_H\right) = 0$. For the installed base we assume that in *T*: $IB_G = 0$ (The proof will follow later). Then $\Delta\, n^{IB} = 0$ in (29). For $\Delta\, f$ follows according to (30):

(40) $$\Delta f = f_H \frac{(\alpha_H - \alpha_G)}{\gamma}.$$

Using these results we obtain from (33) with $x_G^N = 0$

(41) $$f_G(0)\, e^{rT} = \frac{3\tau + (c_H - c_G)}{\alpha_G - \alpha_H}.$$

We assume that $\alpha_G > \alpha_H$, i.e. if prices f_H and $f_G\, e^{rT}$ are equal, the α_G-effect of cars run by gasoline has a stronger negative effect on utility v_i in (23) and (24) than the environmentally friendly α_H -effect. This is how we consider the negative externality of fossil fuels in the utility function. If τ in (41) is high (strong preferences for the good at either end of the product line), the demand for cars run by gasoline will be zero only when the gasoline price has reached a high level $f_G(T)$. If $\alpha_G - \alpha_H$ is high (strong negative externality of cars run by gasoline), the demand for gasoline cars will be zero already when the gasoline price has reached a relatively low level $f_G(T)$. Condition (41) can be used to solve for $f_G(0)$ as a function of *T*. Now only a value for *T* is needed. This value can be determined from the finiteness of the resource crude oil given the value of $f_G(0)$, i.e.

(42) $$\int_0^T \rho \cdot x_G\left(IB_H(t),\, f_G(0)\, e^{rt}\right) dt = S_0$$

where S_0 is the initial oil stock and ρ is a coefficient which transforms the portion of cars run by gasoline into gasoline consumption. Here we must bear in mind that (41) and (42) form a simultaneous system for the determination of *T* and $q_G(0)$. Figure 1 clarifies our considerations. The shaded area represents the initial stock of oil. It is exactly exhausted at the same time (*T*) when the price of oil reaches the price of the industrial substitute.

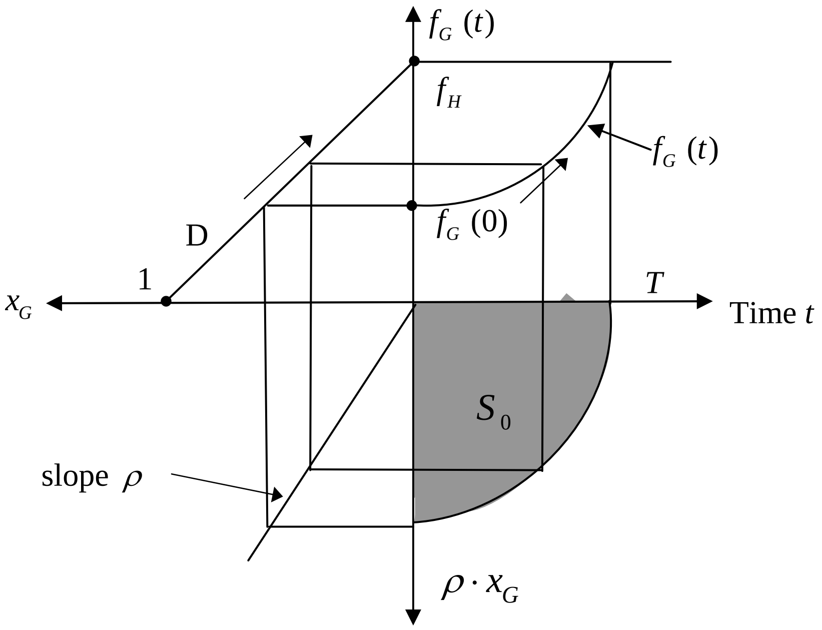

Fig. 1: Market share x_G of firm *G* and oil extraction $\rho \cdot x_G$ until the gasoline price f_G approaches the price of the backstop technology, f_H .

3.4 Analysis of the steady state

The open questions we haven't answered yet are (i) whether the sponsor will invest in compatibility $\left(I_H(t) > 0 \right)$ although he will bear a loss in the first periods, and (ii) whether he will invest until full compatibility is reached $\left(IB_H = SIB \right)$, i.e. all gas stations provide hydrogen. For that purpose we first write the profit function in the variables $I_H, IB_H, \Delta f$ by using the prices and market shares in (31) to (34):

$$\pi_G = \frac{1}{18\,\tau}\left[3\,\tau - \left(c_G - c_H\right) + \gamma\left(\Delta\, n^{IB} + \Delta\, f\right)\right]^2 \tag{43}$$

$$\pi_H = \frac{1}{18\,\tau}\left[3\,\tau + \left(c_G - c_H\right) - \gamma\left(\Delta\, n^{IB} + \Delta\, f\right)\right]^2 - C\left(I_H\right). \tag{44}$$

It is

(45) $$\frac{\partial \pi_H}{\partial I_H} = -C'\left(I_H\right) < 0,$$

i.e. in each particular period remodeling I_H gas stations reduces profit. The positive effect will come later once the compatibility is established. To determine the size of the installed base IB_H^* in the steady state, we have to solve $\frac{\partial \pi_H}{\partial IB_H} = 0$ for IB_H^*.[29] As shown in the appendix, it is $IB_H^* = 1$ and $s_H\left(IB_H^*\right) = 1$. All gas stations in the steady state provide gasoline as well as natural gas, and firm *H* has invested in the network of gasoline stations to achieve full compatibility.

In Table 5 we distinguished two periods of a steady state. There is a time period T^* where a steady state is reached but the path of the gasoline price is still below f_H; i.e. $f_H > f_G\left(0\right)e^{rt}$ for $T^* \le t \le T$. In period T, we assumed that $f_H = f_G\left(0\right)e^{rT}$ and oil is exhausted. This then implies a steady state with $x_G = 0$ and permits to solve for $f_G\left(0\right), T$ and f_H. Figure 2 shows the situation where a steady state is reached but the exploited stock of oil S^* is still below the proven reserves S_0.

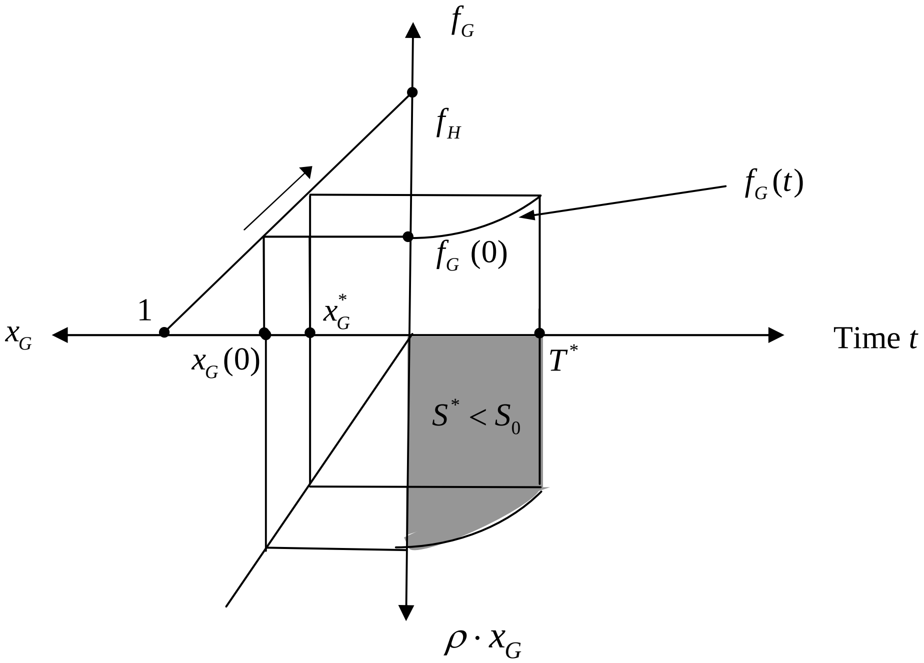

Fig. 2: A steady state is reached (full compatibility) before the stock of proven oil reserves is exhausted.

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[29] It is $\dot{\mu} = \mu = 0$ in (37) for the steady state. See the appendix for a proof of $IB_H^* = 1$.

In the steady state with oil still available $\left(I_H^*(t)=0\,, IB_H^*(t)=1, IB_G^*(t)=0\right.$ and $\Delta n^{IB}=0$ for $\left.T^*\leq t<T\right)$, the market shares follow from (33) and (34)

$$x_G^*(t)=\frac{1}{2}+\frac{1}{6\tau}\left[c_H-c_G+\alpha_H\ f_H-\alpha_G\ f_G(t)\right],$$

$$x_H^*(t)=\frac{1}{2}-\frac{1}{6\tau}\left[c_H-c_G+\alpha_H\ f_H-\alpha_G\ f_G(t)\right] \quad \text{for} \quad T^*\leq t<T.$$

$x_G^*\left(t\right)$ declines in $f_G(t)$ and hence $x_H^*(t)$ increases until $t=T$. Prices are

$$p_G^*\left(t\right)=\frac{1}{3}\left[\left(c_H+2\,c_G\right)+3\tau+\alpha_H\ f_H-\alpha_G\ f_G(t)\right],$$

$$p_H^*\left(t\right)=\frac{1}{3}\left[\left(c_G+2\,c_H\right)+3\tau-\alpha_H\ f_H+\alpha_G\ f_G(t)\right] \quad \text{for} \quad T^*\leq t<T.$$

$p_G^*\ (t)$ declines in $f_G(t)$ and $p_H^*\ (t)$ increases in $f_G(t)$ until $t=T$ is reached. Profits are

$$\pi_G^*(t)=\frac{1}{18\,\tau}\left[3\tau+\left(\alpha_H\ f_H-\alpha_G\ f_G(t)\right)\right]^2, \qquad \pi_H^*(t)=\frac{1}{18\,\tau}\left[3\tau-\left(\alpha_H\ f_H-\alpha_G\ f_G(t)\right)\right]^2$$

with $\pi_G^*(t)$ declining in $f_G(t)$ and $\pi_H^*(t)$ increasing in $f_G(t)$ for $T^*\leq t<T$.

In $T\left(\geq T^*\right)$ we assume that the gasoline price has reached the price of the backstop technology, i.e. $f_H=f_G\left(0\right)e^{rT}$. For a backstop technology, the demand for the former substitute is zero ($x_G^*=0$), hence $f_G(T)$ as in (41). The prices are $p_G=c_G$, $p_H=c_H+2\tau$ and profits are $\pi_G=0$, $\pi_H=2\,\tau$. T follows from (42), i.e.

$$\rho \int_{0}^{T^*} x_G(t)\,dt + \rho \int_{T^*}^{T} x_G(t)\,dt = S_0$$

With $T\left(f_G(0)\right)$ as solution from this resource availability restriction, we obtain $f_G(0)$ from (41).

We finally can do a phase diagram analysis in order to evaluate the slopes of the equations of motion near the steady state. For that purpose we choose $\dot{I}_H$ and $\dot{IB}_H$ as our two equations of motion.[30] The dynamics of IB_H and I_H around the steady state is presented in Figure 3.

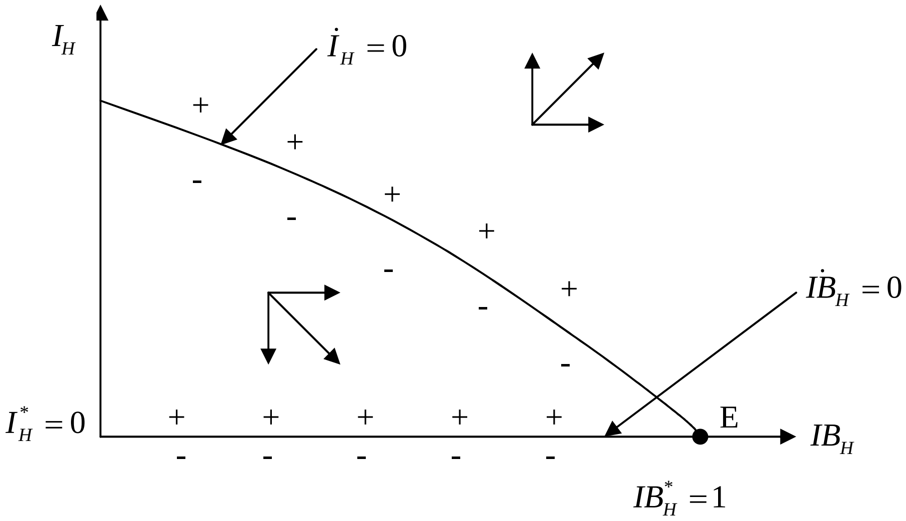

Fig. 3: The dynamics towards the steady state *E*.

As shown in Fig. 3, the control variable I_H is used to guide IB_H from $IB_H(0)=0$ to $IB_H^* = 1$ (solved for) in an optimal way.

4. Conclusion

The existence of network effects plays a crucial role because it can (i) impede the creation of a market, (ii) impede market entrance and (iii) provide market power to the incumbent firm. We considered two

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[30] For details see an Appendix, which will be sent on request by e-mail.

automobile producers producing horizontally differentiated products which are non-compatible with respect to the network which provides a complementary good, fuel. In our static model the size of the network was exogenous but location in terms of energy efficiency was endogenous. The result of our analysis was that the equilibrium of this two stage game could be one with either the incumbent firm as the only producer, or one with the innovative firm as the only producer, or one where both firms share the market. Which equilibrium will emerge depends on the cost of production and on environmental awareness of the consumers. The latter aspect has been introduced to give the innovative firm a chance to stay in the market.

In the first stage of our two-stage game the firms decide on the degree of product differentiation in terms of fuel efficiency. In the standard model of this type, firms choose the end points of the Hotelling 0-1 line. That need not be the case in our model. Now it depends on environmental awareness and the cost of producing energy efficient engines, which type of car will be produced. Optimal product differentiation will not be affected by the network effect; this effect exerts an impact on price competition, the game at the second stage. The higher the strength of the network effect, the lower will be the equilibrium prices. A strong network effect enforces competition and hence profits will be low. The more environmental concern dominates the cost aspect, the higher will be the share of the entrant producing the new technology. If the network effect is very weak, both firms are in the market. If it is strong, only one firm serves the market – either the conventional producer (very weak environmental concern) or the innovative producer (some environmental concern). If environmental concern becomes stronger, firm G approaches energy efficiency of 1, i.e. the quality choice of firm H. We finally determine a socially optimal allocation of the characteristics by maximizing a social welfare function with respect to the two characteristics. The result was that even if private and public environmental awareness coincide, the regulator wishes a more energy efficient engine (a higher q_G) than a private firm develops. By choosing an appropriate subsidy on costs it is however possible that firm G produces a car with a socially optimal energy efficiency.

Our dynamic model has shown that there need not be a market failure if a new technology lacks a network. Although profit π_H of the entrant will decline in I_H in each period, π_H will at the same time increase in IB_H in each period. If the network effect γ is strong enough, then even in the short run the positive effect from $\frac{\partial \pi_H}{\partial IB_H} > 0$ contributes more to profit than the negative effect from $\frac{\partial \pi_H}{\partial I_H} < 0$ reduces profit.[31] Second, our model has pointed out the crucial role of the price path of gasoline and of the price of the backstop technology on network size and price competition. Especially the price path of gasoline forces the incumbent to lower its price p_G and permits the entrant at the same time to raise his price. Nevertheless, the incumbent will lose market shares and the entrant will benefit from that. If the costs of remodeling the installed base IB_G are high, then there could be market failure although the Hotelling price path of oil might help him to make positive profit after some years (note that in (44) $\Delta f > 0$ decline in *t*). According to $\pi_H(1)$ from (44), firm *H* will make a loss in the first period[32] if (*i*) the investment costs for achieving compatibility are high, (*ii*) the network effect $\gamma \cdot \Delta n^{IB}$ is high, (*iii*) unit cost c_H are much higher than c_G, or (*iv*) the price of hydrogen is relatively high (Δf is large). In such a case the government could pay a subsidy such that $\pi_H(1) = 0$ in the first period. As Δf declines in *t* and Δn^{IB} declines in I_H, the loss situation improves from period to period. If there is no subsidy program, cooperative policy between the car producers, the energy companies and the government is required to prevent a situation where the society runs out of oil and huge investment costs emerge all of a sudden to remodel gasoline stations as well as automobile engines. In view of the exhaustion of crude oil within the next decades, the investment in compatibility of existing gasoline stations should be a profit maximizing strategy for the motor vehicle industry.

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[31] For a proof, the difference between the two partial derivatives has to be calculated

[32] That is if $3\tau + (c_G - c_H) - \gamma\left(\Delta n^{IB}(1) + \Delta f(1)\right) < 3\sqrt{C\left(I_H(1)\right) \cdot 2\tau}$.

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Proof of $IB_H^* = 1$

The maximum principle postulates according to (36):

(A7) $$\frac{\partial H}{\partial I_H} = \frac{\partial \pi_H}{\partial I_H} + \mu = 0 .$$

As the installed base changes by $\dot{IB}_H = I_H$, it is $I_H\left(T\right) = 0$ in the steady state (period T). With $C'\left(I_H\right) = 0$ at $I_H\ (T) = 0$,[33] it is $\frac{\partial \pi_H\left(T\right)}{\partial I_H} = 0$ (see (44)); therefore $\mu\left(T\right) = 0$ from (36). Hence (see (37)), we have to solve the equation $\frac{\partial \pi_{IB_H}}{\partial IB_H} = 0$ in order to determine $IB_H\left(T\right)$. According to (44) and (29) we obtain

(A8) $$\frac{\partial \pi_H}{\partial IB_H} = \frac{1}{18\tau} \cdot 2\left[\cdot\right]\left(-\gamma \cdot \left(-1 - s'_H\ IB_G + s_H\right)\right) = 0$$

where $IB_G = 1 - IB_H$ accounts for the last term. As $\left[\cdot\right] \neq 0$, which is the term in brackets in (44), the FOC for IB_H is

$$\left(-1 - s'_H \cdot IB_G + s_H\right) = 0 .$$

With our assumption of $s_H\left(IB_H\right) = IB_H$, the FOC is:

$$-1 - IB_G + IB_H = 0 .$$

Since $IB_G = 1 - IB_H$, we obtain $IB_H^* = 1$, i.e. $s_H\left(IB_H^*\right) = 1$ and $IB_H^* = SIB = 1$.[34]

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[33] e.g. $C\left(I_H\right) = \delta \cdot I_H^2$.

[34] If we had employed the specification $s_H\,(IB_H) = a\ IB_H + \left(1-a\right)\left(IB_H\right)^2$, the result for s_H^* would also have been $s_H^* = 1$ with $IB_H^* = 1$.