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Supply Chain Design and Carbon Penalty: Monopoly vs. Monopolistic Competition

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This paper studies whether imposing carbon costs changes the supply chain structure and social welfare. We explore the problem from a central policymaker's perspective who wants to maximize social welfare. We consider two stakeholders, retailers, and consumers, who optimize their own objectives (i.e., profits and net utility) and three competitive settings (i.e., monopoly, monopolistic competition with symmetric market share, and monopolistic competition with asymmetric market share). For the monopoly case, we find that when the retailer's profit is high, imposing some carbon emission charges on the retailer and the consumers does not substantially change the supply chain structure or the social welfare. However, when the retailer's profit is low, imposing carbon costs optimally can lead to a significant increase in social welfare. Moreover, the impact of imposing carbon emission charges becomes more significant when the degree of competition increases. Additionally, the quantum of benefit may depend only on factors common across industries, such as fuel and carbon costs.

Key words: sustainability; supply chain design; policy making; carbon tax; monopolistic competition
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1. Introduction

Carbon emission has received significant attention in recent years, because it is commonly believed to be one of the contributors to global warming. Central planners have passed various regulations on carbon emission. For instance, the European Union has imposed carbon emission limits but allowed companies to trade their allowances (EC 2005). British Columbia, Canada, imposed a carbon tax (BC 2008), at \$20 per metric ton of CO_2 initially and then increased to \$30 per metric ton from July 2012. While it is difficult to determine the exact cost of carbon emission to the society, the Intergovernmental Panel on Climate Change in 2007 (IPCC 2007) suggested that if we impose \$80 per metric ton of CO_2 to large carbon emitters, then we can prevent severe climate change. Several researchers have documented that the estimated carbon cost can range from \$50 to \$300 per metric ton of CO_2 (Frank 2012, Tol 2008, Johnson and Hope 2012). In the United States, even though there is no regulation yet in place, the Mandatory Reporting of Greenhouse Gases Rule has been issued by the US Environmental Protection Agency, and large greenhouse gas (GHG) emitters need to report GHG data (EPA 2008). Along with the policy changes, the public is also becoming more receptive to the idea of imposing charges to curb carbon emission, and more companies have started to report the carbon footprint of their products and services and are making an effort to reduce their carbon emission. As such, a natural question surfaces whether imposing some carbon emission charges will influence the supply chain structure and consumers' purchasing behavior, and if so, how to optimally determine the carbon emission charges to the companies and consumers from a central planner's perspective.

To address this question, as in Cachon (2014), we focus on the "last mile" supply chain, that is, ranging from retail stores to consumers. However, instead of minimizing the total costs from a monopolistic retailer's perspective, we consider the problem of maximizing social welfare from a central policymaker's perspective with rational retailers and consumers. We allow the retail price to be determined endogenously, and consider three competitive settings: monopoly, monopolistic competition with symmetric market share, and monopolistic competition with asymmetric market share.

In our model, the retailers maximize profits and consumers maximize their utilities, which results in negative externalities for the society by generating carbon emissions. Increased carbon emissions can increase the average temperature on Earth, influence the patterns and amounts of precipitation, reduce the ice and snow coverage, and raise the sea levels (EPA 2012). The objective of the central policymaker in our study is to maximize the social welfare by balancing the retailers' and consumers' self-interest against the negative externalities. More specifically, the central policymaker decides the carbon cost recovery rates to be imposed on the retailers and consumers to maximize social welfare, where the social welfare is defined to be the sum of the consumers' total net utilities and the retailers' total profits less the portion of carbon cost that is not recovered from the consumers and retailers. Levying carbon emission charges over the retailers' and consumers' transportation activities may change their operations and shopping decisions, respectively, and thereby impact social welfare.

We find that the central policymaker prefers to recover more of the carbon costs from the retailers than from the consumers because the retailers are the leaders in the "last mile" supply chain. Moreover, when the optimal carbon cost recovery rates are imposed, a change in carbon cost has a more significant effect on the supply chain structure, the total carbon emission and the social welfare, when the market competition is more intense. Interestingly, we find that an increase of the carbon cost will always reduce the social welfare when the market competition is low (i.e., the monopoly case), but it may either increase or decrease the social welfare when the market competition is high (i.e., the monopolistic competition cases). We also measure the loss of social welfare if the optimal carbon cost recovery rates are not imposed. We find that this loss is substantial when the market competition is intense or the carbon cost is large. Moreover, this loss can often be significant when the retailers' profitability is low (even if the market competition is not intense). Hence, imposing the optimal carbon cost recovery rates can lead to significant benefits for the society.

Our work is related to the recent studies that investigate how carbon emission regulations influence firms' operational decisions. Benjaafar et al. (2013) study a lot-sizing problem with carbon cap, carbon tax, and carbon cap-and-trade. They show that carbon emission can be reduced not just by investing in energy-efficient technologies but also by adjusting some of the operational decisions. To support and complement the numerical findings in Benjaafar et al. (2013), Chen et al. (2013) and Hua et al. (2011) consider economic order quantity (EOQ) models with carbon cap and carbon cap-and-trade constraints, respectively. Chen et al. (2013) show that with the carbon cap regulation, the relative decrease of carbon emission can be much higher than the relative increase of costs, and similarly, Hua et al. (2011) find that carbon emission decreases as the carbon cost increases when the carbon cap-and-trade system is implemented. Differently, Hoen et al. (2014) consider the transportation mode selection decision when carbon emission regulations are imposed. They find that neither carbon tax nor carbon cap-and-trade will change the firms' transportation mode.

Our study follows the modeling approach in Cachon (2014) that studies the "last mile" supply chain structure with carbon emission cost. Cachon shows that improving consumer fuel efficiency is more effective at reducing environmental externalities than imposing a carbon tax. In our study, however, we endogenize the retailers' store opening, stocking and pricing decisions as well as the consumers' shopping decisions. Our monopoly case is the closest to the setting in Cachon (2014), but it too has some differences. In terms of retailer operations, Cachon (2014) considers an economic scale effect associated with retail space. In our study, retailers follow the economic order quantity decision rule to determine the replenishment frequency and truckload. Cachon (2014) focuses on the total cost increase when carbon costs are not imposed, whereas we consider how carbon taxes impact social welfare. Furthermore, we investigate competitive market scenarios and different optimal carbon cost recovery rates over the consumers and the retailers. We find that imposing carbon taxes can improve social welfare when retailer profitability is low or when competition intensifies.

Finally, our work is related to the economics literature that studies excess entry (e.g., Lahiri and Ono 1988, Mankiw and Whinston 1986, Suzumura and Kiyono 1987). In that stream of work it is shown that when there is no entry barrier, an excessive number of firms may enter the market, which reduces social welfare, and thus, imposing some entry cost can be beneficial. Our study employs a similar setting as in the economics literature, but we investigate the impact of carbon emission on the supply chain structure and the optimal carbon cost recovery rates when the objective is to maximize social welfare.

2. Problem Description

In this section, we describe the problem setting. As a default case, we consider carbon emission only from the retailers' and consumers' transportation activities, and later in section 5.2, we will extend our setting to consider carbon emission from cooling and heating activities in the retail stores.

2.1. Transportation Cost

We assume the vehicles used by the consumers are homogeneous, and so are the vehicles of the retailers. The transportation cost follows a similar pattern as that in Cachon (2014), but we also consider a recovery cost for carbon emission. We use the subscript c to denote the consumers and the subscript r to denote the retailers. Specifically, the per-unit transportation cost of a type $t \in \{c,r\}$ vehicle follows:

$$\tau_t(\alpha_t) := v_t + (p_t + \alpha_t c_t e) f_t,$$

where v_t is the nonfuel variable cost per unit of distance (\$ per km), p_t is per unit fuel cost (\$ per liter (L)), α_t is the fraction of carbon cost recovered, c_t is the amount of carbon emission per unit of fuel ($kgCO_2$ per L), e is the carbon cost per unit of emissions (\$ per $kgCO_2$), and f_t is the amount of fuel necessary to transport the vehicle per unit distance (L per km). For simplicity, we use τ_c and τ_r to denote $\tau_c(\alpha_c)$ and $\tau_r(\alpha_r)$, respectively.

2.2. Players

2.2.1. Consumers. The consumers are located evenly in the whole market area. We normalize the consumer density to one. Except for their locations, the consumers are identical. Below, we explain the consumers' problem. Each consumer's demand rate is λ_c. The consumer obtains a utility u_c per unit of consumption. To buy the products, consumer i travels in straight lines to the closest store of a retailer j, and chooses the purchasing quantity per trip, $q_c^{j,i}$. Let $d_c^{j,i}$ be the round-trip distance to the store, and h_c be the cost of holding one unit product per unit time. Suppose the product selling price is p^j. Then, we can formulate consumer i's problem as one of maximizing her utility, $U_c^{j,i}(q_c^{j,i})$:

$$\max_{q_c^{j,i}} U_c^{j,i}(q_c^{j,i}) \equiv \lambda_c(u_c - p^j) - \frac{\lambda_c \tau_c d_c^{j,i}}{q_c^{j,i}} - \frac{h_c q_c^{j,i}}{2}.$$

Recall that τ_c is the unit transportation cost of consumers that depends on α_c.

2.2.2. Retailers. The entire market area is a which is fixed to a single polygonal region. Let k be the number of retailers. Before establishing a product distribution plan to the retail stores, retailer $j \in \{1, 2, \ldots, k\}$ chooses the number of retail stores n^j, serving area $r^j(\leq a)$, and unit selling price p^j given that a fraction m^j of the consumers prefer to shop at retailer j's stores. We assume retailer j's consumers are uniformly distributed in the entire market area a and retailer j's retail stores are also uniformly located in retailer j's serving area r^j.

The store configuration forms a Voronoi diagram which consists of a single regular polygon. A retail store is located in the center of mass of the regular polygon. We let b^j be the shortest distance from the center of mass to the side of the regular polygon covered by retailer j and θ be the smallest angle formed by the shortest line from the center of mass to the side of the regular polygon and the shortest line from the center of mass to the vertex of the regular polygon, that is, $\theta = \pi/s$, where s is the number of sides in the regular polygon. Then,

$$r^j = \frac{1}{2}(b^j)^2(\tan\theta)(2s)n^j \leq a,$$

where $\frac{1}{2}(b^j)^2(\tan\theta)(2s)$ is the area of the regular polygon. Note that we can also express b^j as a function of r^j, that is, $b^j = \left(r^j(s\tan\theta)^{-1}(n^j)^{-1}\right)^{1/2}$.

Retailer j's demand rate λ_r^j follows:

$$\lambda_r^j = r^j m^j \lambda_c,$$

because we normalize the consumer density to one. In other words, the demand rate per unit area is $m^j\lambda_c$ and the total area served is r^j. Retailer j's selling price p^j is the price that makes the utility of the farthest consumer from the nearest store equal to zero, that is, the utility of the consumer at the vertex of the polygon is zero. The round-trip distance to the farthest consumer (i.e., the round-trip distance from the center of mass to the vertex of the regular polygon) is:

$$\begin{aligned} 2\sqrt{(b^j)^2+(b^j)^2(\tan\theta)^2} &= 2\sqrt{r^j(s\cdot n^j)^{-1}(\tan\theta+(\tan\theta)^{-1})} \\ &= 2\sqrt{s^{-1}(\tan\theta+(\tan\theta)^{-1})}\left(\frac{r^j}{n^j}\right)^{1/2} \\ &= \phi_{c1}^2\left(\frac{r^j}{n^j}\right)^{1/2} \end{aligned}$$

where $\phi_{c1} = 2^{1/2}s^{-1/4}(\tan\theta + (\tan\theta)^{-1})^{1/4}$. Hence, the selling price of retailer j can be formulated as:

$$p^j = u_c - \phi_{c1}^2\frac{\tau_c}{q_c^{j,F}}\left(\frac{r^j}{n^j}\right)^{1/2} - \frac{h_c q_c^{j,F}}{2\lambda_c},$$

where F in $q_c^{j,F}$ denotes the farthest consumer. Note that in section 3.2, we show that the improved profitability of the retailers under some reasonable alternative selling price settings is negligible. We assume the procurement cost g_r is the same for all retailers. Therefore, retailer j's revenue and procurement cost per unit time are $\lambda_r^j p^j$ and $\lambda_r^j g_r$, respectively.

Besides the decisions listed above, retailer j needs to choose the distribution quantity per trip q_r^j. As in Cachon (2014): (i) retailer j has a single warehouse and a single vehicle; (ii) the warehouse is co-located with one of the n^j stores and it is the point where the distribution trip starts and ends; (iii) transportation of the products from the supplier to retailer j's warehouse is not considered; (iv) every distribution trip covers all retail stores; (v) the vehicle travels in straight lines and the delivery time is zero; and (vi) retailer j's distance of a distribution trip d_r^j follows $d_r^j = 2b^j n^j = 2\left(r^j (s\tan\theta)^{-1}(n^j)^{-1}\right)^{1/2} n^j = \phi_r^2\left(r^j n^j\right)^{1/2}$ where $\phi_r = 2^{1/2}(s\tan\theta)^{-1/4}$, which is the minimum distance to travel into and out of every regular polygon. Let h_r be the retailer's cost of holding one unit of product per unit time. Then, we can formulate retailer j's problem as one of maximizing his profit rate, $Z^j(q_r^j, n^j, r^j, p^j)$:

$$\max_{q_r^j, n^j, r^j} Z^j(q_r^j, n^j, r^j, p^j) \equiv \lambda_r^j(p^j - g_r) - \frac{\lambda_r^j \tau_r d_r^j}{q_r^j} - \frac{h_r q_r^j}{2}$$

subject to

$$\begin{aligned} r^j &= \frac{1}{2}(b^j)^2(\tan\theta)(2s)n^j \le a \\ \lambda_r^j &= r^j m^j \lambda_c \\ p^j &= u_c - \phi_{c1}^2 \frac{\tau_c}{q_c^{j,F}}\left(\frac{r^j}{n^j}\right)^{1/2} - \frac{h_c q_c^{j,F}}{2\lambda_c} \\ d_r^j &= \phi_r^2\left(r^j n^j\right)^{1/2}. \end{aligned}$$

Recall that τ_r is the unit transportation cost of the retailers that depends on α_r.

2.3. Central Policymaker

In our problem, the retailers distribute products to their retail stores and the consumers travel to the retail stores to buy the products. These actions emit carbon which is costly to the society. The cost of emission is assumed to be recovered by imposing a fee (i.e., a carbon tax) on the fuel price. The fee is proportional to the amount of carbon emission when the retailers and consumers use fuel. For example, if the carbon cost is \$80 per metric ton of CO_2 and the amount of carbon emission per unit of gasoline is 2.325 kgCO_2 per liter (EPA 2005), then the gasoline price increase due to the carbon tax is \$0.186 per liter, that is, \$0.70 per gallon, when the carbon cost is fully recovered.

The role of the central policymaker is to decide the recovery rates α_c and α_r of the carbon costs imposed on the consumers and retailers. The central policymaker's problem is to maximize social welfare, $SW(\alpha_c, \alpha_r)$:

$$\max_{\alpha_c, \alpha_r} SW(\alpha_c, \alpha_r),$$

where $SW(\alpha_c, \alpha_r)$ is the sum of the consumers' total utility and the retailers' total profit less the carbon cost that is not recovered from the consumers and retailers, that is, sum of $U_c^{j,i}(q_c^{j,i}|\alpha_c, \alpha_r) +$ sum of $Z^j(q_r^j, n^j, r^j, p^j|\alpha_c, \alpha_r) - (1-\alpha_c)$ of the carbon cost by consumers $-(1-\alpha_r)$ of the carbon cost by retailers.[1]

Notice that as the carbon cost recovery rates increase, the consumers' utility and the retailers' profit may decrease due to the carbon costs imposed on them.

2.4. Competition

We consider three market settings: the monopoly case, the case of monopolistic competition with symmetric market share, and the case of monopolistic competition with asymmetric market share.

2.4.1. Monopoly. In the monopoly setting, there is a single retailer in the market whose stores are uniformly located in his serving area.

2.4.2. Monopolistic Competition. With competition, multiple retailers coexist in the market. In particular, a fraction m^j of the consumers will prefer to shop at a specific retailer j's stores and the consumers are uniformly distributed in the entire market area a. Therefore, the retailers may serve overlapping regions and may even have their stores co-located with each other. *In the case of monopolistic competition with symmetric market share*, we assume that each retailer has the same market share, and the retailers will keep entering the market until their profits become zero. Therefore, $m^j = 1/k$ for all j where k is the number of retailers in the market. For analytical simplicity, we assume that $k \in \mathcal{R}$.

In the case of monopolistic competition with asymmetric market share, we assume that the number of retailers in the market, k, is a fixed integer and the retailers have different market shares, which are exogenously given, and controlled by some common parameter. We will elaborate upon the market share model in section 4.

2.5. Timeline

In the first stage, the central policymaker decides the carbon cost recovery rates. In the second stage, the retailers decide the number of stores and the serving area which then determine the selling price. In the third stage (the last stage), the consumers decide their purchasing quantity and the retailers decide their distribution quantity per trip.

3. Optimal Decisions

We use the superscripts M, S, and A to denote the association with the cases of monopoly, monopolistic competition with symmetric market share, and monopolistic competition with asymmetric market share, respectively.

3.1. Third Stage

In this stage, the consumers decide their purchasing quantity per shopping trip, $q_c^{j,i}$, to maximize their utility, and the retailers decide their distribution quantity to each store per trip, q_r^j, to maximize their profits. By the EOQ formula (see Cachon and Terwiesch 2009), the optimal purchasing quantity and the associated utility of consumer i are:

$$q_c^{j,i,l} = \sqrt{\frac{2\lambda_c\tau_c d_c^{j,i}}{h_c}} \text{ and}$$
$$U_c^{j,i}(q_c^{j,i,l}) = \lambda_c(u_c - p^j) - \sqrt{2\lambda_c\tau_c d_c^{j,i} h_c},$$

where $l \in \{M,S,A\}$. Similarly, retailer j's optimal delivery quantity and the associated profit are:

$$q_r^{j,l} = \sqrt{\frac{2\lambda_r^j\tau_r d_r^j}{h_r}} \text{ and } Z^j(q_r^{j,l}) = \lambda_r^j(p^j - g_r) - \sqrt{2\lambda_r^j\tau_r d_r^j h_r}.$$

3.2. Second Stage

Given the carbon cost recovery rates (α_c, α_r), retailer j decides the number of retail stores n^j and the serving market area r^j which then determine the selling price p^j.

3.2.1. Monopoly. Proposition 1 gives a monopoly retailer's optimal decisions in the second stage.

PROPOSITION 1. *Suppose* $\tau_c\tau_r \le \frac{\lambda_c^2(u_c-g_r)^4}{2^6(\phi_{c1}\phi_r)^2(h_c h_r)}$ *given* α_c *and* α_r.[2] *In the monopoly case, (i) the whole market area a is served, that is,* $r^M = a$; *(ii) the optimal number of retail stores is* $n^M = a\left(\frac{\phi_{c1}}{\phi_r}\right)^2\left(\frac{\tau_c h_c}{\tau_r h_r}\right)$; *(iii) the resulting unit selling price is* $p^M = u_c - \left(\frac{2\phi_{c1}\phi_r}{\lambda_c}\right)^{1/2}(\tau_c h_c \tau_r h_r)^{1/4}$; *(iv) the demand rate is* $\lambda_r^M = a\lambda_c$; *(v) the distance of a distribution trip is* $d_r^M = \phi_r^2(an^M)^{1/2}$.

Proposition 1 shows that the number of retail stores is linearly proportional to the market area. The retailer's selling price is decreasing in the carbon cost since an increase of carbon cost will make it more costly for the consumers to shop and thus the retailer needs to lower his selling price. The number of retail stores however may not increase the carbon cost because: on one hand, more stores will lower the consumers' transportation cost and thus enable the retailer to charge a higher price, but on the other hand, more stores will also increase the retailer's distribution cost. Moreover, in our context, it is optimal for the retailer to expand his serving area until the total space is covered under the condition $\tau_c\tau_r \le \frac{\lambda_c^2(u_c-g_r)^4}{2^6(\phi_{c1}\phi_r)^2(h_c h_r)}$. This condition guarantees that the retailer's profit is nonnegative at optimum.[3] In addition, this result (i.e., $r^M = a$) is due to the assumption that the selling price is the price that makes the utility of the farthest consumer from the nearest store equal to zero.

The retailer, however, could alternately decide not to cover every consumer within a polygon. For example, the coverage area could be a circle within the polygon. In this case, if the area covered is a circle strictly within the polygon, then the polygon can be shrunk until the circle touches the midpoints of each side. Thus, without loss of generality, the actual resulting price will lie somewhere between the price to entice the consumer at the vertex (our assumption) and the price to entice the consumer at the midpoint of a side of the polygon. Extensive numerical investigations show that setting the price in that way (to cover all consumers within a circle inscribed in the polygon) does not change the profitability of the retailer by more than 1.3% when the polygon is a hexagon.

3.2.2. Monopolistic Competition with Symmetric Market Share. In this symmetric competitive case, the retailers will keep entering the market until the total number of retail stores reaches a level such that their profits become zero. Let tk denote this number of retail stores. Proposition 2 shows the equilibrium results.

PROPOSITION 2. *Suppose* $\tau_c\tau_r \le \frac{\lambda_c^2(u_c-g_r)^4}{2^6(\phi_{c1}\phi_r)^2(h_c h_r)}$ *given* α_c *and* α_r. *In the case of monopolistic competition with symmetric market share, in equilibrium, (i) the whole the market area is served, that is,* $r^{j,S} = a, \ \forall j$; *(ii) the number of retailers in the market is* $k^S = \frac{\lambda_c^2(u_c-g_r)^4}{2^6(\phi_{c1}\phi_r)^2(\tau_c\tau_r h_c h_r)}$; *(iii) each retailer has a number of stores equal to* $n^{j,S} = a\frac{2^6\phi_{c1}^4(\tau_c h_c)^2}{\lambda_c^2(u_c-g_r)^4}$; *(iv) the total number of retail stores is* $tk^S = a\left(\frac{\phi_{c1}}{\phi_r}\right)^2\left(\frac{\tau_c h_c}{\tau_r h_r}\right)$; *(v) the resulting unit selling price is* $p^S = \frac{1}{2}(u_c + g_r)$; *(vi) the demand rate for each retailer is* $\lambda_r^{j,S} = \left(\frac{a}{k}\right)\lambda_c$; *and (vii) the distance of a distribution trip for each retailer is* $d_r^{j,S} = \phi_r^2(an^{j,S})^{1/2}$.

In the symmetric competition case, the retailers also serve the whole market area in equilibrium, which is similar to the monopoly case. The carbon cost influences the number of retailers as well as the number of stores in the market. In particular, we can find that when the carbon cost increases, the number of stores per retailer will increase, while the number of retailers in the market will decrease. As a result, the intensity of competition decreases as the carbon cost increases. It is worth noting that the number of stores per retailer is independent of τ_r and h_r in equilibrium. Even though an increase of τ_r or h_r increases the operating cost of a retailer, it reduces the number of retailers in the market and thus increases the demand rate for each surviving retailer. In equilibrium, these positive and negative forces are canceled out and thus the number of stores per retailer becomes independent of the retailer's transportation and holding costs. In contrast, an increase of the consumers' transportation or holding cost, τ_c or h_c, does increase the number of stores per retailer. This is intuitive because when the consumers bear more cost, it is necessary for the retailers to have more stores to maintain the consumers' utility level (under the condition that the whole market area is covered in equilibrium). It is also interesting to notice that the retail price in equilibrium depends only on the consumers' per unit consumption utility of the product and the retailers' unit procurement cost. This is due to the combined facts that in equilibrium the retailer's profit is driven to zero and the retail price is the one that makes the farthest served consumer's utility zero.[4] Finally, the condition $\tau_c\tau_r \le \frac{\lambda_c^2(u_c-g_r)^4}{2^6(\phi_{c1}\phi_r)^2(h_ch_r)}$ guarantees that there is at least one retailer in the market in equilibrium.

3.2.3. Monopolistic Competition with Asymmetric Market Share. In the asymmetric competition case, the retailers enter the market sequentially (e.g., $j = 1, 2, 3, \ldots$) until it becomes unprofitable for a new retailer to enter. For simplicity, we assume that in equilibrium, the number of retailers is k^A (an integer number) and the market share of a retailer j is m^j (the market share decreases in the sequence from retailer 1 to retailer k^A). (Later, we will use a function to represent m^j and fit it into the real data.) With the above assumptions, Proposition 3 presents the optimal decisions of the retailers and the consumers.

PROPOSITION 3. *Suppose* $\frac{\tau_c\tau_r}{m^{k^A}} \le \frac{\lambda_c^2(u_c-g_r)^4}{2^6(\phi_{c1}\phi_r)^2(h_ch_r)}$ *given* α_c *and* α_r. *In the case of monopolistic competition with asymmetric market share,* (*i*) *the whole market area is served, that is,* $r^{j,A} = a, \forall j$; (*ii*) *the optimal number of stores for retailer* j *is* $n^{j,A} = (am^j)\left(\frac{\phi_{c1}}{\phi_r}\right)^2\left(\frac{\tau_c h_c}{\tau_r h_r}\right)$; (*iii*) *the resulting unit selling price for retailer* j *is* $p^{j,A} = u_c - \left(\frac{2\phi_{c1}\phi_r}{\lambda_c}\right)^{1/2}(\tau_c h_c \tau_r h_r)^{1/4}(m^j)^{-1/4}$; (*iv*) *the demand rate for the retailer* j *is* $\lambda_r^{j,A} = (am^j)\lambda_c$; (*v*) *the distance of a distribution trip for retailer* j *is* $d_r^{j,A} = \phi_r^2(an^{j,A})^{1/2}$.

The market share m^j influences the number of stores that the retailer j has as well as the selling price and demand rate of retailer j. Notice that if $m^1 = 1$, then the results in Proposition 3 will converge to those in the monopoly case; whereas, if m^j is the same for all j, then the above results will converge to those in the symmetric competition case. The condition

$$\frac{\tau_c\tau_r}{m^{k^A}} \le \frac{\lambda_c^2(u_c - g_r)^4}{2^6(\phi_{c1}\phi_r)^2(h_ch_r)},$$

guarantees that the profit of each retailer is nonnegative.

3.3. First Stage

In this subsection, we analyze the central policymaker's decision on the carbon cost recovery rates (α_c, α_r) with the goal to maximize the social welfare. For notational convenience, let $\phi_{c2} := \left(\frac{4\sqrt{2}}{5}\frac{\int_0^{\tan\theta}(1+t^2)^{1/4}dt}{\tan\theta}\right)s^{-1/4}(\tan\theta)^{-1/4}$.[5] In addition, let $\alpha_c^{ub} = \frac{-\phi_{c1}(v_c+f_cp_c)+\phi_{c2}(v_c+f_cp_c+2ec_cf_c)}{ec_cf_c(\phi_{c1}+\phi_{c2})}$, $\alpha_r^{ub} = \frac{-\phi_{c2}(v_r+f_rp_r)+\phi_{c1}(v_r+f_rp_r+2ec_rf_r)}{ec_rf_r(\phi_{c1}+\phi_{c2})}$, $\alpha_c^b = \frac{1}{ef_cc_c}\left(\sqrt{\frac{\phi_{c2}}{\phi_{c1}}\frac{\tau_c(1)}{\tau_r(1)}\cdot\frac{\lambda_c^2(u_c-g_r)^4}{2^6(\phi_{c1}\phi_r)^2(h_ch_r)}} - (v_c + p_cf_c)\right)$, and $\alpha_r^b = \frac{1}{ef_rc_r}\left(\sqrt{\frac{\phi_{c1}}{\phi_{c2}}\frac{\tau_r(1)}{\tau_c(1)}\cdot\frac{\lambda_c^2(u_c-g_r)^4}{2^6(\phi_{c1}\phi_r)^2(h_ch_r)}} - (v_r + p_rf_r)\right)$.

PROPOSITION 4. *The optimal carbon cost recovery rates in each competitive setting are the following:* (*i*) *In the monopoly case and the case of monopolistic competition with asymmetric market share,* (*a*) *if* $\tau_c(\alpha_c^{ub})\tau_r(\alpha_r^{ub}) \le \frac{\lambda_c^2(u_c-g_r)^4}{2^6(\phi_{c1}\phi_r)^2(h_ch_r)}$, *then* $(\alpha_c^M, \alpha_r^M) = (\alpha_c^A, \alpha_r^A) = (\alpha_c^{ub}, \alpha_r^{ub})$; (*b*) *if* $\tau_c(\alpha_c^{ub})\tau_r(\alpha_r^{ub}) > \frac{\lambda_c^2(u_c-g_r)^4}{2^6(\phi_{c1}\phi_r)^2(h_ch_r)}$, *then* $(\alpha_c^M, \alpha_r^M) = (\alpha_c^A, \alpha_r^A) = (\alpha_c^b, \alpha_r^b)$. (*ii*) *In the case of monopolistic competition with symmetric market share,* $(\alpha_c^S, \alpha_r^S) = (\alpha_c^b, \alpha_r^b)$.

Note that the case of monopolistic competition with the asymmetric market share has the same structure in terms of retailer operations as the monopoly case because the retailer's market share is given. In these two cases, $(\alpha_c^{ub}, \alpha_r^{ub})$ are the unconstrained maximizers of the social welfare function. If the condition

$\tau_c(\alpha_c^{ub})\tau_r(\alpha_r^{ub}) \le \frac{\lambda_c^2(u_c-g_r)^4}{2^6(\phi_{c1}\phi_r)^2(h_c h_r)}$ holds, that is, each retailer's profit is nonnegative under $(\alpha_c^{ub}, \alpha_r^{ub})$, then the central policymaker's optimal decision on the carbon cost recovery rates is $(\alpha_c^{ub}, \alpha_r^{ub})$. Notice that $\alpha_c^{ub} < 1$ and $\alpha_r^{ub} > 1$. Therefore, at optimum, the central policymaker should recover less than 100% of the carbon costs from the consumers but more than fully from the retailers. A direct implication is that the consumers will transport more frequently while the retailers will have fewer stores, compared to the scenario in which the central policymaker recovers the full carbon costs from all the parties.

In case the condition $\tau_c(\alpha_c^{ub})\tau_r(\alpha_r^{ub}) \le \frac{\lambda_c^2(u_c-g_r)^4}{2^6(\phi_{c1}\phi_r)^2(h_c h_r)}$ is violated, the policymaker will choose the boundary solution (α_c^b, α_r^b) at which each retailer's profit is zero. Note that both α_c^b and α_r^b can be either smaller or greater than one, but α_c^b is always smaller than α_r^b. Therefore, the central policymaker still recovers relatively more carbon costs from the retailers than from the consumers. The retailers are the leaders in the "last mile" supply chain in our context. They optimize the number of stores as well as the distribution frequency to maximize their profits taking into account the consumers' shopping decision. If the optimal carbon cost recovery rates are not imposed, the retailers tend to have more stores than the socially optimal number in equilibrium. Part of the reason is that the retailers want to have a denser retail network and thus they can charge a higher price. As a result, the policymaker wants to impose a higher carbon cost recovery rate over the retailers than the consumers. This can reduce the number of stores while maintaining the consumers' utility to some level.

Notice also that as the carbon cost increases, α_c^{ub} increases while α_r^{ub} decreases. This is because when the carbon cost increases, the retailers' profitability decreases, which reduces the retailers' incentive to open more stores. As a result, the optimal carbon cost recovery rate over the retailers should decrease. On the other hand, given that the retailers would have fewer stores, consumer transportation cost increases, and thus, it is beneficial, with regard to the social welfare, to increase the carbon cost recovery rate over the consumers.

In the case of monopolistic competition with the symmetric market share, the retailers' profits are always zero and the consumers' total utility is independent of the transportation costs, τ_c and τ_r.[6] Consequently, the central policymaker can always increase the social welfare by increasing the carbon cost recovery rates. However, we need to ensure that there is at least one retailer in the market. Hence, the optimal carbon cost recovery rates are achieved at the boundary with the condition $\tau_c\tau_r = \frac{\lambda_c^2(u_c-g_r)^4}{2^6(\phi_{c1}\phi_r)^2(h_c h_r)}$. That is, the boundary solution (α_c^b, α_r^b) is optimal for the case of monopolistic competition with symmetric market share.

4. Numerical Study

Based on the solution derived in the above, we conduct a numerical study to analyze the extent to which the supply chain structure and the social welfare are influenced by the carbon cost and the carbon cost recovery rates. For the experiment settings, we choose the same values of the transportation parameters, v_t, p_t, c_t, f_t where $t \in \{c,r\}$, as in Cachon (2014), and choose the other parameters as shown in Table 1.[7] We consider two scenarios with respect to the retailers' profitability: (i) relatively high profitability with $\lambda_c = 10$, and (ii) relatively low profitability with $\lambda_c = 5$. In particular, when $\lambda_c = 5$, there will be only one retailer in the market in the competitive settings under the other given parameters.

For the case of monopolistic competition with symmetric market share, we assume in the experiments that the number of retailers is an integer and is greater than or equal to one. For the case of monopolistic competition with asymmetric market share, we assume that the market share of the jth retailer equals

$$m^j := \left(\frac{(1-\gamma)^{j-1}}{k}\right)(1-(j-k)\gamma),$$

where $\gamma \in (0,1)$ denotes the degree of market competition (or market share asymmetry). This special form allows us to vary the analysis from the monopoly case to the case of monopolistic competition with symmetric market share by changing γ. When γ goes to zero, the model converges to the symmetric mar-

Table 1 Parameters

Parameter	Description (unit)	Value(s) chosen
a	Market area (km^2)	300
u_c	Consumer utility per unit of consumption ($ per unit)	0.55
λ_c	Consumer's demand rate (units per week)	10/5
g_r	Retailer's per unit procurement cost ($ per unit)	0.5
(h_c, h_r)	Unit holding cost ($ per unit per week)	(0.0029, 0.0029)
(v_c, v_r)	Nonfuel variable cost per unit of distance ($ per km)	(0.0804, 0.484)
(f_c, f_r)	The amount of fuel consumption per unit of distance (L per km)	(0.111, 0.392)
(p_c, p_r)	Per unit of fuel cost ($ per L)	(0.98, 1.05)
(c_c, c_r)	The amount of carbon emission per unit of fuel ($kgCO_2$ per L)	(2.325, 2.669)

ket share case; whereas, when γ goes to one, the model converges to the monopoly case. Table 2 shows a few examples of asymmetric market shares with different k and γ. For example, if $k = 2$ and $\gamma = 0.1$, then the larger retailer's market share is 0.55, and the smaller retailer's market share is 0.45. This market share function can be fitted based on the real data. In particular, Table 3 shows the market shares of the US major supermarket chains (including Costco, Kroger, Safeway, Target, and Walmart) and the calibrated market shares of those chains based on the m^j function in each market area (the calibration is based on minimizing the squared errors). For example, in the Pacific Coast area, the market share of Walmart is 20%, and the estimated market share of Walmart is 17% with $\gamma = 0.079$.[8] The rationale of this m^j market share function is also aligned with the consumer choice models, for example, the multinomial logit model. To some extent, the m^j function explains the asymmetric market share structure driven by unequal consumer choice probabilities.

4.1. Supply Chain Design

In this subsection, we investigate the impact of carbon cost on the supply chain design with respect to the number of retailers, the total number of retail stores, the total carbon emission, and the social welfare. We assume the optimal carbon cost recovery rates are always imposed in the experiments and we choose the consumer utility per unit of consumption equal to $\lambda_c = 10$ (i.e., the high profitability scenario). We vary the carbon cost from zero to \$1,000 per metric ton of CO_2. Figure 1 reports the results of the experiments.

We can observe from Figure 1 that the number of retailers decreases while the number of total retail stores increases, as the carbon price increases. (Note that the total number of retail stores is always the same across the three competitive market scenarios. This is true because the whole market area is always covered under our setting and the number of retail stores is linearly proportional to the market size.) In particular, in the monopoly case, the change in the number of retail stores is small and thus the impact of the carbon cost on the "last mile" supply chain design is not significant. This is in line with the observation in the literature (e.g., Cachon 2014). However, in the competitive market settings, we can see that the number of retailers in the market may decrease significantly and thus the number of stores per retailer may significantly increase. This observation indicates that an increase of the carbon cost may have an important implication for the design of the supply chains and the impact is more significant if the market competition intensifies.

Figure 1 also shows that the carbon cost will influence the total emission and the social welfare. In particular, the amount of emission always decreases as the carbon cost increases. This is intuitive because the retailers and the consumers will transport less frequently when the cost of emission becomes

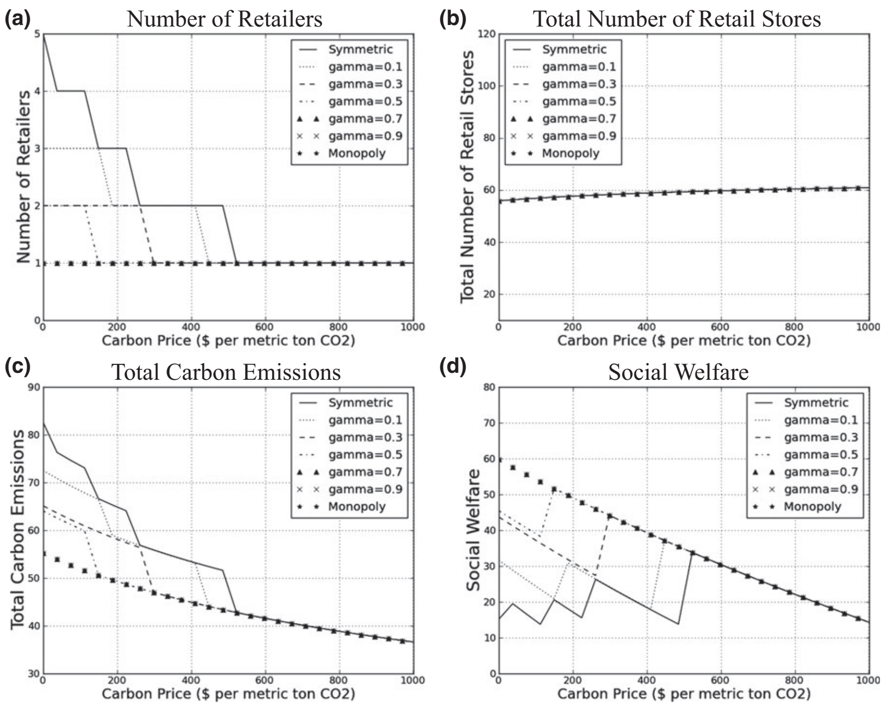
Table 3 Asymmetric Market Share Example in Supermarket Chain Industry

	Costco	Kroger	Safeway	Target	Walmart
Pacific Coast (AK, CA, OR, WA)					
Market Share	26%	20%	21%	12%	20%
$m^j(\gamma = 0.079, k = 5)$	26%	20%	23%	14%	17%
Mountain (CO, ID, NV, MT, UT, WY)					
Market Share	16%	25%	11%	9%	38%
$m^j(\gamma = 0.196, k = 5)$	18%	26%	12%	8%	36%
Southwest (AZ, NM, OK, TX)					
Market Share	8%	16%	8%	11%	58%
$m^j(\gamma = 0.275, k = 5)$	10%	26%	6%	16%	42%
Heartland (IA, KS, MN, MO, NE, ND, SD)					
Market Share	6%	9%	1%	18%	66%
$m^j(\gamma = 0.545, k = 5)$	3%	9%	1%	24%	64%
Southeast (AL, AR, FL, GA, LA, MS, SC)					
Market Share	7%	12%	N/A	12%	69%
$m^j(\gamma = 0.386, k = 4)$	6%	27%	N/A	13%	54%
Midwest (IL, IN, MI, OH, WI)					
Market Share	8%	24%	2%	14%	52%
$m^j(\gamma = 0.390, k = 5)$	6%	26%	3%	13%	51%
Appalachian (KY, NC, TN, VA, WV)					
Market Share	7%	22%	2%	11%	59%
$m^j(\gamma = 0.429, k = 5)$	5%	26%	2%	12%	54%
Mid-Atlantic (DE, MD, NJ, NY, PA)					
Market Share	17%	N/A	7%	19%	57%
$m^j(\gamma = 0.339, k = 4)$	15%	N/A	7%	28%	50%
New England (CT, ME, MA, NH, RI, VT)					
Market Share	14%	N/A	N/A	20%	67%
$m^j(\gamma = 0.399, k = 3)$	12%	N/A	N/A	28%	60%
Hawaii (HI)					
Market Share	47%	N/A	21%	5%	27%
$m^j(\gamma = 0.359, k = 4)$	52%	N/A	14%	7%	28%

Table 2 Asymmetric Market Share

	$\gamma = 0.1$				$\gamma = 0.5$				$\gamma = 0.9$			
k	2	3	4	5	2	3	4	5	2	3	4	5
m^1	0.55	0.40	0.33	0.28	0.75	0.67	0.63	0.60	0.95	0.93	0.93	0.92
m^2	0.45	0.33	0.27	0.23	0.25	0.25	0.25	0.25	0.05	0.06	0.07	0.07
m^3	N/A	0.27	0.22	0.19	N/A	0.08	0.09	0.10	N/A	0.00	0.00	0.01
m^4	N/A	N/A	0.18	0.16	N/A	N/A	0.03	0.04	N/A	N/A	0.00	0.00
m^5	N/A	N/A	N/A	0.13	N/A	N/A	N/A	0.01	N/A	N/A	N/A	0.00

Figure 1 Supply Chain Design and Carbon Cost



higher. Note that the amount of emission is larger when the market is more competitive because there will be more retailers who have their own transportation systems. The impact of carbon cost on the social welfare is much less intuitive. In the monopoly case, the social welfare always decreases in the carbon cost. This is driven by the fact that it will become more costly for the retailer and the consumers to transport when the carbon cost increases. However, in the competitive market settings, the social welfare may also increase in the carbon cost in some specific regions. Note that an increase of carbon cost may reduce the number of retailers in the market. This will first make the transportation system more centralized and thus lead to less emission, and second, it will reduce the competition intensity in the market which can increase the retailers' total profits more than the reduction of consumer utility. Therefore, we observe that when the carbon cost is low or intermediate, an increase of the carbon cost may increase the total social welfare, which is not obvious at the first glance.

4.2. Social Welfare Penalty

In this subsection, we investigate the system social welfare from the central policymaker's perspective. Specifically, we use the social welfare penalty concept, which measures the decrease in social welfare that occurs due to not imposing the optimal carbon emission charges. Note that this concept is similar to the total cost penalty concept defined in Cachon (2014). In our numerical experiments, we consider two types of social welfare penalties: (i) the loss of social welfare by not imposing any carbon emission charges at all, and (ii) the loss of social welfare by imposing the intuitive carbon cost recovery rate for both the retailers and consumers, which is defined as: the 100% recovery rate if the retailers' profits are positive, and the rate at which the retailers' profits reach zero, otherwise. We formulate these two types of social welfare penalties as:

$$SWP(0) := \{SW(\alpha_c^l, \alpha_r^l) - SW(0,0)\}/SW(\alpha_c^l, \alpha_r^l)$$

$$SWP(\alpha^I) := \{SW(\alpha_c^l, \alpha_r^l) - SW(\alpha^I, \alpha^I)\}/SW(\alpha_c^l, \alpha_r^l)$$

where $l \in \{M,S,A\}$, SWP stands for *Social Welfare Penalty*, and α^I denotes the *intuitive* carbon cost recovery rate.

In the following, we discuss two scenarios: the retailers' profitability is relatively high with $\lambda_c = 10$ and relatively low with $\lambda_c = 5$, respectively.

4.2.1. High Retailer Profitability Scenario. We vary the carbon cost from \$50 to \$300 per metric ton of CO_2. For each rate, we compute the optimal carbon cost recovery rates, the number of retailers, and the social welfare penalty. Figure 2 reports the results. Plot (a) affirms the finding elaborated below Proposition 4 that the optimal carbon cost recovery rate imposed by the central policymaker on the retailers is always greater than one, while the rate on the consumers is less than one (when the carbon cost is low, the consumers should even be subsidized to shop in order to maximize the social welfare). Furthermore, when the carbon cost increases, the optimal recovery rate imposed upon the retailers decreases while the rate over the consumers increases.

From plot (b), we observe that the social welfare penalty of not charging any recovery rates can be very significant for the competitive market scenarios, and the significance increases when either the market becomes more competitive or the carbon cost becomes higher. Note that the carbon cost recovery rates influence not only the retailers' and consumers' transportation decisions but also the number of retailers in the market. The former determines each individual player's emission level while the latter influences the market structure. When the market is competitive, the difference of the number of retailers in the market can be large if no recovery rates are imposed vs. if the optimal recovery rates are imposed, which influences the social welfare substantially. On the other extreme, we can observe that in the monopoly case, the social welfare penalty is small even if the carbon cost is high. Plot (c) shows the social welfare penalty of charging the intuitive recovery rates vs. the optimal recovery rates. We can observe that the difference is minimal for all the market scenarios, and thus, when the retailers' profitability is relatively high, the intuitive recovery rates are close to optimal.

4.2.2. Low Retailer Profitability Scenario. In this subsection, we investigate the social welfare penalty when the retailers' profitability is relatively low with $\lambda_c = 5$. Note that under this set of parameters, the number of retailers in the market is one in all the market scenarios in our experiments. That is, the retailer is always a monopolist in the market. We again vary the carbon cost from \$50 to \$300 per metric ton of CO_2 and report the results in Figure 3. We can observe that the social welfare penalties are large even though the retailer is a monopolist (see, plot (b)). Moreover, the penalty is significant even for the case where the intuitive carbon cost recovery rates are imposed (see, plot (c)). Specifically, when the retailer's profitability is low, charging different recovery rates other than the optimal ones does not change the number of retailers in the market but influences the retailer's profit as well as the consumer utility. When the profit the retailer obtains is small, the loss of social welfare caused by inefficient carbon cost recovery rates can be relatively substantial and thus lead to significant percentage penalties. Hence, it is important to apply the optimal carbon cost recovery rates in scenarios in which the retailer's profitability is low.

The above discussion reveals that in general, the social welfare penalty is large when the market is competitive, and it is the most significant in the

Figure 2 Carbon Cost Recovery Rates (CRR), Social Welfare Penalty (SWP), and Difference of Number of Retailers (DNR) When Retailers' Profit is High

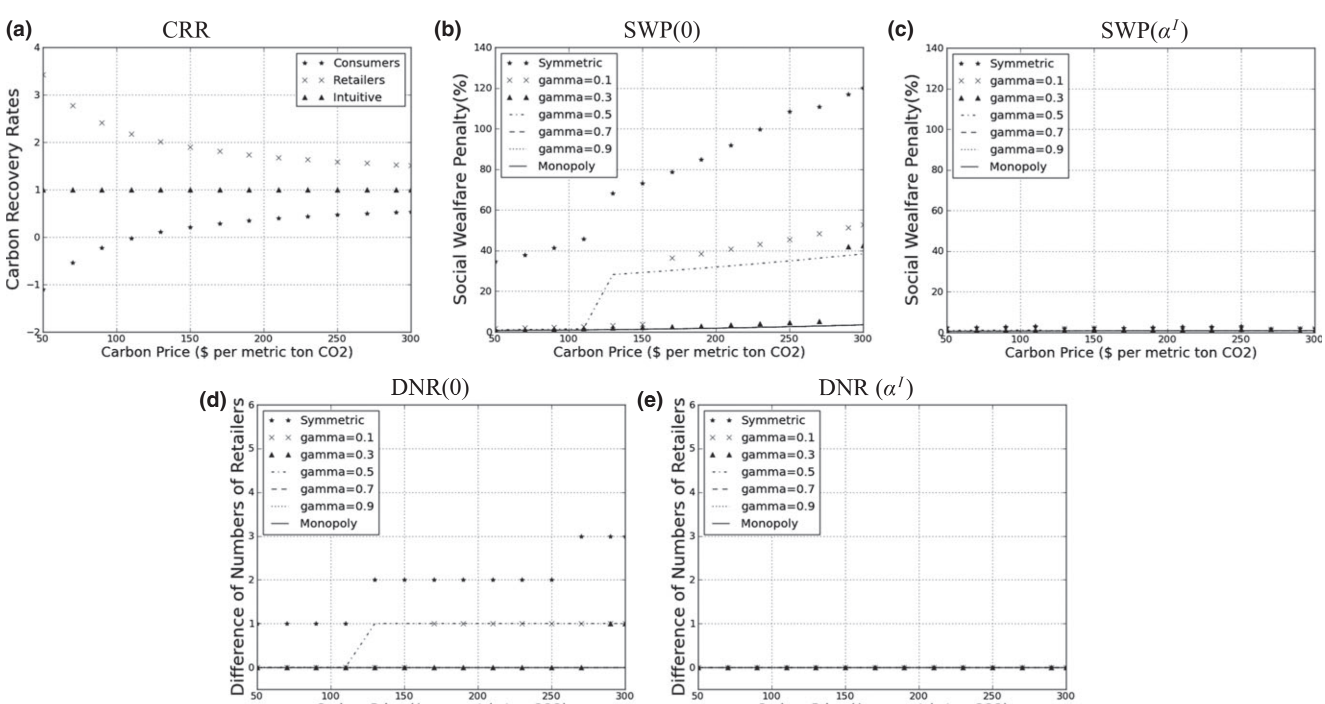
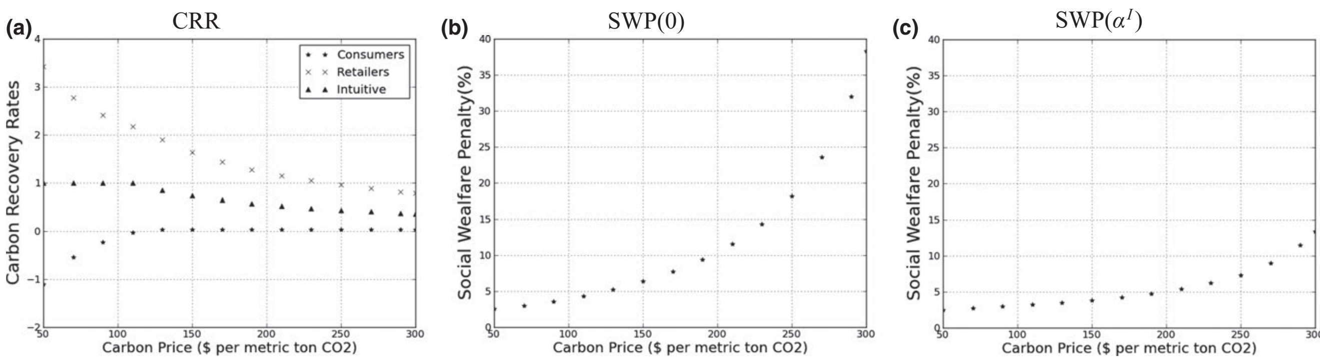


Figure 3 Carbon Cost Recovery Rates (CRR) and Social Welfare Penalty (SWP) When Retailers' Profit is Low (Difference of Number of Retailers (DNR) is always zero)



case of monopolistic competition with symmetric market share. Moreover, the following result indicates that the social welfare penalties in the latter case are independent of the industry-specific parameters, such as, the demand rate or the holding cost. They depend only on the factors that are common across industries, including the fuel cost and carbon cost.

PROPOSITION 5. *In the case of monopolistic competition with symmetric market share, the social welfare penalties are independent of the parameters: a, u_c, λ_c, g_r, h_c, and h_r, but depend on ϕ_{c1}, ϕ_{c2}, and the factors that are included in τ_c and τ_r.*

The result of Proposition 5 is interesting and can be useful for central policy making. That is, when the market competition is intense, the social welfare penalties depend only on a few factors common to industries (e.g., the fuel cost), and thus the optimal carbon policies may not need to be tailored to specific industries. Note however that in the monopoly case and in the case of monopolistic competition with asymmetric market share, the social welfare penalties do depend on the industry-specific parameters, such as, u_c, λ_c, g_r, h_c, and h_r. In our numerical study, we find that the social welfare penalties in these two cases will become more significant when either the retailers' profitability or the consumers' utility decreases, that is, when u_c and λ_c decrease, or g_r, h_c and h_r increase.

5. Extensions

In this section, we provide two natural extensions

5.1. Independent Distribution Systems

In our study, we assumed that the retailers have their own transportation fleets. This assumption reflects the practice in the current retail industry. Most of the major supermarket chains in the United States (see Table 3) have their own distribution systems. Notice that this assumption plays a critical role in our study. As we have revealed in the above section, a competitive market will have more retailers than the monopoly case. Given that the retailers have their own distribution systems, a competitive market will thus have a lower utilization of retailer transportation than that of the monopoly case, which leads to more carbon emission and a lower social welfare.

A natural question that thus emerges is whether a third-party logistics (3PL) system can help improve retailer transportation efficiency and reduce the impact of carbon cost. In fact, we can show that if the retailers are symmetric and they use a common 3PL company to distribute their products, then the total number of retail stores and the retail price will converge to those in the monopoly case. That is, the retailers will act as if they are monopolists in our model. As a result, the social welfare penalty will become the same as that of the monopoly case even if there are multiple retailers in the market. This finding implies that using a common logistics distribution system could be an alternative option to reduce carbon emission and improve social welfare.

5.2. Retail Space Costs

Thus far, we have assumed that there is no cost associated with the retail space. In this subsection, we extend this assumption by introducing a retail space cost. Similar to the transportation cost, the retail space cost consists of the factors considered in Cachon (2014) as well as the carbon cost recovery rate. Specifically, we define the per-unit retail space cost as:

$$v_s + (p_s + \alpha_s c_s e) f_s,$$

where v_s is a variable cost ($ per period), p_s is the per-unit energy cost ($ per unit energy), α_s is the fraction of carbon cost recovered from the retail space usage, c_s is the amount of carbon emission per-unit energy usage ($kgCO_2$ per unit energy), e is the carbon cost per unit of emissions (\$ per $kgCO_2$), and f_s is the amount of energy consumption that is necessary to hold a unit of product per period (energy usage per period). Note that both the retail space cost and the holding cost are proportional to the inventory levels. Hence, for notational convenience, we use $\hat{h}_r(\alpha_s)$ to denote the aggregated retail space holding cost, that is, $\hat{h}_r(\alpha_s) := (h_r + v_s) + (p_s + \alpha_s c_s e) f_s$, and we use $\hat{h}_r$ as a shorthand notation of $\hat{h}_r(\alpha_s)$.

Given that we do not introduce any space cost for the consumers, their problem will remain the same as before. The retailer's problem however needs to be modified. Since the aggregated retail space holding cost $\hat{h}_r$ is linearly proportional to the inventory level, we can formulate a retailer j's problem as one of maximizing his profit rate, $Z^j(q_r^j, n^j, r^j, p^j)$:

$$\max_{q_r^j, n^j, r^j} Z^j(q_r^j, n^j, r^j, p^j) \equiv \lambda_r^j(p^j - g_r) - \frac{\lambda_r^j \tau_r d_r^j}{q_r^j} - \frac{\hat{h}_r q_r^j}{2}$$

subject to

$$\begin{aligned} r^j &= \frac{1}{2}(b^j)^2(\tan\theta)(2s)n^j \le a \\ \lambda_r^j &= r^j m^j \lambda_c \\ p^j &= u_c - \phi_{c1}^2 \frac{\tau_c}{q_c^{j,F}}\left(\frac{r^j}{n^j}\right)^{1/2} - \frac{h_c q_c^{j,F}}{2\lambda_c} \\ d_r^j &= \phi_r^2 (r^j n^j)^{1/2}. \end{aligned}$$

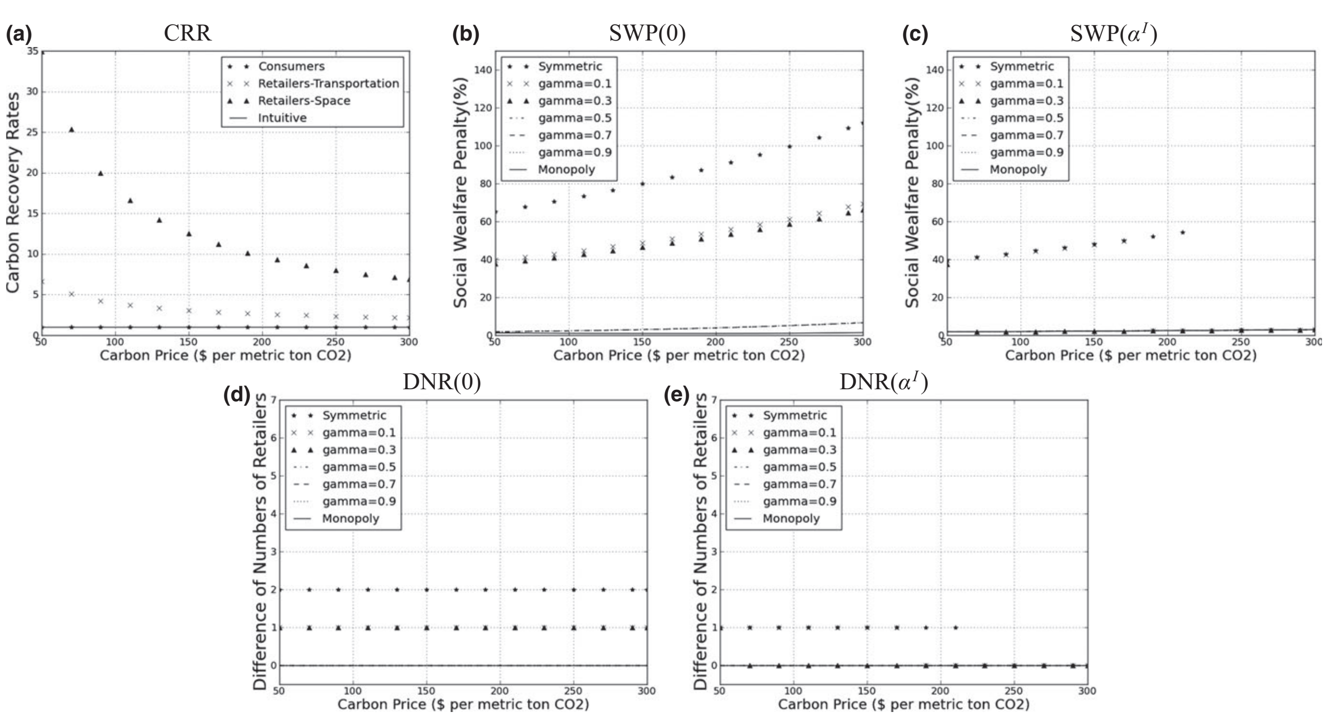
The central policymaker's problem is to maximize the adjusted social welfare, $SW(\alpha_c, \alpha_r, \alpha_s)$:

$$\max_{\alpha_c, \alpha_r, \alpha_s} SW(\alpha_c, \alpha_r, \alpha_s).$$

In the following, we examine how the retail space cost affects the social welfare. Replacing h_r by $\hat{h}_r$ in section 3, we can derive the optimal decisions with the consideration of the retail space cost. We use the same parameter values as those in Table 1 and set $\lambda_c = 10$ (i.e., the high retailer profitability scenario). For $\hat{h}_r$, we follow Cachon (2014) by assuming a storage size of 3,000 units per m^2, a variable cost of \$212.85/3,000/52 per week per unit, an energy consumption cost of \$22.85/3,000/52 per week per unit, and an amount of carbon emission \$126.1/3,000/52 $kgCO_2$ per week per unit. As an example, if the carbon cost is \$200 per metric ton of CO_2 and the carbon cost recovery rate is one, then the retail space cost is \$0.0017 per week per unit, and $\hat{h}_r$, the aggregated retail space holding cost, is \$0.0046 per week per unit.

We plot Figure 4 which shows how the optimal carbon cost recovery rates, the social welfare penalties, and the difference of the number of retailers vary as the carbon cost increases. From the figure, we observe that the social welfare penalties tend to become more significant with the consideration of the retail space cost, which is in line with the observation in Cachon (2014). In particular, we can see that even the social

Figure 4 Carbon Cost Recovery Rates (CRR), Social Welfare Penalty (SWP), and Difference of Number of Retailers (DNR) When Retailers' Profit is High



welfare penalty by charging the intuitive recovery rates can become very significant when the market competition is intense. This is mainly driven by the fact that the difference of the number of retail stores becomes larger after we consider the retail space cost when the optimal carbon emission recovery rates are not imposed. Hence, if the retail space emits a significant amount of carbon, then it becomes more crucial to impose the optimal carbon cost recovery rates from the central policymaker's view.

6. Conclusion

In this study, we investigate how the carbon cost influences the consumers' shopping decisions and the retailers' operations. We further analyze the impact of the carbon cost on the equilibrium supply chain structure and the social welfare. We find that the carbon cost can influence the supply chain structure significantly when the market competition is intense. This complements the findings in the literature often with a monopoly setting. In addition, we show that the social welfare may either increase or decrease as the carbon cost increases. We also explore the optimal carbon emission recovery rates from a central policymaker's perspective to maximize the social welfare. We find that the optimal carbon cost recovery rate for the retailers is generally larger than that for the consumers. Moreover, the loss of social welfare due to not imposing the optimal carbon emission recovery rates can be significant even in the monopoly case, and this loss is sizeable when the market competition level increases. Our results suggest the importance of imposing the optimal carbon tax to curb emission and provide quantification of the benefit. We also find that in a competitive market scenario, using a common third-party logistic distribution system can help reduce carbon emission and improve the social welfare, which might complement the carbon regulations.

The carbon cost recovery rates considered in our paper can be implemented by carbon taxes. Another major carbon policy in practice is cap-and-trade. The carbon cap-and-trade policy may not be effective when the supply of carbon emission allowance is greater than the demand. Companies can emit almost freely despite the social cost. This happened in the European Union (EU) carbon market which is the biggest carbon trading market in the world. In April 2013, the EU Allowance price was less than \$4, that is, the carbon emitters only needed to pay \$4 per metric ton of CO_2, which is significantly lower than the social cost of carbon which ranges from \$50 to \$300 per metric ton of CO_2. According to the International Center for Climate Governance, the low price was mainly caused by the recent recession from 2008 (ICCG 2013). It reduced firms' activities and thus the demand of carbon emission allowance. This difference between the supply and demand of carbon emission allowance (about 800 million metric tons) made the carbon trading market almost ineffective (Reed and Scott 2013).

Carbon tax can be more effective to reduce carbon emission. According to Elgie and McClay (2013), after British Columbia, Canada imposed a carbon tax from 2008, carbon emissions in British Columbia reduced by 10%; whereas, the reduction in the rest of Canada was only 1.1%. The main concern of carbon tax is whether it will weaken the economy. However, from 2008 to 2011, the GDP *per capita* in British Columbia reduced only by 0.15%, while it was 0.23% in the rest of Canada. Moreover, carbon tax is much easier to implement and also more robust than the carbon cap-and-trade system.

The impact of carbon emission costs on operations is apparent, as we observe from the changes in Canada. For instance, the fuel consumption per capita in British Columbia decreased by 17.4% from 2008 to 2012; whereas, the consumption in the rest of Canada increased by 1.5% (Elgie and McClay 2013). In addition, we observe that the number of retail stores of Costco in British Columbia increased by 8%, while, it was 13% in the rest of Canada (Costco , 2008, 2012). With the implemented carbon taxes, consumers and retailers tend to consume less fuel; moreover, retailers become reluctant to open new stores. It is expected that more countries and regions will impose carbon regulations. Hence, having more carbon efficient supply chains (e.g., use a third-party logistics system) will be important for companies.

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Notes

[1]The consumers' total utility, that is, sum of $U_c^{j,i}(q_c^{j,i}|\alpha_c, \alpha_r)$, is derived as follows. First, each retailer j's serving area is divided into $2sn^j$ number of indifferent small areas in which the consumers are uniformly located. Given the consumer's optimal decision $q_c^{j,i}$, the utility can be expressed as a function of $d_c^{j,i}$. Hence, the total utility of the consumers served by retailer j is $2sn^j \int_0^b \int_0^{x \tan\theta} U_c^{j,i}(d_c^{j,i})dydx$, where $d_c^{j,i} = 2\sqrt{x^2 + y^2}$, and by aggregation of the retailers, we can derive the total consumer utility: $\sum_{j=1}^k 2sn^j \int_0^b \int_0^{x \tan\theta} U_c^{j,i}(d_c^{j,i})dydx$.

[2]τ_c and τ_r depend on α_c and α_r, respectively.

[3]Recall that the retailer's profit function, the serving area, the demand rate, and the distance of a distribution trip are $Z = \lambda_r(p - g_r) - \sqrt{2\lambda_r\tau_r d_r h_r}$, $r = b^2(\tan\theta)sn$, $\lambda_r = r\lambda_c$, and $d_r = \phi_r^2(rn)^{1/2}$, respectively. Substituting the latter three into the profit function, we obtain $Z = n[\{b^2(\tan\theta) s\lambda_c(p - g_r)\} - \sqrt{2^2(\tan\theta)sb^3\lambda_c\tau_r h_r}]$. The selling price is determined as the one that makes the utility of the farthest consumer in the given polygon from the center store equal to zero. Therefore, the retailer's profit is linearly proportional to n. If the expression in the bracket is positive, the retailer will open as many stores as possible until the whole market space is covered; in contrast, if the expression in the bracket is negative, the retailer will not open any store. The condition, $\tau_c\tau_r \le \frac{\lambda_c^2(u_c - g_r)^4}{2^6(\phi_{c1}\phi_r)^2(h_c h_r)}$, assures that the retailer's profit is positive at optimum and thus the whole market space is covered. The shape of the polygon has little effect on the retailer's optimal profit.

[4]Recall that $p^j = u_c - \phi_{c1}^2 \frac{\tau_c}{q_c^{j,F}}\left(\frac{r^j}{n^j}\right)^{1/2} - \frac{h_c q_c^{j,F}}{2\lambda_c}$. Then, by the EOQ formula and $r^{j,S} = a$, $\forall j$, p^j can be simplified to $u_c - \phi_{c1}\sqrt{\frac{2\tau_c h_c}{\lambda_c}}(a/n^j)^{1/4}$. Note that n^j is proportional to $(\tau_c h_c)^2$, ϕ_{c1}^4, $1/\lambda_c^2$ and a, which results in the selling price being a function of u_c and g_r only.

[5]ϕ_{c2} is the coefficient that captures the sum of the square root of the round-trip distance of consumers. For example, in the monopoly case, this sum is $2sn^M\int_0^b\int_0^{x\tan\theta}\sqrt{d_c^{i,M}}dydx$, and it can be simplified to $\phi_{c2}a^{5/4}(n^M)^{-1/4}$. Notice that the sum is used to derive the total consumer utility and the social welfare. See the proof of Proposition 4 for the details.

[6]Recall that the individual consumer utility follows $\lambda_c(u_c - p^j) - \sqrt{2\lambda_c\tau_c d_c^{j,i}h_c}$. From Proposition 2, $p^S = \frac{1}{2}(u_c + g_r)$, and thus, the first term of the consumer utility is independent of the transportation costs. The integration of the second term (i.e., $\sqrt{2\lambda_c\tau_c d_c^{j,i}h_c}$) with respect to $d_c^{j,i}$ to derive the total consumer utility is also independent of the transportation costs.

[7]In the experiments, we choose the market size as 300. Note however that the social welfare penalties are independent of the market size because the social welfare and carbon emissions are linearly proportional to the market size and the market size value will cancel out when we calculate the social welfare penalties. We set the annual holding cost equal to 30% of the procurement cost. The other parameter values are difficult to estimate from the real data, but our results are relatively robust to those values. In addition, we assume that the Voronoi diagram generated by the retail stores consists of hexagons, that is, $s = 6$; the results are robust if we change s to $s = 3$ (triangle) or $s = 4$ (square). Notice that under our parameter values, the net profit margin is about 2% when the carbon price is zero and $\gamma = 0.3$.

[8]We calculate the sales of each supermarket chain in each area by multiplying the number of retail stores in that area by the sales per retail store. The number of retail stores in each area is found in each firm's annual report or website. The sales per retail store is estimated by dividing total sales by the total number of retail stores of each retailer. In addition, we divide the US market into ten areas, and each area has similar geographic features (AL 2013).

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. Proofs.