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Vehicles Assignment With Over-Emission Intensity Considerations: A Perspective on Integrating the Market Mechanism With Government Control

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ABSTRACT In this paper, we consider the effect of carbon emission regulations on the vehicles assignment optimization problem. We propose a mathematical model, in which the choice of vehicles (between the traditional and new environmental-friendly ones) and the proper assignments to customers are the decision variables. We introduce a new measure, called the over-emission intensity (OEI) factor, with which the government can control the amount of carbon emission of companies. Based on this proposal, we establish a new mechanism, known as the cap-and-trade program with OEI, and incorporate it into the optimization model. This novel model is then validated and used to study the impacts of OEI, carbon emission quota, emission price, and budget, on the operational performance and optimal decision of the company. We demonstrate the usefulness of the model by illustrating the effect of market regulation and government's macrocontrol on the reduction of carbon emission. We also show how the OEI affects the company's total cost, total amount of carbon emission, and the optimal vehicles assignment scheme. Finally, we argue that integrating the government macrocontrol scheme with the market mechanism is an effective measure.

INDEX TERMS Transportation, carbon emission, cap and trade, vehicles assignment, over emission intensity, logistics management.

I. INTRODUCTION

Transportation is a critical area of supply chain systems engineering [1]. The transportation and its related industries are notorious for being responsible for a huge portion of carbon emissions. In particular, transport companies use heavy-duty diesel vehicles which lead to the release of toxic air pollutants and global greenhouse gases. The US Environmental Protection Agency [44] listed in 2008 nearly 200 toxic air pollutants, including nitrogen oxides and carbon monoxides, which are all generated by heavy-duty diesel vehicles. In the literature, Ohnishi [32] points out that the percentage of total greenhouse gas (GHG) emissions from transportation rises from 24.9% to 27.3% between 1990 and 2005, with road transportation accounting for 78% of the emissions produced by all transportation modes. According to [13], the heavy-duty diesel vehicles constitute only a small portion of the "on-road vehicles" but they release more than 45% of the nitrogen related pollutants generated by all vehicles. It can be seen from Fig.1a (see [35]) that the transportation sector accounts for 14% of the total GHG emissions. As we know, the heavy-duty and light-duty vehicles are just the most widely used vehicles in road transportation [34].

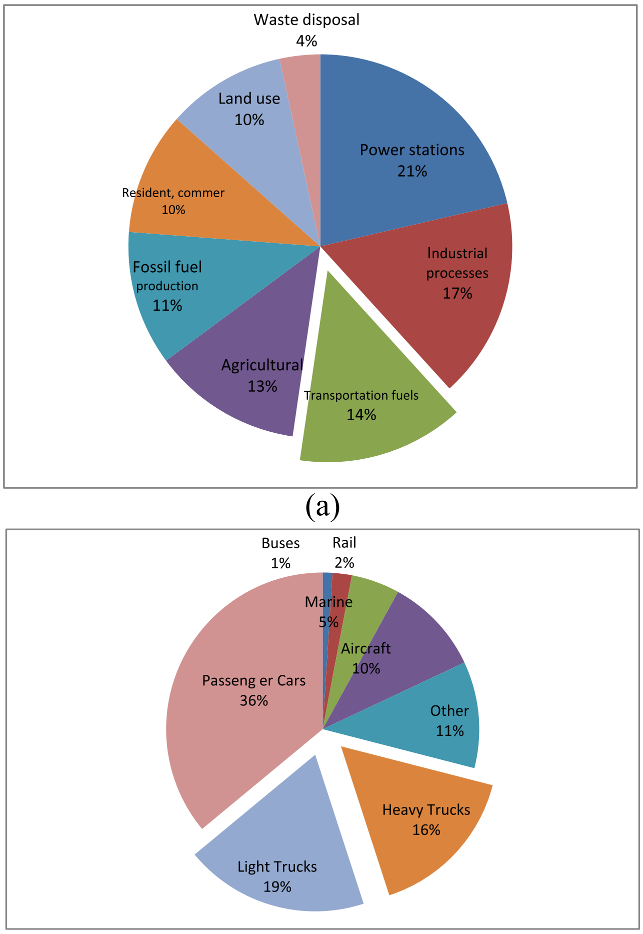

FIGURE 1. **(a) GHG emissions by sectors. (b) Transport GHG emissions [35].**

Fig.1b (see [35]) shows that about 35% of carbon emissions come from the heavy-duty vehicles and light-duty vehicles.

Owing to the reasons mentioned above, vehicle assignment and vehicle routing problems are catching attention from both academic researchers and industrialists. This research area is especially important nowadays owing to the pressure from environmental pressure groups, corporate funding and governmental initiatives. As a result, researchers have suggested that decision makers for transportation and vehicle routing problems should focus on environmental and social factors instead of the sole objective of profit (e.g. [31], [42]). Motivated by this, in order to reduce carbon emissions of freight transportation, we suggest in this paper two lines of actions. The first action is the replacement of heavy-duty diesel vehicles with the environmental friendly new energy vehicles. These environmental friendly new energy vehicles use alternative fuels-bio-diesel, liquefied natural gas [3] and compressed natural gas [38], which emit a much smaller amount of carbon pollutants. The second line of action is the assignment of vehicles suitably to the customers in an economically and environmentally friendly way. We integrate these two actions into a mathematical optimization model to achieve the goals of energy savings and emission reductions for sustainable economic development. As a remark, our model underpins the above two lines of actions by a mechanism that incorporates market activities through carbon trading, and government's macro control via the over-emission intensity (OEI) factor. We have demonstrated that these two measures, the carbon market trading and the government's macro control, play complementary roles in achieving the above mentioned goals. Furthermore, our research applies very well to transport companies that use both light trucks and heavy trucks.

II. LITERATURE REVIEW AND CONTRIBUTIONS

A. VEHICLE ROUTING AND ASSIGNMENT PROBLEM IN FREIGHT TRANSPORT

The vehicle routing problem is a well-explored topic in the literature. The commonly adopted objective in the vehicle routing problem is either total distance minimization or total cost minimization. Most studies have not considered the negative effect of vehicle routing decision on the environment. With the increasing social awareness of environmental protection and sustainability, a few researchers have explored the vehicle routing (and assignment) problem with the consideration of environmental factors [21]. For example, Figliozzi [15] develops a carbon emission minimization model by choosing the optimal departure times of vehicles. The author shows that high emissions occur when vehicles run through a congested path. Bektas and Laporte [8] incorporate a broader and comprehensive objective function into the model to include not just the traveling distance, but also the amount of GHG emissions, fuels, travel times and their costs. Ramos et al. [39] suggest a model where the objective is to reduce the amount of carbon emission. Research works with a similar theme can be found in Fagerholt et al. [14] and Palmer [36]. Observe that the above studies only target at reducing the distance-based cost and carbon emissions by adjusting the objective function of the traditional vehicle routing problem. In addition, only one vehicle is investigated in the above reviewed studies, and there are no provisions to include new energy vehicles alongside the traditional vehicles. Moreover, the cost calculation is independent of the company's total operating cost. These are some critical differences between the reviewed studies and this paper.

In a recent study, Kopfer and Kopfer [24] consider the vehicle routing problem for emissions minimization using a heterogeneous fleet. However, the computational experiments are performed on relatively small sized instances (with up to 10 customers) only. Kopfer et al. [25] analyze the potential of reducing carbon emissions by using an unlimited heterogeneous fleet of vehicles of different sizes. Kwon et al. [26] also consider the heterogeneous fixed fleet vehicle routing problem with the objective of minimizing carbon emissions. A mathematical model is presented which enables decision makers to perform a cost-benefit assessment of the value of purchasing or selling carbon emission rights. For some other related works, see [11], [28], [31], [42], [46] and the recent survey reported in [12].

From our review of the current literature, we observe that there lacks a comprehensive mathematical optimization model that encompasses the relevant participants and factors (such as the transportation companies, the market mechanism and the government policy [49]). The major aim of this paper is to propose such a mathematical optimization model, apply it and generate management insights.

B. TRANSPORTATION MODE SELECTION

A lot of research works have been conducted on optimal transportation mode selection (e.g. trains, ships and vehicles). In fact, the transportation mode selection problem in freight transportation could be dated back to the 1980s (see, [2], [4], [6], [43]). In this domain, the classic studies have been extended by a number of researchers [10], [37] to include the carbon emission cost. Benefits of the combined modes of transportation, especially in reducing carbon emissions, have also been discussed in a number of papers [5], [29], [47]. In particular, Arteconi et al. [3] discuss the reduction of carbon emissions through a proper design of intermodal transportation. Ramudhin et al. [40] develop a supply chain network design by incorporating carbon trading into the selection of transportation modes. Kim et al. [22] use the multi-objective optimization model, which is based on cost and carbon emission considerations, to obtain the optimal solution in which a balance between the two is sought. Kjetil and Haugen [23] use the game theory approach to discuss the problem of transportation modes selection in freight transportation.

In addition to combining different modes of transportation, some researchers have discussed how to select different vehicles in the same type of transportation mode. For instance, Bauer et al. [7] consider adjusting the service frequency of trains in order to reduce carbon emissions when a portfolio of trains has been used. Paksoy [33] employs different types of vehicles in addressing carbon emission reduction issues in a supply chain network.

Previous studies have also examined the effect of new energy vehicles on carbon emission reduction. For example, Li and Head [27] offer a trade-off analysis on the operating costs and carbon emissions in the bus-scheduling problem under a capital budget constraint. Mao et al. [30] study the effects of policy instruments such as the carbon-emission tax, energy tax, and subsidies for new energy vehicles on carbon emission reduction. Hoen et al. [19] study a GHG producer that has outsourced transportation with a cap on its carbon emissions from outbound logistics for a group of customers. For other related studies, readers can refer to [18] and [45]. As a remark, the above research works have not considered a framework or model that rewards (penalizes) the companies that have incurred fewer (more) carbon emissions. We hence develop such an optimization model, solve it and generate the corresponding insights in this paper.

C. THE CAP AND TRADE MECHANISM AND EMISSION POLICY

Transportation policies and the ‘‘cap and trade policy’’ have been the focus of recent research on carbon emission reduction. In the related literature, Zanni and Bristow [48] demonstrate, using past data in London, that transportation policies do affect the transport emissions. They conclude by claiming that proper policy guidance is essential for achieving effective emission reduction. Flachsland et al. [16] find that the market-based instrument, such as the cap and trade mechanism, is complementary to other non-market based policies. Positive effects of the cap and trade mechanism on carbon emissions in freight transportation are found by German [17] for the case with the light-duty vehicle. Raux [41] analyzes the potential of carbon trading in transportation for personal cars and vehicles. He points out that the rational use of carbon emission trade can help control carbon emissions from transportation effectively. Hua et al. [20] pioneer a study on carbon emission management in inventory control. Choi [9] discusses effects of carbon emission taxation on quick response logistics systems.

Many companies, out of their sense of social responsibilities and pressure from the environmental groups, do strive hard to reduce carbon emissions by managing the fleet of their vehicles as well as optimally arranging the routes of the vehicles. However, these companies usually only focus on either maximizing profits or minimizing costs; unfortunately, the regulation on carbon emissions and the control of operating costs are usually conflicting in nature. Therefore, intuitively, it is imperative to use both the power of law, and the cap and trade mechanism to force companies to reduce carbon emissions in freight transportation.

D. MOTIVATION, FINDINGS, AND CONTRIBUTION

To address the issue of carbon emissions, the literature we reviewed above has considered a number of strategies (such as distance minimization, transportation mode selection or the cap and trade mechanism) in isolation (but not together). However, none of the prior studies have comprehensively examined all these important factors together. They also have not examined the relative effectiveness between the market mechanism and the government control.

Motivated by the current deficiency of the related models, we introduce a new measure called the over-emission intensity (OEI) factor which the government can impose on companies. Based on this concept, we propose a new mechanism (i.e., a cap-and-trade program with OEI) to deal with the challenge on reducing carbon emissions. This mechanism integrates the market control via the carbon trading mechanism and the government macro control into the optimization model. This model is novel and comprehensive in which three critical factors are all incorporated into it; these factors are (a) the OEI measure; (b) the capital budgets for new energy friendly vehicles to replace the traditional heavy pollution diesel vehicles; (c) carbon emission quotas allocated to companies, which are integrated with the cap and trade mechanism. We also modify the objective function of the traditional vehicle assignment problem, and hence we have extended the traditional vehicle assignment problem's objective to account for environmental and social factors.

Through our analysis, we show that the market mechanism alone may not work well without the support of government's control using OEI. By using this concept, we illustrate the effects of integrating market control with the government's macro control on companies' total operating costs, total emissions and vehicle assignment schemes. Our result demonstrates that some strategies can benefit both the government and the enterprises, while some do not. Moreover, we have revealed that there is an additional operating cost involved in some strategies. The environmental-friendly companies can trade their surplus carbon emission credits in the carbon market and get additional incomes. From the above analysis, we find that the company may also benefit from taking some social responsibility to reduce emissions. The above details highlight the core findings and contribution of this paper.

III. PROBLEM DESCRIPTIONS & BASIC MODEL

Before presenting the mathematical model, we describe the problem that we intend to solve. We have used a real case inspired hypothetical freight company called Company C to illustrate the problem and help demonstrate the results in the next section. To be specific, we illustrate our problem with a simple example: In a market like Dalian City (in China), a fast food company needs to distribute semi-finished food to its stores every day. Suppose that it hires a freight transportation company, called Company C, to help ship the food from the starting points (called ''garages'') to the destinations (the store locations, called ''customer locations'' in this paper) in the early morning every day. Because the traffic conditions are less congested at that time, Company C can choose the shortest route, which is ''optimal'', to complete this delivery job. In this case, the route is fixed and hence the routing decision is fixed and not considered in the decision making process of the optimization problems. Instead, how to match the vehicles of Company C to different customers is the critical decision considered in this paper. Suppose that currently, Company C only has traditional diesel vehicles which have different emission rates. The diesel vehicles can provide a strong power for distributing goods with a very low operating cost, but the disadvantage of these vehicles is that they are associated with high carbon emissions. In order to classify the traditional vehicles into different groups, we put the vehicles with the same emission rate into the same garage. Different garages have different vehicles according to their emission rates. The total number of vehicles in every group is the capacity of that garage. Notice that these operational assumptions reflect the real world practices. In fact, from our discussions with the companies in Dalian City, we note that the logistics firm would group trucks into different garages according to the times the trucks are bought and used, i.e., trucks are grouped into one group if they are used for 2 years to 3 years. In this paper, we assume that emissions they generate are higher if the trucks have been used for a longer period of time. So we consider the case in which the trucks used for a long time have a high emission rate.

As a way to improve, we introduce the new energy vehicles in the optimization problem for Company C with budget constraints. Company C can buy the new energy vehicles using its budget and assign them to serve the customers. In order to balance between total costs and total emissions, Company C has to make a decision on whether it needs to acquire the new energy vehicles and if yes, how many. The purchase of the new energy vehicles means the replacement of the traditional diesel vehicles with the new energy vehicles. The new energy vehicles bought are placed into a new garage since they have a different emission rate. The number of new energy vehicles in the new garage is the capacity of the new garage. As a result, the capacity of the new garage is linked to the capital budget of Company C. There are two decision processes involved in the optimization problem: 1. Purchase of the new energy vehicles, and 2. the assignments of all types of vehicles to customers. These decisions are all subject to constraints.

We now discuss the constraints involved in the mathematical model under both the cap and trade mechanism and the government's macro control. In order to fulfill its commitments to carbon emissions reduction, the government imposes a carbon emission quota on Company C. By this quota, the government can affect the emission behavior of Company C. Under the cap and trade mechanism, Company C can freely trade its emission credit in the carbon market. If the actual emission of Company C exceeds the quota, it should buy some emission credits to offset the over-emission (otherwise, Company C can sell the surplus emission credit to other companies). There is, however, a limited capital budget for Company C. On the other hand, if the amount of purchased emission credit exceeds the highest emission limit (HEL) set by the government, the company would be forced to close down.

A ''deadheading trip'' means a trip in which the ''truck without loading'' returns. The amount of carbon emission from ''deadheading trips'' is very important for the calculation. So we have counted such emission into our ''total carbon emission'' expression in the model. The vehicles should return to the garages which they left from. They are fully loaded when they begin serving the customers (forward journey) and empty-loaded when they return back to the garages (backward journey). We now present the variables and the parameters of our mathematical model with the joint consideration of market control and governmental macro control (see Fig. 2).

There are two kinds of garages. One kind is used to store the traditional vehicles, and we denote it by PO. The other kind is used to store the new energy vehicles, and it is denoted by PN. Define $P = PO \cup PN$. The costs of fuel consumption, Sets:

- I the set of customers
- P the set of garages
- $PO \in P$ the set of garages for traditional diesel vehicles
- $PN \in P$ the set of garages for new energy vehicles

Parameters:

- c_1^p the unit operating cost for using a vehicle from garage p when it is full-loaded i.e. cost for forward journey.
- c_2^p the unit operating cost for using a vehicle from garage p when it is empty-loaded i.e. cost for backward journey from the customer to the garage.
- e_1^p the unit carbon emission for using a vehicle from garage p when it is full-loaded i.e. the emission rate for the forward journey.
- e_2^p the unit carbon emission for using a vehicle from garage p when it is empty-loaded i.e. the emission rate for backwards journey. Different vehicles from different garages have different emission rates both for forwards and backwards journeys.
- C_p the unit price of new energy vehicles.
- B the capital budget for purchasing new energy vehicles.
- d_{pi} the distance between garage p to customer i.
- CO_2^{CUR} the amount of actual carbon emissions from Company C (e.g. carbon dioxide and so on).
- CO_2^{QUO} the amount of carbon emission quota given by the government.
- θ the unit cost of the carbon emission credit.
- μ the Over Emission Intensity (OEI) factor.
- K_p the capacity of garage p (the number of the vehicles in the garage).

Decision variables:

- X_1^{pi} the binary variable equals 1 if a vehicle is assigned from garage p to serve the customer i, and 0 otherwise. The decision of purchasing new energy vehicles is included here.
- X_2^{ip} the binary variable equals 1 if a vehicle from garage p drives back from customer i to garage p, and 0 otherwise.

FIGURE 2. Notation.

daily maintenance and labor salary have been incorporated into c_1^p and c_2^p. The depreciation costs from traditional diesel vehicles are not included into the unit operation costs because the traditional vehicles are owned by Company C, i.e. they are the company's assets. The depreciation costs of new energy vehicles are integrated into the unit operation costs, because Company C needs to spend from its own capital budget to buy them. Notice that the capital budget B for new energy vehicles is a very important factor to balance the relationship between the total operating costs and total amount of carbon emissions. If Company C uses off B, it has to change the vehicles assignment scheme for reducing carbon emissions. θ is the price of emission credits, which is totally decided by the market. CO_2^{CUR} is the actual amount of carbon emission of Company C, and it relates to the company's vehicles assignment scheme and the type of vehicles. CO_2^{QUO} is the emission quota given by the government. μ is called the "*Over Emission Intensity*" (OEI) factor which relates to the company's actual amount of carbon emission and the emission quota given by the government. Under the cap and trade mechanism, Company C's actual emission is allowed to exceed the emission quota. However, Company C should buy the additional emission credit to offset its over emissions. Observe that under the cap and trade mechanism with OEI, the amount of the additional credit bought by Company C is limited by the highest emission limit (HEL) (μCO_2^{QUO}) which is set by the government. Notice that the usual cap and trade program means that a company can buy as many emission credits as it needs. In this paper, we propose a new regulatory mechanism, called the cap and trade program with OEI. Under the newly proposed scheme, the amount of "quota" a company can buy must be less than or equal to OEI minus the cap. Once the amount of emission the firm generated is larger than OEI, the government would stop the firm from operating. This new mechanism efficiently integrates the market mechanism and government macro control function together. This scheme can be implemented across different industries and companies in the market by the government following a certain formula in calculating the OEI (e.g., with respect to the specific industry, size of the company, etc).

If the amount of carbon emission of Company C exceeds the HEL, it would be forced to close down by the government. When the amount of carbon emission of Company C does not exceed the quota, it can trade the emission credit in the market without the governmental interference.

With the above details, we now present the 0-1 integer programming model for the proposed vehicles assignment problem as follows:

$$\min \sum_{p\in P}\sum_{i\in I} c_1^p d_{pi} X_1^{pi} + \sum_{p\in P}\sum_{i\in I} c_2^p d_{pi} X_2^{ip} + \theta(CO_2^{CUR} - CO_2^{QUO})$$

s.t.

$$\sum_{p\in P} X_1^{pi} = 1 \quad \forall i \in I \tag{1}$$

$$\sum_{i\in I} X_1^{pi} = \sum_{i\in I} X_2^{ip} \quad \forall p \in P \tag{2}$$

$$\sum_{p\in P}\sum_{i\in I} e_1^p d_{pi} X_1^{pi} + \sum_{p\in P}\sum_{i\in I} e_2^p d_{pi} X_2^{pi} = CO_2^{CUR} \tag{3}$$

$$\sum_{p\in PN}\sum_{i\in I} C_P X_1^{pi} \le B \tag{4}$$

$$\sum_{i\in I} x_1^{pi} \le K_p \quad \forall p \in PO \tag{5}$$

$$CO_2^{CUR} \le \mu CO_2^{QUO} \tag{6}$$

$$X_1^{pi} \in \{0,1\} \quad \forall i \in I;\ \forall p \in P \tag{7}$$

$$X_2^{ip} \in \{0,1\} \quad \forall i \in I;\ \forall p \in P \tag{8}$$

Observe that the above objective function has three parts. The first part includes the operating cost incurred by assigning vehicles from garages to serve the customers. The second part is the operating cost incurred by vehicles on their backwards journeys. The third part is the carbon emission trade cost from trading the emission credit in the carbon market.

This cost can be negative. When this cost is positive, it shows that the actual amount of carbon emission of the company has exceeded the quota given by the government and the company should buy an additional emission credit to offset the amount of over emission. If the value is negative, it shows that the actual amount of carbon emission of the company has not exceeded the quota. Hence, the company can sell the surplus emission credit to get an additional revenue. Constraint (1) guarantees that each customer will be served by either a traditional diesel vehicle or a new energy vehicle bought within the capital budget. Constraint (2) shows that every vehicle must return to the garage. Constraint (3) calculates the actual amount of carbon emission of Company C. Constraint (4) guarantees that the payment on purchasing new energy vehicles does not exceed the capital budget. Constraint (5) incorporates the capacity constraint of each garage into the optimization problem. Constraint (6) guarantees that the actual amount of carbon emission of company does not exceed the HEL set by the government. Constraints (7) and (8) are binary restrictions.

IV. REAL CASE BASED NUMERICAL EXPERIMENTS[1]

The mathematical model presented in Section III will be numerically tested and validated using a real case based problem in this section. For the setting, numerical experiments are conducted on a server with 3 GHz speed and 2 GB RAM. The model is coded by AIMMS and solved using CPLEX 12.4. Before we validate our model, we present the specific problem as follows.

To be consistent with our earlier description and notation, the real case based company examined in this section is also called "Company C". Based on the real world case in Dalian City (China), the problem we considered consists of four different garages of diesel vehicles and one garage of new energy vehicles. We denote these four garages of diesel vehicles by p1, p2, p3, p4 and denote the garage of new energy vehicles by p5. All vehicles in every garage are homogeneous and have the same emission rate. Here, we do not differentiate one vehicle from another one in the same garage. So the diesel vehicles in different garages are also denoted by p1, p2, p3 and p4, and they are listed based on the emission rate (from the lowest to the highest). Notice that the vehicle (which also implies the respective garage) with the lowest emission rate is the one having the highest operating cost. For example, the vehicles in garage p1 have the lowest emissions rate among the traditional vehicles (i.e. most environmental-friendly) of Company C, but their unit operating cost is also the highest. Similarly, the vehicles in garage p4 have the highest emissions rate and the lowest unit operating cost of Company C. The numbers of traditional diesel vehicles in garage p1, p2, p3, p4 are respectively 30, 60, 60 and 50 (in total 200). The garage p5 is used to store the new energy vehicles bought with the capital budget, and the number of vehicle(s) in garage p5 is a decision variable. The total number of customers needed to be served is 200. The distance between every customer and each garage is known, which ranges from 20 km to 220 km. We assume that these five garages are located side by side. The location of garages is the service starting point, and all vehicles are loaded there and start to serve the customers. The new energy vehicles considered are the Liquefied Natural Gas (LNG) vehicles. According to Kim et al. [22], we have chosen the price of carbon trade to be between 50∼800 $/ton.

The unit carbon emission for the traditional diesel vehicle is 1.6353 kg/km [3] when they are empty-loaded; the data of unit carbon emission for the new energy vehicle (i.e. the LNG vehicle) is 1.4013 kg/km [3]. We assume the vehicles can run up to 500,000 km. We also assume the price of new energy vehicle (the LNG vehicle) is about 210,000 $/unit based on some reports. Using the data mentioned above, we can calculate the unit operating cost and unit carbon emission for each kind of vehicles; the data are shown in Table 1.

[1]This numerical analysis part is based on a real world problem we learnt from some logistics firms and some companies in Dalian City.

TABLE 1. Parameters values, $c_1^P = c_2^P; e_1^P = e_2^P$.

	p1	p2	p3	p4	p5
The unit emissions cost (kg/km) for every vehicle	1.6	1.65	1.7	1.8	1.3
The unit operating costs($/km) for every vehicle	1.05	1	0.95	0.9	1.22
Corresponding colors	Red	yellow	Blue	pink	green

A. IMPACTS OF CARBON EMISSION QUOTA

We have conducted the first experiment to study the effect of the carbon emission quota (in tons) on Company C. Hence, we have used B = 0 with no macro control from the government. The result is presented in Table 2 and Fig. 3. To be specific, Table 2 shows that the total operating cost of Company C increases with the decrease of the carbon emission quota. The actual amount of carbon emission of Company C does not change. Even if the quota goes down to zero, the company does not take any measures to cut down the carbon emissions. It is clear that the carbon emission quota alone cannot force the company to reduce its carbon emission even though the cost increases with the reduced quota. This is a negative result to both Company C and the government because: On one hand, the government fails to control the amount of carbon emission of Company C by using the carbon emission quota. On the other hand, the cost of Company C is increased.

From Fig. 3, according to the distances between the customers and the garages, we have arranged the 200 customers in a line. If the customer has the shortest distance to the garages, we put it at the most "left hand side" of the line, and so on. We put the customer which has the longest distance to travel from the garages at the rightest side of the line. This has created 200 blanks, each for a customer. Since a color

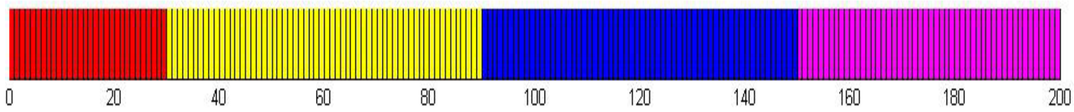

FIGURE 3. Assignment schemes for Table 2.

is used correspondingly to a garage (see Table 1), we assign a color to a customer if it is served by a vehicle from the corresponding garage. Hence, according to the solution of the vehicles assignment scheme, we can fill all 200 blanks with different colors. Fig. 3 shows that Company C uses the vehicles from p1 to serve the nearest customer, and it uses the vehicles from garage p4 to serve the farthest customer. This corresponds to the one with lowest operating cost but highest carbon emission. For this case, there is no new energy vehicle since the government does not force the company to reduce the amount of carbon emission and hence the company would not prepare budget for buying new vehicles, i.e. B = 0. Clearly, this is the least environmental-friendly scheme.

TABLE 2. The effect of emission quota on Company C, B = 0.

CO_2^{QUO}	θ	CO_2^{CUR}	Cost
130	100	124.799	67742.6
110	100	124.799	69742.6
90	100	124.799	71742.6
70	100	124.799	73742.6
50	100	124.799	75742.6
30	100	124.799	77742.6
0	100	124.799	80742.6

Table 2 and Fig. 3 show that Company C will not change its operation if no constraint on OEI is imposed. This is what we study next. The model is now optimized with $\mu = 1.5$ and the results are summarized in Table 3 where the symbol "—" means Company C will be forced to close down by the government. $\mu = 1.5$ means that the HEL allowed by the government is 1.5 times the emission quota set by the government.

We take the emission quota of 80 tons as an example. Since the emission of Company C exceeds 80 tons, it needs to buy an additional emission credit to offset its over-emission. The HEL allowed by the government is 120 tons (80*1.5 = 120 tons). It can be seen at the last row of Table 3 that if emission exceeds 120 tons, Company C will be forced to close down by the government. So, the OEI represents a kind of macro control method by the government. Under these circumstances, the company will control its carbon emission to meet the government requirements through assigning the vehicles properly. From Table 3, we find that if the quota is 90 tons, the optimal vehicles assignment scheme of Company C will have no change. (In fact Fig. 3 of our previous study shows the vehicles assignment schemes for this quota.) When the quota decreases, the vehicle assignment scheme changes with the decrease of the quota (the change of the amount of carbon emission also means the change in the assignment scheme). Unlike the findings in Table 2, we see in Table 3 that when a small change happens on the quota, the actual amount of carbon emission and the optimal vehicles assignment scheme change right away. We can see that the vehicles assignment scheme varies accordingly with the decreasing quota. The schemes B, C and D in Fig. 4 represent the assignment schemes when the quota is 83, 82 and 81 tons, respectively.

TABLE 3. The effect of emission quota on Company C with OEI, $B = 0$, $\theta = 100$, $\mu = 1.5$.

CO_2^{QUO}	CO_2^{CUR}	Cost
90	124.799	71742.6
85	124.799	72242.6
84	124.799	72342.6
83	124.5	72562
82	123	73411.8
81	121.5	74486.2
80	>120	—

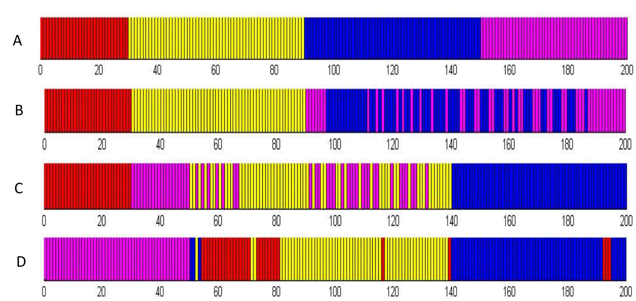

FIGURE 4. Some of assignment schemes for Table 3.

The vehicles assignment scheme A in Fig. 4 corresponds to the carbon emission of 124.799 tons. We can see in scheme A that the arrangement of vehicles is uniform and regular. The red ones denote the vehicles from garage p1 which have the lowest emission rate. Company C assigns these vehicles with the lowest emission rate to serve the nearest customers.

At the same time, the vehicles with the highest emission rate are assigned to serve the farthest customers. This kind of assignment scheme can minimize the total operating cost, but the amount of carbon emission is very high. In order to reach the requirement of carbon reduction, Company C must guarantee that its actual carbon emission is lower than the HEL by adjusting the vehicles assignment scheme. From the change of scheme A to scheme D in Fig. 4, we can observe that Company C begins to use the vehicles with the highest emission rate (pink) to serve the customers who have the shorter distance to the garages step by step, while assigning the environmental-friendly vehicles (represented by "red") to serve the farthest customers. This kind of assignment scheme can reduce the amount of carbon emission of Company C.

B. IMPACTS OF CARBON EMISSION CREDIT's PRICE

We now study the effect of the carbon emission credit's price (we call it the "carbon price" in short). We have optimized the model again with various values of θ, and the corresponding results are summarized in Table 4. The results presented in Table 4 show that the HEL allowed by the government is $1.5*90 = 135$ tons with a quota of 90 tons. The HEL of 135 tons is much higher than 124.799 tons which is the highest carbon emission level of Company C.

TABLE 4. The effect of carbon price on Company C, $B = 0$, $\mu = 1.5$, $CO_2^{QUO} = 90$.

θ	CO_2^{CUR}	Cost
800	121.649	95606.6
700	122.549	92396.7
600	123.899	89051.9
500	124.285	85662
400	124.799	82182.2
300	124.799	78702.3
200	124.799	75222.5
100	124.799	71742.6
50	124.799	71394.6

Table 4 shows that when the carbon price is low (e.g. 50-400 $/ton), Company C does not change the vehicles assignment scheme to reduce the amount of carbon emission (the amount of carbon emission is 124.799 tons). In order to minimize the total operating cost, Company C chooses to purchase an additional emission credit to offset the over-emission without changing the vehicle assignment scheme. This is due to the fact that the cost increased by purchasing an additional emission credit is less than the cost increased by changing the vehicles assignment scheme. Fig. 5 shows the cases of vehicles assignment schemes. Schemes A, B, C, D and E represent the vehicles assignments of Company C for scenarios with the carbon-emission prices of 800$/ton, 700$/ton, 600$/ton, 500$/ton and 400$/ton, respectively. We can see that the company begins to change the vehicles assignment to reduce the amount of carbon emission while the carbon-emission price is increasing.

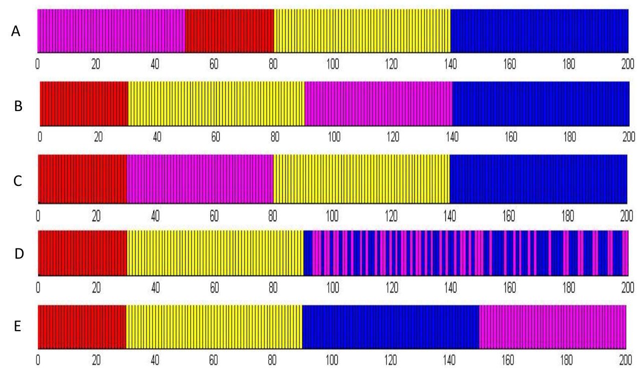

FIGURE 5. Some of assignment schemes in Table 4.

So far, we have discussed the impact of market control and government macro control on the total operating cost and the amount of carbon emission of Company C when there is no budget for purchasing new energy vehicles. We have noticed that both the quota (down) and the carbon-emission price (up) would force Company C to cut down the amount of carbon emission under the OEI constraint. Both of these could lift the total operating cost. It is clear from the results presented in Tables 3 and 4 that the government macro control may function better than the effect of market control.

C. IMPACTS OF MARKET AND MACRO CONTROL WITH A BUDGET CONSTRAINT

The emissions quota given by the government, and the carbon-emission price decided by the market are external factors for Company C; each one of them has an effect on the total operating cost. On the other hand, the capital budget B is the internal factor which can be used to purchase new energy vehicles to replace the traditional diesel vehicles with a goal of reducing the amount of carbon emission. We now study the effect of the capital budget on the amount of carbon emission, the total operating cost and the vehicles assignment scheme of Company C. Results of this study are presented in Table 5, where the data in the second column are the amount in dollars allocated for 100 new energy vehicles (given in the bracket).

Table 5 clearly shows the effect of emission quota on the total operating cost and the actual amount of carbon emission with the budget B for new energy vehicles. It is also evident that the total operating cost of Company C increases much slowly with the respective decrease of quota set by the government. When the quota decreases, the emission level of Company C stays low with the capital budget B than without (i.e. the case without any budget for new energy vehicles). Hence, having the capital budget for new energy vehicles saves more operating cost and reduces more carbon emission.

TABLE 5. The effect of quota on Company C with a budget constraint, $\theta = 100$, $\mu = 1.5$, B = 21000000 (100).

CO_2^{QUO}	CO_2^{CUR}	Cost
85	124.46	72242.6
84	124.46	72342.6
83	124.46	72442.6
82	123	72650.6
81	121.5	72943.5
80	120	73236.4
79	118.5	73555.1
78	117	73992.6

TABLE 6. The effect of quota on vehicles assignment schemes, $\theta = 100$, $\mu = 1.5$, B = 21000000 (100).

CO_2^{QUO}	CO_2^{CUR}	No. of new energy vehicles	Cost
72	108	100	76735.9
71	106.5	100	77225.9
70	105	100	77715.9
69	103.5	100	78259.5
68	102	100	79184.5
67	—	—	—
66	—	—	—

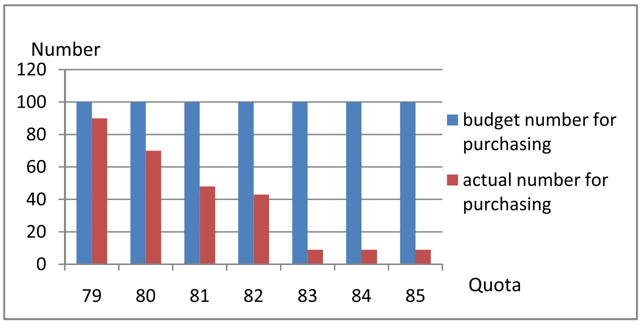

FIGURE 6. The number of new energy vehicles under different quota.

Fig. 6 shows that when the emission quota is high (e.g. 83, 84, 85 tons), the company only purchases 9 vehicles (***red bar***) even if the budget is for 100 vehicles. When the quota decreases, the number of new energy vehicles bought increases. This is because the HEL allowed by the government would decrease with a reduction of the emission quota. It is the target of Company C to keep its amount of emission below the HEL. There are two measures for Company C, namely: 1. To purchase new energy vehicles, and 2. to change vehicles assignment scheme to reduce the amount of carbon emission. Both measures increase the operating cost, but the cost incurred by purchasing new energy vehicles is less than the cost increased by changing the vehicles assignment scheme for the emission quotas given in Table 6. So, Company C chooses to purchase new energy vehicles. The operating cost increases with the purchase of new energy vehicles. Our results show that the company needs to buy a number of new energy vehicles in order to keep the total amount of emission just below the HEL allowed by government. This is an intuitive finding.

If the amount of emission of Company C is lower than the HEL, no new energy vehicles would be bought. If the quota keeps decreasing, the HEL allowed by the government will be lower. At this time, Company C needs to buy more new energy vehicles to reduce the actual amount of carbon emission and meet the HEL requirement. Table 6 shows one important issue that when the budget for the new energy vehicle runs out, Company C is unable to meet the HEL requirement as the quota decreases, and the company will be forced to stop operations by the government.

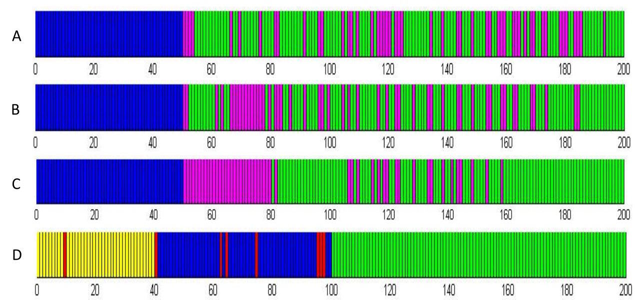

FIGURE 7. Some of assignment schemes in Table 6.

Schemes A, B, C and D in Fig. 7 represent the respective vehicles assignment of Company C when the quotas are 72, 71, 70 and 69 tons given in Table 6. The number of new energy vehicles in all of these schemes is 100. For the high quota case, e.g. with 72 tons, the customers served by new energy vehicles have different features. To be specific, some of the customers served are far from the garages while others are close to the garage p5. This trend changes with a decrease of the quota. It can be seen in scheme D, corresponding to a quota of 69 tons, that the new energy vehicles, which are environmental-friendly, are used to serve the farthest customers as this would lead to a low amount of emission.

We have observed in the above experiments that the government's macro control affects both the purchase of the new energy vehicles and the total operating cost. We now study the effect of market control, e.g. the carbon-emission price, on these. Results of this experiment are presented in Table 7 and Fig. 8. To be specific, Fig. 8 shows that Company C does not purchase any vehicles even if it has a budget sufficient for acquiring new energy vehicles when the carbon-emission price is low (e.g. 50 $/tons). In this situation it is better for Company C to buy an additional emission credit to

TABLE 7. Effects of carbon-emission price $CO_2^{QUO} = 90$, $\mu = 1.5$, B = 21000000 (100).

θ	CO_2^{CUR}	Cost
50	124.799	70002.7
100	124.46	71742.6
200	123.84	75126.6
300	118.768	78148.3
400	103.882	80171.3
500	103.166	81559.5
600	102.936	82853.1
700	102.207	84122.4
800	102.207	85343.1

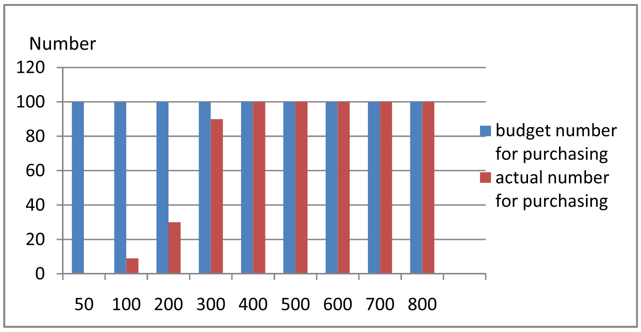

FIGURE 8. The number of new energy vehicles under different carbon-emission price.

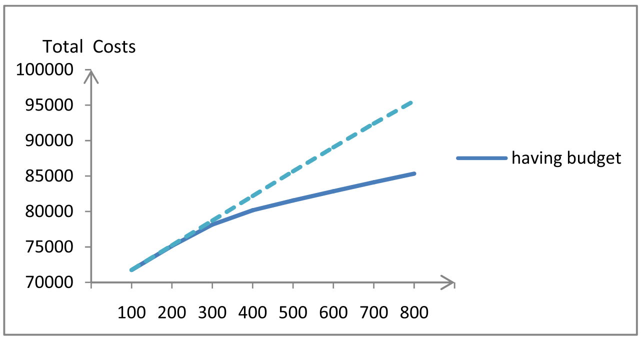

FIGURE 9. Effects of carbon-emission price on Company C.

offset the over-emission than to buy the new energy vehicles. Fig. 8 also shows that the situation changes with the increase of carbon-emission price. Clearly, the total emission decreases with the purchase of new energy vehicles as we can observe from Table 7. The effect of carbon-emission price on the purchase of new energy vehicles is clearly established in Fig. 8. Moreover, Tables 4 and 7 show that the carbon price affects the total operating costs for B = 0 and B = 21000000 cases, respectively. The growth of the total cost for B = 0 and B = 21000000 is shown in Fig. 9 which indicates a significant difference on the respective total operating costs. Company C would enjoy a significant cost advantage in the presence of a capital budget for new energy vehicles when the carbon price increases.

TABLE 8. The effect of OEI on the amount of carbon emission, $CO_2^{QUO} = 90$, $\theta = 50$, B = 21000000 (100).

μ	No. of new energy vehicles	CO_2^{CUR}
1.5	0	124.799
1.45	0	124.799
1.4	0	124.799
1.35	50	121.5
1.3	95	117
1.25	100	112.5
1.2	100	108
1.15	100	103.5
1.1	—	—

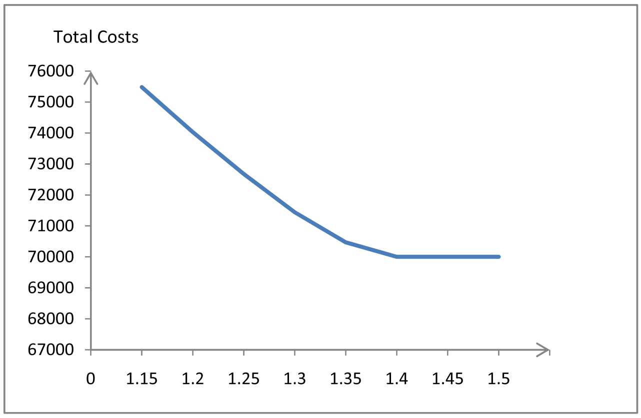

FIGURE 10. The total cost and the OEI.

D. IMPACTS OF OEI ON CARBON EMISSIONS REDUCTION

The OEI has been introduced in this paper to represent the impact of government macro control on carbon emissions reduction and energy savings. We have shown that Company C is not sensitive to the quota given by the government when there is no OEI constraint. The carbon-emission quota affects the total operating cost of Company C directly, but it alone does not affect the vehicles assignment scheme and the reduction on carbon emission. In fact, in Table 2, we have demonstrated the necessity of using the OEI. The government measure certainly affects the operations of Company C. We now study the effect of HEL on the amount of carbon emission and the total operating cost of Company C. Results of this study are summarized in Table 8 and Fig. 10. In particular, Fig. 10 shows that a high OEI has no impact on the total operating cost of Company C, i.e. the total cost does not change in the presence of a large μ. For a smaller value of μ, the carbon emissions limit (μCO_2^{QUO}) becomes smaller. Hence Company C must try to cut down the amount of carbon emission by purchasing more new energy vehicles or changing the vehicles assignment schemes resulting in a larger total operating cost. This can be seen in Fig. 10.

Table 8 shows the impact of OEI on the amount of carbon emission of Company C and the number of new energy vehicles purchased. We can see from Table 8 that, while the OEI factor is high, Company C does not take any measures to reduce the amount of carbon emission. The number of new energy vehicles purchased is hence zero, and the actual amount of carbon emission of Company C does not change, too. On the other hand, if the OEI keeps decreasing, the decision of Company C changes. The amount of carbon emission of Company C will be reduced because of the purchase of new energy vehicles. If, however, the OEI set by government is too low, Company C is unable to meet the requirement of HEL even if all the budgets are used to purchase the new energy vehicles. In this case, Company C will be closed down by the government. Obviously, both the government and Company C are unwilling to see such a situation from happening. So, when the government sets the HEL to control the emissions of Company C, it must also consider the actual situation of the industry (i.e. Company C and other related companies). A realistic value of OEI should push the companies in the respective industrial sector to properly reduce the amount of carbon emissions while they can still survive and sustain.

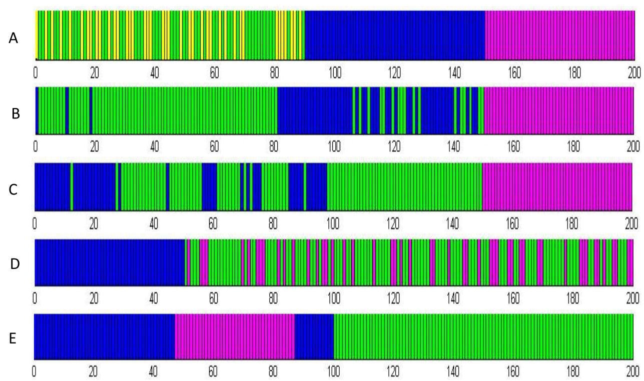

FIGURE 11. Some of vehicles assignment schemes in Table 8.

Fig. 11 shows the vehicles assignment schemes A, B, C, D and E corresponding to the OEI with values of 1.35, 1.3, 1.25, 1.2 and 1.15, respectively. Fig. 11 shows that the customers served by new energy vehicles would be changed with a change of the OEI value. Scheme A, corresponding to $\mu = 1.35$, shows that only 50 new energy vehicles are purchased and they serve the nearer customers. On the other hand, scheme E, corresponding to $\mu = 1.15$, shows that 100 new energy vehicles are bought and they serve the customers far from the garages.

V. CONCLUDING REMARKS

We have considered the effect of carbon emission regulations, based on the government macro control policy and the market mechanism (i.e. the cap and trade mechanism), on the vehicles assignment problem which arises in logistics and transportation companies. In order to address this problem, we have introduced a new concept called the *over-emission intensity* (OEI), which is a factor the government can impose on the companies. Based on this concept, we have proposed a new mechanism (i.e., the cap-and-trade program with OEI) to address the issue of carbon emission reduction. To be specific, the cap-and-trade program with OEI is a mechanism which combines the market mechanism (via the carbon trading) and the government macro control together. We have established a formal vehicle-assignment optimization model under the cap-and-trade program with OEI. The choice of vehicles, both the traditional and new energy vehicles, and assignments to customers are taken as the decision variables. As a remark, the proposed cap-and-trade program with OEI can be implemented in different industries and companies in the market by the government following a certain formula in calculating the OEI (e.g., with respect to the specific industry, size of the company, etc). This is the same logic as the implementation of carbon footprint taxation which on one hand is a macro government measure (for all industries), on the other hand, it does affect and relate to every single company in the industry.

The mathematical optimization model suggested in this paper has been validated with meaningful results obtained during a series of numerical experiments. The findings obtained in this paper argue that it is very important for the government to use the OEI factor as a measure of macro control to force the companies to reduce their levels of carbon emissions. When a company has an insufficient amount of budget for purchasing the environmental-friendly new energy vehicles, it changes the vehicles assignment scheme to reduce the actual amount of carbon emission and hence meet the HEL requirement set by the government. When the company has a sufficient amount of budget for buying the new energy vehicles, it purchases a suitable number of new energy vehicles according to the OEI and the quota set by the government. Our findings have also revealed that, in order to save costs, the most environmental-unfriendly traditional vehicles will be replaced by the new energy vehicles when new energy vehicles are used to serve the customers. In this situation, the government can decrease the value of OEI so that the company can eliminate the most environmental-unfriendly traditional vehicles. This, however, would lead to an increase of the total cost of the company.

We have also compared the two distinct methods, namely the method of government macro control and the method of market control. Our results suggest that integrating the government macro control with the market control may efficiently reduce carbon emissions. Our results further illustrate that the cap-and-trade program with OEI not only lets the company have a high chance of being benefitted but also motivates the company to enhance its level of social responsibility. Based on the analysis in this paper, we further uncover that the cap-and-trade program with OEI, i.e. an integration of the government macro control with the market mechanism, is an effective way to reduce the amount of carbon emission. This combined mechanism may be even more effective than the market mechanism alone.

For research limitations, this paper explores the case when all problem model parameters are fixed, i.e. it is a deterministic optimization problem. In the future, we can extend the analysis to the stochastic case in which uncertainty is incorporated into the optimization problem (e.g., on costs). In such a new setting, new insights on, e.g., business risk analysis [50], can be further derived. Furthermore, the current paper considers a single stage problem. Future extensions to a multi-stage problem can hence be made.

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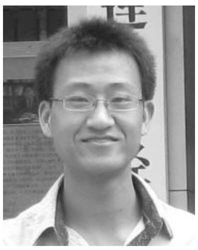

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