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Green product design in supply chains under competition

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A R T I C L E I N F O

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A B S T R A C T

In this paper, we investigate the green product design issues in supply chains under competition. Our research questions address how supply chains' decisions on the "greenness" of products are affected by factors such as supply chain structures (centralized and decentralized), the green product types (development-intensive product or marginal-cost intensive product), and the types of competition (price competition and greenness competition). With a game-theoretic approach, our model starts with a simple supply chain with one manufacturer and one retailer. Then the model is expanded to include a horizontal retailer competition case and six cases of competing supply chains. Our results indicate that, 1. the distortion from a non-coordinated supply chain (the double marginalization effect) has counter-intuitive impact on the degree of product "greenness"; 2. supply chain price competition at the retailer level may positively influence the equilibrium greenness while the product greenness competition reduces the equilibrium greenness, and the joint impact from price and greenness competition on equilibrium greenness depends on the relative strength of the two types of competition.

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1. Introduction

Sustainable operations and supply chain management have received a lot of attention during the past twenty years. According to Tang and Zhou (2012), OR/MS research in sustainable operations includes the following topics: product design, technology selection, strategic issues in remanufacturing, supply chain design/restructuring, supply chain operations, and reverse supply chain operations. From this perspective, our paper is related to both sustainable product design and sustainable supply chain management as we study the green product design issues under supply chain settings.

We start our first motivation case with the emissions regulations in the automotive industry. In 1970, U.S. Congress passed the Clean Air Act and established the first tailpipe emissions standards that started to take effect in 1975. Then, the standards were tightened significantly during 1977 and 1988. For example, the NO*x* standard was reduced from 3.1 grams per mile (GPM) in 1975 to 2.0 GPM between 1977 and 1979 and then was further reduced to 1.0 GPM in 1981 (EPA, 1999). Chen, Abeles, and Sperling (2004) in their report prepared for California EPA illustrated the auto-makers' strong resistance to the emissions regulations. On March 13, 1973 Chrysler posted a whole page of advertisement on New York Times regarding the proposed 1975–1976 federal emissions standards, claiming that an average consumer could pay as much as 1300 dollars extra to own and drive a car after 1975 but in return the consumers would get very little more than they already had (Chrysler, 1973). The technologies available to meet the 1975 standards by that time included: oxidation catalyst to modify conventional gasoline engine, carbureted stratified-charge engine, the Wankel engine with exhaust thermal reactor, and the diesel engine (Chen et al., 2004). The winner turned out to be the catalytic converter because it did not require major changes to the power-train technologies (Lee, Veloso, Hounshell, & Rubin, 2010). By 1975 model year, 85% of the vehicles were equipped with catalytic converter and by 1977 model year, 90% (Chen et al., 2004). Emissions control devices also came with different levels. For example, more costly three way catalysts were used in large vehicles while less costly oxidation catalysts could be used in smaller vehicles in order to comply with the 1977 and 1978 regulations (Chen et al., 2004). Recently, even more costly catalysts that use precious metals are needed to meet even higher standards (Truett & Beene, 2014).

In general, new technologies always come with additional costs. The major costs associate with the emissions regulation compliance include the costs of tooling new machinery for the new control devices, R&D expenditures to develop the devices and redesign the vehicles to comply with tighter regulations, and finally, the emissions control equipment installed in every vehicle (Chen et al., 2004). Clearly at the beginning of the emissions

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regulation compliance, the emissions control devices installed are the direct reason the vehicles become “greener”. As a result, the cost of emissions control largely attributes to the cost of the emissions control systems, which peaked in the early 1980s range from 875 dollars to 1350 dollars per vehicle (Chen et al., 2004). Newer regulations of emissions continue to raise the bar. Most recently, in 2014, EPA proposed an even tighter tier 3 standards that will be in effective in 2017 (EPA, 2014). With near-zero or zero emissions target, the traditional emissions control equipments such as catalytic converters and exhaust manifolds may not be enough. Eventually, more innovative technologies that will fundamentally change the design of the vehicles are necessary.

Contrary to the compliance with emissions regulations, automakers embrace the regulations of corporate average fuel economy (CAFE) with relative welcoming attitude. According to NRC (2002), in order to increase the fuel efficiency to meet the current and future CAFE standards, there are generally two types of technologies that can be developed and used to achieve the goal – production-intent technologies, which can be applied immediately to the production vehicles, and emerging technologies, which require significant R&D effort before they can be realistically applied (NRC, 2002). Examples of production-intent technologies are variable valve timing in engines, automatic transmissions with more gears, and aerodynamic drag reduction on vehicle designs. Those technologies usually increase the manufacturing cost per vehicle. Since emerging technologies requires significant R&D effort to make the vehicle technologically and/or economically available to more consumers, the major cost to implement the technologies are R&D cost, not the manufacturing cost per vehicle. Among the emerging technologies, one of the most promising ones is electric vehicle technology.

We now take a closer look at the case of electric vehicles, especially electric cars. To the surprise of most people, the electric vehicles have a much longer history than they think (the first small model of electric vehicle was invented in 1828 by a Hungarian inventor Ányos Jedlik, DOE, 2014). As a matter of fact, electric vehicles had been a competing technology with the gasoline-powered vehicles at the very early stage for quite a long time: by 1900 about 38% of US automobiles, 33,842 cars, were powered by electricity while 40% by steam and 22% by gasoline (Shahan, 2014). It was the mass production of Henry Ford’s model T finally beat the electric cars economically in a significant way in 1913. Gasoline-powered cars finally brought the demise of the electric cars in US market by 1935 (DOE, 2014). After more than 30 years, several factors sparked the interests in electric car technologies again (DOE, 2014). One factor was the rising cost and shortage of gasoline especially during the 1973 Arab Oil Embargo. In 1976, the U.S. Congress passed the Electric and Hybrid Vehicle Research, Development, and Demonstration Act to encourage the development of electric vehicle technologies. The CAFE standards also raised the bar of fuel economy for the gasoline-powered technologies as we illustrated in our second example. Another factor, which is the more and more stringent emissions standards and eventually zero emissions requirement, makes electric vehicle one of the most promising solutions to meet the standards. The rise of modern electric vehicle technologies was marked by two important events (DOE, 2014). The first one was the introduction of the Toyota’s Prius model with hybrid technologies, which was the first mass-production hybrid electric car. The second was the birth of a Silicon Valley startup Tesla Motors that later started to produce a luxury electric sports car that could go for more than 200 miles per charge (DOE, 2014). The electrification of vehicles promises to kill two birds with one stone: the hybrid electric cars have great gas economy and the plugin electric cars do not even need gasoline; at the same time both types of electric cars have much less or even zero non-CO_2 emissions.

However, electric car technologies are dramatically different from most of the previously mentioned traditional technologies. The traditional technologies that drive the greening of vehicles, such as the catalytic converters to reduce pollution or the variable valve timing technology to improve fuel economy, all incur additional costs in manufacturing since they require additional devices to install, more material and parts in the vehicles, more expensive material and parts to use, and more assembly work to make the vehicles. Those additional costs are what we call variable manufacturing costs (or simply variable costs) since they are costs per vehicle and therefore are in proportion to the production volume or the sales volume. For those green products of which the driving force of product greenness primarily impacts the variable manufacturing costs as in this case, we call them marginal cost-intensive green products or MIGP’s. On the other hand, large scale adoption of the electric vehicles in the consumer markets requires significant investment in R&D to develop new technologies, especially the battery technologies. These R&D costs are one of the main sources of fixed costs since they are not in proportion to the production volume. At the same time, another source of fixed cost comes from the infrastructure setup cost of the nation-wide charging facilities. In this paper, we call these costs “fixed” to follow the traditional cost accounting convention, and they are the main drivers of electric vehicle development. Therefore, for the products of which the driving force of greenness primarily influences the fixed costs, we call them development-intensive green products or DIGP’s.

The last case to motivate our research is related to competitions (more specifically, the competition on quality and the competition on price) among automotive supply chains. The first part of the case demonstrated an example of competition on quality, in this case, on greenness. According to Miller and Solomon (2009), California first adopted the technology-following approach to the emissions reduction regulations. This approach requires automobiles to install pollution control devices only after two or more vendors have successfully developed the technologies to meet the emissions standard at a reasonable cost. As a consequence of this approach, competition on greenness is induced. The race starts when the greenness target is announced and finishes when the top runner passes the finishing line. The rest of the companies who failed to pass the finishing line will have to purchase the technology from the winner. The technology being regulated in this case is for MIGP since the greenness level of the product depends on the pollution control device. In March 1964, all major auto-makers claimed that they could not meet the new California emissions standards before 1967. However, only three months later, four independent vendors had their emissions control devices certified by the state regulators and none of these vendors were from the major auto-makers (Miller & Solomon, 2009). The major automakers reacted quickly to develop engine modification solutions two months after the certification of the four devices. Eventually, none of the four certified devices were used by the auto-makers. As a result, many independent suppliers left the emissions control market since the investment to develop emissions control technologies cannot be justified in this situation. This dramatic incident eventually resulted in an anti-trust action by the US justice department against the major auto-makers (Miller & Solomon, 2009). In this case competition on greenness failed to achieve its intended purpose to improve the greenness level.

The second part of this case is an example of price competition among automotive supply chains. The State of California learned from the above-mentioned lesson and shifted to technology-forcing approach (Miller & Solomon, 2009). This approach involves a negotiation/consulting process between the regulator and the companies being regulated in order to establish a greenness target and a date to enforce the target. As a result,