

Greening Transportation Fleets

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ABSTRACT

The greening of organizational transportation fleets, especially trucks and automobiles, has gained increasing attention by companies in a variety of industrial sectors. The reasons for this concern and attention are due to regulatory and competitive pressures, but also increasing costs of fossil-fuels. Surprisingly the amount of research and modeling for fleet management overall has been rather limited, with the focus on managing green vehicle investments virtually non-existent. In this study we develop a two-stage game theoretic model that helps evaluate, from both policy and organizational perspectives, the implications of greening of transportation fleets. Various parameters are evaluated including factors such as innovations in green vehicle technology, levels of service differences, cost of fuel, adjusting tax policy, regulatory compliance requirements, and adaptation costs. This evaluation provides practical insights into actions that could be considered by regulators and organizations to encourage environmental investments.

Keywords: Transportation Fleet Management, Environmental, Game Theory, Regulatory Policy, Investment Justification

INTRODUCTION

Within organizations, transportation and distribution activities are major contributors to environmental degradation and resource consumption. The emissions from transportation vehicles and related organizational activities contribute to air emissions that can cause local (smog), regional (acid rain), and global (climate change) environmental implications (Calef and Goble, 2007; Orsato and Wells, 2007). In addition, energy resource consumption from transportation activities by organizations in logistics and transportation industries result in some of their largest operational expenses. Most of these deliveries and logistics activities utilize energy produced by petroleum that is a very volatile commodity whose available inventory as a natural resource is rapidly depleting (Bakhtiari, 2004; Jeffers, 1978; Meng and Bentley, 2008). As environmental concerns are increasingly attracting attention from the public, a widespread adoption of a clean-technology for delivery vehicles has been of critical importance for the practitioners in this industry.

Many alternative energy-based vehicle designs, compared to traditional internal combustion engines, exist including full electric vehicles (MacCready 2004), hydrogen/fuel cell vehicles (Lovins and Cramer 2004; Sperling and Ogden 2004), internal combustion/electric hybrids (Demirdoven and Deutch 2004), biofuels (Rostrup-Nielsen 2005), and compressed natural gas (MacLean and Lave 2003). Each of these technologies has their strengths and weaknesses on various dimensions such as operational performance, environmental, and economic dimensions.

Recent significant developments in consideration and adoption of alternative energy vehicles, especially electric/internal combustion engine hybrids, have started to occur among companies in a wide variety of companies and industries. Some examples include logistics and delivery services such as UPS (Gallagher, 2007) and Fedex (Birchall, 2006); retail giant Wal-Mart (Birchall, 2006); telecommunications and utilities such as AT&T (Energy Resource, 2008) and Verizon (Wireless News, 2008); large and small beverage companies such as Coca-Cola (Cioletti, 2008), Pepsi (Deierlein, 2007) and VinLux Fine Wine (Mele, 2008); and even companies within the forestry (Fleet Equipment, 2007) and banking industries (Carr, 2007). Even though some of these companies have trucking and transportation fleets that number in the tens of thousands, most are only considering to adopt or adopting dozens of vehicles. Thus, there is ample room to grow in the adoption of these vehicles, but careful competitive, strategic and operational considerations must be made. Also, guidance, support and encouragement from policy makers and regulators may provide different environmental contexts for the adoption of these types of vehicles.

In this paper, we will investigate how external policies and internal organizational decisions play a role in these environmentally oriented investment decisions, such as greening transportation fleets for organizations, using a two stage game theoretic framework. The specific problem environment in this paper focuses on determination of the level of hybrid or alternative energy delivery fleet for a logistics and transportation company. In this framework firms choose the adoption level and the percentage of their fleet that should be 'green', in the first stage, and the optimal level of price in the second stage. We assume an asymmetry between the firms by initially crediting high environmentally oriented quality service for one firm when compared to

competing firm. This high-low environmental quality difference is derived from the model and is treated as an exogeneity; this situation not only reflects the fact that firms generally have different market shares in equilibrium, but it is also useful for investigation of insightful propositions which cannot be drawn from a symmetrical model. After presenting the model and solving for equilibrium conditions, we provide some exemplary and illustrative results of the effects of the change in important organizational and policy parameters. These parameter scenario analyses provide additional insights for organizational and regulatory policy issues, which can then be used for evaluation and justification of alternative decisions facing investments in environmentally oriented transportation technology, specifically alternative energy transportation vehicles and/or technology. We conclude with an overview summary and possible extensions to this work.

REGULATORY AND ORGANIZATIONAL EVALUATION OF ENVIRONMENTAL INNOVATION

To exemplify some of the nuances of environmentally-oriented organizational decisions for transportation fleet management let us consider the case of FedEx, one of the leading organizations in developing and adopting an alternative energy, hybrid transportation fleet. Environmental Defense and FedEx had been collaborating to source a new generation of delivery trucks since 2000, which was expected to bring a huge improvement in fuel efficiency and pollution emission. As a reasonable course of this collaboration, FedEx joined forces with manufacturers to develop the necessary technology for its trucks and purchased a number of clean, relatively energy efficient trucks, known as hybrid delivery fleet. The multiple partnerships involved technological supporting groups, like Eaton Corporation (transmission technology) and Freightliner (chassis technology). Environmental Defense estimated that for every 10,000 conventional FedEx delivery trucks, which cause serious environmental and health damages through diesel exhaust, replaced by cleaner hybrids, pollution reduction of 2,000 tons per year would occur. Moreover, diesel fuel usage would be reduced by 6.5 million gallons per year bringing significant benefits to the organization, according to the estimate. A study prepared for the Texas Council on Environmental Technology

(TCET) estimated that the future price of diesel electric hybrid trucks would be 30% higher than that of the conventional ones if the production reaches to the mature stage, while the maintenance cost would be 10% lower through electric power supplements¹. These estimated results occurred even before the costs of petroleum more than doubled in more recent years.

The decision for adoption of these types of alternative energy and hybrid vehicles may bring improved environmental performance for the benefit of society. But it is expected that this adoption contributes to additional financial burdens for organizations, in some areas, on initial investment, operational, and maintenance costs, especially over a short time span.

An organizational justification issue now arises based on these tradeoffs. What benefit could be accrued for organizations where they would be willing to adopt a short-term cost burden from this environmentally oriented investment strategy of greening their transportation fleets? This is where organizations need to make the 'business case' for these types of investment. Making the business case for environmentally sound practices is not always a trivial decision (Presley and Sarkis, 1994; Presley et al., 2007). The business case involves both operational and strategic costs and benefits that need to be integrated into an evaluation. The difficulty with environmental issues and concerns are the many possible scenarios, both competitively and regulatory based that can effect the organization's decisions.

There are at least two broadly-defined alternative ways of approaching this problem; one is related to issues of responding to governmental and regulatory behavior on environmental issues, and the other is concerning the firm's long run, competitive perspective. Regulators are consistently under pressure by their constituencies to introduce frameworks and policies for reducing the level of the environmental damage caused by organizational production processes, products and activities. The policy frameworks may include a variety of instruments but can generally be grouped to include 'carrots', as well as 'sticks' (Meyer, 1999; Kassinis and Vafeas, 2006). That is, governmental regulators could provide subsidies for R&D projects designed for a

¹ Stanford Graduate School of Business, "FedEx and Environmental Defense : Building a Hybrid Delivery Fleet", Case SI-82, Jan, 2006

reduction of the pollution level, or give tax and price incentives for a spread of emission-free equipment and facilities (Fronde!, et al., 2008), the carrot approach. Regulators may also specify a standard for a maximum level of environmental damage or tax a firm that contributes to these negative externalities, the stick approach. For example, in California, policymakers used a “technology-forcing approach,” setting ambitious goals such as zero emission *vehicles*, established strict deadlines and issued penalties for non-compliance. In France similar regulations, albeit more flexibly oriented, were also introduced to increase the use of hybrid and low-emission vehicles (Calef and Goble, 2007). These behaviors of governments will generally impose certain responses from a firm related to their own internal environmental issues and policies.

The second possible way of evaluating and addressing the issue of organizational investment in green technologies such as environmentally oriented vehicles, may come from consideration of a firm’s long run competitive stance (Berchicci and King, 2007; Rugman and Verbeke, 1998; Sarkis and Cordeiro, 2008). A firm may pursue investments regardless of whether there is short term loss, which usually occurs because of other competitive reasons that may not be easily quantifiable such as an environmentally-friendly public image as a very important asset for success in its future businesses (Konar and Cohen, 2001). The benefits of a good public image may come through various sources like a firm’s savings in advertisement cost, relatively high willingness to pay for its products from the consumers, and productivity increases from a higher morale of workers (Lyon and Maxwell, 2008; Mahenc, 2008; Miles and Covin, 2000). Given the cost and benefit of adopting an environment-friendly new technology or new equipment, we might ask what will happen to the optimal level of adoption if there is a change in the circumstances in which a firm is doing business. For instance, how would the optimal level of adoption change if governments move towards ‘carrots’ rather than ‘sticks’? Which would be more effective for increasing the optimal level, an R&D subsidy or price subsidy on new equipment? These and other issues have been of concern, but have not really been fully considered in the research literature, especially with respect to the issue of organizational investment in greening their transportation fleets. Also, even though the recognition of the importance of operations research tools to environmental management problems has some history (e.g. Allet, 1986; Jeffers, 1978; Lenihan, 1986;

Somerville, 1986; Sarkis and Cordeiro, 2008), the visibility and application of these tools has been relatively limited (Midgley and Reynolds, 2001). The applications to specific organizational investments and adoption of practices, especially within a transportation investment perspective, are virtually non-existent. We begin to address this issue and gaps in the research with the models and experimentation in this paper.

STRATEGIC CHOICE OF AN ENVIRONMENTALLY-FRIENDLY, ‘GREEN’, TRANSPORTATION FLEET: A MODEL FORMULATION

For our model development we initially consider a duopoly model with vertical differentiated products (Mussa and Rosen, 1978). In this duopoly game two firms (A and B) offer transportation logistics, distribution, and delivery service to potential customers. Their services are differentiated with respect to the quality of delivery service (i.e., delivery time, reliability, customer service, etc) and environmentally-friendly deliveries (which require new investment in transportation equipment) (i.e., reduction in the relative ratio of emissions). In this paper, we assume a fixed quality of delivery service γ_j ($j = A, B$) since our focus will be on decisions facing a firm’s greening of its transportation fleet. The delivery fleet of each firm, initially, consists of T traditional trucks (i.e., diesel powered trucks) which emit pollutant Θ per truck (we assume that each delivery requires one truck). Therefore, the level of total emissions equals $\Theta \cdot T$. Each firm is assumed to have an option to replace its old trucks with environment-friendly trucks (i.e., hybrid or green trucks) with improved fuel efficiency and environmental performance, lessened emissions. If firm j adopts the new greener trucks, the new formation of its fleet becomes $T \equiv O_j + N_j$ where the number of old trucks and new trucks are denoted by O_j and N_j respectively. This replacement decision carries a trade-off in the sense that each replacement improves fuel efficiency and environmental performance at the expenses of new procurement cost and infrastructure requirement. Therefore, the delivery firms choose their optimal numbers of new trucks carefully balancing these factors.

We now introduce the aspect of improved environmental performance into our model. Compared to the level of per-truck emissions of the old truck Θ , the green truck

is assumed to reduce its emission level by $\alpha \cdot \Theta$ where the parameter α captures the technological efficiency of reducing emissions with $\alpha \in [0,1]$.

Given the choice of an adoption level of the new greener trucks (N_j), the level of total emission is equal to $\Theta O_j + (1 - \alpha) \Theta N_j$, which becomes $\Theta(T - N_j) + (1 - \alpha) \Theta N_j$.

For computational convenience, we assume that the ratio of new greener trucks ($\frac{N_j}{T} = n_j$) with T normalized to 1 as a choice variable in the first stage of the game. We assume that the government (local or national) regulatory policy requires that firms deliver items in an environment-friendly to comply the maximum level of emissions, denoted by $\bar{\Theta}$. For notational simplicity, we define the relative measure of the level of emissions by $\theta \equiv \Theta / \bar{\Theta}$, with $\theta \in [1, \infty)$. Note here that with this definition, a tougher government regulation would imply $\bar{\Theta} \downarrow \Rightarrow \theta \uparrow$, and a more lax governmental regulation would dictate $\bar{\Theta} \uparrow \Rightarrow \theta \downarrow$.

In the framework of vertical differentiation it is assumed that customers are heterogeneous in their marginal benefit of delivery service, which is denoted by v . For example, v can be a measure of a marginal impact on its public image when it uses more environmentally efficient delivery service. The differentiation in customer expectations from an environmental expectations perspective is well studied in the green marketing literature (Ginsberg and Bloom, 2004). Consumers have been studied and grouped into those that are extremely environmentally conscious ‘true-blue’ greens to those that are apathetic or ‘grousers’ or ‘basic browns’ (Doane, 2005). Organizational environmental sensitivity of organizations will drive industrial markets and is also dependent on various stakeholder pressures that they may face from their customers, their supply chains, and regulatory forces (Zhu and Sarkis, 2006). Given these practical industrial situations and market differences, we assume there is a population of customers whose total number is equal to m and that each customer buys at most one unit service from delivery firms. For simplicity, we assume that a uniform distribution of customer types and their marginal benefits is given by $v_i \in U[0,1]$. We assume that consumers will appreciate a firm’s endeavors to contribute to cleaner air and other environmental benefits of greener vehicles. Thus, consumer’s expected valuation with respect to environmental

performance is given by $0(1-n_j)+\alpha\theta n_j$, and hence $s_j=\gamma_j+\alpha\theta n_j$, where s_j denotes the sum of the quality of delivery service and the relative reduction in emissions. Using this setup, the net utility for a customer with v_i can be represented as (1):

$$u(v_i) \stackrel{def}{=} \underline{s} + s_j v_i - p_j = \underline{s} + [\gamma_j + \alpha\theta n_j] v_i - p_j \quad (1).$$

for a given price p_j and a formation of the delivery fleet (O_j, N_j) with $j = \{A, B\}$. Here we assume that an organization's decision to lower a pollution emission related to its delivery service by employing greener trucks is recognized and acknowledged by consumers exactly to the extent it lowers by an adopting a greener transportation fleet. In this paper, note that the emission reduction is a voluntary activity since each firm is assumed to be endowed with a minimum quality level \underline{s} , large enough to cover the market.²

Adoption of green technology also affects fuel efficiency and the cost structure associated with vehicle investment, operation and maintenance. We assume that the marginal cost of delivery by firm j is initially c per delivery, which can be reduced by $\delta \cdot c$ when adopting n_j new greener trucks, or greening the organization's transportation fleet. Therefore, the total energy fuel cost becomes $C(n_j, q_j) = [c(1-n_j) + (1-\delta)cn_j]q_j = c[1-\delta n_j]q_j$ where q_j denotes firm j 's demand for its delivery service which will be derived explicitly in stage two. Adopting a new technology, however, will increase other costs. The procurement cost of new hybrid trucks is higher than the traditional trucks. Also there are adaptation costs for workers, retraining for the new technologies in the trucks, and facilities and infrastructure to support the new technology. A firm is assumed to pay μ more per new greener truck (annually calculated) which measures an extra cost a firm should pay in excess of comparable traditional trucks. Also the green trucks with new technology will incur maintenance and infrastructure costs (adaptation costs) to ensure green trucks operate

² A covered market means that the minimal expectations of all customers are met with this level of quality. Some papers adopt a vertical differentiated product model with covered market. See Crampes and Hollander (1995), Boom (1995), Ecchia and Lambertini (1997), Maxwell (1998), Wang and Yang (2001), and Wang (2003).

properly, which is assumed to be an increasing convex function of the rate of adoption. This cost may be defined as $I(n_j) = \omega n_j^2 + \mu n_j$, where ω captures the marginal impact of the adaptation costs. Finally, we introduce a government or regulatory penalty cost to make environmental regulation compliance binding for a firm's decisions. Note that when $\theta < \frac{1}{1-\alpha}$, the emission level of new greener truck passes a set governmental regulation: $\frac{\Theta}{\bar{\Theta}} < \frac{1}{1-\alpha} \Rightarrow (1-\alpha)\Theta < \bar{\Theta}$. Therefore, the penalty cost may exhibit two different cases depending on the values of parameters as shown in expression (2).

$$F(n_j, q_j) = \begin{cases} \tau [(\theta-1)(1-n_j) + ((1-\alpha)\theta-1)n_j] \cdot q_j = \tau [\theta-1-\alpha\theta n_j] \cdot q_j & \text{if } \theta \geq \frac{1}{1-\alpha} \\ \tau [(\theta-1)(1-n_j)] \cdot q_j = \tau [(\theta-1)(1-n_j)] \cdot q_j & \text{if } \theta < \frac{1}{1-\alpha} \end{cases} \quad (2)$$

where τ is the marginal rate of tax charged on the relative level of pollution emissions. Combining all of these costs, we derive the total cost function (3).

$$TC(n_j, q_j) = C(n_j, q_j) + F(n_j, q_j) + I(n_j) \quad (3)$$

SOLVING FOR EQUILIBRIUM IN THE TWO-STAGE GAME

To help solve the adoption problem we consider a two-stage game with the following stages:

Stage one: Each delivery service firm (A and B) chooses n_j for its formation of the green transportation fleet (O_j, N_j) to improve fuel efficiency and environmental performance.

Stage two: Each firm chooses its price (p_j) to maximize its profit.

To find the Subgame Perfect Nash equilibrium (SPNE), we begin with period two.

1. Stage Two: price competition with given adoption rate

In Stage Two, with given quality levels (s_A, s_B) , which is determined by (n_A, n_B) in stage one, the two firms (A and B) compete for customers in terms of pricing. Even though there are pricing expectations, it is assumed that due to competitive reasons the environmental performance expectations are at a minimal level or higher in this green environment competitive market. When customers make their purchase decision, they choose the option that yields the highest net utility. We consider the case of $s_A > s_B$, without loss of generality, where firm A is competing primarily on maintaining higher environmental performance/image than its competitors and firm B will have the option to further improve its environmental performance or further compete on pricing. In this case, a customer's optimal choice between products or companies for a given price and environmental performance level can be divided as follows:

$$\begin{aligned} \frac{p_A - p_B}{\alpha\theta(n_A - n_B) + (\gamma_A - \gamma_B)} &\leq v && \text{purchase product from Firm A} \\ v < \frac{p_A - p_B}{\alpha\theta(n_A - n_B) + \gamma_A - \gamma_B} &&& \text{purchase product from Firm B} \end{aligned}$$

Thus, for a given price and environmental performance level, there will be a customer with environmental performance expectations denoted by \hat{v} that is indifferent between buying a transportation or logistics service from firm A and B if $\underline{s} + [\gamma_A + \alpha\theta n_A]\hat{v} - p_A = \underline{s} + [\gamma_B + \alpha\theta n_B]\hat{v} - p_B$.

This feature of the self-selection choice of customers between companies is shown in Figure 1.

Figure 1 about here

Each firm's product demand then can be described as

$$q_A = m(1 - \hat{v}) = m \left(1 - \frac{(p_A - p_B)}{\alpha\theta(n_A - n_B) + (\gamma_A - \gamma_B)} \right) \text{ and}$$

$$q_B = m\hat{v} = \frac{m(p_A - p_B)}{\alpha\theta(n_A - n_B) + (\gamma_A - \gamma_B)} \quad (4).$$

Given the cost function described above, firm j maximizes its profit by

$$\text{Max}_{p_j} \pi_j = p_j q_j - C(n_j, q_j) - F(n_j, q_j) - I(n_j) \quad (5).$$

By solving each team's profit maximization problem, we derive the equilibrium price (p^*) and market share (q^*) as follows.

$$p_A^*(n_A, n_B) = \begin{cases} \frac{1}{3} [3(c + (\theta - 1)\tau) - 2(\delta c + \alpha\theta(\tau - 1))n_A - (\delta c + \alpha\theta(2 + \tau))n_B + 2(\gamma_A - \gamma_B)] & \text{if } \theta \geq \frac{1}{1 - \alpha} \\ \frac{1}{3} [3(c + (\theta - 1)\tau) - 2(\delta c - \alpha\theta + (\theta - 1)\tau)n_A - (\delta c + 2\alpha\theta + (\theta - 1)\tau)n_B + 2(\gamma_A - \gamma_B)] & \text{if } \theta \leq \frac{1}{1 - \alpha} \end{cases}$$

(6a),

$$p_B^*(n_A, n_B) = \begin{cases} \frac{1}{3} [3(c + (\theta - 1)\tau) - (\delta c + \alpha\theta(\tau - 1))n_A - (2\delta c + \alpha\theta(1 + 2\tau))n_B + (\gamma_A - \gamma_B)] & \text{if } \theta \geq \frac{1}{1 - \alpha} \\ \frac{1}{3} [3(c + (\theta - 1)\tau) + (-\delta c + \alpha\theta + \tau(1 - \theta))n_A - (2\delta c + \alpha\theta + 2\tau(\theta - 1))n_B + (\gamma_A - \gamma_B)] & \text{if } \theta \leq \frac{1}{1 - \alpha} \end{cases}$$

(6b),

$$q_A^*(n_A, n_B) = \begin{cases} \frac{m[(c\delta + \alpha\theta(2 + \tau))(n_A - n_B) + 2(\gamma_A - \gamma_B)]}{3(\alpha\theta(n_A - n_B) + \gamma_A - \gamma_B)} & \text{if } \theta \geq \frac{1}{1 - \alpha} \\ \frac{m[(c\delta + 2\alpha\theta + (\theta - 1)\tau)(n_A - n_B) + 2(\gamma_A - \gamma_B)]}{3(\alpha\theta(n_A - n_B) + \gamma_A - \gamma_B)} & \text{if } \theta \leq \frac{1}{1 - \alpha} \end{cases} \quad (7a),$$

$$\text{and } q_B^*(n_A, n_B) = \begin{cases} \frac{m[(c\delta + \alpha\theta(\tau - 1))(n_A - n_B) - (\gamma_A - \gamma_B)]}{3(\alpha\theta(n_A - n_B) + \gamma_A - \gamma_B)} & \text{if } \theta \geq \frac{1}{1 - \alpha} \\ \frac{m[-(c\delta - \alpha\theta + (\theta - 1)\tau)(n_A - n_B) + (\gamma_A - \gamma_B)]}{3(\alpha\theta(n_A - n_B) + \gamma_A - \gamma_B)} & \text{if } \theta \leq \frac{1}{1 - \alpha} \end{cases} \quad (7b).$$

The corresponding equilibrium profits are as follows

$$\pi_A^*(n_A, n_B) = \begin{cases} \frac{m \left[(c\delta + \alpha\theta(2+\tau))(n_A - n_B) + 2(\gamma_A - \gamma_B) \right]^2}{9(\alpha\theta(n_A - n_B) + \gamma_A - \gamma_B)} - \mu n_A - \omega n_A^2 & \text{if } \theta \geq \frac{1}{1-\alpha} \\ \frac{m \left[(c\delta + 2\alpha\theta + (\theta-1)\tau)(n_A - n_B) + 2(\gamma_A - \gamma_B) \right]^2}{9(\alpha\theta(n_A - n_B) + \gamma_A - \gamma_B)} - \mu n_A - \omega n_A^2 & \text{if } \theta \leq \frac{1}{1-\alpha} \end{cases}$$

(8a) and

$$q_B^*(n_A, n_B) = \begin{cases} \frac{m \left[(c\delta + \alpha\theta(\tau-1))(n_A - n_B) - (\gamma_A - \gamma_B) \right]^2}{9(\alpha\theta(n_A - n_B) + \gamma_A - \gamma_B)} - \mu n_B - \omega n_B^2 & \text{if } \theta \geq \frac{1}{1-\alpha} \\ \frac{m \left[-(c\delta - \alpha\theta + (\theta-1)\tau)(n_A - n_B) + (\gamma_A - \gamma_B) \right]^2}{9(\alpha\theta(n_A - n_B) + \gamma_A - \gamma_B)} - \mu n_B - \omega n_B^2 & \text{if } \theta \leq \frac{1}{1-\alpha} \end{cases}$$

(8b).

2. Stage one: choice of environment-friendly quality investment and quality level

At stage one, we now turn to firm j 's optimal choice on its transportation fleet formation. The objective is to simply maximize equation with respect to n_j , which yields the following necessary first-order condition:

$$\frac{d\pi_A^*(n_A, n_B)}{dn_A} = \begin{cases} \frac{1}{9} \left(\frac{4c\delta m + 4\alpha\theta m(1+\tau) - 9\mu - 18\omega n_A}{(\alpha\theta(n_A - n_B) + \gamma_A - \gamma_B)^2} + \frac{2m(c\delta + \alpha\theta\tau)^2(n_A - n_B)}{\alpha\theta(N_A - N_B) + \gamma_A - \gamma_B} \right) & \text{if } \theta \geq \frac{1}{1-\alpha} \\ \left(\frac{(p_A^*(n_A, n_B) - c(1-\delta n_A) - \tau(\theta-1)(1-n_A))m(c\delta + \tau(\theta-1))(\gamma_A - \gamma_B)}{3(\alpha\theta(n_A - n_B) + \gamma_A - \gamma_B)^2} + \frac{1}{3}(2c\delta + \alpha\theta + 2\tau(\theta-1))q_A^*(n_A, n_B) - \mu - 2\omega n_A \right) & \text{if } \theta \leq \frac{1}{1-\alpha} \end{cases}$$

(9a),

$$\begin{aligned}
& \frac{d\pi_B^*(n_A, n_B)}{dn_B} \\
& = \begin{cases} \left(\frac{1}{9} \left(\frac{2c\delta m - \alpha\theta m - 9\mu - 18\omega n_B}{\left(\alpha\theta(n_A - n_B) + \gamma_A - \gamma_B \right)^2} + \frac{2m(c\delta + \alpha\theta\tau)^2(n_A - n_B)}{\alpha\theta(N_A - N_B) + \gamma_A - \gamma_B} \right) \right. & \text{if } \theta \geq \frac{1}{1-\alpha} \\
\left. \left(\left(p_B^*(n_A, n_B) - c(1 - \delta n_B) - \tau(\theta - 1)(1 - n_B) \right) \frac{m(c\delta + \tau(\theta - 1))(\gamma_A - \gamma_B)}{3(\alpha\theta(n_A - n_B) + \gamma_A - \gamma_B)^2} \right. \right. & \text{if } \theta \leq \frac{1}{1-\alpha} \\
\left. \left. + \frac{1}{3}(c\delta + \alpha\theta + \tau(\theta - 1))q_B^*(n_A, n_B) - \mu - 2\omega n_B \right) \right) &
\end{cases}
\end{aligned}$$

(9b).

EMPIRICAL INVESTIGATION AND DISCUSSION

Due to the complex algebraic expressions in equations (9a) and (9b), it is mathematically intractable to derive the optimal equilibrium environmental performance level choice of the firms in explicit functional forms. To understand the decision mechanism of the firms and the results from the equilibrium of this game, we execute some numerical analyses using a simulation method. In this empirical analysis, we compare the effects on the decision variables (adoption level of new greener trucks by firms A and B (n_A^*, n_B^*) , and price (p_A^*, p_B^*)) of the exogenous parameters, α (a marginal increase in environmental performance), c (unit fuel cost), δ (factor of marginal increase in fuel efficiency), θ (marginal increase of government regulation on the relative level of emissions), μ (new technology procurement cost), $\gamma_A - \gamma_B$ (the quality gap between firms' delivery services), and τ (marginal tax rate on pollution emissions).

In this two stage duopoly game, it is important for a meaningful simulation to have an interior solution as a benchmark case. At first, we approach this task by approximating some of the parameter values to those of the real world. For instance, we set $\alpha = 1$ and $\delta = 1$. Other parameters like c , τ , $\gamma_A - \gamma_B$ are initially set to 1 without loss of generality. Since n_j is assumed to be less than 1 (it is expressed as a relative ratio to T), the optimal value of n_j is more sensitive to μ , rather than ω . It was also sensitive to

m (the total population of consumers). We initially fixed m first, then found ω and μ , for an interior solution satisfying $0 \leq n_j^* \leq 1$, where $n_A > n_B$. A relatively stable initial equilibrium solution³ was provided by $\omega = 300$, $\mu = 5$.

After finding a reasonable numerical instance of an equilibrium solution, we completed a simulation that is stable around this local equilibrium. The results were relatively robust and stable. Since we are more interested in the direction of the changes of decision variables affected by a change in exogenous parameters, we completed a simulation centering on this initial equilibrium as a benchmark. The following simulation results show equilibrium changes from this initial equilibrium, given changes in a specific parameter concerned. By this method, we could derive some insightful observations concerning key policy and organizational decision issues.

Basic results

We initially frame the competitive situation with firm A producing a qualitatively better product and service and adopting higher levels of green technology, and thus we identify it as the first mover. By the same token, let's call firm B the late comer or laggard.

Result 1 (the effect of the improvement in green technology): Our first situation is to focus on the efficiency of the green technology (α) through improved engines, motors, drive trains, battery power, or even weight of vehicle with fewer emissions. Let us assume that the technology may improve and reduces pollution emission at greater rates. As seen in Table 1 we increase the value of α from .1 to .2. The first mover firm A in this case will increase the adoption rate (n_A^*), while the laggard, firm B will slightly decrease it (n_B^*). But in total, this change will induce more adoption in the industry (i.e., $n_A + n_B$ increases). Both firms will tend to set higher prices (p_A^* and p_B^*), but the price competition will be less intense, as firm A becomes more aggressive in raising its price. This result, interestingly, will benefit both firms, leading to higher

³ To determine well-behaved interior solutions without discontinuous jumps or kinks in the optimal price and n , we find these values of parameters after a large number of calculations.

profits. But the first mover will tend to get a slightly larger sales or market share (q_A^*) and become the larger beneficiary of the improved environmental efficiencies. This is an interesting case in the sense that with improved green technology, both firms will gain by widening environmental performance (n_A^*/n_B^*) and price differences. Of course, as prices go up, customers will ultimately have to pay.

Table 1 about here

Result 2 (the effect of fuel cost): As energy cost (i.e., gas prices) increases, both firms will increase their adoption rates of greener transportation fleets by making a larger percentage of their vehicles greener. Yet, the late comer firm B will be more aggressive in its adoption, see Table 2. Hence, the relative ratio of adoption rate (n_A^*/n_B^*) will decrease. Both firms would set higher prices, but the price competition becomes more intense, since the late comer will increase their price faster. Nonetheless, the first mover will ultimately gain since its market share and profit will be larger. Clearly, economic forces will play a much larger role in getting laggards to adopt environmentally sound, conserving energy. An implication here is that increased gas taxes may be useful to get organizations to adopt these greener vehicles.

Table 2 about here

Result 3 (the effect of energy efficiency improvement): As the new greener truck becomes more efficient in energy usage, both firms will increase their adoption rate, as shown in Table 3. The late comer will be more aggressive in adoption, decreasing the gap of adoption rates (n_A^*/n_B^* gets smaller) but at larger efficiency rates (larger than $\delta = 0.3$) we see that the leading firm (A) takes more adoption initiative, increasing the gap. The price gap lowers since firm A will decrease its price at a faster rate. Both companies will tend to decrease their prices. As price competition in the market increases, firm A will ultimately gain market, while firm B will lose market share. Major winners

in this scenario are customers who will gain through improved prices and price competition. As a result, cost savings are passed on to them.

Table 3 about here

Result 4 (the effect of tougher regulatory policy on emission levels): As the regulators ratchet up standards, lowering levels of emissions, (i.e., higher θ), both firms would increase the adoption level (Table 4, n_A^* and n_B^*). Firm A, the environmental leading first mover firm, adopts at a faster rate as emissions regulations tighten. The prices charged customers will tend to increase for both companies (p_A^* and p_B^*). Firm A will charge higher prices at an increasing rate, as seen in the increase in the price gap (p_A^*/p_B^*). Interestingly, the market will further differentiate on environmental performance, causing firm A to ultimately gain with higher market share and profit.

Table 4 about here

Result 5 (the effect of initial quality difference in service): We now consider what happens when operational quality differences in terms of delivery and service occur between the two firms. As the difference in quality increases (see Table 5), Firm B, the laggard in adoption of green vehicles, becomes more aggressive in adopting the green vehicles, increasing its percentage of green vehicles in its transportation fleet, other things being equal. Firm A, the first mover and the firm providing better quality service, will actually lower the adoption rate as the initial difference in quality becomes larger. This result decreases the gap between the two firms adoption of the new greener trucks. Interestingly, the overall adoption rate of the green vehicles ($n_A^* + n_B^*$) does not change for both firms. Prices for both firms will increase, but the effect of initial quality differences and investments made in them will dominate as firm A will increase price faster than firm B, resulting in a wider price gap. Both firms will benefit by this change (profits will increase), but the late comer will benefit more since it gets a slightly higher market share (q_A^*/q_B^*) and faster increase in profit (π_A^*/π_B^*). This is a case where a shift in operations strategy to a quality oriented competition may benefit both firms, while it hurts customers through higher prices. We also note that Firm A, as a leading firm in environmental areas, tends to invest less in an environmentally sound transportation fleet as this shift to quality

competition increases. The lagging company Firm B shifts to an environmental focus, realizing that it cannot compete as effectively on operational and quality measures. Firm A will lose some of its market share to Firm B within this situation.

Table 5 about here

Result 6 (the effect of adaptation costs): As the expected adaptation costs increase, both firms will decrease the adoption of new technology, but the first mover, firm A will decrease at a faster rate (see Table 6). Prices will go up, but the price gap will become slightly wider since firm A will be faster in setting higher prices. Firm B will ultimately gain a larger market share and higher profit, i.e., as the cost of adoption due to adaptation costs for supporting systems becomes higher, the first mover advantage backfires.

Result 7 (the effect of marginal tax rate on pollution emission): As the government charges more penalties on a firm's violation of emission standards, both firms will increase greening their transportation fleets (Table 7). In this situation the late comer will complete this greening at a faster rate. Prices set by both firms will tend to increase but the price gap will lessen as firm B's price increases at a higher rate. The intensified price competition will be beneficial to firm A as their environmental leadership position will allow them acquire more market share and higher profit. In this scenario, all other factors being equal, Firm B, the laggard company will lose. The first mover definitely will be at an advantage.

Discussion of Results

Policy and Organizational Implication 1: Pollution standards vs. Taxation.

To improve the environmental quality, the government can use two different policies. One is to tighten the pollution standards, and the other is to tax the violation more severely. Essentially, this approach is based on either command-and-control or market based mechanism approaches. In this two stage quality-price competition model,

both policies will help to increase the adoption rate of green technology by increasing the percentage of new greener trucks adopted for an organizational delivery fleet. These policies also increase the prices for the organizational services (and hence are detrimental to customers). But, some differences do exist. First, with tighter regulatory standards, the first mover organization will move faster, increasing adoption rates for greener transportation fleets at higher rates. More severe tax regulations will cause faster adoption rates for environmentally-friendly fleets for the late comer in adoption. In other words, a tighter regulation on standards will induce more response from the first mover in adoption rate, while a strengthened tax regulation will influence the late comer more sensitively. The implication for policy makers is relatively clear here, if they wish to get organizations that have lagged in their implementation of green vehicles, then taxing emissions may provide a more effective adoption strategy.

Another issue here is that more restrictive regulatory standards will induce relatively faster increases in firm A's price leading to a widened price gap. Tax regulation will drive firm B, the follower organization to raise prices more quickly resulting in a more intense price competition. Combined, both measures will induce higher adoption of green technology, but a tighter standards regulation will be more effective in this model setting. An organizational implication here is which policy the firm should support. In both regulatory cases, firm B tends to lose market share and profitability relative to firm A. But, using our ranges and scales, firm B's market share (q_B^*) is decreasing at a faster rate under the more strict command and control policy (about a 5% difference), than under the penalties and taxes policies (about a 2% difference). In this situation, firm B, given that they will inevitably face one of these policies, may wish to lobby regulators for a tax on emissions rather than making more strict regulatory standards.

In summary, standards regulation is more effective for inducing greener fleets within industry, but can cause increased prices and widening the price gap. This means that there is greater differentiation in environmental strategy (environmentally-friendly fleet adoption) and price differences become more prevalent with lesser competition in price.

Policy Implication 2: Direct Cost subsidy vs. R&D subsidy.

Governments can also provide some “carrots” rather than “sticks”. Here we compare two different methods of subsidizing the industry. First, the government may subsidize R&D endeavors leading to an increase in the efficiency of the technologies needed for green vehicles. In our model, this may be interpreted as an exogenous increase in α . Second, governments may provide direct subsidies lightening the burden of the adjustment costs for an adoption. This effect may be reasoned through an exogenous decrease in ω or μ in our model. As already mentioned, direct subsidy on the adaptation cost will bring more adoption in both firms with larger rate of response in greening their transportation fleet from the first mover, firm A. Prices in this situation will be lowered by both firms. This is a larger drop in the price of firm A, with price competition becoming more intense. This situation will benefit firm A and cause firm B to be at a disadvantage. The effects of an R&D subsidy are more impressive in the sense that both firms benefit. The first mover will definitely respond positively, increasing both adoption rate and price, while the late comer does not respond favorably in this exercise; firm B will have a slightly lower the adoption rate, but will increase its price. In this situation firm B will choose a strategy to widen the environmental quality-price difference, to garner extra profit. This situation is good for firms, but bad for customers who seek lower prices; in this framework, a direct subsidy for adaptation will be more beneficial to customers since it will lower the price of the final product and service, while the R&D subsidy ultimately will push prices upward, though it will benefit firms. In sum, direct subsidies will be more effective for greening transportation fleets, and more beneficial to customers since it will lower the final price. Consumer advocate groups may wish to lobby for direct subsidies instead of R&D subsidies, where they can get better service, better environmental performance, and solid service.

CONCLUSION

Environmental concern is increasingly gaining weight in every industry throughout the world. One of the major areas that industry causes substantial environmental burden is in its transportation and logistics activities. A major factor in transportation and delivery environmental implications is the characteristics of the transportation fleets for organizations. Many organizations in a wide variety of industries

have recognized that planning and managing their transportation fleets requires consideration of their environmental burden. Thus, there is an increasing awareness of and responses to the importance of greener vehicle technology and a few meaningful changes are in progress.

Firms are not playing competitive games in a vacuum and they are constantly under significant competitive pressures. For a meaningful understanding of this interaction and the resulting equilibrium behavior of firms, we analyzed the situation with the help of a quality-price two stage game theoretic model developed and used in economics literature. By applying the widely acknowledged solution concept of the model, we derived numerous insightful results. First, R&D subsidy, or investment, for basic technology development may be beneficial to organizations by increase firm profits, but it may occur at the expense of customers with higher prices charged. Of course these customers will benefit from improved environmental results from greener transportation fleets. Second, energy price shocks will help to induce a better response from the industry as a whole for an adoption of greener transportation technology. The resulting intensified price competition will put organizational late comers at a disadvantage. Third, as the energy saving aspect of alternative fuel and energy technologies becomes clearer, late comers will be more aggressive in adoption, leading to intensified price competition. This situation also will benefit customers through lowered final prices. Fourth, as the regulators become stricter in environmental regulations, overall industry will adopt greater amounts of greener vehicle technologies. Customers in this situation will face through higher prices. The first mover will reap the gain from this government intervention in both cases, raising standards regulations will lead to more quality competition, while tax regulation is likely to induce more price competition. Fifth, subsidizing directly for adaptations costs related to the adoption of greener technology might induce better results in the sense that it will induce more adoption and lowered prices than R&D subsidies. Sixth, a wider initial quality difference in services and products will induce a greater response from late comer firms, which may be a larger percentage of firms overall, and be better for firms since it reduces price competition but with a general increase in prices.

These results are generated based on an initial equilibrium calculation we found with specific parameter values, which were presupposed outside the model. Therefore, there might be a problem of 'status quo bias' in the sense that the simulation results are dependent on the initial equilibrium we selected. Additional sensitivity analysis varying parameters is required to detect further nuances. Yet, the qualitative results and insights from our simulation show the capabilities of the game theoretic model here to provide some very robust analysis. Intuitively, we can safely state that the analysis does make sense.

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Table 1. Numerical Analysis with respect to a marginal increase in environmental performance (α)

(with $m = 1000, c = 1, \delta = .1, \gamma_A = 2, \gamma_B = 1, \theta = 1.1, \mu = 5, \omega = 300, \tau = 1$)

α	n_A^*	n_B^*	p_A^*	p_B^*	q_A^*	q_B^*	π_A^*	π_B^*	$n_A^* + n_B^*$	n_A^*/n_B^*	p_A^*/p_B^*	q_A^*/q_B^*	π_A^*/π_B^*
0.1	0.224	0.043	1.747	1.419	678.507	321.493	453.385	104.655	0.267	5.236	1.231	2.110	4.332
0.11	0.232	0.041	1.748	1.420	679.150	320.850	454.604	104.634	0.273	5.720	1.231	2.117	4.345
0.12	0.240	0.038	1.750	1.421	679.787	320.213	455.885	104.636	0.279	6.259	1.231	2.123	4.357
0.13	0.249	0.036	1.751	1.422	680.416	319.584	457.227	104.662	0.285	6.862	1.232	2.129	4.369
0.14	0.257	0.034	1.753	1.423	681.036	318.964	458.631	104.712	0.291	7.542	1.232	2.135	4.380
0.15	0.265	0.032	1.755	1.424	681.649	318.351	460.096	104.785	0.297	8.312	1.232	2.141	4.391
0.16	0.274	0.030	1.757	1.425	682.253	317.747	461.622	104.882	0.303	9.194	1.232	2.147	4.401
0.17	0.282	0.028	1.759	1.427	682.847	317.153	463.209	105.002	0.309	10.213	1.233	2.153	4.411
0.18	0.290	0.025	1.761	1.428	683.433	316.567	464.858	105.145	0.316	11.403	1.233	2.159	4.421
0.2	0.307	0.021	1.766	1.431	684.575	315.425	468.337	105.502	0.328	14.507	1.234	2.170	4.439

Table 2. Numerical Analysis with respect to a marginal increase in unit fuel cost (c)

(with $m = 1000, \alpha = .1, \delta = .1, \gamma_A = 2, \gamma_B = 1, \theta = 1.1, \mu = 5, \omega = 300, \tau = 1$)

c	n_A^*	n_B^*	p_A^*	p_B^*	q_A^*	q_B^*	π_A^*	π_B^*	$n_A^* + n_B^*$	n_A^*/n_B^*	p_A^*/p_B^*	q_A^*/q_B^*	π_A^*/π_B^*
1	0.224	0.043	1.747	1.419	678.507	321.493	453.385	104.655	0.267	5.236	1.231	2.110	0.224
1.1	0.232	0.046	1.845	1.517	679.393	320.607	453.737	104.017	0.278	5.021	1.216	2.119	0.232
1.2	0.239	0.049	1.942	1.615	680.310	319.690	454.099	103.355	0.289	4.839	1.202	2.128	0.239
1.3	0.247	0.053	2.039	1.713	681.260	318.740	454.471	102.668	0.300	4.683	1.190	2.137	0.247
1.4	0.255	0.056	2.136	1.811	682.242	317.758	454.853	101.956	0.311	4.548	1.179	2.147	0.255
1.5	0.263	0.059	2.233	1.909	683.259	316.741	455.248	101.219	0.322	4.431	1.170	2.157	0.263
1.6	0.271	0.063	2.330	2.007	684.309	315.691	455.654	100.457	0.333	4.329	1.161	2.168	0.271
1.7	0.279	0.066	2.426	2.104	685.394	314.606	456.074	99.670	0.344	4.239	1.153	2.179	0.279
1.8	0.287	0.069	2.523	2.202	686.516	313.484	456.508	98.858	0.356	4.161	1.146	2.190	0.287
1.9	0.295	0.072	2.619	2.299	687.674	312.326	456.957	98.021	0.367	4.091	1.139	2.202	0.295

Table 3. Numerical Analysis with respect to a marginal increase in fuel efficiency (δ)
(with $m = 1000, \alpha = .1, c = 1, \gamma_A = 2, \gamma_B = 1, \theta = 1.1, \mu = 5, \omega = 300, \tau = 1$)

δ	n_A^*	n_B^*	p_A^*	p_B^*	q_A^*	q_B^*	π_A^*	π_B^*	$n_A^* + n_B^*$	n_A^*/n_B^*	p_A^*/p_B^*	q_A^*/q_B^*	π_A^*/π_B^*
0.1	0.224	0.043	1.747	1.419	678.507	321.493	453.385	104.655	0.267	5.236	1.231	2.110	0.224
0.15	0.263	0.059	1.733	1.409	683.259	316.741	455.248	101.219	0.322	4.431	1.230	2.157	0.263
0.2	0.303	0.075	1.715	1.396	688.869	311.131	457.422	97.158	0.378	4.031	1.228	2.214	0.303
0.25	0.343	0.090	1.695	1.382	695.446	304.554	460.031	92.467	0.433	3.821	1.227	2.283	0.343
0.3	0.385	0.103	1.671	1.365	703.125	296.875	463.229	87.138	0.489	3.724	1.224	2.368	0.385
0.35	0.429	0.116	1.644	1.346	712.078	287.922	467.216	81.165	0.544	3.708	1.221	2.473	0.429
0.4	0.474	0.126	1.613	1.325	722.521	277.479	472.252	74.547	0.600	3.761	1.217	2.604	0.474
0.45	0.521	0.134	1.579	1.303	734.727	265.273	478.674	67.287	0.656	3.883	1.212	2.770	0.521
0.5	0.571	0.140	1.542	1.279	749.041	250.959	486.929	59.403	0.711	4.085	1.206	2.985	0.571
0.55	0.624	0.142	1.501	1.254	765.906	234.094	497.613	50.933	0.767	4.393	1.197	3.272	0.624

Table 4. Numerical Analysis with respect to a marginal increase on government regulation on the relative level of emissions (θ)
(with $m = 1000, \alpha = .1, c = 1, \gamma_A = 2, \gamma_B = 1, \delta = .1, \mu = 5, \omega = 300, \tau = 1$)

θ	n_A^*	n_B^*	p_A^*	p_B^*	q_A^*	q_B^*	π_A^*	π_B^*	$n_A^* + n_B^*$	n_A^*/n_B^*	p_A^*/p_B^*	q_A^*/q_B^*	π_A^*/π_B^*
1	0.140	0.010	1.666	1.332	670.963	329.037	449.464	109.602	0.150	14.447	1.250	2.039	0.140
1.1	0.224	0.043	1.747	1.419	678.507	321.493	453.385	104.655	0.267	5.236	1.231	2.110	0.224
1.2	0.247	0.047	1.843	1.516	680.954	319.046	455.266	103.313	0.294	5.202	1.215	2.134	0.247
1.3	0.262	0.049	1.941	1.615	682.599	317.401	456.920	102.583	0.311	5.380	1.202	2.151	0.262
1.4	0.278	0.050	2.039	1.714	684.327	315.673	458.700	101.828	0.328	5.556	1.190	2.168	0.278
1.5	0.293	0.051	2.138	1.812	686.135	313.865	460.609	101.047	0.344	5.732	1.179	2.186	0.293
1.6	0.309	0.052	2.236	1.911	688.024	311.976	462.651	100.243	0.361	5.907	1.170	2.205	0.309
1.7	0.324	0.053	2.334	2.010	689.990	310.010	464.828	99.415	0.378	6.082	1.161	2.226	0.324
1.8	0.340	0.054	2.432	2.109	692.034	307.966	467.143	98.564	0.394	6.259	1.154	2.247	0.340
1.9	0.356	0.055	2.531	2.207	694.152	305.848	469.598	97.692	0.411	6.438	1.146	2.270	0.356

*Numbers with bold represent the optimal values under $\theta \geq \frac{1}{1-\alpha}$

Table 5. Numerical Analysis with respect to a marginal increase on the quality gap between firms' delivery services ($\gamma_A - \gamma_B$)
(with $m = 1000, \alpha = .1, c = 1, \theta = 1.1, \gamma_B = 1, \delta = .1, \mu = 5, \omega = 300, \tau = 1$)

$\gamma_A - \gamma_B$	n_A^*	n_B^*	p_A^*	p_B^*	q_A^*	q_B^*	π_A^*	π_B^*	$n_A^* + n_B^*$	n_A^*/n_B^*	p_A^*/p_B^*	q_A^*/q_B^*	π_A^*/π_B^*
1	0.224	0.043	1.747	1.419	678.507	321.493	453.385	104.655	0.267	5.236	1.231	2.110	0.224
1.1	0.224	0.043	1.814	1.453	677.422	322.578	497.784	115.761	0.267	5.201	1.249	2.100	0.224
1.2	0.223	0.043	1.881	1.486	676.519	323.481	542.190	126.867	0.267	5.173	1.266	2.091	0.223
1.3	0.223	0.043	1.947	1.519	675.756	324.244	586.602	137.975	0.267	5.149	1.282	2.084	0.223
1.4	0.223	0.044	2.014	1.553	675.102	324.898	631.019	149.082	0.267	5.129	1.297	2.078	0.223
1.5	0.223	0.044	2.081	1.586	674.537	325.463	675.440	160.191	0.267	5.112	1.312	2.073	0.223
1.6	0.223	0.044	2.147	1.619	674.042	325.958	719.863	171.299	0.267	5.096	1.326	2.068	0.223
1.7	0.223	0.044	2.214	1.653	673.606	326.394	764.289	182.408	0.267	5.083	1.340	2.064	0.223
1.8	0.223	0.044	2.280	1.686	673.218	326.782	808.718	193.518	0.267	5.071	1.353	2.060	0.223
1.9	0.223	0.044	2.347	1.719	672.872	327.128	853.147	204.627	0.267	5.061	1.365	2.057	0.223

Table 6. Numerical Analysis with respect to a marginal increase on the adaptation cost (ω)

(with $m = 1000, \alpha = .1, c = 1, \theta = 1.1, \gamma_B = 1, \delta = .1, \gamma_A = 2, \mu = 5, \tau = 1$)

ω	n_A^*	n_B^*	p_A^*	p_B^*	q_A^*	q_B^*	π_A^*	π_B^*	$n_A^* + n_B^*$	n_A^*/n_B^*	p_A^*/p_B^*	q_A^*/q_B^*	π_A^*/π_B^*
260	0.259	0.049	1.744	1.417	680.346	319.654	454.850	103.673	0.308	5.295	1.231	2.128	0.259
270	0.249	0.047	1.745	1.418	679.835	320.165	454.440	103.945	0.296	5.278	1.231	2.123	0.249
280	0.240	0.046	1.746	1.418	679.360	320.640	454.062	104.198	0.286	5.263	1.231	2.119	0.240
290	0.232	0.044	1.747	1.419	678.918	321.082	453.711	104.435	0.276	5.249	1.231	2.114	0.232
300	0.224	0.043	1.747	1.419	678.507	321.493	453.385	104.655	0.267	5.236	1.231	2.110	0.224
310	0.217	0.041	1.748	1.420	678.121	321.879	453.081	104.861	0.258	5.223	1.231	2.107	0.217
320	0.210	0.040	1.748	1.420	677.761	322.239	452.797	105.055	0.250	5.212	1.231	2.103	0.210
330	0.203	0.039	1.749	1.421	677.422	322.578	452.531	105.237	0.242	5.201	1.231	2.100	0.203
340	0.197	0.038	1.750	1.421	677.103	322.897	452.281	105.408	0.235	5.191	1.231	2.097	0.197
350	0.192	0.037	1.750	1.421	676.802	323.198	452.046	105.570	0.229	5.182	1.231	2.094	0.192

Table 7. Numerical Analysis with respect to a marginal increase in penalty or tax rate (τ)
(with $m = 1000, \alpha = .1, c = 1, \theta = 1.1, \gamma_B = 1, \delta = .1, \gamma_A = 2, \omega = 300, \mu = 5$)

τ	n_A^*	n_B^*	p_A^*	p_B^*	q_A^*	q_B^*	π_A^*	π_B^*	$n_A^* + n_B^*$	n_A^*/n_B^*	p_A^*/p_B^*	q_A^*/q_B^*	π_A^*/π_B^*
0.1	0.155	0.011	1.675	1.342	671.859	328.141	450.529	109.284	0.167	13.611	1.248	2.047	<i>0.155</i>
0.2	0.163	0.015	1.684	1.351	672.485	327.515	450.825	108.868	0.178	10.875	1.246	2.053	<i>0.163</i>
0.3	0.170	0.019	1.692	1.360	673.139	326.861	451.125	108.427	0.189	9.201	1.244	2.059	<i>0.170</i>
0.4	0.178	0.022	1.700	1.369	673.820	326.180	451.430	107.962	0.200	8.072	1.242	2.066	<i>0.178</i>
0.5	0.186	0.026	1.709	1.377	674.529	325.471	451.740	107.472	0.211	7.262	1.240	2.072	<i>0.186</i>
0.6	0.193	0.029	1.717	1.386	675.266	324.734	452.055	106.958	0.222	6.652	1.239	2.079	<i>0.193</i>
0.7	0.201	0.033	1.724	1.394	676.031	323.969	452.377	106.419	0.233	6.178	1.237	2.087	<i>0.201</i>
0.8	0.208	0.036	1.732	1.403	676.827	323.173	452.705	105.856	0.244	5.800	1.235	2.094	<i>0.208</i>
0.9	0.216	0.039	1.740	1.411	677.651	322.349	453.041	105.268	0.256	5.491	1.233	2.102	<i>0.216</i>
1	0.224	0.043	1.747	1.419	678.507	321.493	453.385	104.655	0.267	5.236	1.231	2.110	0.224

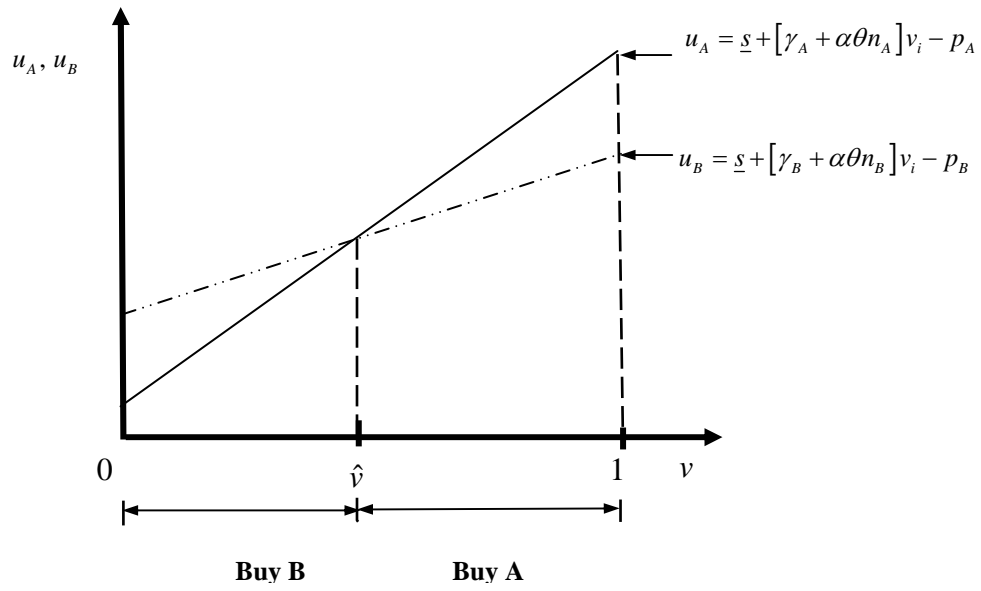


Figure 1. Customer's quality choice/perception ranges and utility values