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A Strategy-Proof and Budget Balanced Mechanism for Carbon Footprint Reduction by Global Companies

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Abstract— **The problem addressed in this paper is concerned with an important issue faced by any green aware global company to keep its emissions within a prescribed cap. The specific problem is to allocate carbon reductions to its different divisions and supply chain partners in achieving a required target of reductions in its carbon reduction program. The problem becomes a challenging one since the divisions and supply chain partners, being autonomous, may exhibit strategic behavior. We use a standard mechanism design approach to solve this problem. While designing a mechanism for the emission reduction allocation problem, the key properties that need to be satisfied are dominant strategy incentive compatibility (DSIC) (also called strategy-proofness), strict budget balance (SBB), and allocative efficiency (AE). Mechanism design theory has shown that it is not possible to achieve the above three properties simultaneously. In the literature, a mechanism that satisfies DSIC and AE has recently been proposed in this context, keeping the budget imbalance minimal. Motivated by the observation that SBB is an important requirement, in this paper, we propose a mechanism that satisfies DSIC and SBB with slight compromise in allocative efficiency. Our experimentation with a stylized case study shows that the proposed mechanism performs satisfactorily and provides an attractive alternative mechanism for carbon footprint reduction by global companies.**

Keywords – **Carbon emission reduction, emission cap, emission reduction allocation, mechanism design, incentive compatibility, budget balance, allocative efficiency, Vickrey-Clarke-Groves mechanism.**

I. Introduction

Climate change and global warming represent issues of serious concern and the whole world is actively engaged in initiating and undertaking measures to mitigate the dangerous effects of these phenomena. In this context, countries and global companies are now striving to reduce carbon emissions as far as possible.

Under emission trading mechanisms developed, countries mutually trade emission allocation using the *cap and trade* scheme. A cap and trade system allows corporations or national governments to trade emission allowances under an overall cap, or limit, on their emissions. This mechanism involves two parties, the governing body and the regulated entities that emit pollution. The governing body allocates a limit on the total amount of emissions that could be emitted in a given period, called as *cap* and would issue rights, or allowances, corresponding to that level of emissions. Regulated entities would be required to hold equal or more allowances than their cap for their emissions. Normally the cap on a regulated body is equal or less than the emissions caused by it. A cap on emissions limits the total amount of allowable emissions and it can be lowered to achieve stricter environmental standards.

This paper looks at the problem of emission reduction from the perspective of a global company which has many internal divisions and strategic supply chain partners. The specific problem we address is that of allocating a given target of carbon reduction units among the constituent divisions and partners. To solve this problem in an optimal way, the company needs to know the cost curves for emission reduction from the different divisions and partners. Since the divisions and partners are often autonomous entities and could exhibit strategic behavior, the company may not be able to elicit the cost curves truthfully. In this paper, we use techniques from game theory and mechanism design to solve this problem on the lines of [1], [2].

Let us consider a global company(refer to fig 1) that gets a cap on its overall emissions. To honor the cap, the company has to reduce its Green House Gas (GHG) emissions. As an example, suppose the company currently emits X units of GHG and the regulatory authority has stipulated a cap of Y emission units. The company is then required to reduce $M = X - Y$ emission units (called emission reduction units).

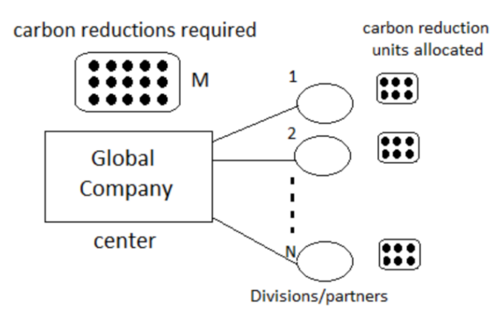

Fig.˜1.˜˜ Allocation of carbon emission reductions among divisions

In order to accomplish this, the company would look at its sub-units (or divisions) and supply chain partners to

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help reduce emissions by the required amount. The effort of emission reduction involves cost which could vary among the divisions and partners. We will use the phrase *emitting agents* to describe the divisions and partners involved. Some emitting agents will incur higher costs than others in the task of achieving a certain amount of emission reduction. The challenge for the global company here is how to allocate the required reductions in a fair manner among the emitting agents, such that the total cost of reduction is minimized. In this paper, we first formulate this problem and then explore a mechanism design approach to solve the problem.

A. Contributions and Outline

In this paper, the primary contribution is to propose a new mechanism for allocating emission reductions to different divisions in a global company based on reduction costs reported by the different divisions. The mechanism proposed satisfies two key properties, namely dominant strategy incentive compatibility (DSIC) and strict budget balance (SBB). The DSIC property (also called strategy-proofness) ensures that each division reports its emission cost curves truthfully irrespective of what is reported by the other divisions. The SBB property guarantees that there is no need for any monetary support from an external agency for implementing the mechanism and there is no leakage of revenue.

This work complements and supplements earlier work of the authors [2] where mechanisms were proposed for this problem satisfying the DSIC property and the allocative efficiency (AE) property. AE ensures that the emission reductions are allocated to the divisions that incur the least costs of reduction. It is a standard result in mechanism design theory that the properties DSIC, SBB, and AE cannot be simultaneously satisfied [3], [4]. Thus a mechanism which is DSIC and AE would result in a budget imbalance and one of the objectives of the work [2] was to minimize the budget imbalance using redistribution mechanisms.

Budget imbalance invariably leaves a certain no-zero surplus with the social planner (in this case the global company) which essentially means that the divisions are being forced to make certain payments beyond the costs incurred for emission reduction. This looks somewhat unreasonable and artificial since we are dealing with a company and its own divisions/partners. Of course, in return for this, we achieve DSIC and AE. If we are willing to compromise on AE a little bit and achieve SBB, then the above anomaly can be overcome. This is the primary motivation for this paper.

The rest of the paper is organized as follows. In Section II, we describe the emission reduction allocation problem. We present the relevant work in the literature on this topic and briefly describe the DSIC and AE mechanism developed in [2]. In Section III, we describe the proposed DSIC and SBB mechanism and illustrate it with an example. In Section IV, we discuss a stylized case study and provide numerical results using the proposed mechanism. In Section V, we present a summary and a few directions for future work.

II. The Problem and Relevant Work

A. Emission Reduction Allocation Problem

We consider a global company that has several independent emitting agents. These emitting agents could be the different divisions of the company and also its supply chain partners. The motivation for undertaking the mandate to reduce the emissions can be interpreted in following ways:

- The industry undertakes the emission reduction initiative under corporate social responsibility initiative. Hence rather than buying the emission reduction units from third party carbon markets, the industry wants to make best use of its internal divisions and partners for this initiative.
- The industry considers the emission reduction initiative as a part of their branding activities. This could be a factor in attracting prospective clients who focus on emission neutral solutions.
- The industry wishes to reduce its emission footprints, but the solution of buying emission reduction units from an outside carbon market may be higher than the cost that the industry incurs through an internal drive.
- The industry has been mandated a carbon cap by a regulatory authority and the company has to honor this cap by achieving the required quantum of reductions.

Let us assume that the company has a total of n such agents. Emission reduction incurs cost and the cost will vary among the agents. We consider that all players are intelligent and have the capability to compute their own emission levels and have an accurate knowledge of cost curves for reducing emissions. The cost curve is private information of the emitting agent. For the purposes of this paper, we assume that the cost curve of each agent is a marginally increasing piecewise constant cost curve as shown in Figure 2. This is a reasonable assumption to make since the marginal cost typically increases with the quantum of emission reduction required. A realistic assumption to make is that each agent has an upper bound on the number of emission reductions possible.

A typical cost curve as described above can be described by a sequence of tuples <p, u, c>, where p denotes the agent, u is the number of emission units that can be reduced by p at a cost c. The tuples for agent i are given as $< i, u_{i1}, c_{i1} >$, $< i, u_{i2}, c_{i2} >$, $\ldots$, $< i, u_{it}, \infty >$ where t is the number of tuples in the type of agent i such that $u_{i(t-1)}$ is the maximum reduction that can be achieved by player i [5]. Here c_{ik} is the cost of per unit of reduction for the range $[u_{i(k-1)} + 1, u_{ik}]$. For the first tuple for player i, the cost is for $[1, u_{i1}]$. Also we have $u_{i1} < u_{i2} < ... < u_{it}$ and $c_{i1} < c_{i2} < ... < c_{it}$ (refer Figure 2).

Example: Suppose the bid by player A is <A, 25, 50>, <A, 50, 100>, <A, 75, 125>, <A, 100, ∞>. The cost of 75 *units of reduction by player A is* 6875.

The global company in question could be regarded as a social planner having the objective of achieving maximum possible reduction through the emitting agents at minimum

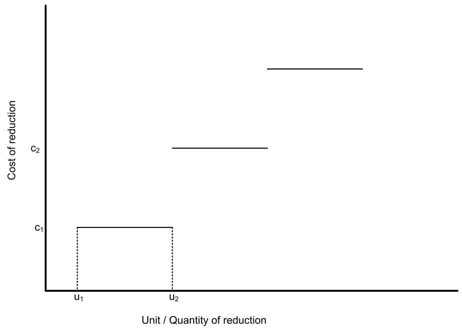

Fig.~2.~~ Cost curves for different agents representing carbon reduction costs

cost. Let M denote the number of emission reduction units the industry wishes to reduce. The problem is to allocate these M units to n emitting agents. In order to allocate the emission reductions units efficiently among its divisions, the company uses the cost curves reported by the agents.

Mathematically,

$$\text{Minimize} \sum_i \sum_j (u_{ij} - u_{i(j-1)}) c_{ij} \qquad (1)$$

$$\text{subject to} \sum_i \sum_j (u_{ij} - u_{i(j-1)}) \geq M$$

$$i = 1, \ldots, n$$

To solve the above optimization problem, the company needs to know the cost curves for emission reduction from the different emitting agents. Since the divisions and partners are often autonomous entities and could exhibit strategic behavior, the company may not be able to elicit the cost curves truthfully. In this paper, we use techniques from mechanism design [3], [4] to solve this problem.

B. Review of Relevant Work

For the problem that we are interested, namely allocating emission reductions among divisions and partners, the most important properties are incentive compatibility (preferably DSIC), strict budget balance (SBB), allocative efficiency, cost minimization, and individual rationality. One way to achieve incentive-compatibility is the Vickrey-Clarke-Groves (VCG) tax mechanism. But any tax mechanism produces a surplus of taxes that cannot be redistributed completely to the divisions without losing the incentive compatible property, i.e. they are not strictly budget balanced (SBB) [6].

Besides DSIC and SBB, another property that would be desirable is allocative efficiency (AE). But it is well known that it is impossible to design any mechanism that satisfies allocative efficiency in addition to DSIC and SBB [7], [8], [9], [10]. Since DSIC and SBB are two fundamental properties that we do not want to compromise, the best we can do is to seek mechanisms that satisfy DSIC and SBB and make the mechanism as efficient as possible.

The paper by Radhika et al. [1], introduces carbon economics issues in the world today and next focuses on carbon economics problems facing global industries. The paper identifies four problems faced by global industries: carbon credit allocation (CCA), carbon credit buying (CCB), carbon credit selling (CCS), and carbon credit exchange (CCE). Further the paper argues that these problems are best addressed as mechanism design problems and describes in detail the carbon credit allocation problem. Another paper by Radhika et al.[5] further explores the carbon credit allocation problem for a global industry that wants to reduce their own carbon footprints. The paper assumes that the industry has multiple divisions which have their own cost curves for emission reduction and develops a mechanism to allocate the total emission reduction units to the divisions such that the total cost of reducing the emission is minimum. Both of these papers contain an appropriate model for the carbon reduction allocation within an organization but the approach assumes the emitting agents are honest and report their cost curves truthfully.

The paper by Bagchi et al. [2] addresses the carbon emission reduction allocation problem and uses a mechanism design approach to solve the problem. The paper assumes that the industry has multiple divisions which have their own cost curves for emission reduction and develops a mechanism to allocate the total emission reduction units to the divisions such that the total cost of reducing the emission is minimum. The authors first propose a strategy-proof and allocative efficient reverse auction protocol to allocate the emission reduction units among the strategic emitting agents and use redistribution mechanisms to reduce the budget imbalance. Then they propose a forward auction protocol which is also strategy-proof and allocative efficient and reduces the budget imbalance further. However, the solution is still not strongly budget balanced. Budget imbalance inevitably leaves a certain no-zero surplus with the social planner (in this case the global company) which essentially means that the divisions are being forced to make certain payments beyond the costs incurred for emission reduction. This looks somewhat unreasonable and artificial since we are dealing with a company and its own divisions/partners. If we are willing to compromise on allocative efficiency a little bit and achieve SBB, then the above anomaly can be overcome. Such a mechanism which is SBB and DSIC is what we propose in this paper.

III. A Strictly Budget Balanced and Strategy-Proof Mechanism for Allocation of Emission Reduction Units

In this section, we propose a forward auction scheme for the carbon emission reduction allocation problem. Let $N = \{1, 2, \ldots, n\}$ be the divisions in the company. In this scheme, each of the n divisions bids for *escape permits* to avoid reductions. Let us say that each division can perform a maximum of k reductions. Then the maximum number of reductions possible is nk. Let M be the number of reductions required by the company. Then there are a total of $nk - M$ escape permits for sale. Now, we can simply run a VCG auction for the $nk - M$ permits. The VCG payment made by a division depends on the number of permits bought by it to avoid reductions. We can call this VCG payment as Green Tax. The higher the number of escape permits a division buys, the higher is the tax it would pay.

In general, in an auction, the taxes collected from the agents can be used to make a payment to the seller of the goods; however, in our problem, the company is not trying to sell any goods. The company is like a social planner trying to allocate escape permits among the divisions that wish to avoid emission reductions. Although the VCG mechanism is strategy-proof and efficient, it is not strictly budget balanced. It produces a surplus of taxes that cannot be redistributed to the agents without losing either incentive compatible property or allocative efficiency. Using the idea of slightly compromising on allocative efficiency, we present a mechanism which is strategy-proof and strictly budget balanced and leaves no surplus in the system.

The basic idea is to randomly select a division or a group of divisions and omit the constraints corresponding to the above division(s) in the optimization problem. In return, this division or group of divisions will be distributed the tax collected from the remaining divisions which buy the escape permits. This protocol is by definition budget balanced since all taxes are redistributed among the omitted divisions themselves. Since the divisions receiving the tax have no influence on the bids and thus the taxes of the remaining divisions, the scheme preserves the incentive compatibility property of the original mechanism. The random selection of divisions ensure incentive compatibility. However, it may choose a solution that is not allocative efficient.

We now present a strictly budget balanced mechanism based on this idea. The center first seeks a bid from each division consisting of cost curves.

Details of the Mechanism:

- Each division $i \in N$ announces its bid (that is its cost curve).
- Choose an coalition E of one or more divisions randomly using a method that does not depend on the bids announced by the divisions. The divisions included in the set E are identified for omission from the mechanism and for receiving the taxes.
- If X is the maximum number of reductions possible by all the divisions and M is the number of reductions required by the company, then there are $X - M$ escape permits that can be given to the divisions. Allocate these permits to the divisions in the set $N \setminus E$ in decreasing order of their per unit reduction costs using VCG mechanism.
- The tax collected from the divisions in the set $N\backslash E$ is redistributed to the divisions in the set E according to some predetermined scheme.

The divisions to be omitted may be chosen by any method that does not depend on the bids of the divisions. In the interest of fairness, it will often be useful to make this choice randomly. The omitted set can consist of one or more divisions. For the sake of simplicity and convenience and to make the mechanism as allocatively efficient as possible, in our work, we omit only a single division and let the mechanism take into account the bids of the remaining $(n-1)$ divisions. Since the set $N\backslash E$ has maximum cardinality of $(n-1)$, allocative efficiency is affected in a minimal way.

Observation 1: The above mechanism is DSIC.
Proof: Consider a division i. When $i \in E$, the agent's bid have no influence on the outcome nor its tax (which is equal to 0), so it cannot gain by misreporting. When $i \notin E$, agent i pays the appropriate VCG tax and this tax is computed using Clarke's payment rule [11] which makes the mechanism incentive compatible.

Observation 2: The above mechanism is strictly budget balanced.
Proof: All taxes collected from the divisions in the set $N\backslash E$ are paid to divisions in the omitted coalition E, so no tax surplus or deficit remains to be distributed.

Example 3: Let there be 4 divisions and assume each division can perform one unit of emission reduction. Let the company be interested in procuring 2 emission reduction units from its four divisions. Let the cost of reduction of the divisions 1 to 4 be 20, 12, 4, 30 respectively. Assume that the mechanism chooses to randomly omit each of the 4 divisions individually with probability $\frac{1}{4}$. When a certain division is omitted, we need to procure 2 reduction units from among the remaining 3 divisions. This means there is one escape permit that can be granted. We then have the following payments:

		Div 1	Div 2	Div 3	Div 4
per unit cost		20	12	4	30
Division omitted	Permits allocated	Tax by Div 1	Tax by Div 2	Tax by Div 3	Tax by Div 4
1	$<0,0,0,1>$	-12	0	0	12
2	$<0,0,0,1>$	0	-20	0	20
3	$<0,0,0,1>$	0	0	-20	20
4	$<1,0,0,0>$	12	0	0	-12

TABLE I

ESCAPE PERMITS AND GREEN TAX COMPUTED BY THE MECHANISM

Table I shows the division that is omitted, the number of escape permits allocated and tax paid by each division. Consider the case when division 1 is omitted. Now we sell escape permits to the remaining divisions. Using the VCG mechanism, the allocation vector of escape permits to divisions 2, 3, 4 respectively is $k = <0,0,1>$. This means 0 permits are given to division 2; 0 to division 3 and 1 to division 4. The VCG payments (or green tax paid) by the divisions 2 to 4 to division 1 are: $<0,0,12>$ i.e. division 1 is paid an amount 12.

Consider the case when division 2 is omitted. Now we sell escape permits to the remaining divisions. Using the VCG mechanism, the allocation vector of escape permits to divisions 1, 3, 4 respectively is $k = <0,0,1>$. This means 0 permits are given to division 1; 0 to division 3; and 1 to division 4. The VCG payments (or green tax paid) by the divisions 1, 3 and 4 respectively to division 2 are:$< 0, 0, 20 >$ i.e. division 2 is paid an amount 20.

In this example, if we observe the cost curves, the cost of reduction of division 4 is higher compared to the rest. Hence division 4 buys more permits and pays the tax to the rest of the divisions. Since the tax collected is redistributed to the excluded division, the payments are equal to the receipts and hence the mechanism is strictly budget balanced.

IV. An Illustrative Case Study

In this section, we describe a stylized case study involving a global company consisting of 5 divisions which contribute to carbon emissions by the company. The system studied here is the same as the one in [2]. In [2], the experimentation is with respect to a DSIC and AE mechanism whereas here it is with respect to the proposed DSIC and SBB mechanism. We experiment with two representative cases of cost curves for the divisions. In the first case, the cost curves are some what similar and only have minor variations across the divisions. The second case examines a situation where the cost curves exhibit some extreme characteristics. The purpose of the experimentation is to examine how the proposed mechanism handles the allocations and payments.

Case 1: Cost Curves with Minor Variations

Here, we consider the case of divisions which have comparable costs for reductions. The cost curves are provided below. Consider division 1. The per unit cost of reduction if the number of carbon emission units to be reduced is less than or equal to 10 is 4. If the number to be reduced lies between 11 and 20, then the first 10 units have a per unit reduction cost of 4 while the next 10 unit reductions will have a per unit cost of 6 etc. Assume that the number of reduction units required by the company (center) be 120.

Division 1: $((1-10,4),(11-20,6),(21-30,8),(31-40,10))$
Division 2: $((1-10,3),(11-20,6),(21-30,9),(31-40,12))$
Division 3: $((1-10,6),(11-20,6),(21-30,6),(31-40,6))$
Division 4: $((1-10,8),(11-20,8),(21-30,8),(31-40,8))$
Division 5: $((1-10,6),(11-20,7),(21-30,8),(31-40,9))$

In this example there are 5 divisions. We omit one division at a time with probability $\frac{1}{5}$ and sell escape permits to the remaining divisions. In the current problem, the total number of reductions that are possible when all the divisions are present is 200. Since we are omitting one division, the total number of reductions that are possible is 160. As the number of reduction units required by the company is 120, there are 40 escape permits that can be given to the divisions. Table II shows the results for this setting. The table shows the division that is omitted, the number of escape permits allocated and tax paid by each division.

Consider the case when division 1 is omitted. Now we sell escape permits to the remaining divisions. Using the VCG mechanism, the allocation vector of escape permits to divisions 2, 3, 4, 5 respectively is $k =< 20, 0, 10, 10 >$. This means 20 permits are given to division 2; 0 to division 3; 10 to division 4; and 10 to division 5. The VCG payments (or green tax paid) by the divisions 2 to 5 to division 1 are: $< 160, 0, 80, 80 >$.

Consider the case when division 2 is omitted. Using the VCG mechanism, the allocation vector of escape permits to divisions 1, 3, 4, 5 respectively is $k =< 20, 0, 10, 10 >$. This means 20 permits are given to division 1; 0 to division 3; 10 to division 4; and 10 to division 5. The VCG payments (or green tax paid) by the divisions 1, 3, 4 and 5 respectively to division 2 are: $< 160, 0, 80, 80 >$.

Division omitted	Permits allocated	Tax by Div 1	Tax by Div 2	Tax by Div 3	Tax by Div 4	Tax by Div 5
1	$< 0, 20, 0, 10, 10 >$	-320	160	0	80	80
2	$< 20, 0, 0, 10, 10 >$	160	-320	0	80	80
3	$< 10, 20, 0, 0, 10 >$	80	160	-320	0	80
4	$< 10, 20, 0, 0, 10 >$	80	160	0	-320	80
5	$< 20, 20, 0, 0, 0 >$	160	160	0	0	-320

TABLE˜II
Case 1: Bid curves with minor variations

From the table II we can observe that the tax is collected only from the divisions trying to buy escape permits and avoid emission reduction. In this example, if we observe the cost curves, the cost of reduction of divisions 1 and 2 is higher compared to divisions 3 and 4. Hence divisions 1 and 2 buy more permits and pay the tax to the rest of the divisions.

Case 2: Cost Curves with Extreme Variations

Now we consider cost curves which have wide variations. Let the number of reduction units required by the company be 90. The cost curves are as follows.

Division 1: $((1-40,50))$
Division 2: $((1-20,4),(21-40,60))$
Division 3: $((1-20,5),(21-30,8),(31-40,\infty))$
Division 4: $((1-20,3),(21-40,\infty))$
Division 5: $((1-20,5),(21-40,10))$

In case 2, there are 5 divisions. We omit one division at a time with probability $\frac{1}{5}$ and sell escape permits among the remaining divisions. In the current problem, the total number of reductions that are possible when all the divisions are present is 170 and the number of reduction units required by the company is 90. Table III shows the results for this setting. The table shows the division that is excluded, the number of escape permits allocated and tax paid by each division.

Consider the case when division 1 is omitted. Since we are excluding one division, the total number of reductions that are possible is 130 and as the number of reduction units required by the company is 90, the number of escape permits that can be given to the divisions is 40. Now we sell escape permits to the remaining divisions. Using the VCG mechanism, the allocation vector of escape permits to divisions 2, 3, 4, 5 respectively is $k =< 20, 0, 0, 20 >$. This means 20 permits are given to division 2; 0 to division 3;

0 to division 4; and 20 to division 5. The VCG payments (or green tax paid) by the divisions 2 to 5 to division 1 are: $< 13, 0, 0, 13 >$.

Consider the case when division 3 is omitted. Now the total number of reductions that are possible is 140 and as the number of reduction units required by the company is 90, the number of escape permits that can be given to the divisions is 50. Using the VCG mechanism, the allocation vector of escape permits to divisions 1, 2, 4, 5 respectively is $k =< 30, 20, 0, 0 >$. This means 30 permits are given to division 1; 20 to division 2; 0 to division 4; and 0 to division 5. The VCG payments (or green tax paid) by the divisions 1, 2, 4 and 5 respectively to division 2 are: $< 25, 60, 0, 0 >$.

Division omitted	Permits allocated	Tax by Div 1	Tax by Div 2	Tax by Div 3	Tax by Div 4	Tax by Div 5
1	$< 0, 20, 0, 0, 20 >$	-26	13	0	0	13
2	$< 40, 0, 0, 0, 0 >$	33	-33	0	0	0
3	$< 30, 20, 0, 0, 0 >$	25	60	-85	0	0
4	$< 40, 20, 0, 0, 0 >$	33	20	0	-53	0
5	$< 20, 20, 0, 0, 0 >$	13	100	0	0	-113

TABLE˜III

CASE 2: BID CURVES WITH SIGNIFICANT VARIATIONS

From the table III we can observe that the tax is collected only from the divisions trying to buy escape permits and avoid emission reduction. In this example, if we observe the cost curves, the cost of reduction of divisions 1 and 2 is higher compared to divisions 3, 4 and 5. Also, from the table III we can observe that the tax paid by divisions 1 and 2 is higher compared to the tax paid by divisions 3, 4 and 5. That is, the higher the cost of reduction, the higher is the tax paid and divisions with low cost of reduction pay less tax.

Summary of Experiments

We summarize the results of our experiments below.

- Tax is paid by only those divisions who buy escape permits to avoid emission reduction. The divisions that do not buy any escape permits do not pay any tax since they are allocated zero escape permits and hence the VCG payment they incur is zero. The higher the number of escape permits they buy, the higher would be the tax they will have to pay.
- Also, divisions with higher cost of reduction pay more tax compared to divisions with lower cost of reduction.
- Since the tax collected is redistributed completely to the divisions itself, the mechanism is strictly budget balanced.

It is to be noted that our mechanism is not allocatively efficient because of which the total cost of emission reductions is not minimal. There are certain pathological situations (such as in the second case with extreme variations) where this could result in marked loss of allocative efficiency. However, we have observed in a range of experiments, that the loss in allocative efficiency is insignificant. With a light compromise in allocative efficiency, we are able to ensure that the divisions do not need to incur costs other than required for emission reductions. The proposed mechanism has another attractive feature: there always exists a division which actually gets a bonus payment - it is a different matter that the division that receives the bonus is randomly selected.

V. CONCLUSION AND FUTURE WORK

In this paper, we proposed a mechanism that a global company may use in allocating emission reductions to its different divisions and supply chain partners towards achieving a required target in its carbon footprint reduction program. The proposed mechanism is strategy-proof and strictly budget balanced and has the additional feature that we randomly exclude one division and allocate escape permits among the remaining $n1$ divisions. The green tax collected from the other divisions is redistributed to the omitted division. This work complements and supplements earlier work of the authors [2] where mechanisms were proposed for this problem satisfying the strategy-proofness and allocative efficiency property. There is a plenty of scope for further work on this problem. First of all, a more extensive set of experiments would have to be conducted to gain deeper insights. On the mechanism design side, instead of looking for DSIC property, we could either look for approximate DSIC or for the much weaker Bayesian incentive compatibility property (each agent is truthful whenever other agents are also truthful). Under these notions of incentive compatibility, it is possible to achieve both allocative efficiency and strict budget balance [3], [4].

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