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Effects of carbon emission reduction policies on transportation mode selections with stochastic demand

Abstract: We are witnessing more frequent extreme weather events due to the global warming. There is an urgent need for governments, industries, general public, and academics to take coordinated actions in order to tackle the challenges imposed by the climate change. It is essential to incorporate the environmental objective in the transportation mode selection problem as transportation is a main contributor to carbon emissions. With this in mind, our paper studies the retailer's ordering and transportation mode selection problem using stochastic customer demand and investigates the optimal ordering and transportation mode selection decisions under different carbon emission reduction policies. Our analytical results reveal that there are some important transportation mode shifting thresholds under different carbon emissions reduction policies. These findings do not only help firms to make optimal decisions under different carbon emission reduction policies but also support policy makers to develop effective policies on carbon emissions reduction.

1 Introduction

Over the last few decades, global warming has received an increasing attention as it has led to more frequent extreme weather events (Dai 2011; Wheeler and vo Braun 2013; Revesz et al. 2014). In recent years, we have witnessed more catastrophic incidents such as the extraordinary heavy winter storm in the US, the damages brought to the Philippines by the strongest ever Typhoon Haiyan, and the draught in some parts of Africa. These incidents do not only significantly affect production of many products such as foods but also caused severe disruptions in global transportation, on which the global economy is heavily dependent. The stability of supply chains may be exposed to risks under climate change since it could be affected in several ways ranging from direct effects on production of goods, to changes in markets, and supply chain infrastructures. The increase of greenhouse gas (e.g. carbon emissions) is regarded as one of the main drivers of global warming (Chen and Hao, 2015). In response to the challenges due to the climate change, governments and regulators have introduced a range of carbon emissions reduction policies including mandatory carbon emission capacity, cap, carbon emission tax, and cap-and-trade etc. Consumers have been more aware of environmental issues and therefore, are more sensitive towards low carbon products (Upham et al. 2011; Vanclay et al. 2011; cohen and Vandenbergh 2012). Many companies have also realized the importance of carbon emission reduction and incorporated this objective in their operational decisions.

As a consequence, a wide range of studies on green supply chain management (Srivastava 2007; Sarkis et al. 2011; Gunasekaran et al. 2015), green logistics (Dekker et al. 2012; Demir et al. 2014), and low carbon manufacturing (Tridech and Cheng 2011) have

been reported in the past two decades. It is also well known that the transportation during the inbound or outbound logistics contributes a significant portion of carbon emission throughout the whole supply chain life cycle (Dekker et al., 2012; Wang et al. 2015b). One of the main decisions that companies have to make on transportation is the choice of transportation mode as each mode has different characteristics that lead to different economic and environmental performance (Meixell and Norbis 2008). There are a few operational research papers that deal with this issue (Leal and D'Agosto 2011; Hoen et al. 2014a, b; Konur and Schaefer 2014). However, very few studies have examined the effect of incorporating environmental objectives in the transportation mode selection and ordering decision on firms' optimal solutions under different carbon reduction policies. Less frequently, researchers have looked at the consequence of derived optimal operational decision on the risk level of the logistics and supply chain system (Wang et al. 2012). Our research aims to address this gap in the literature through investigating the following key questions:

- What is the impact of different carbon emission reduction policies on the ordering and transportation mode selection decisions?

- How do the optimal operational decisions under different carbon policies affect the economic and environmental performance?

- How does the incorporation of carbon emission reduction objective in the ordering and transportation decisions affect the risk of the logistics and supply chain system?

To answer these questions, a one-period two-echelon supply chain is considered consisting of a supplier and a retailer. The supplier manufactures products with limited shelf life. The retailer orders from the supplier and sells to end-users with a stochastic demand. Our

analysis aims to obtain the optimal ordering and transportation mode selection decision in order to improve both economic and environmental performance. Among many carbon emissions reduction policies, the cap policy and the cap-and-trade policy are the policy approaches that attract much attention. The cap policy sets an overall cap on carbon emissions. In addition to an overall cap, the cap-and-trade policy allows companies to trade the unused portion of their cap to other companies with high greenhouse gas emissions. Accompanied by complementary regulatory measures, cap-and-trade is a sufficient or necessary condition for carbon emissions reduction (Hanemann, 2010). Cap-and-trade policy, such as the European Union Emissions Trading Scheme, has been proven to be an important tool to address climate change, and becomes a major choice for investors to decentralize their investment risks (Zhu and Wei, 2013). In this paper, we examine the impact of two different carbon reduction polices: carbon emission cap and cap-and-trade on the retailer's optimal solutions as well as its profit and overall carbon emission. Through a comparison of the supply and demand risks under three different scenarios, we intend to understand the effect of carbon emission reduction objective and different carbon reduction policies on the risk of the logistics and supply chain system.

The rest of this paper is organized as follows. After a survey of related literature is presented in Section 2, Section 3 describes the model formulation and assumptions. In section 4, we establish the basic model, in which the optimal ordering and transportation mode selection solution is obtained without considering carbon emissions. In Section 5 and 6, we investigate the optimal solutions and their impact on profits, carbon emissions and supply chain risk under the carbon emission cap policy and the cap-and-trade policy respectively.

Finally, we discuss some key research findings in Section 7 and draw the conclusions in Section 8.

2 Literature review

To highlight our contributions, a literature review was conducted and constructed following the three key streams: (i) Carbon management in transportation research, (ii) Transportation mode selection considering carbon emission, and (iii) Carbon efficient logistics systems with risk consideration.

With respect to carbon management, transportation is one of the most visible aspects that significantly contribute to total emissions of supply chains. As a result, it has attracted considerable academic attention, which is reflected in recently published literature reviews on the topic. For example, Dekker et al. (2012) provided a comprehensive review of operations research on green logistics which integrates environmental aspects in logistics. While an overview of green logistics aspects and issues were presented in their review, they also concluded that operations research should emphasize its value for the environment and develop new models to address the multitude of decisions required to improve the environmental performance. Mansouri et al. (2015) provided a systematic review of the literature on multi-objective optimisation and decision support for environmental sustainability in maritime shipping. The review pointed out that further research is required in both theoretical development and applications of multi-objective optimisation based decision support systems for sustainable maritime transport. Demir (2014) focused more specifically on green road freight transportation and provided a review of recent research on the topic.

They extensively surveyed the existing vehicle emission models and analysed the factors contributing fuel consumption, which directly relates to the negative environmental externalities including carbon emissions. In term of specific models, Bae et al. (2011) proposed a two-stage game theoretic model to evaluate the implications of green transportation fleets from both policy and organisational perspectives. Many factors such as green vehicle technologies, expense of fuel, levels of service differences, and regulatory compliance requirements were evaluated in their model. Considering carbon emission reduction targets and state subsidy level, Chen et al. (2014) developed a new model for coastal liner route design for intermodal networks characterized by competition between costal shipping service and trucks. Rodrigues et al. (2015) evaluated possible carbon mitigation strategies for UK supply chains by assessing five scenarios that use a different combination of alternative ports and multimodal freight transport.

Transportation mode selection is another research stream (Tsamboulas et al. 2007; Meixell and Norbis 2008) that plays an important role in carbon emission reduction in the transportation and logistics system as the selection decision makes a significant impact on the economic and environmental performance of individual firms and their supply chain as a whole. For instance, Noen et al. (2013) found in their case study of a bulk liquids producer that carbon emission can be reduced by 10% by switching transport modes with only a 0.7% increase in total logistics cost. Among the few studies that incorporate the carbon emission reduction objectives in the production and transportation mode selection decision, Bauer et al. (2010) incorporated greenhouse gases related costs in intermodal freight transportation planning and applied to a rail service network design. Leal and D'Agosto (2011) presented a

fieldwork that used the modal choice method to select alternative ways of transporting bio-ethanol taking the economic and socio-environmental objectives in consideration. They found that long distance road transport appeared to be the worst of the alternative considered while local road transport as the best choice to feed long distance pipelines. Bloemhof et al. (2011) concluded in their investigation on the environmental impacts of inland navigation compared to rail and road transport that road transport remained the largest contributor of emissions despite a substantial improvement in emission reduction in recent years. Zhang et al. (2013) proposed an optimization model of multimodal network considering the costs of carbon emissions and economic scale. They applied the model to the Dutch container terminal network configuration and the analysis results showed that the increase in carbon emission prices can reduce the total system cost. Konur and Schaefer (2014) incorporated two transportation modes: less-than-truckload and truck load into the economic order quantity model to examine the impact of different carbon emission reduction polices on retailer's decision. Their finding indicated that regulation parameters have an effect on the retailer's carrier preference.

The main principle behind the green or carbon efficient logistics is the trade-off between transportation costs and emission costs as the environmental objective related factors come into the equation (Dekker et al. 2012; Wang et al. 2012; Demir 2014). While increasing carbon emission-caused environmental risk is one of the main drivers for green logistics, incorporating carbon emission reduction objective into operations decisions has also an inverse effect on the level of conventional supply chain risks. Despite its strategic importance, very few studies have examined the impact of incorporating a carbon emission reduction

objective in the production and transportation decisions on the risks of the logistics and supply chain system. Among them, Choi (2013) examined the impacts of carbon footprint tax on local sourcing and quick response system in the fashion apparel industry. His research finding revealed that the carbon foot print taxation scheme has an effect on the optimal choice of sourcing decision. More specifically, a proper design scheme can successfully entice the fashion retailer to locally purchase as well as reduce the risk level of the fashion retailer. Wang et al. (2012) proposed a risk assessment model of implementing alternative green initiatives in the fashion supply chain. They analysed the associated risks of different green alternatives subject to different business scenarios. Kengpol et al. (2015) developed a decision support framework to assess risk in multimodal green logistics using a combination of qualitative and quantitative models. Although their framework enabled to prioritise and optimise routes in green logistics, experts' inputs were also required in order to reach a decision.

Similar to this study, Hoen et al. (2014a) incorporated the network for transport and environment method into an inventory model and examined the effect of carbon emission regulations on transportation mode selection under stochastic demand. However, their study did not incorporate the different carbon emission regulations such carbon tax and emission cap in their model. Instead, the authors numerically analysed the effect of different regulations on transport mode selection problem. Wang et al. (2015a) examined the effects of carbon emission taxes on transportation mode selection decision and social welfare. Their research mainly focused on the effects of carbon emission taxes but not the cap and cap-and-trade policies. Different to above mentioned studies, considering both environmental

and financial objectives, our research integrates the transportation mode selection into a retailer ordering decision with stochastic customer demand. We analyse the effect of different carbon emission reduction policies including emission cap and cap-and-trade on the retailer's optimal ordering and transportation mode selection decision. Furthermore, in addition to the evaluation of the impact of different carbon emission reduction policies on retailer's financial and environmental performance, we also discuss the implications of these decisions on the supply chain risks. The research will provide important managerial and policy implications that support firms making important operational and strategic decisions to improve their financial performances and help governments develop effective carbon emission reduction polices to meet their environmental targets without compromising the sustainable development of the economy.

3 Model descriptions and assumption

We consider a one-period two-echelon supply chain consisting of a supplier who manufactures short shelf-life products and a retailer who orders from the supplier and sells to end-users with stochastic demand. Before the beginning of the selling season, the retailer receives an initial allocation of emission allowance from the government. The retailer can also buy additional allowance from or sell them to the outside market. Then the retailer places an order and transports the products from the supplier to the retailer. There are two transportation modes for the retailer to choose: the first one has low unit transportation cost and high unit carbon emissions, and the other has high unit transportation cost and low unit carbon emissions. At the beginning of selling season, the retailer obtains the products and

then sells to the customers during the selling season. After the selling season, the excessive product can be salvaged, and the retailer should not discharge more emissions than the allowance they hold. So, the retailer should decide the order quantity, transportation mode selection and carbon emission trading quantity before the customers' demands are arrived so as to achieve his maximum expected profit.

Throughout this paper, we use the parameters and variables as the following notations in Table 1.

Table. 1 Notations

Notation	Descriptions
D	The stochastic market demand.
$f(x)$	Probability density function for the stochastic market demand.
$F(x)$	Distribution function for the stochastic market demand, which is differentiable, invertible and strictly increasing.
p	Unit retail price of product.
w	Unit wholesale price of product.
v	Units salvage value of product.
g	Retailer's unit penalty cost for demand that cannot be filled
q	Retailer's order quantity.
K	Initial carbon emission allowance from government.
k_0	Unit carbon emission during retail period
k_1 and k_2	Unit carbon emission of transportation mode 1 and transportation mode 2 respectively.
c_1 and c_2	Unit transportation cost of transportation mode 1 and transportation mode 2 respectively.
e	Unit price of carbon emission trading with the outside market.
E	Carbon emission trading quantities with the outside market.
θ	The ratio of retailer adopting transportation mode 1, $0 \leq \theta \leq 1$.

In addition, we assume that the parameters satisfy the following conditions:

(1) $c_1 < c_2$ and $k_1 > k_2$. This condition means that the transportation mode 1 has lower unit transportation cost and higher unit transportation carbon emissions than these of the transportation mode 2.

(2) $p > w + c_2 > s > 0$. This condition states there is a positive profit margin for retailer to sell a product to the consumer market. On the other hand, the salvage value is less than the order and transportation costs, which implies that there is a loss if a product is not sold.

4 The basic model

We firstly consider the basic model without carbon emissions policy. The unit transportation cost is $\theta c_1 + (1 - \theta)c_2 = c_2 - \theta(c_2 - c_1)$. The retailer's profit, denoted $\pi_n(q, \theta)$, is

$$\pi_n(q, \theta) = p\min(q, D) + v(q - D)^+ - g(D - q)^+ - wq - [c_2 - \theta(c_2 - c_1)]q \quad (1)$$

The first term is retail revenue, the second term is the salvage value, and the last three terms represent the shortage cost, purchase cost and transportation cost respectively.

The retailer's expected profit without carbon emissions policy, denoted $E[\pi_n(q, \theta)]$, is

$$E[\pi_n(q, \theta)] = [p + g - w - c_2 + \theta(c_2 - c_1)]q - (p + g - v)\int_0^q F(x)\,dx -$$

$$g\int_0^{+\infty} xf(x)\,dx \quad (2)$$

As to the optimal ratio of retailer adopting transportation mode 1 (θ^n) and optimal order quantity (q^n) in the basic model without carbon emissions policy, the following proposition is obtained.

Proposition 1: *Without carbon emissions policy, $\theta^n = 1$ and $q^n = F^{-1}\left(\frac{p+g-w-c_1}{p+g-v}\right)$.*

This proposition means that in the basic model without carbon emissions policy, the retailer will select the transportation mode only according to the unit transportation cost, and prefer to choose transportation mode 1 and will gain more profit. Without carbon emissions policy, the risk faced by retailer is only from the uncertain nature of stochastic demand. The retailer's optimal quantity is a decreasing function of unit retail price of product, unit wholesale price of product, retailer's unit penalty cost for demand that cannot be filled, and unit transportation cost of transportation mode 1, and is an increasing function of units salvage value of product.

5 The cap model

In the cap model, the government sets a cap (K) on the quantity of pollution that the retailer can emit in a given period. The unit carbon emission of mixed transportation modes is $\theta k_1 + (1 - \theta)k_2 = k_2 + \theta(k_1 - k_2)$. The decision problem faced by the retailer is to decide the optimal transportation mode and optimal ordering quantity and so as to maximize his profit $E[\pi_n(q, \theta)]$, subject to the carbon emission constraint being satisfied. The decision problem faced by the retailer is

$$\max_{q,\theta} E[\pi_n(q, \theta)]$$

$$\text{s.t } [k_0 + k_2 + \theta(k_1 - k_2)]q \leq K \quad (3)$$

5.1 The optimal transportation mode selection and ordering policies

Set $K_1 = (k_0 + k_2)q^*$ and $K_2 = (k_0 + k_1)q^n$. As to the optimal ratio of retailer adopting transportation mode 1 (θ^c) and retailer's optimal order quantity (q^c) in the cap model, the following proposition is obtained.

Proposition 2: *In the cap model, if $K \geq K_2$, then $\theta^c = 1$ and $q^c = q^n$; if $K_1 < K < K_2$,*

then $\theta^c = \frac{K-(k_0+k_2)q^*}{(k_1-k_2)q^*}$ and $q^c = q^*$; if $K \leq K_1$, then $\theta^c = 0$ and $q^c = \frac{K}{k_0+k_2}$, where

$$q^* = F^{-1}\left[\frac{p+g-w-\frac{c_2(k_0+k_1)-c_1(k_0+k_2)}{k_1-k_2}}{p+g-v}\right].$$

This proposition indicates that with the cap policy, the retailer's optimal transportation mode selection decision and optimal order quantity are existence and unique. This proposition also indicates there are two important *transportation mode shifting thresholds: K_1 and K_2. K_1* means the retailer's total carbon emissions with transportation mode 2 and K_2 means the retailer's total carbon emissions with transportation mode 1.

According to the value of the government's initial carbon emission quota (K), there are three intervals as illustrated in Figure 1. The first interval is that the government's initial carbon emission quota is higher than the *transportation mode shifting threshold, (K_2).* In this interval, the carbon emissions quota is not binding, then the retailer will choose a cheaper and dirtier mode (transportation mode 1), and the retailer's optimal order quantity is fixed. The second interval is that the government's initial carbon emission quota is less than the *transportation mode shifting threshold K_2* and higher than the *transportation mode shifting threshold K_1.* In this interval, the carbon emissions quota is binding. Then the retailer would like to reduce the order quantity and choose mixed transportation modes to meet the carbon emissions quota binding. The retailer's order quantity is fixed. Part of the order is translated by the cheaper and dirtier mode (transportation mode 1) and the rest part of the order is switched to the more expensive and less polluting mode (transportation mode 2). The optimal ratio of retailer adopting transportation mode 1 (θ^c) is an increasing function of the government's initial carbon emission quota. That is, with the decreasing of the government's

initial carbon emission quota, the optimal ratio of retailer adopting transportation mode 1 is decreasing and the optimal ratio of retailer adopting transportation mode is increasing. The third interval is that the government's initial carbon emission quota is less than the *transportation mode shifting threshold* K_1. In this interval, the government's initial carbon emission quota is very low, then switching to more expensive and less polluting mode (transportation mode 2) is preferred. The retailer's optimal order quantity is an increasing function of the government's initial carbon emission quota. That is, with the decreasing of the government's initial carbon emission quota, the retailer's optimal order quantity is decreasing.
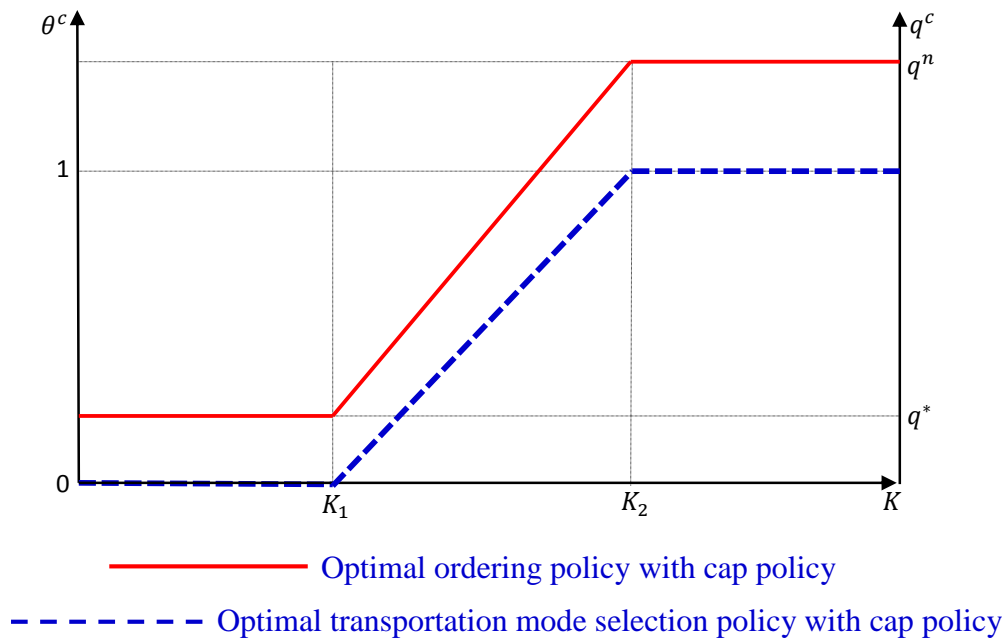
Figure 1. Optimal transportation mode selection and ordering policies with cap

From the view of the government or policy maker, with the cap policy, the retailer can be motivated to adopt less polluting transportation mode and order reasonable product quantity through adjusting the government's initial carbon emission quota.

5.2 The effect of the cap policy

Below we discuss the effect of the cap policy on the retailer's optimal ordering quantity and maximum expected profit. As to the effect of the cap policy on the retailer's optimal ordering quantity, the following proposition is obtained.

Proposition 3: If $K \geq (k_0 + k_1)q^n$, then $q^c = q^n$; if $K < (k_0 + k_1)q^n$, then $q^c < q^n$.

This proposition shows that if the government's initial carbon emission quota (K) is high and not binding, then the retailer's optimal ordering quantity (q^c) is equal to that without considering carbon emissions (q^n). If the government's initial carbon emission quota (K) is low and binding, then the retailer's optimal ordering quantity (q^c) is less than that without considering carbon emissions (q^n). That is, the retailer optimizes the transportation mode selection decision and orders less number of products to reduce the total carbon emissions and environment risk, but will face increased understock risk caused by the uncertain nature of stochastic demand and less order quantity at the same time.

As to the effect of the cap policy on retailer's maximum expected profit, the following proposition is obtained.

Proposition 4: If $K \geq (k_0 + k_1)q^n$, then $E[\pi_n(q^c, \theta^c)] = E[\pi_n(q^n, \theta^n)]$; if $K < (k_0 + k_1)q^n$, then $E[\pi_n(q^c, \theta^c)] < E[\pi_n(q^n, \theta^n)]$.

This proposition means that if the government's initial carbon emission quota (K) is high and not binding, then the retailer's maximum expected profit with the cap policy ($E[\pi_n(q^c, \theta^c)]$) is equal to that without considering carbon emissions ($E[\pi_n(q^n, \theta^n)]$). If the government's initial carbon emission quota (K) is low and binding, then the retailer's maximum expected profit with the cap policy is less than that without considering carbon

emissions. In a word, the retailer's maximum expected profit with the cap policy is less than or equal to that without considering carbon emissions. So, from the retailer's point of view, he would not voluntarily reduce the amount of carbon emissions up to a certain level without considering a carbon cap regulatory policy.

6 The cap-and-trade model

In this section, we discuss the cap-and-trade model. With the cap-and-trade policy, if the retailer does not use up its entire cap, it can sell its remaining quota to the outside market. If the retailer needs additional quota, it can purchase the shortage quota from the outside market. The decision problem faced by the retailer is to decide the optimal transportation mode selection, ordering and carbon emission trading policies. The retailer's decision making model is

$$\max_{q,\theta} E[\pi_e(q,\theta)] = \max_{q,\theta}[E[\pi_n(q,\theta)] - eE]$$

$$\text{s.t } [k_0 + k_2 + \theta(k_1 - k_2)]q = K + E \ (4)$$

This constraint means that the retailer's total carbon emission is equal to the sum of initial carbon emission cap set by the government and the trading quantity of carbon emission with the outside market. When $E > 0$, it means that the retailer will buy carbon emission quota from the outside market. When $E = 0$, it means that the retailer will not trade with the outside market. When $E < 0$, it means that the retailer will sell carbon emission quota to the outside market.

6.1 The optimal transportation mode selection, ordering and carbon emission trading policies

As to the optimal ratio of retailer adopting transportation mode 1 (θ^e), the retailer's optimal order quantity (q^e) and optimal carbon emission trading policy (E^e) in the cap-and-trade model, the following proposition is obtained.

Proposition 5: *With cap-and-trade policy, if* $e > \frac{c_2 - c_1}{k_1 - k_2}$, *then* $\theta^e = 0$, $q^e = F^{-1}\left[\frac{p+g-w-c_2-e(k_0+k_2)}{p+g-v}\right]$ *and* $E^e = (k_0 + k_2)q^e - K$; *if* $e < \frac{c_2 - c_1}{k_1 - k_2}$, *then* $\theta^e = 1$, $q^e = F^{-1}\left[\frac{p+g-w-c_1-e(k_0+k_1)}{p+g-v}\right]$ *and* $E^e = (k_0 + k_1)q^e - K$.

This proposition means that with the cap-and-trade policy, the retailer's optimal transportation mode selection policy, optimal order quantity and optimal carbon emission trading policy are existence and unique. From this proposition, we also know that the threshold $\frac{c_2 - c_1}{k_1 - k_2}$ is important. Set $e_0 = \frac{c_2 - c_1}{k_1 - k_2}$. e_0 represents the *transportation mode shifting threshold* under the cap-and-trade policy. e_0 is decided by the unit carbon emission and unit transportation cost of two transportation modes, but it has no relationship with the initial government carbon emissions quota.

According to the unit price of carbon emission trading with the outside market (e), there are two intervals. The first interval is that the unit price of carbon emission trading with the outside market is higher than the *transportation mode shifting threshold* (e_0). In this interval, the increased unit carbon emissions cost caused by using transportation mode 1 is higher than the decreased unit transportation cost, then the retailer will prefer the more expensive and less polluting mode (transportation mode 2). The retailer's optimal order quantity is fixed. The second interval is that the unit price of carbon emission trading with the outside market is lower than the *transportation mode shifting threshold* (e_0). In this interval, the increased unit carbon emissions cost caused by using transportation mode 1 is lower than the decreased unit

transportation cost, then switching to the cheaper and dirtier mode (transportation mode 1) is preferred. The retailer's optimal order quantity is also fixed. If the unit price of carbon emission trading with the outside market (e) is equal to the *transportation mode shifting threshold* (e_0), that is, the increased unit carbon emissions cost caused by using transportation mode 1 is equal to the decreased unit transportation cost, then the two transportation modes are equal.

From the view of the government or policy maker, with the cap-and-trade policy, the retailer can be encouraged to adopt less polluting transportation mode and order reasonable product through adjusting the unit price of carbon emission trading with the outside market.

6.2 The effect of the cap-and-trade policy

Now we discuss the effect of the cap-and-trade policy on the retailer's optimal ordering quantity, total carbon emissions, and maximum expected profit.

Denote the unit transportation carbon emissions with the cap-and-trade policy is k_e. From proposition 5, we get that if $e > \frac{c_2 - c_1}{k_1 - k_2}$, then $k_e = k_2$; if $e < \frac{c_2 - c_1}{k_1 - k_2}$, then $k_e = k_1$. As to the effect of the cap-and-trade policy on the retailer's optimal ordering quantity and total carbon emissions, the following proposition is obtained.

Proposition 6: $q^e < q^n$ *and* $(k_0 + k_e)q^e < (k_0 + k_1)q^n$.

This proposition indicates that the retailer's optimal ordering quantity with the cap-and-trade policy is less than that without considering carbon emissions, and the retailer's total carbon emissions with the cap-and-trade policy is less than that without considering carbon emissions. That is, with the cap-and-trade policy, the retailer takes the environment risk into consideration and reduces the total carbon emissions through transportation mode

selection and less order quantity, but the understock risk caused by uncertain demand is increased with less order quantity.

As to the effect of cap-and-trade policy on the retailer's maximum expected profit, the following proposition is obtained.

Proposition 7: *If* $K > K^*$, *then* $E[\pi_e(q^e, \theta^e)] > E[\pi_n(q^n, \theta^n)]$; *if* $K = K^*$, *then* $E[\pi_e(q^e, \theta^e)] = E[\pi_n(q^n, \theta^n)]$; *if* $K < K^*$, *then* $E[\pi_e(q^e, \theta^e)] < E[\pi_n(q^n, \theta^n)]$, *where* $K^* = [k_0 + k_2 + \theta^e(k_1 - k_2)]q^e + \frac{1}{e}\{E[\pi_n(q^n, \theta^n)] - E[\pi_n(q^e, \theta^e)]\}$.

This proposition means that the retailer's optimal profit with the cap-and-trade policy can be higher than, equal to, or less than that without considering carbon emissions. It all depends on the government's initial carbon emission quota. That is, if the government's initial carbon emission quota is high, then the retailer's optimal profit with the cap-and-trade policy is higher than that without considering carbon emissions. If the government's initial carbon emission quota is medium, then the retailer's optimal profit with cap-and-trade policy is equal to that without considering carbon emissions. If the government's initial carbon emission quota is low, then the retailer's optimal profit with the cap-and-trade policy is less than that without considering carbon emissions.

7 Discussions

In this section, we summarize the key findings of the research and discuss the insights and implications of our findings. First, our analytical results reveal that there are two important transportation mode shifting thresholds under the emission cap policy. If the government's initial carbon emission quota is more than the first threshold, $K_1 = (k_0 + k_1)q^n$, the retailer

will choose the cheaper transportation mode with high carbon emission. If the quota is less than the second threshold, $K_2 = (k_0 + k_2)q^*$, companies will choose the more expensive transportation mode with low carbon emissions. More interestingly, if the quota is within the interval between the two thresholds, the retailer will select a mixed transportation mode and the distribution between the two modes is dependent on the initial quota.

For the cap-and-trade policy, there is also an important transportation mode shifting threshold, which depends on the unit carbon emissions and the unit transportation costs of two transportation modes. Different to the cap policy, the initial government carbon emissions quota has no effect on this threshold under the cap-and-trade policy. If the unit price of carbon emission trading with the outside market is higher than the threshold, the retailer will select the more expensive transportation mode with low carbon emissions. In contrast, if the unit price of carbon emission trading is lower than the threshold, the retailer will switch to a cheaper mode with high carbon emissions. The two transportation modes make no difference if the threshold is equal to the unit price of carbon emission trading.

The above two findings provide some important insights, which do not only help firms to make optimal decisions to improve their economic performance under different carbon emission reduction policies but also support government policy making on carbon emission reduction. For instance, they can decide a lower initial carbon emission quota under the cap policy to encourage firms to choose more carbon efficient transportation mode in order to meet carbon emission reduction targets. Under the cap-and-trade policy, instead of setting up a lower initial carbon emission quota, a more effective option to meet the carbon emission

reduction target is to increase the unit price of carbon emission trading with the outside market.

Our findings also indicate that incorporating the carbon emission reduction objective in the ordering and transportation mode selection decision will help to reduce the environmental risk under different carbon emission reduction policies. However, it will have a knock-on effect on supply chain risks. For instance, under both the cap policy and the cap-and-trade policy, it will increase the understock risk because a retailer intends to order lower quantity of product to reduce the carbon emission cost while facing uncertain demand. Firms may have to consider the trade-off between the additional cost incurred by the increased supply chain risk and the financial benefit of reduced carbon emission when making such decisions.

8 Conclusions and future research

Taking both the financial and environmental objectives into consideration, this paper studies the retailer's ordering and transportation mode selection problem using stochastic customer demand. We obtained the optimal ordering and mode selection decision under different carbon emission reduction policies. By comparing the optimal solutions and performances under different policies to the basic model in which only financial cost is considered, we evaluate the impact of different policies on retailer's financial and environmental performance and discuss the risk implications of these decisions on the supply chain.

This research makes several key contributions. First, theoretically, our research is one of few studies that have examined the effect of different carbon emissions reduction policies on firms' ordering and transportation mode selection problem considering both economic and

environmental objectives. Furthermore, we discuss the implications of derived optimal solutions on the logistics and supply chain risks. Second, our research findings provide interesting managerial insights that will support firms making important operational and strategic decisions in order to improve their financial and environmental performances. For instance, firms can derive the optimal ordering quantity and select the correct transportation mode under different carbon emission policies. Our findings will give firms a better understanding of the supply and demand risks imposed by these ordering and transportation mode selection decisions, and therefore, take more proactive actions to mitigate supply chain risks. Finally, our research findings also have some important policy implications that governments can use to develop effect carbon emission reduction polices in order to meet their overall carbon emission reduction targets without compromising the sustainable development of the economy.

Similar to many other previous studies, this research has some limitations which open avenues for future research. For example, this paper only considers one retailer's ordering and transportation mode selection problem. It can be extended by considering the transportation mode selection of both inbound and outbound logistics and, alternatively, incorporating supplier's inventory control decision in the model. Moreover, the stochastic demand function used in the paper does not consider the competition between rival competitors. One interesting research extension is to incorporate horizontal competition in the demand function. In addition to the cost and carbon emission considered in this research, transportation mode selection decisions are also influenced many other factors such as lead time (Kiesmüller et al. 2005), fuel consumption (Demir et al. 2014), supply chain power

structure (Chen et al. 2015; Chen and Wang 2015), and social welfare (Wang et al. 2015a). It will be useful but a more challenging research if these factors are considered. While some of the factors can be incorporated in the modelling, others may not be realistically modelled. More importantly, we also recognize the value of examining actual responses from organisations to carbon quotas. One future research extension is to seek to ascertain how organisations actually respond to these situations and to unearth other variables that include the decision making processes.

Acknowledgments

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Appendix

The proof of proposition 1

From (2), we get $\frac{\partial E[\pi_n(q,\theta)]}{\partial \theta} = (c_2 - c_1)q > 0$, that is, $E[\pi_n(q,\theta)]$ is an increasing function of θ. Recalling $0 \le \theta \le 1$, $\theta^n = 1$.

Replace θ^n to (2), we get $E[\pi_n(q,\theta^n)] = (p + g - w - c_1)q - (p + g - v)\int_0^q F(x)\,dx -$

$g\int_0^{+\infty} xf(x)\,dx$. Then, $\frac{dE[\pi_n(q,\theta^n)]}{dq} = (p + g - w - c_1) - (p + g - v)F(q)$ and

$\frac{d^2 E[\pi_n(q,\theta^n)]}{dq^2} = -(p + g - v)f(q) < 0$, that is, $E[\pi_n(q,\theta^n)]$ is a concave function of q.

Let $\frac{dE[\pi_n(q,\theta^n)]}{dq} = 0$, we get $q^n = F^{-1}\left(\frac{p+g-w-c_1}{p+g-v}\right)$.

So, without carbon emissions policy, $\theta^n = 1$ and $q^n = F^{-1}\left(\frac{p+g-w-c_1}{p+g-v}\right)$. This completes

the proof.

The proof of proposition 2

From proposition 1, we get $[k_0 + k_2 + \theta^n(k_1 - k_2)]q^n = (k_0 + k_1)q^n$.

(1) If $K \geq (k_0 + k_1)q^n$, that is, the cap is satisfied automatically and the cap is not binding.

Then, $q^c = q^n = F^{-1}\left(\frac{p+g-w-c_1}{p+g-v}\right)$ and $\theta^c = \theta^n = 1$.

(2) If $K < (k_0 + k_1)q^n$, that is, the cap is not binding. According to the KKT condition, the

optimal solution satisfies the following conditions:

$$\lambda_1\{[k_0 + k_2 + \theta(k_1 - k_2)]q - K\} = 0$$

$$-\lambda_2 q = 0$$

$$-\lambda_3 \theta = 0$$

$$p + g - w - c_2 + \theta(c_2 - c_1) - (p + g - v)F(q) - \lambda_1[k_0 + k_2 + \theta(k_1 - k_2)] + \lambda_2 = 0$$

$$(c_2 - c_1)q - \lambda_1(k_1 - k_2)q + \lambda_3 = 0$$

$$\lambda_1 \geq 0, \ \lambda_2 \geq 0, \ \lambda_3 \geq 0$$

Then，if $K > (k_0 + k_2)q^*$, then $\theta^c = \frac{K - (k_0 + k_2)q^*}{(k_1 - k_2)q^*}$ and $q^c = q^*$; if $K \leq (k_0 + k_2)q^*$, then

$\theta^c = 0$ and $q^c = \frac{K}{k_0 + k_2}$, where $q^* = F^{-1}\left[\frac{p + g - w - \frac{c_2(k_0 + k_1) - c_1(k_0 + k_2)}{k_1 - k_2}}{p + g - v}\right]$.

So, in the cap model, if $K \geq (k_0 + k_1)q^n$, then $\theta^c = 1$ and $q^c = q^n$; if $(k_0 + k_2)q^* <$

$K < (k_0 + k_1)q^n$, then $\theta^c = \frac{K - (k_0 + k_2)q^*}{(k_1 - k_2)q^*}$ and $q^c = q^*$; if $K \leq (k_0 + k_2)q^*$, then $\theta^c = 0$

and $q^c = \frac{K}{k_0 + k_2}$, where $q^* = F^{-1}\left[\frac{p + g - w - \frac{c_2(k_0 + k_1) - c_1(k_0 + k_2)}{k_1 - k_2}}{p + g - v}\right]$. This completes the proof.

The proof of proposition 3

From proposition 2, we get that if $K \geq (k_0 + k_1)q^n$, then $q^c = q^n$.

Recalling $c_1 < c_2$ and $k_1 > k_2$, then $c_1 - \dfrac{c_2(k_0+k_1)-c_1(k_0+k_2)}{k_1-k_2} = \dfrac{(c_1-c_2)(k_0+k_1)}{k_1-k_2} < 0$, that is,

$c_1 < \dfrac{c_2(k_0+k_1)-c_1(k_0+k_2)}{k_1-k_2}$. So from proposition 1 and proposition 2, we get $q^c = q^* =$

$F^{-1}\left[\dfrac{p+g-w-\frac{c_2(k_0+k_1)-c_1(k_0+k_2)}{k_1-k_2}}{p+g-v}\right] < F^{-1}\left(\dfrac{p+g-w-c_1}{p+g-v}\right) = q^n$, that is, if $(k_0 + k_2)q^* < K <$

$(k_0 + k_1)q^n$, then, $q^c < q^n$.

If $K \leq (k_0 + k_2)q^*$, from proposition 2, we get $q^c = \dfrac{K}{k_0+k_2} < q^* < q^n$, that is, $q^c < q^n$.

Hence, if $K \geq (k_0 + k_1)q^n$, then $q^c = q^n$; if $K < (k_0 + k_1)q^n$, then $q^c < q^n$. This completes the proof.

The proof of proposition 4

From proposition 2, if $K \geq (k_0 + k_1)q^n$, then $\theta^c = \theta^n = 1$ and $q^c = q^n$, so $E[\pi_n(q^c, \theta^c)] = E[\pi_n(q^n, \theta^n)]$.

From proposition 1 and proposition 2, if $K < (k_0 + k_1)q^n$, then $\theta^c < \theta^n$ and $q^c < q^n$. Considering the maximum of $E[\pi_n(q, \theta)]$, we get $E[\pi_n(q^c, \theta^c)] < E[\pi_n(q^n, \theta^n)]$.

So, if $K \geq (k_0 + k_1)q^n$, then $E[\pi_n(q^c, \theta^c)] = E[\pi_n(q^n, \theta^n)]$; if $K < (k_0 + k_1)q^n$, then $E[\pi_n(q^c, \theta^c)] < E[\pi_n(q^n, \theta^n)]$. This completes the proof.

The proof of proposition 5

From (4), we get $E = [k_0 + k_2 + \theta(k_1 - k_2)]q - K$, then $E[\pi_e(q, \theta)] = E[\pi_n(q, \theta)] - e\{[k_0 + k_2 + \theta(k_1 - k_2)]q - K\}$. Then, we get $\dfrac{\partial E[\pi_e(q,\theta)]}{\partial \theta} = (c_2 - c_1)q - e(k_1 - k_2)q = [(c_2 - c_1) - e(k_1 - k_2)]q$.

If $e > \dfrac{c_2-c_1}{k_1-k_2}$, then $\dfrac{\partial E[\pi_e(q,\theta)]}{\partial \theta} < 0$, that is, $E[\pi_e(q, \theta)]$ is a decreasing function of θ, then $\theta^e = 0$; if $e = \dfrac{c_2-c_1}{k_1-k_2}$, then $\dfrac{\partial E[\pi_e(q,\theta)]}{\partial \theta} = 0$, that is, $E[\pi_e(q, \theta)]$ has no relationship with θ; if $e < \dfrac{c_2-c_1}{k_1-k_2}$, then $\dfrac{\partial E[\pi_e(q,\theta)]}{\partial \theta} > 0$, that is, $E[\pi_e(q, \theta)]$ is an increasing function of θ, then $\theta^e = 1$.

For a given θ, $\frac{dE[\pi_e(q,\theta)]}{dq} = p + g - w - c_2 + \theta(c_2 - c_1) - (p + g - v)F(q) - e[k_0 + k_2 + \theta(k_1 - k_2)]$ and $\frac{d^2 E[\pi_e(q,\theta)]}{dq^2} = -(p + g - v)f(q) < 0$, that is, $E[\pi_e(q,\theta)]$ is a concave function of q. Let $\frac{dE[\pi_e(q,\theta)]}{dq} = 0$, we get $q^e = F^{-1}\left\{\frac{p+g-w-c_2+\theta(c_2-c_1)-e[k_0+k_2+\theta(k_1-k_2)]}{p+g-v}\right\}$.

So, if $e > \frac{c_2-c_1}{k_1-k_2}$, then $\theta^e = 0$, $q^e = F^{-1}\left[\frac{p+g-w-c_2-e(k_0+k_2)}{p+g-v}\right]$ and $E^e = (k_0 + k_2)q^e - K$

If $e < \frac{c_2-c_1}{k_1-k_2}$, then $\theta^e = 1$, $q^e = F^{-1}\left[\frac{p+g-w-c_1-e(k_0+k_1)}{p+g-v}\right]$ and $E^e = (k_0 + k_1)q^e - K$.

This completes the proof.

The proof of proposition 6

From proposition 1, we get $q^n = F^{-1}\left(\frac{p+g-w-c_1}{p+g-v}\right)$.

If $e > \frac{c_2-c_1}{k_1-k_2}$, from proposition 5, we get $q^e = F^{-1}\left[\frac{p+g-w-c_2-e(k_0+k_2)}{p+g-v}\right]$. Considering $c_1 <$

c_2, then $q^e = F^{-1}\left[\frac{p+g-w-c_2-e(k_0+k_2)}{p+g-v}\right] < F^{-1}\left(\frac{p+g-w-c_1}{p+g-v}\right) = q^n$, that is, $q^e < q^n$. If $e <$

$\frac{c_2-c_1}{k_1-k_2}$, from proposition 5, we get $q^e = F^{-1}\left[\frac{p+g-w-c_1-e(k_0+k_1)}{p+g-v}\right]$. Then $q^e =$

$F^{-1}\left[\frac{p+g-w-c_1-e(k_0+k_1)}{p+g-v}\right] < F^{-1}\left(\frac{p+g-w-c_1}{p+g-v}\right) = q^n$, that is, $q^e < q^n$. So, $q^e < q^n$.

If $e > \frac{c_2-c_1}{k_1-k_2}$, then $k_e = k_2 < k_1$. Recalling $q^e < q^n$, then $(k_0 + k_e)q^e < (k_0 + k_1)q^n$. If

$e < \frac{c_2-c_1}{k_1-k_2}$, then $k_e = k_1$. Recalling $q^e < q^n$, then $(k_0 + k_e)q^e < (k_0 + k_1)q^n$. So,

$(k_0 + k_e)q^e < (k_0 + k_1)q^n$. This completes the proof.

The proof of proposition 7

From (4), we get $E = [k_0 + k_2 + \theta(k_1 - k_2)]q - K$, then $E[\pi_e(q,\theta)] = E[\pi_n(q,\theta)] - e\{[k_0 + k_2 + \theta(k_1 - k_2)]q - K\}$.

If $K \leq [k_0 + k_2 + \theta^e(k_1 - k_2)]q^e$, we get $E[\pi_e(q^e,\theta^e)] = E[\pi_n(q^e,\theta^e)] - e\{[k_0 + k_2 + \theta^e(k_1 - k_2)]q^e - K\} \leq E[\pi_n(q^e,\theta^e)]$. Considering the maximum of $E[\pi_n(q,\theta)]$, we get $E[\pi_n(q^e,\theta^e)] < E[\pi_n(q^n,\theta^n)]$. Then $E[\pi_e(q^e,\theta^e)] \leq E[\pi_n(q^e,\theta^e)] < E[\pi_n(q^n,\theta^n)]$, that is, $\pi_e(q_1^e,q_2^e) < \pi_n(q_1^n,q_2^n)$. If $K \geq [k_0 + k_2 + \theta^n(k_1 - k_2)]q^n$, considering the

maximum of $E[\pi_e(q, \theta)]$, we get $E[\pi_e(q^e, \theta^e)] > E[\pi_n(q^n, \theta^n)] - e\{[k_0 + k_2 + \theta^n(k_1 - k_2)]q^n - K\} > E[\pi_n(q^n, \theta^n)]$, that is, $E[\pi_e(q^e, \theta^e)] > E[\pi_n(q^n, \theta^n)]$. So, there always exist a $K^* \in ([k_0 + k_2 + \theta^e(k_1 - k_2)]q^e, [k_0 + k_2 + \theta^n(k_1 - k_2)]q^n)$ that satisfies $E[\pi_e(q^e, \theta^e)] = E[\pi_n(q^n, \theta^n)]$, that is, $E[\pi_n(q^e, \theta^e)] - e\{[k_0 + k_2 + \theta^e(k_1 - k_2)]q^e - K\} = E[\pi_n(q^n, \theta^n)]$, which implies $K^* = [k_0 + k_2 + \theta^e(k_1 - k_2)]q^e + \frac{1}{e}\{E[\pi_n(q^n, \theta^n)] - E[\pi_n(q^e, \theta^e)]\}$. Since $E[\pi_e(q^e, \theta^e)]$ increases in K, so if $K > K^*$, then $E[\pi_e(q^e, \theta^e)] > E[\pi_n(q^n, \theta^n)]$; if $K = K^*$, then $E[\pi_e(q^e, \theta^e)] = E[\pi_n(q^n, \theta^n)]$; if $K < K^*$, then $E[\pi_e(q^e, \theta^e)] < E[\pi_n(q^n, \theta^n)]$. This completes the proof.