Price Competition and Product Differentiation when Goods have Network Effects

Klaus Conrad
University of Mannheim

Abstract

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 products are costlier to produce. As an example, we refer to automobile producers, offering cars with a gasoline powered engine and one with a natural gas powered engine. The network of petrol stations provide the complementary good. The fulfilled expectation equilibrium could be either one with the firm offering the conventional engine as the only producer, one with the firm offering the new technology as the only producer, or one in which 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 order to find out whether private decision on the type of engine coincides with a socially optimal product differentiation, we determine the position of the two types of engine by a welfare maximizing authority.

Keywords: Price competition; Quality competition; Environmental awareness; Network effects; Automobiles.

JEL classification: L 11, Q 38, H 23 ; L 62

University of Mannheim, Department of Economics, L7, 3-5, D-68131 Mannheim
Tel.: +49 621 181 1896, Fax: +49 621 181 1893, e-mail: kconrad@rumms.uni-mannheim.de

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). The value of consuming a particular good from afore mentioned industries 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. The number of units of the good that are sold will depend on the service network which, in turn, will increase if more goods have been sold (e.g. foreign car producers entering the car market). 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 which is available at a wide variety of gasoline stations, and more gasoline stations are likely to associate with a specific 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

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

since only a few petrol stations are equipped with natural gas pumps. This small network will reduce his initial willingness to pay for such a motor vehicle.

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 (in a number of cases even 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 attributed to the reduction of space for the backseats and for luggage compartment, which is needed for the two fuel tanks.

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 short running exhaustible resource. In addition to the expected price increase of oil, a further reason for a switch to hydrogen is global warming.[4] As 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

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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.

[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.

type of fuel. Two competing firms simultaneously and independently from each other choose their technology, which is represented by their locations in a horizontal product differentiation dimension on the unit interval. This location also corresponds to how environmentally friendly a product is. We will analyze a modified two-stage Hotelling duopoly in which products also have a “vertical” dimension. Consumers differ in their preferences for the product attributes but they all share the same preference concerning the environmental aspect of the product. The product characteristics as well as the environmental quality are measured on the same unit interval, i.e. a certain product characteristic is associated with a unique environmental quality. Environmentally friendly products are more costly to produce and the cost increases in direct proportion to the product’s location on the unit interval. We are interested in the case where the innovative firm offers an entirely environmentally friendly product located at the upper endpoint of the interval and consider the parameter restrictions that yield such an outcome. The main objective of the paper is to show how product characteristics, prices, market shares, profits (in a Nash-equilibrium) change with an increase in the parameters of consumers’ environmental awareness and in production costs, that is, to check under which green preferences and production costs one automobile producer offers cars with an engine powered by gas/hydrogen and the other one offers cars with an engine powered by gasoline and which properties with respect to environmental friendliness the latter cars have. In order to relate the private choice of characteristics to welfare and environmental policy, we also determine the environmental characteristics preferred by an environmental authority. In case these characteristics differ from the outcome under duopolistic competition, we will suggest policy instruments in order to prevent market failure.

2. Related Literature

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 completely satisfy 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, 8]

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. Given the possibility of multiple equilibria in their model (as well as in our model) when products are incompatible, firms' reputations may play a major role in determining which equilibrium actually occurs. 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.[9] Our results conform with their results although we use a different model. 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,

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

[7] Crampes and Hollander (1995) have shown that when setting a minimum quality standard, the firm, producing the lower quality, will gain and the high-quality firm will lose profits. Ronnen's (1991) result is that implementing a quality standard narrows the quality gap between firms and brings about a more intensive competition in prices.

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

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

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 gas station compatible, we can not utilize these models for our case because they compare equilibrium profits and welfare under compatibility and incompatibility.

3. Assumptions

3.1 Concise statements

Our non-cooperative game considers 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 1 decides to produce the conventional product whereas firm 2 intends to produce an innovative product, i.e., it is a "sponsor"[10] of technology 2, and introduces this new product to the market. We assume that it is possible for firm 1 to bring out improved versions of its technology, and that firm 2 can introduce only a single version of its technology. Therefore firm 2 will produce the characteristic at the upper end of the zero-one characteristic line. Firm 1 adheres to the conventional technology but will use its option to vary its characteristics. Both firms include installed base considerations.

Consumers base their purchase decision on prices, product differentiation (a characteristic *q* which affects the willingness to pay of a potential customer), and on the network effect. There is a continuum of consumers uniformly distributed over Hotelling's [0, 1] interval. Each consumer buys one unit of the product. The net-utility of consumer $\theta \in [0,1]$ for a unit of the good of quality q_1 is defined by

(1) $$v(q_1,\theta) = r - t(q_1-\theta)^2 - d(1-q_1) - p_1 + \gamma \cdot n_1(\tau)$$

in which *r* stands for the gross, intrinsic utility a consumer derives from consuming one unit of the product.[11] The term $t(q_1-\theta)^2$ represents the costs a consumer, located at $\theta \in [0,1]$, bears if he does not get his preferred characteristic as he buys from firm 1 selling characteristic q_1. The parameter *t* 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 $d \cdot (1-q_1)$ we express the awareness of a negative externality caused by the product, i.e.

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

environmental concern. It is modelled as a burden of guilt 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.[12] This "warm glow" effect means that individuals perceive utility by providing a small amount of a public good.[13] The "warm glow" effect has been recognized in the literature on the valuation of environmental quality as one of the potentially important factors behind the willingness to pay for environmental quality (see Kriström (1999)).[14]

The price of firm 1 is p_1 and the term $\gamma \cdot n_1(\tau)$ is the network benefit for good 1 where τ is the expected market share of firm 2, i.e. $n_1(0) = n$ at the beginning, *n* is 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 $n_1(\tau)$. The network gains importance as γ increases. Since $n_1 + n_2 = n$, $n_2(\tau)$ are the customers of firm 2 $(n_2(0) = 0)$. The network benefit for firm 1 decreases, i.e. will become less important when the number of consumers $n_2(\tau)$, connected to the competing network of good 2, increases. Hence, the utility that a given user derives from the good depends upon the number of other users who are in the same network as he is. All *n* consumers have bought the product of firm 1 in the past. Its characteristic could have been $q_1 = 0$ whereas firm 2 considers producing only the new, energy efficient product, i.e. $q_2 = 1$. 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 $q_1 > 0,\ q_2 = 1$ 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 2 is:

(2) $$v(q_2, \theta) = r - t(q_2 - \theta)^2 - d(1 - q_2) - p_2 + \gamma\, n_2(\tau).$$

Even if the attribute is highly esteemed (e.g. $q_2 = 1$) and the good not expensive, the innovative firm might be unsuccessful because the installed base does not exist. After the

[12] See Conrad (2002) for a model with care for the environment.

[13] In (1) 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_1 yields $\theta + \frac{d}{2t}$ as the bliss point.

[14] See section 3.2 for some additional remarks on this term.

outcome of the game, all n customers will be served. As $n_2(0)$ 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. $n-n_2$) of the existing technology.

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.[15] Such a fulfilled expectation equilibrium results in:

(3) $$n_1\left(1-\hat{\theta}\right)=n\cdot\hat{\theta} \qquad n_2\left(1-\hat{\theta}\right)=n\cdot\left[1-\hat{\theta}\right],$$

where $\hat{\tau}=\left(1-\hat{\theta}\right)$ is the expected market share of firm 2 (consumers to the right of $\hat{\theta}$) and $\hat{\theta}$ is the expected market share of firm 1 (consumers to the left of $\hat{\theta}$) and by $\hat{\theta}$ we denote the critical consumer who is indifferent between consuming q_1 or q_2.

3.2 Motivation of assumptions using the automobile market

In our model firm 1 produces the gasoline powered engine whereas firm 2, the sponsor, has invested in the production of a hydrogen powered engine because environmental concern and the prospect of running out of oil in the near future offers a good chance of profits.[16] Depending on environmental concern and cost aspects, firm 1 will use its option to improve gasoline efficiency within the $[0,1]$ interval. 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. In the automobile market, compatibility of the new product of firm 2 with the installed base of firm 1 is not a meaningful strategy as it is for a PC producer offering an IBM

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[15] 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 $\left(n=n^e\right)$.

[16] At the end of this section we will derive an interval of parameters for environmental (energy efficiency) and cost trade-off such that offering hydrogen driven cars is a rational strategy.

compatible PC which can use the standard software.[17] A natural gas powered car is not compatible with the existing network of gasoline stations.[18]

Consumers' awareness in our model is equivalent to 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 their different willingness to pay. Some customers consider gas-guzzlers as comfortable cars although they are extreme 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. 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, 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 $q_2 > q_1$ and prices are equal, all consumers purchase the environmentally friendlier car with q_2. 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, $u(q_1,\theta)-u(q_2,\theta)$ if product characteristics q_1 and q_2 differ, is positive for some consumers and negative for others.

By the term $d\cdot(1-q_i)$ we have incorporated the aspect that individual environmental awareness gives some utility on its own even if it does not lead to a better environmental quality. When $q_1 = 0$, then *d* represents the highest money-metric disutility from emissions (environmental damage) including excessive fuel consumption. When $q_1 = 1$, there is no

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

[18] We 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.

disutility because the consumer has decided in favour of the most environmentally friendly and efficient technology.[19]

As an example, at the beginning of the market game all households own a gasoline powered car. Firm 2 can only produce cars with $q_2 = 1$ whereas firm 1 can improve fuel efficiency of its engine by raising q_1 from $q_1 = 0$ (10 ltr./100 km) to $q_1 = 0.5$ (6 ltr./100 km) or finally towards $q_1 = 1$ (3 ltr./100 km). In the case of $q_1 = 1$, 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:

(4)
$$v(q_1,\theta) - v(q_2,\theta) = \underbrace{p_2 - p_1}_{\text{price effect}} - t\underbrace{\left[(q_1-\theta)^2 - (q_2-\theta)^2\right]}_{\text{horizontal product differentation}} \underbrace{-d\cdot(q_2-q_1)}_{\text{image concern}} + \underbrace{\gamma\left(n_1(\tau) - n_2(\tau)\right)}_{\text{network effect}}$$

Firm 1 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.

4. Results

4.1 Equilibrium prices, market shares and characteristics

We are interested in finding a consumer $\hat{\theta} \in (0,1)$ who is indifferent at prices p_1, p_2 to purchase from producer 1 (to the left of $\hat{\theta}$) or from producer 2 (to the right of $\hat{\theta}$). From $v\left(q_1,\hat{\theta}\right) = v\left(q_2,\hat{\theta}\right)$ and the condition, that the networks, expected by the consumer, are the actual networks, i.e. (3), we can solve for $\hat{\theta}$ to get firm 1's specific demand function $D_1(p_1, p_2) = \hat{\theta}$:

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[19] The term $d(1-q_1)$ could also be interpreted in the following sense. If a car to the left has more horse power, then everybody will prefer it, so the quality part could be written as $\bar{t}(1-q_1)$, and the environmental part as $-\bar{d}(1-q_1)$ (the "warm glow" effect). We do not separate the two but assume that in $\left(\bar{t}-\bar{d}\right)(1-q_1)$ with $d := \bar{t} - \bar{d}$ the environmental concern dominates the horse power quality aspect (which in principle is vertically differentiated). That is, we focus on horizontal product differentiation by assuming that the environmental parameter is relatively more important to the average driver than the horse power quality aspect. The fuel bill is taken into account by defining r as a net intrinsic utility adjusted for fuel costs. The difference in fuel consumption is captured by $d(1-q_1)$.

(5) $$D_1(p_1,p_2)=\hat{\theta}=\frac{p_2-p_1+(q_2-q_1)[q_1+q_2-d]-\gamma\cdot n}{2(q_2-q_1)-2\gamma n}$$

where t 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 2); b) $\hat{\theta}=0$, $1-\hat{\theta}=1$ (market exit of firm 1); 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.

The demand function for firm 2 is

(6) $$D_2(p_1,p_2)=1-\hat{\theta}=\frac{p_1-p_2+(q_2-q_1)[2+d-q_1-q_2]-\gamma n}{2(q_2-q_1)-2\gamma n}.$$

We observe that the price response of market demand is higher if there is a network effect. A marginal decrease of firm 2's price raises its demand by $1/2(q_2-q_1)$ if $\gamma=0$, but by the higher factor $1/[2(q_2-q_1)-2\gamma n]$ under network effects. Demand is raised by the non-network factor $1/2(q_2-q_1)$ which raises expectations of a higher market share. This in turn raises demand beyond this factor.[20]

In producing the two characteristics we assume that there is a marginal cost c to increasing quality q_i. 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) $$\pi_1=p_1\,n_1-c\,q_1\,n_1=n(p_1-c\,q_1)\cdot\hat{\theta}(p_1,p_2)$$

and

(8) $$\pi_2=p_2\,n_2-c\,q_2\,n_2=n(p_2-c\,q_2)\cdot\left(1-\hat{\theta}(p_1,p_2)\right).$$

[20] In order to check for a unique equilibrium consumer partition which is associated with any given price pair we can follow Grilo et al. (2001). They determine the necessary and sufficient conditions for θ defined by (5) to belong to $(0,1)$. Then they characterize the price pairs ensuring that a single firm serves the whole consumer population. By exchanging $\beta\,n_i^2$ in their terms by $d\cdot(1-q_i)$ we end up with the same conclusion of a unique equilibrium.

Lemma 1: The Nash equilibrium in prices p_1^*, p_2^*, derived from the FOCs of maximizing (7) and (8) is:

(9) $$p_1^* = \frac{1}{3}\left[(q_2 - q_1)[2 + q_1 + q_2 - d] - 3\gamma n + c(q_2 + 2q_1)\right]$$

(10) $$p_2^* = \frac{1}{3}\left[(q_2 - q_1)[4 - q_1 - q_2 + d] - 3\gamma n + c(q_1 + 2q_2)\right]$$

Under price competition, the network effect lowers the equilibrium prices of both firms.

The equilibrium market shares follow from (5) and (6) by inserting p_1^*, p_2^* from (9) and (10):[21]

(11) $$\theta^*(q_1, q_2) = \frac{(q_2 - q_1)[2 + q_1 + q_2 - d] - 3\gamma n + c(q_2 - q_1)}{6[q_2 - q_1 - \gamma n]}.$$

(12) $$1 - \theta^*(q_1, q_2) = \frac{(q_2 - q_1)\left[4 - (q_1 + q_2 - d)\right] - 3\gamma n - c(q_2 - q_1)}{6[q_2 - q_1 - \gamma n]}.$$

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 are interested in a situation where firm 2 commits to $q_2 = 1$, i.e. it produces natural gas driven cars, or it does not produce at all. Only firm 1 will use the option to vary q_1 in terms of fuel efficiency. In order to get a subgame perfect equilibrium in the quality choices q_1 and q_2, firm 1 determines

$$\max_{q_1} \quad \pi_1(q_1, q_2) = \left[p_1^*(q_1, q_2) - c\, q_1\right] n \cdot \theta^*(q_1, q_2)$$

A solution q_1^* follows from $\frac{\partial \pi_1}{\partial q_1} = 0$. The FOC is

(13) $$3q_1^{*2} + q_1^*\left(-4q_2 + 2 - (d - c) + 4\gamma n\right) + q_2^2 - q_2\left(2 - (d - c)\right) + 2\gamma n\left(1 - (d - c)\right) - \gamma n = 0$$

Hence we have to solve a quadratic equation in q_1^*.

Similarly, the problem of firm 2 is:

$$\max_{q_2} \quad \pi_2(q_1, q_2) = \left[p_2^*(q_1, q_2) - c\, q_2\right] \cdot n \cdot \left(1 - \theta^*(q_1, q_2)\right).$$

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

The FOC for q_2^* is

(14) $-3\,q_2^{*2}+q_2^*\left(4\,q_1+4+d-c+4\,\gamma\,n\right)-q_1^2-q_1\left(4+d-c\right)-2\,\gamma\,n\left(3+d-c\right)+2\,\gamma\,n=0.$

By adding up equations (13) and (14), it is possible to find the following solution in qualities:[22]

(15) $q_1^*=-\frac{1}{4}+\frac{d-c}{2}$, $q_2^*=\frac{5}{4}+\frac{d-c}{2}$.

An immediate implication of (15) is that the locational game never has an equilibrium where both firms choose interior values in (0,1) as $d-c$ can not be $\geq 1/2$ and $\leq -1/2$. For an equilibrium with $q_2^*=1$, we require $d-c\geq -1/2$.

Proposition 1:

The net effect of environmental concern and cost of quality, i.e. $d-c$, must be at least $-1/2$ for an equilibrium with $q_2^*=1$.

Proposition 1 implies that in case the government wishes that there is a sponsor who is willing to offer the new technology, it has to raise environmental concern *d* in the population or it has to subsidize the cost of production, *c*.

Since we set q_2^* equal to one, q_1^* in (15) is no more the best response to $q_2^*=1$. We therefore have to determine the best response of firm 1 to $q_2^*=1$, and then have to check, whether the best response of firm 2 on that q_1 is still a $q_2^*\geq 1$. To calculate the best response $q_1=q_1^R\left(q_2^*=1\right)$ we solve (13) for $q_1\geq 0$. For example, if $\gamma\,n=0$, then $q_1=q_1^R\left(1\right)=\left(\left(d-c\right)-1\right)/3$. If $d-c\leq 1$, then $q_1=0$ as q_1 must not be negative; if $\left(d-c\right)\in\left(1,4\right)$ then $q_1\in\left(0,1\right]$. Next we have to check whether $q_2^*=1$ is still the best response of firm 2 on $q_1=q_1^R\left(1\right)$, i.e. we have to check for $q_2\left(q_1^R\left(1\right)\right)\geq 1$ by solving (14) for q_2. With $\gamma\,n=0$ the solution is

$$q_2=q_2^R\left(q_1^R\left(1\right)\right)=\frac{\left(4+\left(d-c\right)+q_1^R\left(1\right)\right)}{3}>1.$$

[22] Several other pairs of solution did not satisfy either the restriction $\gamma>0$, or the denominator in θ^* became zero for the q_1,q_2 pair. Such a solution was $q_1=\frac{1}{2}+\frac{d-c}{2}-\frac{\gamma\,n}{2}$ and $q_2=\frac{1}{2}+\frac{d-c}{2}+\frac{\gamma\,n}{2}$.

Therefore, the Nash-equilibrium for the case $\gamma\, n = 0$ and $d-c \in [-1/2, 1]$ is $q_1^* = 0$, $q_2^* = 1$, and for $d-c \in (1, 4]$ it is $q_1^* = ((d-c)-1)/3 > 0$, $q_2^* = 1$. In an analogous way we can determine Nash-equilibria $q_1^* \geq 0$, $q_2^* = 1$ for $d-c \in [-1/2, 4]$ and $\gamma\, n \geq 0$. As mentioned before, we do not analyse the dynamics of market entry when network effects may deter it. We only do comparative statics by comparing an equilibrium at the beginning (only firm 1 exists) with an equilibrium where either firm 1 or firm 2 exists, or where both firms compete in the market. We consider two cases of $d-c$. One where the difference is less than 1 and one where it is greater than 1.

4.2 Characteristics and market shares under weak environmental concern

We label the case $(d-c) \in [-1/2, 1]$ as weak environmental concern and it implies that we have obtained a corner solution for $q_i\,(q_1^* = 0, q_2^* = 1)$. The formula for the market share θ^* is then as presented in Table 1.

Table 1: Weak environmental concern: $(d-c) \in \left[-\frac{1}{2}, 1\right]$					
$q_1^* = 0$, $q_2^* = 1$, $\theta^* = \frac{1}{2} - \frac{d-c}{6(1-\gamma\, n)}$					
	$d-c=-1/2$	$(d-c)\in(-1/2,0)$	$d-c=0$	$(d-c)\in(0,1)$	$d-c=1$
	values of θ^*				
$\gamma\, n = 0$	.583		$1/2$		$1/3$
$\gamma\, n = .05$	.588	$\frac{\partial\,\theta^*}{\partial\,(d-c)} < 0$	$1/2$	$\frac{\partial\,\theta^*}{\partial\,(d-c)} < 0$	.325
$\gamma\, n = .1$	.592		$1/2$		.314
$\gamma\, n = .2$	.604	$\frac{\partial\,\theta^*}{\partial\,\gamma\, n} > 0$	$1/2$	$\frac{\partial\,\theta^*}{\partial\,\gamma\, n} < 0$	.292
$\gamma\, n = .3$	.619		$1/2$		.262
$p_1^* = 1 - \frac{d-c}{3} - \gamma\, n$, $p_2^* = 1 + \frac{d-c}{3} - \gamma\, n + c$					
$\frac{\partial\, p_1^*}{\partial\,(d-c)} < 0$, $\frac{\partial\,\pi_1^*}{\partial\,(d-c)} < 0$, $\frac{\partial\, p_2^*}{\partial\,(d-c)} > 0$, $\frac{\partial\,\pi_2^*}{\partial\,(d-c)} > 0$, $\frac{\partial\, p_i^*}{\partial\,(\gamma\, n)} < 0$, $\frac{\partial\,\pi_i^*}{\partial\,(\gamma\, n)} < 0$					

If 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 $\left(\gamma\, n=5/6\right)$ (not presented in Tab. 1)[23]. Then firm 1 will remain a monopoly producing energy inefficient $\left(q_1^{*}=0\right)$ products at low costs $\left(q_1^{*}\, c=0\right)$, i.e. without investment costs for improved energy efficiency. If the supporting network effect is weak, the market share declines towards $7/12\left(=.583\right)$ and firm 2 can reach up to $5/12$ market share. Its products are costly $\left(q_2^{*}\, c=c\right)$, but environmentally concerned consumers find them attractive and the network is not an obstacle to buy them.

Proposition 2:
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 1.

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 $p_1=1-\gamma\, n$ for the cheaper, energy inefficient product or $p_2=1+c-\gamma\, n$ for the more expensive but energy efficient one.

If the *d*-effect dominates the *c*-effect (i.e. $d-c>0$), then firm 1 will account for less than $1/2$ market share, irrespective of the network effect (column 6). The dominating *d*-effect operates in favour of firm 2. 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 ($\gamma\, n=2/3$; not presented in Tab. 1), firm 1 will be driven out of the market because competition forced it to charge a price $p_1^{*}=0$ (for firm 2 it is $p_2^{*}=c+2/3$). As the partial derivatives indicate, the market share θ^{*} decreases in $d-c$ (column 5).

In Table 1 we present also the price and profit situation under the different environmental concerns and network impacts. As we know from (9) and (10), a well developed network enforces price competition. Prices are the highest if no network is required

[23] The SOC of (7), i.e. $2\left(q_2^{*}-q_1^{*}\right)-2\,\gamma\, n>0$ restricted the value of $\gamma\, n$. If $q_1^{*}=0$ then $\gamma\, n<1$.

$(\gamma = 0)$. For each $d - c$, profits of both firms decrease if the network effect becomes stronger ($\partial \pi_i / \partial (\gamma n) < 0$).

Proposition 3:

As far as profits are concerned the worst case for firm 1 is a strong network effect ($\gamma n = 2/3$) and environmental concern, dominating the cost aspect $(d - c = 1)$.[24] The worst case for firm 2 is also a strong network effect in addition with a cost aspect that dominates environmental concern $(d - c = -1/2)$.[25]

The intuition for the first statement is that firm 1 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. The reason for the second statement is that the high-cost firm 2 with the environmentally friendly product has problems to get support from the network effect if customers do not care much about the environment (its market share is zero). If environmental concern increases, firm 1 lowers its price to prevent a decline in its market share ($\partial p_1^* / \partial (d - c) < 0$), but firm 2 can increase its price because its product becomes more attractive ($\partial p_2^* / \partial (d - c) > 0$).

Firm 2's first best case is if no network effect is required ($\gamma = 0$) and concern for the environment is high ($d - c = 1$). In that case, price competition is weak and environmentally concerned consumers ($1 - \theta^* = 2/3$ or 66%) are ready to pay a high price for those products $(p_2^* = 4/3 + c)$. Firm 1 also prefers $\gamma = 0$, but when the cost effect dominates environmental concern ($d - c = -1/2$). It then makes a high profit by selling at a relatively high price $(p_1^* = 6/5)$ to 58% of the consumers. In each of these two cases both firms operate in the market.

4.3 Characteristics and market shares under strong environmental concern

Table 2 presents the change in the market structure and in environmental quality when environmental concern becomes stronger. As in this case firm 1's market share drops below

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[24] It is $p_1^* = 0, \quad \theta^* = 0$ according to the formulas for p_1^* and θ^* in Tab. 1.

[25] For $\gamma n = 5/6$ it is $p_2^* = c$ and $1 - \theta^* = 0$.

$1/2$, it raises its environmental quality q_1^* and it could even match with $q_2^* = 1$ when $d - c = 4$. Although profits then approach zero for both firms, strong environmental concern has compelled firm 1, however, to produce its environmentally most friendly version of an engine.

Table 2: Strong environmental concern: $d - c \in [1.5, 4]$					
$q_1^* > 0$, $q_2^* = 1$, $\theta^* = \frac{(1-q_1^*)[3+q_1^*-(d-c)]-3\gamma n}{6[1-q_1^*-\gamma n]}$					
	$d-c=1.5$	$d-c=2$	$d-c=2.5$	$d-c=3.5$	$d-c=4$ [1)]
$\gamma n = 0$ [2)]	$q_1^* = 1/6$ $\theta^* = .277$	$q_1^* = 1/3$ $\theta^* = .222$	$q_1^* = 1/2$ $\theta^* = .166$	$q_1^* = 5/6$ $\theta^* = .055$	$q_1^* = 1$ $\theta^* = 0$
$\gamma n = .05$	$q_1^* = .139$ $\theta^* = .259$	$q_1^* = .29$ $\theta^* = .193$	$q_1^* = .433$ $\theta^* = .122$	$q_1^* = 2/3$ $\theta^* = 0$	$\theta^* < 0$
$\gamma n = .1$	$q_1^* = .108$ $\theta^* = .238$	$q_1^* = .244$ $\theta^* = .162$	$q_1^* = .366$ $\theta^* = .077$	$\theta^* < 0$	$\theta^* < 0$
$\gamma n = .2$	$q_1^* = .038$ $\theta^* = .192$	$q_1^* = .144$ $\theta^* = .09$	$\theta^* < 0$	$\theta^* < 0$	$\theta^* < 0$
$\gamma n = .3$	$q_1^* = 0$ $\theta^* = .142$	$q_1^* = .037$ $\theta^* = .025$	$\theta^* < 0$	$\theta^* < 0$	$\theta^* < 0$
$p_1^* = (1-q_1)[3+q_1-(d-c)]/3 - \gamma n + q_1 c$, $p_2^* = (1-q_1^*)[3-q_1^*+(d-c)]/3-\gamma n + c$					
$\frac{\partial q_1^*}{\partial (d-c)} > 0$, $\frac{\partial q_1^*}{\partial \gamma n} < 0$, $\frac{\partial \theta^*}{\partial (d-c)} < 0$, $\frac{\partial \theta^*}{\partial \gamma n} < 0$ $\frac{\partial p_1^*}{\partial (d-c)} ?$, $\frac{\partial p_2^*}{\partial (d-c)} < 0$, $\frac{\partial \pi_i^*}{\partial (d-c)} < 0$, $\frac{\partial p_i^*}{\partial (\gamma n)} < 0$, $\frac{\partial \pi_i^*}{\partial (\gamma n)} < 0$					
[1)] This case should be interpreted as a limiting value for $q_1^* \to 1$ (homogeneous products) as for $d-c=4$ the numerator and denominator become zero. [2)] The SOC of (7) is $2(q_2^* - q_1^*) - 2\gamma n > 0$ and implies values of γn no larger than $q_2^* - q_1^*$.					

If environmental concern increases from $d - c = 1$ to $d - c = 1.5$, firm 1 raises its quality q_1^* from 0 to $q_1^* = 1/6$ but will not gain a market share θ^* beyond $1/2$ (column 2 in Tab. 2). Since the market share does not exceed 0.277, a strong network effect finally leads to market exit of firm 1. It reacts to its declining market share by lowering q_1^* to save costs and to achieve higher prices from moving away from $q_2^* = 1$. However, the more intensive price competition under a higher γ will finally lead to market exit.[26]

Proposition 4:

When environmental concern increases $(d - c \geq 1.5)$, firm 1 raises its quality q_1^* but nevertheless loses market shares. A strong network effect works again in favour of the dominant firm; this time it is firm 2 which has a market share above $1/2$. If $\gamma\, n$ increases, the market share of firm 1 will soon approach zero.

Finally, the case presented in the 6th column of Table 2 implies that both firms choose $q_1^* = q_2^* = 1$. This would imply that they share the market and charge a price $p_1^* = p_2^* = c - \gamma\, n$ below unit cost. This market structure does not occur because both firms would make a loss.[27]

As in Table 1, 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 1 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_1 dominates the competition effect, then firm 1 might increase its price (see the last row in Tab. 2). As under weak environmental concern firm 1 sticks to $q_1^* = 0$, more environmental concern permits firm 2 to raise its price (see last row in Table 1). The opposite is the case when firm 1 responds by increasing its quality q_1^* because then the products become more homogeneous.

5. Application to environmental policy

5.1 Socially optimal position of environmentally friendly engines

We finally check whether the private choice of the characteristics q_1^* and q_2^* coincides with the socially optimal ones, preferred by an environmental authority. For that purpose we define social welfare as a function of q_1 and q_2. It is equal to the aggregate willingness to pay minus cost of production. However, the authority is not satisfied with drivers' environmental concern, *d*, but considers in addition environmental damage from automobile use. We

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[26] It is $\theta^* = 0$ and $p_1^* = 0$ for $\gamma\, n = .5$, according to the formulas for θ^* and p_1^* in Table 2.

[27] The SOC of (6) and (7), i.e. $2\left(q_2^* - q_1^*\right) - 2\,\gamma\, n > 0$, cannot be satisfied because of the restriction $\gamma \geq 0$.

therefore denote with $\bar{d}$ the damage parameter which consists of the environmental damage from air pollution as well as of the loss in consumers' utility from insufficient environmental awareness, i.e. d is part of $\bar{d}$ and $\bar{d}-d$ is environmental damage. Therefore,[28]

(16)
$$W(q_1,q_2)=\int_0^{\bar{\theta}} \left[r-(q_1-\theta)^2-\bar{d}\cdot(1-q_1)+\gamma\cdot n\,\theta-c\,q_1\right]d\,\theta$$
$$+\int_{\bar{\theta}}^{1} \left[r-(q_2-\theta)^2-\bar{d}\cdot(1-q_2)+\gamma\cdot n\,\theta-c\,q_2\right]d\,\theta.$$

For maximizing welfare in (16) with respect to q_1 and q_2, we first integrate W with respect to θ, and then we set the partial derivatives of $W(q_1,q_2)$ equal to zero. Solving the two FOCs for q_1 and q_2 yields the characteristics which maximize social welfare:[29]

(17)
$$\hat{q}_1=\frac{\bar{d}-d}{2}+\frac{d-c}{2}+\frac{1}{4}\quad,\qquad \hat{q}_2=\frac{\bar{d}-d}{2}+\frac{d-c}{2}+\frac{3}{4}.$$

The optimal characteristics consist of two terms. The first term suggests a shift towards the environmentally more friendly engine if social environmental concern is adjusted by private environmental concern and positive (i.e. $\bar{d}-d>0$). In that case there is a real environmental damage. The second term takes into account costs and private environmental awareness and adjusts the position of the social optimal characteristics $1/4$ and $3/4$, obtained in the standard model ($\bar{d}=d=c=0$).[30]

Our next step is to compare the Nash-equilibrium in characteristics, q_i^*, with the socially optimal ones, $\hat{q}_i$ in (17). We will assume that firm 2 as well as the environmental authority are interested in the option $q_2^*=1$. For firm 2 this implied $d-c\geq -1/2$, and for the authority it implies $\bar{d}-d\geq 1$ in (17) for the case of weak environmental concern, i.e. for

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[28] The market share $\bar{\theta}$ separates the consumers with higher welfare from q_1 from those with higher welfare from q_2; i.e. $r-(q_1-\bar{\theta})^2-\bar{d}(1-q_1)+\gamma\,n\,\bar{\theta}-c\,q_1=r-(q_2-\bar{\theta})^2-\bar{d}(1-q_2)+\gamma\,n\,\bar{\theta}-c\,q_2$. This condition yields $\bar{\theta}=\frac{1}{2}(q_1+q_2-d+c)$.

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

[30] Inserting $\hat{q}_i$ in (17) into $\bar{\theta}$, explained in footnote 28, yields $\bar{\theta}=1/2$ for the location of the indifferent consumer.

$d-c \in [-1/2, 1/2]$. Then $q_2^* = \hat{q}_2 = 1$. In order to demonstrate how the environmental authority can regulate firm 1 to build environmentally more friendly engines we choose cases of parameter constellations which permit to solve the optimal response $q_1^R(q_2 = 1)$ in (13) explicitly. First, we concentrate on the interval $(d-c) \in [-1/2, 1/2]$ where the private choice is $q_1^* = 0$. Second, we set $\bar{d} - d = 1$ which implies $\hat{q}_2 \geq 1$ for $(d-c) \in [-1/2, 1/2]$ and $\hat{q}_1 > q_1^* = 0$; i.e., energy efficiency is below the social standard $\hat{q}_1$. And third, we choose $\gamma\, n \in [0,\ 0.3]$ which implies non-negative market shares for the parameter constellations under consideration. Since $q_1^* = 0, q_2^* = 1$ for this case, the market share of firm 1 is

(11') $$\theta^* = \frac{1}{2} - \frac{d-c}{6(1-\gamma\, n)}.$$

The socially optimal energy efficiency should be

(17') $$\hat{q}_1 = \frac{3}{4} + \frac{d-c}{2} \qquad \text{as} \qquad \bar{d} - d = 1.$$

5.2 Choosing environmental policy instruments for improving energy efficiency

In order to achieve that q_1^* is equal to $\hat{q}_1$, we have to introduce a policy parameter as an incentive for firm 1 to produce $\hat{q}_1$. One possibility is to set $\bar{c} = c - s$ where *s* would be a subsidy $(s > 0)$ on the marginal cost of quality because q_1^* is too low. We are therefore interested in finding a value of *s* such that

(18) $$q_1^R(c-s) = \hat{q}_1 = \frac{3}{4} + \frac{d-c}{2} \qquad \text{with} \qquad q_1^R(c-s) \text{ from (13).}$$

If we insert $q_1^R(c-s) = \hat{q}_1$ into the market share (11) we obtain

$$\theta_S = \frac{(1-\hat{q}_1)\left[3+\hat{q}_1-(d-c)-s\right]-3\,\gamma\, n}{6\left[1-\hat{q}_1-\gamma\, n\right]}.$$

We consider two parameter variations, presented in Table 3. In one variation we set $\gamma\, n = 0$ and increase $d - c$ from $-1/2$ to $1/4$ (see first row of Table 3). In a second one we set $d - c = -1/2$ and increase $\gamma\, n$ from 0 to $1/12$ (see first column in Table 3). In these cases all variables, shown in Table 3, can easily be calculated. We have excluded cases like $d - c \in [1/2, 1]$ which would imply $q_1^R(c - s) = \hat{q}_1 = 1$, i.e. the products are homogeneous (a 3 ltr./100 km car and a hydrogen powered engine) and prices drop below marginal cost $\left(p_i^* = c - \gamma\, n\right)$. Such an outcome is not of interest for the regulator.

Tab. 3: Subsidizing marginal cost of quality for environmental regulation[1]

	$d - c = -1/2$	$d - c = 0$	$d - c = 1/4$
$\gamma\, n = 0$	$q_1^* = 0\,;\quad \theta = .583$ $s = 3$ $\hat{q}_1 = 1/2\,;\quad \theta_S = 1/6$	$q_1^* = 0\,;\quad \theta = 1/2$ $s = 3\ 1/4$ $\hat{q}_1 = 3/4\,;\quad \theta_S = 1/12$	$q_1^* = 0\,;\quad \theta = 11/24$ $s = 3\ 3/8$ $\hat{q}_1 = 7/8\,;\quad \theta_S = 1/24$
$\gamma\, n = 1/16$	$q_1^* = 0\,;\quad \theta = .588$ $s = 3\ 1/3$ $\hat{q}_1 = 1/2\,;\quad \theta_S = .127$	Partial derivatives at $\gamma\, n = 0$ or at $d - c = -1/2$ $\frac{\partial s}{\partial (d-c)} > 0\,;\qquad \frac{\partial s}{\partial \gamma\, n} > 0$ $\frac{\partial \theta}{\partial (d-c)} < 0\,;\qquad \frac{\partial \theta}{\partial \gamma\, n} \begin{cases} > 0 & for\ \ d - c < 0 \\ = 0 & for\ \ d - c = 0 \\ < 0 & for\ \ d - c > 0 \end{cases}$ $\frac{\partial \theta_S}{\partial (d-c)} < 0\,;\qquad \frac{\partial \theta_S}{\partial \gamma\, n} < 0$	
$\gamma\, n = 1/12$	$q_1^* = 0\,;\quad \theta = .591$ $s = 3\ 1/2$ $\hat{q}_1 = 1/2\,;\quad \theta_S = 0$		

[1] The first row in a rectangle shows quality and market share of firm 1 without regulation, the second row gives the size of the subsidy and the third row shows the social optimum achieved by the subsidy.

Let us first consider the case of no network effect (first row in Tab. 3). An increasing subsidy is required if environmental concern tends to dominate the cost effect because the social optimal quality should be at least $1/2$. In spite of the subsidy, the market share of firm 1 declines drastically. The reason for that is that firm 2, producing already the environmentally friendly engine, also gets the subsidy because $\bar{c} = c - s$ is the marginal cost of quality for both firms. Next, we fix $d - c = -1/2$ and increase the network effect. As we have seen in the previous section, prices decrease if the network effect matters, because the firms compete for market shares above 50 percent. Producing a quality of $\hat{q}_1 = 1/2$ instead of $q_1^* = 0$ raises costs and prices. Hence higher subsidies are required to induce firm 1 to choose $\hat{q}_1 = 1/2$. Nevertheless it loses market shares as firm 2 benefits from the subsidy too.

To reduce transportation emissions and energy consumption, policymakers typically employ one of two approaches – changing technology or changing behaviour. An alternative policy to raise q_1^* could be a campaign to enhance environmental awareness, *d*, of the consumers by δ (advertising, TV spots, education about environmental impacts). The equivalent condition to (19) is

$$q_1^R\left(d+\delta\right) = \hat{q}_1 = \frac{3}{4} + \frac{d-c}{2}.$$

The size of the required impact on environmental awareness, δ, is equal to *s* in Table 3; hence the values of the variables are the same. Now firm 2 does not benefit from a subsidy because it has produced the clean technology anyway, but because of higher environmental awareness of all motorists. 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.

6. Summary and Conclusion

We considered a duopoly producing horizontally differentiated products which are non-compatible with respect to a network which provides a complementary good. 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. As an example we referred to two automobile producers, one offering cars with an engine powered by gasoline and the other one offering cars with an engine powered by natural gas. The network is petrol stations which at present only in a few cases provide two kinds of fuel. We specified a network effect which is strengthened by the market share of a firm. The equilibrium of the two stage game could be either one with 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, on the network effect, 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 extreme position, i.e. the end points of the Hotelling 0-1 line. That need not be the case in our model. Now which type of car will be produced, will depend on environmental awareness and the cost of producing energy efficient engines. We have also shown that the network effect exerts an impact on optimal product differentiation as well as on price competition, the game at the second stage. The higher the strength of the network effect, the lower will be the equilibrium prices and the more will firm 1 downgrade its quality to relax price competition. If a firm has a market share above $1/2$, then its share will increase with the strength of the network effect. As a strong network effect enforces competition, profits will be low. The more environmental concern dominates the cost aspect, the lower will be the market share of the firm that produces energy inefficient engines, and the higher will be the share of the entrant producing the new technology. The effort of the conventional firm to produce an energy efficient engine, equivalent to the natural gas powered engine, ends in fierce price competition and struggle for the network support with losses for both firms.

We finally determine a socially optimal allocation of the characteristics on the $[0,1]$ Hotelling line by maximizing a social welfare function with respect to the two characteristics. The result was that the regulator wishes a more energy efficient engine (a higher q_1) than a private firm develops. By choosing an appropriate subsidy on costs it is however possible that firm 1 produces a car with a socially optimal energy efficiency.

The objective of our approach has been to sketch a model which captures product differentiation under environmental aspects, the necessity of support by a network, and price competition whereby environmental friendly products are costlier to produce. A topic for future research could be to model the dynamics in an intertemporal setting with control variables (quality, price) and stock variables (market shares). Another topic could be to extend our two stage game by a first stage with competition in compatibility to the network. Such an approach could examine the success of firms that produce cars with two tanks – one for gasoline and one for natural gas.

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