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Optimal Contract Design for the Exchange of Tradable Truck Permits at Multiterminal Ports

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1 Introduction

Over the past decades, the volume of containers delivered by maritime transport, the most cost-efficient transportation mode, has been increasing significantly due to the rapid development of economic globalisation and international trade. As a result, container traffic at port is also increasing significantly. Since trucks are commonly used for moving containers into/out of container port, increased container ports traffic often causes severer road traffic congestions in port hinterland areas. Road traffic congestions not only jeopardise the efficiency of container flow but also cause the emission of green house gases and some other harmful pollutants. The delays caused by truck congestions reduce the efficiency of truck operations as well as the profits of all stakeholders involved in container supply chains such as shippers, terminal operators and truck drivers (Huynh et al., 2016). Research has shown that 65 percent of delays in shipping is related to port congestions (Lee, C.Y. and Meng, 2015) of which truck congestion is a major contributing factor. Truck congestions in port hinterland also cause environmental issues. Morais Philippe and Lord (2006) analysed the relevant data collected from the South Coast Air Quality Management District (SCAQMD) and the Bay Area Air Quality Management District (BAAQMD) in the coastal area in California in 2003, and found that NO_X emissions were 1300 ton/yr, PM emissions were 55 ton/yr, CO emissions were 1530 ton/yr. Another study conducted by (Sharif et al., 2011) also drew a similar conclusion, and found that truck idling caused by traffic congestion led to serious emission problems.

There are many different reasons for truck congestions in port hinterland such as bad weather, inappropriate documents and fluctuation in truck arrival time (Maloni and C. Jackson, 2005; Sharif et al., 2011). However, it has been widely agreed that the main reason for truck congestion is that most trucks may arrive during peak hours and exceed the maximum gate capacity(Phan and Kim, 2015). The severity of truck congestion may be even worse in the hinterland of a large port with several terminals or at the ports close to large cities(Phan and Kim, 2015). Although congestions may occur anywhere on the road network in port hinterland area, the most severe congestion is often observed at the public road shared by a number of terminals. This is because all the truck flows will eventually merge at these shared roads, which become bottleneck for the whole road network in the port hinterland area.

As an effort to resolve the issue of truck congestion in port hinterland area, Truck Appointment System (TAS) has been proposed as a solution in shipping practice. The examples of the application of this system include Hong Kong International Terminal (Katta G. Murty et al., 2005) and Los Angeles/Long Beach ports (Giuliano et al., 2007). According to a study conducted by Morais Philippe and Lord (2006) in 2002, by applying TAS system, the total in-terminal time of all vehicles was reduced by 48 percent. Also, the research also revealed there was positive impact of TAS on the environmental aspect. They found that, comparing with the scenario without applying TAS, the NO_X emissions were reduced by 61.5 percent, PM emissions were reduced by 63.5 percent and CO emissions were reduced by 64 percent.

Besides the efforts made in industry, in recent years, many academic studies have been conducted to reduce the congestion and its resultant emission. Chen and Yang (2010) proposed a Genetic Algorithm to determine the position and the length of a time window for a truck to visit port. A further study conducted by Chen et al. (2013b) proposed a method called vessel dependent time windows (VDTWs), which can minimize the total system cost based on the estimated queue length and truck arrival time. Chen et al. (2013c) developed a queuing model to determine the optimal hourly quota of entry appointments for TAS. Chen et al. (2013a) proposed a bi-objective model to control truck arrival pattern in order to reduce truck related emissions at port. Chen et al. (2011) suggested time-varying tolls to control truck arrival at ports. Guan and Liu (2009) applied multiple server queuing theory to quantify truck waiting times, and also developed an optimisation model to make a trade-off between gate opening costs and truck waiting costs. Li et al. (2018) proposed a response strategy to manage disrupted truck arrival at a container terminal. Sharif et al. (2011) developed an agent-based simulation model to evaluate how live views of port gates via webcams may affect gate congestion. Zhang et al. (2019) developed a vacation queuing model to optimise truck appointment system. Azab et al. (2019) employed a simulation based optimisation method to coordinate the booking of TAS with yard opperation. . Zehendner and Feillet (2014)explored and developed a mixed integer linear programming to determine the appointments number from a systemic point of view. The developed method can minimize the total delay in the terminal taking into account the overall workload and handling capacity. Although many existing studies showed that TAS may be useful to reduce truck congestions and emissions, some researchers also pointed out some issues relating to TAS. Huynh et al. (2016) highlighted shortcomings of TAS based on a review of the practical applications and the related academic studies. Among many issues, one issue they raised is that TAS is operated by each terminal independently at multi-terminal ports, and there is no "port-wide real-time system visibility" of information. This actually gives truck drivers little chance to schedule matching appointment across terminals. For example, a truck driver may need to drop off a container at a terminal and then pick up another container at a different terminal in the same port. The truck driver needs to book two appointments from each terminal, respectively, but may be unable to minimise the waiting time between two appointments due to the invisibility of information. Giuliano et al. (2007) also observed at the Ports of Los Angeles and Long Beach that TAS may be unable to help to reduce the length of truck queue if the terminals and truck companies only consider their own benefits selfishly. The two studies(Huynh et al., 2016; Giuliano et al., 2007) actually revealed a very important issue: – there is lack of coordination between the various TASs at multiterminal port as normally each terminal runs their own TAS independently.

A research stream that closely relates to TAS is container drainage that involves transporting containers via truck for short distance (Zhang et al., 2020). In some studies focusing on container drayage, TAS has been considered. For example, Namboothiri and Erera (2008) studied the impact of TAS on the productivity of drayage operations. In their research, integer programming heuristic has been developed to measure the impact. They found that drayage fleet efficiency can be increased by 10 - 24 percent when total access capacity of TAS is increased by 30 percent. Yi et al. (2019) proposed a scheduling method in a TAS that determines truck availability and container pickup/drop-off. Torkjazi et al. (2018) designed a TAS considering container drayage routing. Shiri and Huynh (2016) formulated container drayage problem as a multiple traveling salesman problem with time windows considering truck appointment via TAS.

Different from the aforementioned studies, the focus of our study will be on promoting the collaboration between TASs rather than improving the efficiency of an individual TAS or synchronising the planning of TAS and container drayage. To the best of our knowledge, no studies have been carried out with regard to the problem discussed above although there are some studies investigating collaboration issues at container port. For example, Phan and Kim (2016) investigated the collaboration between trucking companies and a container terminal.

We will apply the concept of "Tradable Bottleneck Permits" (TBP) proposed for urban transport network (Akamatsu et al., 2006; Akamatsu and Wada, 2017; Wada and Akamatsu, 2011; Fan and Jiang, 2013) into the issue of truck congestion in port hinterland. Adapted from the early concept of "advance highway booking" (Liu et al., 2015; Wong, 1997), the idea of TBP requires drivers to bid for the right to use a particular road at a pre-specified time through internet based auction market operated by the road infrastructure manager. In our study, however, we have slightly modified the concept of TBP, and proposed a new type of permit termed as Tradable Truck Permit (TTP) for the specific the context of TAS coordination at multiterminal port. The key features of TTP are twofold:

- A terminal or TAS operator, rather than a individual truck driver, needs to obtain permits from government in order to use public road to accommodate any truck;

- A terminal can sell(purchase) their permits to(from) the other terminals when needed.

Our research aims to identify the best permit trading mechanism which can maximise the overall benefits of all the TAS operators(terminals) and thus achieve systematic optimality. Different from previous studies relating to TAS, we do not aim to optimise the benefits of an individual TAS operator or terminal. Instead, we will focus on how to improve the overall profits of a collection of TAS operators relating to a multiterminal port while recognising the TAS operators have conflicting interests in sharing public road. To address our proposed research question the issue, we will develop a research framework based on game theory. At the end of our study, we will prove that a buy-back contract can achieve the goal and coordinate the permit trading between the TAS operators involved at a multiterminal port.

The contributions of our research are threefold:

- a new concept of tradeable truck permit for TAS has been proposed
- a game theoretical modelling framework has been developed to design the mechanism to coordinate the decision making of multiple TASs with conflicting interests at a multiterminal port
- a buy-back contract has been approved to be the optimal mechanism for trading truck permits

The remainder of the paper is structured as follows. In section 2, we will define the research problem as well as the notations. In Section 3, we will formulate the case of perfect collaboration where all the stakeholders are deemed as a single organisation; we will then formate the case of contract based collaboration in Section 4, and also design the best mechanism to coordinate the decision-making of TASs and permit exchange activities at multiterminal port. In the last section, the conclusions and the further study are presented.

2 Problem Definition

2.1 Notation

Variables:

p^a : the number of permit that terminal A bought from the government;

d^a : the number of permit requested by the customer of terminal A;

d^b : the number of permit requested by the customer of terminal B;

q : the number of permit exchanged between terminal A and B;

b : the buy-back price per permit between terminal A and B;

s : the wholesale price per permit between terminal A and B;

Parameters:

N : the total number of permit the government issued;

c : the price the government charged per permit;

g^a : goodwill penalty per unsatisfied permit of terminal A ;

g^b : goodwill penalty per unsatisfied permit of terminal B ;

r^a : profit of terminal A generated through per permit ;

r^b : profit of terminal B generated through per permit ;

m : administration fee per permit for permit exchanging;

Note:

$q > 0$, when terminal A sell permit to B,

$q < 0$, when terminal A buy permit from B.

2.2 Problem Description

TAS was first introduced to shipping practice in early 2000s in USA marine container terminals such as the Seaside Transportation Service (Evergreen) terminal and the West Basin Container Terminal in Los Angeles, and Total Terminals Internationals Pier T in Long Beach (Huynh et al., 2016). Nowadays TAS is a very common IT system for marine container port worldwide. Its primary goal is to control the number of trucks that can come to a terminal, and thus to reduce gate congestion and improve efficiency and punctuality of container drayage.

However, TAS has some deficiency at multiterminal ports which is very common in shipping industry since there is a lack of coordination across TASs operated by the terminals associated with the same port. In practice, a terminal at multiterminal port is likely to be operated by a company independently and has their own TAS. Since the terminal operators associated with the same port are competitors, and they are quite reluctant to share information. As a result, each terminal has to allocate time slots to trucks without the knowledge of truck appointments at the other terminals. In this situation, each terminal may just try to choose any time slots favorable for their customers' trucks to maximise their own benefits. The uncoordinated decision making in arranging truck appointments causes a large number of trucks to use the public roads during the popular times slots, e.g., in the morning, which subsequently lead to traffic congestion. The disorder of appointment booking control is one of the major contributing factors for truck congestions in port hinterland area.

It will be a challenging task to coordinate the decision making between these terminal operators as their business are almost identical and they are literally competitors of each other. In this study, we will attempt to resolve the issue by introducing a concept of Tradable Truck Permit(TTP), an adaption of Tradable Bottleneck Permit(TBP) as discussed early, and designing a mechanism to promote the collaboration of terminal operators through the exchange of permits. Our mechanism will ensure each TAS will be better off than the current industrial practice without collaboration. Also, the mechanism will ensure the total profits that TAS operators can gain under the mechanism will be the same as that under perfect cooperation where all the terminals work like a single company.

We assume that terminals have already obtained a certain number of TTPs issued by their local government. The government would issue a fixed amount of permits to ensure high level of transport service provided in port hinterland area, and requests each truck must have a permit to use public road to go into a terminal. The permit is valid in a certain time period, and if not used, will expire afterwards. The government allows that unused valid permits can be traded between different terminals, and the terminals can decide the price they would like to charge each other.

We consider a stylised multiterminal port with two terminals operated independently: terminal A and terminal B. Both terminals need to receive an uncertain number of trucks that may need to pick up or drop off containers. Each terminal makes its internal and external decision independently to maximise its own profit. As a consequence, when they use TASs to manage the arrival time and the amount of trucks, they do not consider the social benefit of the port hinterland as a whole system, e.g., traffic congestion on the road. Further, because of the competition between each other, their decisions are nontransparent to each other. Each terminal makes their purchasing decision on the number of permits based on an estimate of customer demands. As the estimated customer demands are very likely to be different from the actual ones at each terminal, the number of permits a terminal has may be higher or lower than what would be required. To maximise their profits, one way is to sell the spare permits to the other terminal. The amount of permits that can be traded between the two companies is affected by a set of parameters, e.g., the initial number of permits held by each individual terminal, the different amount of profits generated by one permit at each terminal, the selling price per permit, and customer demands.

Let N denote the total number of government issued permits that is available for terminal A and B to purchase. c denotes the price that the government charges per permit. The number of permits terminal A purchases from the government is denoted by p^a and thus $N - p^a$ will be that of company B. d^a, d^b are two random numbers following a certain distribution, and denote the customer demands of terminal A and B, respectively. r^a, r^b represents the profits generated from one permit at terminal A and B correspondingly. The lost sales costs incurred at terminal A is g^a, and g^b at company B when the terminals have no permits to receive their customers' trucks. A terminal can sell their spare permits to the other but an adminstration fee of m per permit will be applied. The goals of the two terminals are to maximise their own profits, and the decisions the two terminals need to make are: the number of permit exchanged between terminal A and B, q, which is positive when terminal A sells permit to B, and vice vera; and the price, b, which the terminals should charge each other. The key task of our research is to set up a contract to coordinate the decision making of the two terminals and maximise the profits of the entire system. By assigning proper values to the paramors in the contracts, the two companies will choose an exchange amount which can maximise the total profit of the system even though two terminals still make decisions unilaterally.

We will apply game theory to investigate the aforementioned issue. Two types of collaboration modes and the corresponding decision making frameworks will be considered:

- Perfect collaboration under centralised decision making
- Collaboration via contract under decentralised decision making

Under the perfect collaboration mode, the decision will be made in a centralised manner, and the two terminals are practically deemed as a single organisation. We will determine the optimal amount of permits traded between the two terminals as well as their overall profits for the perfect collaboration, and then use the result to benchmark the contract or the mechanism we will try to design for decentralised decision making.

Under the decentralised decision making framework, two terminals make decisions independently. Each terminal will attempt to maximise their own profit regardless of the other's decision making. In fact, this is what terminals at multiterminal port are doing in practice, and also the main cause of truck congestion. Our research will attempt to design a contract or mechanism to coordinate the decision makings of the two terminals. The contract or mechanism under development is expected to perform as well as centralised decision making framework in terms of profits generated for all the stakeholders. The contract will specify how they charge each other for permit exchanging. Following the contract, the decision makings of the two terminals will be coordinated in the sense that the performance of decentralised decision making will be the same as that of centralised one.

In the following, we will present our mathematical formulation and analysis for the two collaborations modes.

3 Perfect Collaboration under Centralised Decision Making

Let $Q^a(p^a, q)$ denote the fulfilled number of permits in terminal A:

$$Q^a(p^a, q) = min\{p^a - q, d^a\}$$

Let $U^a(p^a, q)$ denote the unsatisfied number of permits in terminal A:

$$U^a = [d^a - (p^a - q)]^+$$

For terminal B, the fulfilled number of permits and unsatisfied number of permits can be defined as follows:

$$Q^b(N - p^a, q) = min(N - p^a + q, d^b)$$

$$U^b = [d^b - (N - p^a + q)]^+$$

As discussed above, the terminals can trade permits with additional adminstration cost m per permit paid by the seller. Based on the above assumptions, when considering a decentralized situation where terminal A and B operate separately and make decisions only target to maximize its own profit, the profit of terminal A can be formulated as the following equation $\Pi_a(p^a, q)$:

$$\max \quad \Pi_a(p^a, q) = -c \cdot\ p^a + r^a \cdot \mathbb{E}Q^a + s \cdot\ q + m \cdot\ q^+ - g^a \cdot \mathbb{E}U^a$$

The profit function of terminal B can be formulated as $\Pi_b(p^a, q)$:

$$\max \quad \Pi_b(p^a, q) = -c \cdot\ (N - p^a) + r^b \cdot \mathbb{E}Q^b - s \cdot\ q + m \cdot\ q^- - g^b \cdot \mathbb{E}U^b$$

If the two companies are practically deemed as a single company, and operated under a centralised decision making system, the permit held by the two companies could be shared without charging each other. The only cost element relating to permit exchange will the administration cost m. The objective fundtion is to maximise the system profit $\Pi(p^a, q)$, which can be formulated as follows:

$$\max \quad \Pi(p^a, q) = -c \cdot \; N + r^a \cdot \mathbb{E}Q^a - g^a \cdot \mathbb{E}U^a + r^b \cdot \mathbb{E}Q^b - g^b \cdot \mathbb{E}U^b + m \cdot \; |q|$$

It should be noted that, when $q = 0$, $\Pi(p^a, q)$ is not differentiable.

Proposition 1 $\Pi(p^a, q)$ *is strictly concave in* q.

Proof.

$$\begin{aligned} \max \quad \Pi(p^a, q) &= -c \cdot N + r^a \cdot \mathbb{E}Q^a - g^a \cdot \mathbb{E}U^a + r^b \cdot \mathbb{E}Q^b - g^b \cdot \mathbb{E}U^b - m \cdot |q| \\ &= -c \cdot N + r^a \cdot \mathbb{E}min\{p^a - q, d^a\} - g^a \cdot \mathbb{E}(d^a - p^a + q)^+ \\ &+ r^b \cdot \mathbb{E}min\{N - p^a + q, d^b\} - g^b \cdot \mathbb{E}(d^b - N + p^a - q)^+ - m \cdot \; |q| \\ &= -c \cdot \; N + r^a \cdot \left[p^a - q - \int_0^{p^a - q} F_a(x)dx\right] \\ &- g^a \cdot \left[\mu_a - (p^a - q) + \int_0^{p^a - q} F_a(x)dx\right] + r^b \cdot \left[N - p^a + q - \int_0^{N - p^a + q} F_b(x)dx\right] \\ &- g^b \cdot \left[\mu_b - (N - p^a + q) + \int_0^{N - p^a + q} F_b(x)dx\right] - m \cdot \; |q| \end{aligned}$$

For any $q \neq 0$,

$$\frac{\partial \Pi(p^a, q)}{\partial q} = -(r^a + g^a) \cdot \int_{p^a - q}^{\infty} f_a(x)dx + (r^b + g^b) \cdot \int_{N - p^a + q}^{\infty} f_b(x)dx - r^a \quad + r^b - m \cdot sgn(q)$$

Because $\pi(p^a, q)$ is not differentiable at $q = 0$, the difference between its right derivative and left derivative is: $-2m$. Since $m > 0$, $-2m < 0$.

For any other points, $\pi(p^a, q)$ are differentiable, thus

$$\frac{\partial^2 \Pi(p^a, q)}{\partial q^2} = -(r^a + g^a) \cdot f_a(p^a - q) - (r^b + g^b) \cdot f_b(N - p^a + q) < 0.$$

Therefore, $\Pi(p^a, q)$ is strictly concave in q.

According to Proposition 1, the total profit of all terminals $\Pi(p^a, q)$ changes with the permit exchanging number. There exists the optimal transfer amount of permits which can maximise $\Pi(p^a, q)$. If the permit exchange number is smaller than the optimal one,

$\Pi(p^a, q)$ increases in q; when the exchanging permit number is bigger than the optimal one, $\Pi(p^a, q)$ decreases in q. The practical implication for container terminals is that they should dynamically adjust the number of permits to be exchanged in practice with respect to the total profits obtained. Given the convexity, an approximate gradient search method may be effective to identify the optimal exchange amount if the cost structure is complex in practice.

From the conclusion of Proposition 1, for any given p^a, we know there is only one permit exchanging amount, $q^0 \in [-(N-p^a), p^a]$, which can maximise the profit of the whole system. The condition for the profit of the entire system (including both terminal A and B)being maximized is to make $\frac{\partial \Pi(p^a,q)}{\partial q} = 0 (q \neq 0)$. Let q^* and q^{**} denote the optimal exchange amount of permits, and $\Pi^+(p^a, q)$, $\Pi^-(p^a, q)$ the corresponding profits when $q \to 0^+$ and $q \to 0^-$, respectively. q^* , q^{**} will be the solutions to the following two equations, respectively,

$$\frac{\partial \Pi^+(p^a, q)}{\partial q} = -(r^a + g^a) \cdot \int_{p^a - q}^{\infty} f_a(x)dx + (r^b + g^b) \cdot \int_{N-p^a+q}^{\infty} f_b(x)dx - r^a + g^b - m = 0$$

$$\frac{\partial \Pi^-(p^a, q)}{\partial q} = -(r^a + g^a) \cdot \int_{p^a - q}^{\infty} f_a(x)dx + (r^b + g^b) \cdot \int_{N-p^a+q}^{\infty} f_b(x)dx - r^a + g^b + m = 0$$

The maximum number of permits that can be exchanged is always no more than the permits each terminal purchased from the local government, i.e., p^a for terminal A and $N - p^a$ for terminal B. By considering the relationship between p^a, $N - p^a$, p^*, and p^{**}, we can identify five cases with each having a different value for the optimal permit exchanging amount.

Case 1: If $0 < p^a < q^*$

As q^* is the optimal solution to maximise the total profit of terminal A and B when $q > 0$, and $\Pi(p^a, q)$ is a concave function for q, this means that the system profit will increase with q when $q \in [0, q^*]$. Therefore, the optimal exchange amount $q^0 = p^a$.

Case 2: If $0 < q^* < q^a$

let

$$\frac{\partial \Pi^+(p^a, q)}{\partial q} = 0$$

Since q^* is the optimal solution and no more than the number of permits on hand, q^a, the optimal exchanged amount $q^0 = q^*$

Case 3: If $-(N-p^a) \leq q^{**} \leq 0$

let

$$\frac{\partial \Pi^-(p^a, q)}{\partial q} = 0$$

Similar to case 2, the optimal amount of permits to be exchanged is q^{**}.

Case 4: If $q^{**} < -(N-p^a) < 0$

Similar to case 1, the optimal exchanged amount of permit is $-(N-p^a)$.

Case 5: If $q^* < 0 < q^{**}$

$$\frac{\partial \Pi^+(p^a, q)}{\partial q}\Big|_{q=0} < 0$$
$$\frac{\partial \Pi^-(p^a, q)}{\partial q}\Big|_{q=0} > 0$$

which indicates that $\Pi(\cdot)$ achieve the extreme value when $q = 0$. In this case, the terminal A and B should keep their own permits and do not exchange them with the other.

The above discussion can be summarized as the following proposition:

Proposition 2 *The optimal transfer amount of permit q^0 is :*

$$q^0 = \begin{cases} p^a & \text{if} \quad 0 < p^a < q^* \\ q^* & \text{if} \quad 0 < q^* < q^a \\ q^{**} & \text{if} \quad -(N-p^a) \leq q^{**} \leq 0 \\ -(N-p^a) & \text{if} \quad q^{**} < -(N-p^a) < 0 \\ 0 & \text{if} \quad q^{**} < 0 < q^* \end{cases}$$

According to Proposition 2, in case 1 and 4, the system profit can be improved by purchasing more permits from government; however, in case 2 and 3, increasing the number of permits purchased does not help to improve the profits of terminals; in case 5, it can be found that no permits exchange is the optimal choice.

As discussed early, the overall profit of the entire system is equal to the sum of the profit of terminal A and that of terminal B minus the administration cost of permit exchanging between the terminals. To maximise the total profits, under full collaboration mode, the principle is that the terminal that has higher profit margin should have higher priority in permit allocation.

4 Collaboration via Contract under Decentralised Decision Making

In this section, Terminal A and Terminal B are considered as two independent companies. They make their decisions on permit purchasing and trading to optimise its own profit. The lack of information transparency between the two terminals may result in a suboptimal condition for the entire system as well as each individual terminal. The permit exchange between the two terminals can be considered as an inventory transshipment game. In the following part of this section, the game between the two players will be investigated, and a contract will be designed to collaborate the decision making between the two terminals and optimise the profits of individual stakeholder as well as the whole system.

4.1 Buy-back contract

The truck operation permits can be traded between terminals, and a terminal may buy/sell permits from/to the other terminal. In practice, the demands of each terminal are dynamic and uncertain, consequently it is inevitable for them to face the risk of permit over-stocking or under-stocking. To mitigate this risk, a buy-back contract is designed to enhance the cooperation between the two stakeholders. In the study, the buy-back contract works in the following way: a terminal sells permits to the other with a unit wholesale price of s, and pay an additional administration fee of m; the other terminal is allowed to return the purchased, but not used, permits, with an unit buying-back price of b. The principle of the buy-back will be followed when a terminal purchases the permits from the other, and only applied to the permits purchased rather than any leftover for any reason. For the sake of fairness, we assume the buy-back prices of terminal A and B are the same.

Let s denote the wholesale price per permit, b the buy-back price per permit. The payment $F(\cdot)$ made by terminal A to B for permit exchanging can be formulated as:

$$\begin{aligned} F(q,p^a,b) = {} & s \cdot q^+ - b \cdot \mathbb{E}min\{(p^a - q - d_a), q^+\} - s \cdot (-q)^+ \\ & + b \cdot \mathbb{E}min\{(N - p^a + q - d_b), (-q)^+\} \end{aligned}$$

In the above equation, the first item in the equation means the wholesale revenue terminal A may receive from selling q^+ permits; and the second item represents the payment made by terminal A for buying-back the sold but unused permits. The third and the four items are similar, but used for computing the exchange payment for the case where terminal

A is short of permits.

The profit function of Terminal A can be defined as:

$$\begin{aligned}\Pi^a(q,,N,m,p^a,b) = &-c\cdot\ p^a + r^a\cdot\mathbb{E}min\{p^a-q,d^a\} - g^a\cdot\mathbb{E}(d^a-p^a+q)^+\\ &+s\cdot q^+ - b\cdot\mathbb{E}min\{(p^a-q-d^a),q^+\} - s\cdot(-q)^+\\ &+b\cdot\mathbb{E}min\{(N-p^a+q-d_b),(-q)^+\} - m\cdot q^+\end{aligned}$$

The profit function of Terminal B can be written as:

$$\begin{aligned}\Pi^b(q,N,p^a,m,b) = &-c\cdot(N-p^a) + r^b\cdot\mathbb{E}min\{N-p^a+q,d^b\} - g^b\cdot\mathbb{E}(d^b-N+p^a+q)^+\\ &-s\cdot q^+ + b\cdot\mathbb{E}min\{(p^a-q-d^a),q^+\} + s\cdot(-q)^+ - m\cdot(-q)^+\\ &-b\cdot\mathbb{E}min\{(N-p^a+q-d_b),(-q)^+\}\end{aligned}$$

Terminal A and Terminal B make their decisions on the permit exchange independently based on the number of permits they purchased from government, the wholesale price and the buy-back price per permit. In other words, each terminal decides whether they will sell or buy permits from the other terminal. Let q^a, q^b denote the amount of permits to be exchanged at Terminal A and Terminal B, respectively. Please note that q^a, q^b can be either positive or negative. $q^a > 0$ indicates that Terminal A has surplus permits and need to sell some of them to Terminal B; $q^a < 0$ means Terminal A is short of permits to fulfil his demand and need to buy from the other terminal. It should be pointed out that q^b has the opposite physical meaning for for Terminal B. A positive q^b means Terminal B need to buy permits from the other terminal and a negative q^b means Terminal B need to sell its spare permits.

The transaction of permits between the two companies has two scenarios: 1) Terminal A has a permit surplus, and terminal B has a permit deficit; 2) Terminal A has a shortage of permits; and Terminal B has a surplus of permits. The permit exchange amount q^* is the smaller of the exchange requirements of the two terminals, i.e. $q^* = min\{q^a, q^b\}$.

Proposition 3 *The system will never be coordinated when the two companies operate independently without additional contract mechanism.*

Proof:

When the two terminals are deemed as a centralised organization, the permits to be exchanged between the two only incur adminstration costs. The systematic optimal exchange amount q_0 was obtained for this scenario. For the decentralised decision making scenario, the exchange cost per permit include the whole sale price which is more than the administration cost. It's clear that the increment of cost for obtaining permit will result in the deduction of exchange amount. This means that the exchange amount between the companies under pure decentralised scenario will always smaller than q_0, and their profits will not be better than that under perfect collaboration. In other words, the system will never be coordinated.

Condition 1: $0 \leq b \leq min\{(r^a + g^a), (r^b + g^b)\}$

Condition 1 implies, when one terminal buy back the unused permits from the other after permit exchanging, the buy back price paid would be a value between 0 and the minimum value of the profit generated by a permit in terminal A and B.

Proposition 4 *Profit function of Terminal A and Terminal B are all strictly concave in q when **condition 1** is satisfied.*

Proof:

The profit function of Terminal A is:

$$
\begin{aligned}
\Pi^a(q, p^a, N, b) = & -c \cdot \ p^a + r^a \cdot \mathbb{E}min\{p^a - q, d^a\} - g^a \cdot \mathbb{E}(d^a - p^a + q)^+ \\
& + s \cdot q^+ - b \cdot \mathbb{E}min\{(N - p^a + q - d^b)^+, q^+\} - s \cdot (-q)^+ \\
& + b \cdot \mathbb{E}min\{(p^a - q - d^a)^+, q^+\} - m \cdot q^+
\end{aligned}
$$

Let:

$$\mu_a = \mathbb{E}(d^a)$$

$$\mu_b = \mathbb{E}(d^b)$$

if $q > 0$,

$$
\begin{aligned}
\Pi^a(q,p^a,N,b) &= -c\cdot\ p^a + r^a\cdot \mathbb{E}min\{p^a-q,d^a\} - g^a\cdot\mathbb{E}(d^a-p^a+q)^+ \\
&+ s\cdot q^+ - b\cdot\mathbb{E}min\{(N-p^a+q-d^b)^+,q^+\} - m\cdot q \\
&= -c\cdot\ p^a + r^a\cdot\left[p^a-q-\int_0^{p^a-q}F_a(x)dx\right] - g^a\cdot\left[\mu_a-(p^a-q)+\int_0^{p^a-q}F_a(x)dx\right] \\
&+ s\cdot q^+ - b\cdot\left[\int_0^{N-p^a}F_b(x)dx - \int_0^{N-p^a+q}F_b(x)dx\right] - m\cdot q \\
\frac{\partial\Pi^a(q,p^a,N,b)}{\partial q} &= -(r^a+g^a)\cdot\int_{p^a-q}^{\infty}f_a(x)dx + s - b\cdot\int_0^{N-p^a+q}f_b(x)dx - m \\
\frac{\partial^2\Pi^a(q,p^a,N,b)}{\partial q^2} &= -(r^a+g^a)\cdot f_a(p^a-q) - b\cdot f_b(N-p^a+q) < 0
\end{aligned}
$$

if $q < 0$,

$$
\begin{aligned}
\Pi^a(q,p^a,N,b) &= -c\cdot\ p^a + r^a\cdot \mathbb{E}min\{p^a-q,d^a\} - g^a\cdot\mathbb{E}(d^a-p^a+q)^+ \\
&- s\cdot(-q)^+ + b\cdot\mathbb{E}min\{(p^a-q-d_a)^+,(-q)^+\} \\
&= -c\cdot\ p^a + r^a\cdot\left[p^a-q-\int_0^{p^a-q}F_a(x)dx\right] - g^a\cdot\left[\mu_a-(p^a-q)+\int_0^{p^a-q}F_a(x)dx\right] \\
&- s\cdot(-q) + b\cdot\left[\int_0^{p^a}F_a(x)dx + \int_0^{p^a+q}F_a(x)dx\right] \\
\frac{\partial\Pi^a(q,p^a,N,b)}{\partial q} &= -(r^a+g^a)\cdot\int_{p^a-q}^{\infty}f_a(x)dx + s - b\cdot\int_0^{p^a-q}f_a(x)dx \\
\frac{\partial^2\Pi^a(q,p^a,N,b)}{\partial q^2} &= -(r^a+g^a-b)\cdot f_a(p^a-q) < 0
\end{aligned}
$$

The profit function of Terminal B is:

$$
\begin{aligned}
\Pi^b(q,p^a,N,b) &= -c\cdot(N-\ p^a) + r^b\cdot\mathbb{E}min\{N-p^a+q,d^b\} - g^b\cdot\mathbb{E}(d^b-N+p^a-q)^+ \\
&- s\cdot q^+ + b\cdot\mathbb{E}min\{(N-p^a+q-d^b)^+,q^+\} + s\cdot(-q)^+ \\
&- b\cdot\mathbb{E}min\{(p^a-q-d^a)^+,q^+\} - m\cdot(-q)^+
\end{aligned}
$$

If $q > 0$,

$$\begin{aligned}
\Pi^b(q,p^a,N,b) &= -c\cdot(N-p^a)+r^b\cdot\mathbb{E}min\{N-p^a+q,d^b\}-g^b\cdot\mathbb{E}(d^b-N+p^a-q)^+\\
&-s\cdot q^+ + b\cdot\mathbb{E}min\{(N-p^a+q-d^b)^+,q^+\}\\
&= -c\cdot(N-\ p^a)+r^b\cdot\left[N-p^a+q-\int_0^{N-p^a+q}F_b(x)dx\right]\\
&-g^b\cdot\left[\mu_b-(N-p^a+q)+\int_0^{N-p^a+q}F_b(x)dx\right]\\
&-s\cdot q^+ + b\cdot\left[\int_0^{N-p^a}F_b(x)dx-\int_0^{N-p^a+q}F_b(x)dx\right]\\
\frac{\partial\Pi^b(q,p^a,N,b)}{\partial q} &= (r^b+g^b)\cdot\int_{N-p^a+q}^{\infty}f_b(x)dx-s+b\cdot\int_0^{N-p^a+q}f_b(x)dx\\
\frac{\partial^2\Pi^b(q,p^a,N,b)}{\partial q^2} &= -(r^b+g^b-b)\cdot f_b(N-p^a+q)<0
\end{aligned}$$

If $q<0$,

$$\begin{aligned}
\Pi^b(q,p^a,N,s,b) &= -c\cdot(N-\ p^a)+r^b\cdot\mathbb{E}min\{N-p^a+q,d^b\}-g^b\cdot\mathbb{E}(d^b-N+p^a-q)^+\\
&+s\cdot(-q)^+ - b\cdot\mathbb{E}min\{(d^a-p^a+q),(-q)^+\}-m\cdot(-q)^+\\
&= -c\cdot(N-\ p^a)+r^b\cdot\left[N-p^a+q-\int_0^{N-p^a+q}F_b(x)dx\right]\\
&-g^b\cdot\left[\mu_b-(N-p^a+q)+\int_0^{N-p^a+q}F_b(x)dx\right]\\
&-s\cdot(-q)^+ - b\cdot\left[\int_0^{p^a}F_a(x)dx+\int_0^{p^a+q}F_a(x)dx\right]-m\cdot(-q)^+\\
\frac{\partial\Pi^b(q,p^a,N,b)}{\partial q} &= (r^b+g^b)\cdot\int_{N-p^a+q}^{\infty}f_b(x)dx-s+b\cdot\int_0^{p^a-q}f_a(x)dx+m\\
\frac{\partial^2\Pi^b(q,p^a,N,b)}{\partial q^2} &= -(r^b+g^b)\cdot f_b(N-p^a+q)-b\cdot f_a(p^a-q)<0
\end{aligned}$$

From above discussion, it can be concluded that when the buy-back price b satisfying Condition 1, the profit of the two terminals are strictly concave in q. This means that under Condition 1, there exists the optimal amount of exchanging permit which can maximise terminal A's profit. There is another amount of exchanging permit which can maximise terminal B's profit. However, the two amounts might be different. This leads to the following proposition.

Proposition 5 *When condition 1 is satisfied, each terminal has and only has one optimal* *permit transfer amount denoted as q_a^* and q_b^* which can guarantee respectively each terminal can obtain its highest profit.*

Based on Proposition 5, Terminal A will gain the maximum profits when its exchange amount is q_a^*. However, a notable fact is that the transfer of q_a^* permits from Terminal A to Terminal B is conditional on whether terminal B is willing to purchase the amount of permits. Actually, it is more often that the amount of Terminal B needs to purchase is different from terminal A's optimal selling amount, q_a^*. The similar situation is also applied to terminal B. Due to the difference between one terminal's selling amount of permits and the other terminal's purchasing amount, the gaming process between the two terminals will lead to a Nash equilibrium, and consequently, the following proposition can be derived.

Proposition 6 *Under condition 1, there exists Nash equilibrium for the permit exchanging game, which is a Pareto Optimal. The optimal permit transfer amount under Nash equilibrium can be denoted as* $\{min[(q_a^+)^*, (q_b^+)^*] - min[-(q_a^-)^*, -(q_b^-)^*]\}$.

Proof:
Under this equilibrium, The optimal permit transfer amount can be calculated by $\{min[(q_a^+)^*, (q_b^+)^*] - min[-(q_a^-)^*, -(q_b^-)^*]\}$. There are three possibilities for transfer amount in equilibrium: q_a^*, q_b^* and 0. As the profit function of each terminal is concave, no one can improve its own profit level without doing harm to the other's profit. This equilibrium is Pareto optimal.

4.2 Contract Design

In this section, a bilateral buy-back contract will be designed for the two terminals to coordinate their decisions which may lead to the Nash equilibrium discussed in Proposition 6. The related parameters in the contract will also be determined. The target of the contract is to ensure the entire system as well as each individual terminal can achieve its maximum profit.

In Section 3, we obtained the optimal permit exchanging amount under perfect collaboration, q_0. If we let Terminal A to exchange the same amount of permits under decentralised decision-making case, the profits terminal A can gain are $\Pi^a(q_0, p^a, N, s, b)$. Let $\Pi^a(0, p^a, N, s, b)$ denote the profits also in the decentralised decision making case, but with no permits exchanged. The profit difference of the two cases can be formulated as,

$$
\begin{aligned}
\triangle\Pi^a(p^a,N,s,b) &= \Pi^a(q_0,p^a,N,s,b) - \Pi^a(0,p^a,N,s,b) \\
&= r^a \cdot \mathbb{E}min\{p^a - \ q_0, d^a\} - g^a \cdot \mathbb{E}(d^a - p^a + q_0)^+ \\
&+ s \cdot q_0^+ - b \cdot \mathbb{E}min\{(N - p^a + q_0 - d^a), q_0^+\} - s \cdot q_0^- \\
&+ b \cdot \mathbb{E}min\{(p^a - q_0 - d^a), q_0^+\} - m \cdot q_0^+ - r^a \cdot \mathbb{E}min\{p^a, d^a\} + g^a \cdot \mathbb{E}(d^a - p^a)^+
\end{aligned}
$$

If $q > 0$,

$$
\begin{aligned}
\triangle\Pi^a(p^a,N,s,b) &= r^a \cdot \left[p^a - q_0 - \int_0^{p^a-q_0} F_a(x)dx\right] \\
&- g^a \cdot \left[\mu_a - (p^a - q_0) + \int_0^{p^a-q_0} F_a(x)dx\right] \\
&+ s \cdot q_0 - b \cdot \left[\int_0^{N-p^a} F_b(x)dx - \int_0^{N-p^a+q_0} F_b(x)dx\right] - m \cdot q_0 \\
&- r^a \cdot \left[p^a - \int_0^{p^a} F_a(x)dx\right] + g^a \cdot \left[\mu_a - p^a + \int_0^{p^a} F_a(x)dx\right] \\
&= -(r^a + g^a - s - m)q_0 + (r^a + g^a)(\int_0^{p^a} F_a(x)dx - \int_0^{p^a-q_0} F_a(x)dx) \\
&- b \cdot \int_0^{N-p^a} F_a(x)dx + b \cdot \int_0^{N-p^a+q_0} F_a(x)dx
\end{aligned}
\tag{Eq: F1}
$$

If $q < 0$,

$$
\begin{aligned}
\triangle\Pi^a(p^a,N,s,b) &= r^a \cdot \left[p^a - q_0 - \int_0^{p^a-q_0} F_a(x)dx\right] \\
&- g^a \cdot \left[\mu_a - (p^a - q_0) + \int_0^{p^a-q_0} F_a(x)dx\right] \\
&- s \cdot (-q_0) + b \cdot \left[\int_0^{p^a} F_a(x)dx + \int_0^{p^a+q_0} F_a(x)dx\right] \\
&- r^a \cdot \left[p^a - \int_0^{p^a} F_a(x)dx\right] + g^a \cdot \left[\mu_a - p^a + \int_0^{p^a} F_a(x)dx\right] \\
&= -(r^a + g^a + s)q_0 + (r^a + g^a)(\int_0^{p^a} F_a(x)dx - \int_0^{p^a-q_0} F_a(x)dx) \\
&+ b \cdot \left[\int_0^{p^a} F_a(x)dx + \int_0^{p^a+q_0} F_a(x)dx\right]
\end{aligned}
$$

Similarly, the profit difference of Terminal B can be calculated as:

$$
\begin{aligned}
\triangle\Pi^b(p^a, N, s, b) = \quad & \Pi^b(q_0, p^a, N, s, b) - \Pi^b(0, p^a, N, s, b) \\
& = r^b \cdot \mathbb{E}min\{N - p^a + q_0, d^b\} - g^b \cdot \mathbb{E}(d^b - N + p^a - q_0)^+ \\
& - s \cdot q_0^+ + b \cdot \mathbb{E}min\{(N - p^a + q - d^b)^+, q_0^+\} + s \cdot (-q_0)^+ \\
& - b \cdot \mathbb{E}min\{(p^a - q_0 - d^a), (-q_0)^+\} - m \cdot (-q_0)^+ \\
& - r^b \cdot \mathbb{E}min\{N - p^a, d^b\} + g^b \cdot \mathbb{E}(d^b - N + p^a)^+
\end{aligned}
$$

If $q_0 > 0$,

$$
\begin{aligned}
\triangle\Pi^b(p^a, N, s, b) = & \, r^b \cdot \left[N - p^a + q_0 - \int_0^{N-p^a+q_0} F_b(x)dx\right] \\
& - g^b \cdot \left[\mu_b - (N - p^a + q_0) + \int_0^{N-p^a+q_0} F_b(x)dx\right] \\
& - s \cdot q_0^+ + b \cdot \left[\int_0^{N-p^a} F_b(x)dx - \int_0^{N-p^a+q_0} F_b(x)dx\right] \\
& - r^b \cdot \left[N - p^a - \int_0^{N-p^a} F_b(x)dx\right] \\
& + g^b \cdot \left[\mu_b - (N - p^a) + \int_0^{N-p^a} F_b(x)dx\right] \\
& = (r^b + g^b - s)q_0 - (r^b + g^b)\left(\int_0^{N-p^a+q_0} F_b(x)dx - \int_0^{N-p^a} F_b(x)dx\right) \\
& + b \cdot \left[\int_0^{N-p^a} F_b(x)dx - \int_0^{N-p^a+q_0} F_b(x)dx\right]
\end{aligned}
$$

If $q_0 < 0$,

$$\begin{aligned}
\triangle\Pi^b(p^a,N,s,b) &= r^b\cdot\left[N-p^a+q_0-\int_0^{N-p^a+q_0}F_b(x)dx\right]\\
&- g^b\cdot\left[\mu_b-(N-p^a+q_0)+\int_0^{N-p^a+q_0}F_b(x)dx\right]\\
&- s\cdot(-q_0)-b\cdot\left[\int_0^{p^a}F_a(x)dx+\int_0^{p^a+q_0}F_a(x)dx\right]\\
&- m\cdot(-q_0)^+-r^b\cdot\left[N-p^a-\int_0^{N-p^a}F_b(x)dx\right]\\
&+ g^b\cdot\left[\mu_b-(N-p^a)+\int_0^{N-p^a}F_b(x)dx\right]\\
&= (r^b+g^b+s+m)q_0-(r^b+g^b)(\int_0^{N-p^a+q_0}F_b(x)dx-\int_0^{N-p^a}F_b(x)dx)\\
&- b\cdot\left[\int_0^{p^a}F_a(x)dx+\int_0^{p^a+q_0}F_a(x)dx\right]
\end{aligned}$$

The profit difference of the system under decentralised decision making in the two cases with the exchange amounts, q_0 and 0 is:

$$\triangle\Pi(p^a,N) = \quad \Pi(q_0,p^a,N)-\Pi(0,p^a,N).$$

From previous discussion, we know that $\triangle\Pi(p^a,N)=\triangle\Pi^a(p^a,N,s,b)+\triangle\Pi^b(p^a,N,s,b)$. We define the marginal profit as the first order derivative of profit increment with respect to q.

The marginal profit of Terminal A is :

$$\frac{\partial\triangle\Pi^a(q,p^a,N,s,b)}{\partial q}=\begin{cases} -(r^a+g^a)\cdot\int_{p^a-q}^{\infty}f_a(x)dx+s-b\cdot\int_0^{N-p^a+q}f_b(x)dx-m, & q>0\\[2ex] -(r^a+g^a)\cdot\int_{p^a-q}^{\infty}f_a(x)dx-s-b\cdot\int_0^{p^a-q}f_a(x)dx, & q<0\end{cases}$$

The marginal profit of Terminal B is :

$$\frac{\partial\triangle\Pi^b(q,p^a,N,s,b)}{\partial q}=\begin{cases} (r^b+g^b)\cdot\int_{N-p^a+q}^{\infty}f_b(x)dx-s\\ +b\cdot\int_0^{N-p^a+q}f_b(x)dx, \quad q>0\\[2ex] (r^b+g^b)\cdot\int_{N-p^a+q}^{\infty}f_b(x)dx+s\\ +b\cdot\int_0^{p^a-q}f_a(x)dx+m, \quad q<0\end{cases}$$

In the following, five different cases will be discussed to identify the condition that the parameters in the buy-back contract need to satisfy to coordinate the system.

(1) $q_0 = p^a$

In this case, terminal A sells permit to terminal B. The exchange amount is the total number of permits terminal A bought from the government. The system profit increment is:

$$\begin{aligned}\triangle\Pi(p^a, N) &= \Pi(q_0, p^a, N) - \Pi(0, p^a, N)\\ &= \triangle\Pi^a(p^a, N, s, b) + \triangle\Pi^b(p^a, N, s, b)\\ &= -(r^a + g^a - r^b - g^b - m)q_0 + (r^a + g^a)(\int_0^{p^a} F_a(x)dx - \int_0^{p^a - q_0} F_a(x)dx)\\ &\quad - (r^b + g^b)(\int_0^{N-p^a+q_0} F_b(x)dx - \int_0^{N-p^a} F_b(x)dx)\end{aligned}$$

For each terminal, the motivation to transfer permit is that it can have positive marginal profit, that is :

$$\begin{cases} \frac{\partial\triangle\Pi^a(q_0,p^a,N,s,b)}{\partial q} \geqslant 0 \\ \frac{\partial\triangle\Pi^b(q_0,p^a,N,s,b)}{\partial q} \geqslant 0 \end{cases}$$

$$\begin{aligned}\Rightarrow (r^a + g^a) \cdot \int_{p^a - q}^{\infty} f_a(x)dx + m + b \cdot \int_0^{N-p^a+q} f_b(x)dx \leq \quad & s\\ \leq \quad (r^b + g^b) \cdot \int_{N-p^a+q}^{\infty} f_b(x)dx + b \cdot \int_0^{N-p^a+q} f_b(x)dx &\end{aligned}$$

From Eq: F1, it is clear that for any given b, the profit of terminal A is increasing in s. When $s = (r^b + g^b) \cdot \int_{N-p^a+q}^{\infty} f_b(x)dx + b \cdot \int_0^{N-p^a+q} f_b(x)dx$, terminal A can achieve its highest profit. By plugging $s = (r^b + g^b) \cdot \int_{N-p^a+q}^{\infty} f_b(x)dx + b \cdot \int_0^{N-p^a+q} f_b(x)dx$, into the following equation,

$$\begin{aligned}\triangle\Pi^a(p^a, N, s, b) = -(r^a + g^a - s - m)q_0 + (r^a + g^a)(\int_0^{p^a} F_a(x)dx - \int_0^{p^a-q_0} F_a(x)dx)\\ - b \cdot \int_0^{N-p^a} F_a(x)dx + b \cdot \int_0^{N-p^a+q_0} F_a(x)dx\end{aligned}$$

We can have,

$$\begin{aligned}\triangle\Pi^a(p^a,N,s,b) = &-(r^a+g^a-m)q_0-\left[(r^b+g^b)\cdot\int_{N-p^a+q}^{\infty}f_b(x)dx+b\cdot\int_0^{N-p^a+q}f_b(x)dx)\right]q_0\\ &+(r^a+g^a)(\int_0^{p^a}F_a(x)dx-\int_0^{p^a-q_0}F_a(x)dx)\\ &-b\cdot\int_0^{N-p^a}F_a(x)dx+b\cdot\int_0^{N-p^a+q_0}F_a(x)dx\end{aligned}$$

As:

$$q_0\int_0^{N-p^a+q_0}f_b(x)dx+\int_0^{N-p^a+q_0}F_b(x)dx-\int_0^{N-p^a}F_b(x)dx>0$$

The profit difference is increasing in the buy back price b. To ensure the concavity of the profit function of the two companies, the following condition need to be met: $0<b\le min\{(r^a+g^a),(r^b+g^b)\}$.

If $(r^a+g^a)>(r^b+g^b)$, then $b^*=r^b+g^b$ and $\triangle\Pi^a(p^a,N,s,b)$ is maximised. By plugging $b^*=r^b+g^b$ into $s=(r^b+g^b)\cdot\int_{N-p^a+q}^{\infty}f_b(x)dx+b\cdot\int_0^{N-p^a+q}f_b(x)dx$, we can get $s=r^b+g^b$.

Similarly, if $(r^a+g^a)<(r^b+g^b)$, then $b=r^a+g^a$, $s=r^b+g^b-[r^b+g^b-(r^a+g^a)]\cdot\int_0^{N-p^a+q}f_b(x)dx$, $\triangle\Pi^a(p^a,N,s,b)$ achieve its maximum value.

The lower bound of $\triangle\Pi^a(p^a,N,s,b)$ is achieved when $b=0$ then $s=(r^b+g^b)\cdot\int_{N-p^a+q}^{\infty}f_b(x)dx$.

(2) $q^0=0$

In this case, no permit exchange is the optimal solution for the terminals. The entire system has no profit increment and each terminal only keeps its own profit. In order for $q^0=0$, the following conditions need to be satisfied.

$$\begin{cases}\frac{\partial\triangle\Pi^a_+(q_0,p^a,N,s,b)}{\partial q}\le 0\\ \frac{\partial\triangle\Pi^b_+(q_0,p^a,N,s,b)}{\partial q}\le 0\\ \frac{\partial\triangle\Pi^a_-(q_0,p^a,N,s,b)}{\partial q}\geqslant 0\\ \frac{\partial\triangle\Pi^b_-(q_0,p^a,N,s,b)}{\partial q}\geqslant 0\end{cases}$$

By plugging the first order of derivatives of profit increment, we can have,

$$
\begin{aligned}
(r^b+g^b)\cdot\int_{N-p^a}^{\infty} f_b(x)dx + b\cdot\int_0^{N-p^a} f_b(x)dx \leq \quad & s \\
\leq \quad (r^a+g^a)\cdot\int_{p^a}^{\infty} f_a(x)dx + m + b\cdot\int_0^{N-p^a} f_b(x)dx, & \\
(r^a+g^a)\cdot\int_{p^a}^{\infty} f_a(x)dx + b\cdot\int_0^{p^a} f_a(x)dx \leq \quad & s \\
\leq \quad (r^b+g^b)\cdot\int_{N-p^a}^{\infty} f_b(x)dx + m + b\cdot\int_0^{p^a} f_a(x)dx, &
\end{aligned}
$$

(3) $q^0 = q^*$

In this case, terminal A provides permits to terminal B. q^* is the optimal exchange amount under perfect collaboration for the case $q \in (0, +\infty)$. To ensure the optimal exchange amount to be q^* under decentralised decision making, the derivative of the increment of system profit with regard to q should be 0. Also, it should be profitable to exchange permit for each terminal. Consequently, the derivative of profit increment of each terminal with regard to q should also be 0. Thus, we have,

$$
\begin{cases}
\frac{\partial \triangle \Pi^a(q_0,p^a,N,s,b)}{\partial q} = 0 \\
\frac{\partial \triangle \Pi^b(q_0,p^a,N,s,b)}{\partial q} = 0
\end{cases}
$$

By expanding the Left-Hand-Side of the equations, we can have

$$
\begin{aligned}
(r^a+g^a)\cdot\int_{p^a-q*}^{\infty} f_a(x)dx + m + b\cdot\int_0^{N-p^a+q*} f_b(x)dx = \quad & s \\
= \quad (r^b+g^b)\cdot\int_{N-p^a+q*}^{\infty} f_b(x)dx + b\cdot\int_0^{N-p^a+q*} f_b(x)dx &
\end{aligned}
$$

By substituting s into the profit increment function of terminal A, we can get

$$
\begin{aligned}
\triangle\Pi^a(q^*,p^a,N,s,b) &= \Pi^a(q^*,p^a,N,s,b) - \Pi^a(0,p^a,N,s,b) \\
&= -(r^a+g^a-s-m)q^* + (r^a+g^a)(\int_0^{p^a} F_a(x)dx - \int_0^{p^a-q^*} F_a(x)dx) \\
&\quad - b\cdot\int_0^{N-p^a} F_a(x)dx + b\cdot\int_0^{N-p^a+q_*} F_a(x)dx
\end{aligned}
$$

When $b = r^b + g^b$ and $s = r^b + g^b$, the Terminal A achieve its maximum profit and when $b = 0$,then $s = (r^b + g^b) \cdot \int_{N-p^a+q*}^{\infty} f_b(x)dx$, Terminal A obtains its minimum profit.

(4) $q^0 = q^{**}$

In case 4, terminal B provides permits to terminal A. q^{**} is the optimal exchange amount under perfect collaboration for the case $q \in (-\infty, 0)$. Similar to case 3, the following condition needs to be met,

$$\begin{cases} \frac{\partial \triangle \Pi^a(q_0,p^a,N,s,b)}{\partial q} = 0 \\ \frac{\partial \triangle \Pi^b(q_0,p^a,N,s,b)}{\partial q} = 0 \end{cases}$$

$$\Rightarrow \quad -(r^a + g^a) \cdot \int_{p^a-q^{**}}^{\infty} f_a(x)dx - b \cdot \int_0^{p^a-q^{**}} f_a(x)dx = s$$

$$= -(r^b + g^b) \cdot \int_{N-p^a+q^{**}}^{\infty} f_b(x)dx - b \cdot \int_0^{p^a-q^{**}} f_a(x)dx + m,$$

$$\begin{aligned} \triangle \Pi^a(q^{**}, p^a, N, s, b) &= \Pi^a(q^{**}, p^a, N, s, b) - \Pi^a(0, p^a, N, s, b) \\ &= -(r^a + g^a - s - m)q^{**} + (r^a + g^a)(\int_0^{p^a} F_a(x)dx - \int_0^{p^a-q^{**}} F_a(x)dx) \\ &- b \cdot \int_0^{N-p^a} F_a(x)dx + b \cdot \int_0^{N-p^a+q^{**}} F_a(x)dx \end{aligned}$$

When $b = 0$ and $s = -(r^b + g^b) \cdot \int_{N-p^a+q^{**}}^{\infty} f_b(x)dx + m$, the Terminal A achieve its maximum profit and when $b = r^a+g^a$,then $s = -(r^a+g^a)$, Terminal A obtains its minimum profit.

(5) $q^0 = -(N - p^a)$

In case 5, if terminal B provides permits to terminal A and the exchange amount is the total number of permits terminal B purchased from the government:

$$\begin{cases} \frac{\partial \triangle \Pi^a(q_0,p^a,N,s,b)}{\partial q} \leq 0 \\ \frac{\partial \triangle \Pi^b(q_0,p^a,N,s,b)}{\partial q} \leq 0 \end{cases}$$

$$\Rightarrow \quad (r^b + g^b) \cdot \int_0^{\infty} f_b(x)dx + b \cdot \int_0^N f_a(x)dx + m \quad \leq s \leq \quad (r^a + g^a) \cdot \int_N^{\infty} f_a(x)dx + b \cdot \int_0^N f_a(x)dx$$

The terminal A's profit is increased by :

$$
\begin{aligned}
\triangle\Pi^a(q^0,p^a,N,s,b) &= \Pi^a(q^0,p^a,N,s,b) - \Pi^a(0,p^a,N,s,b)\\
&= -(r^a+g^a-s-m)q^0 + (r^a+g^a)(\int_0^{p^a} F_a(x)dx - \int_0^{p^a-q^0} F_a(x)dx)\\
&- b\cdot\int_0^{N-p^a} F_a(x)dx + b\cdot\int_0^{N-p^a+q^0} F_a(x)dx
\end{aligned}
$$

As $q^0 = -(N-p^a) < 0$, for any given b, the profit difference of terminal A is reducing in s. When s is set to be its minimum value $s = (r^b+g^b)\cdot\int_0^\infty f_b(x)dx + b\cdot\int_0^N f_a(x)dx + m$,the terminal A can achieve its maximum profit.

$$
\begin{aligned}
\triangle\Pi^a(q^0,p^a,N,s,b) &= \Pi^a(q^0,p^a,N,s,b) - \Pi^a(0,p^a,N,s,b)\\
&= (r^a+g^a-s-m)(N-p^a) + (r^a+g^a)(\int_0^{p^a} F_a(x)dx - \int_0^{N} F_a(x)dx)\\
&- b\cdot\int_0^{N-p^a} F_a(x)dx
\end{aligned}
$$

It is decreasing in b. When $b=0$, $\triangle\Pi^a(q_0,p^a,N,s,b)$ obtain its maximum value:

$$
\triangle\Pi^a(q^0,p^a,N,s,b) = (r^a+g^a-s-m)(N-p^a) + (r^a+g^a)(\int_0^{p^a} F_a(x)dx - \int_0^{N} F_a(x)dx)
$$

Terminal A obtains the minimum profit increment when $b = r^a+g^a$,$s = r^a+g^a$.

To summarise, the system is coordinated when the constraints of the whole sale price and buy back price can satisfy the following certain constrains,

$$
\begin{cases}
(1) when \quad q^0 = p^a \\
\quad (r^a + g^a) \cdot \int_{p^a - q}^{\infty} f_a(x)dx + m + b \cdot \int_0^{N-p^a+q} f_b(x)dx \leq \quad s \\
\leq \quad (r^b + g^b) \cdot \int_{N-p^a+q}^{\infty} f_b(x)dx + b \cdot \int_0^{N-p^a+q} f_b(x)dx, \\
(2) when \quad q^0 = 0 \\
(r^b + g^b) \cdot \int_{N-p^a}^{\infty} f_b(x)dx + b \cdot \int_0^{N-p^a} f_b(x)dx \leq \quad s \\
\leq \quad (r^a + g^a) \cdot \int_{p^a}^{\infty} f_a(x)dx + m + b \cdot \int_0^{N-p^a} f_b(x)dx, \\
(r^a + g^a) \cdot \int_{p^a}^{\infty} f_a(x)dx + b \cdot \int_0^{p^a} f_a(x)dx \leq \quad s \\
\leq \quad (r^b + g^b) \cdot \int_{N-p^a}^{\infty} f_b(x)dx + m + b \cdot \int_0^{p^a} f_a(x)dx, \\
(3) when \quad q^0 = q^* \\
(r^a + g^a) \cdot \int_{p^a - q*}^{\infty} f_a(x)dx + m + b \cdot \int_0^{N-p^a+q*} f_b(x)dx = \quad s \\
= \quad (r^b + g^b) \cdot \int_{N-p^a+q*}^{\infty} f_b(x)dx + b \cdot \int_0^{N-p^a+q*} f_b(x)dx \\
(4) when \quad q^0 = q^{**} \\
-(r^a + g^a) \cdot \int_{p^a - q^{**}}^{\infty} f_a(x)dx - b \cdot \int_0^{p^a - q^{**}} f_a(x)dx = s \\
= -(r^b + g^b) \cdot \int_{N-p^a+q^{**}}^{\infty} f_b(x)dx - b \cdot \int_0^{p^a - q^{**}} f_a(x)dx + m, \\
(5) when \quad q^0 = -(N - p^a) \\
(r^b + g^b) \cdot \int_0^{\infty} f_b(x)dx + b \cdot \int_0^N f_a(x)dx + m \quad \leq s \leq \quad (r^a + g^a) \cdot \int_N^{\infty} f_a(x)dx + b \cdot \int_0^N f_a(x)dx
\end{cases}
$$

The centralised decision making mode depicts an ideal cooperated situation for multiple terminals at port. In the ideal scenario, the permits exchanged aim to maximise the total profits of all terminals. However, in the real world, the terminals are operated independently, and each terminal makes decisions on permit exchanging only considering its own profit. Therefore, the optimal permit exchange amount from the perspective of an individual company is very likely to be different from the optimal exchange permit number of the entire system. To enable the system to be coordinated and achieve the same profits as that under the centralised mode, a buyback contract is required. The above five different cases define the conditions involving the wholesale price and the buyback price to coordinate the system. Once a buyback contract meets the conditions, the profit obtained under the decentralised decision making mode can be the same as that under the ideal collaboration - the centralised decision making.

5 Numerical Experiment

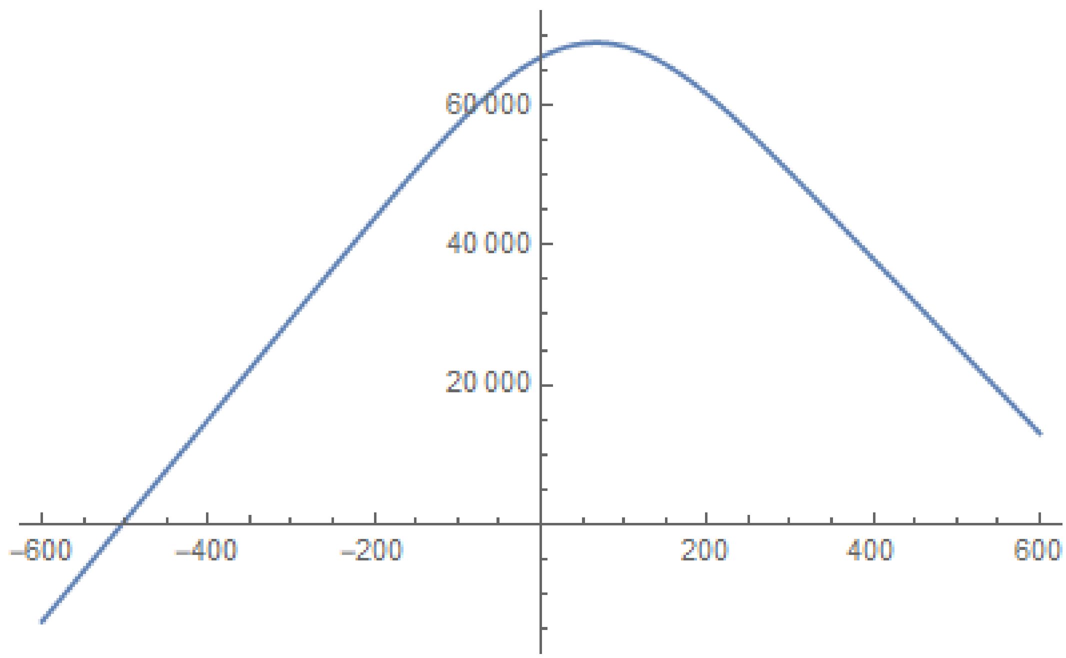
In section 4, the coordination of the system is achieved by applying the designed buyback contract mechanism. In this section, numerical example will be conducted.

The parameters are set as follows:

$p^a = 600$, $c = 20$, $N = 1000$, $r^a = 80$, $r^b = 120$, $g^a = 40$, $g^b = 30$
$X1 \sim Normal(600, 100)$, $X2 \sim Normal(500, 100)$, $m = 5$.

We will determine a set of contract parameters including wholesale price s, buy-back price b, and permit exchange number q, to coordinate the entire system. In other words, by applying a contract with the optimal parameters, the decentralised system can achieve the maximised profit that is the same as or very close to the maximum system profit under centralised mode(ideal case). The numerical example is conducted using Mathematica.

We first analyse the system when it is operated under a centralised decision making mode. The relationship between the entire system profit and the number of transferred permit can be plotted using Mathematica and shown in the following figure:



The diagram is in line with $Proposition 1$. The system profit is strictly concave in q. Therefore, there exists a q^* $(0 < q^* < p^a)$which can lead to the maximum system profit. When the permit exchange number $q = 83$, the system profit reaches its maximum value, 69039.7.

When the two terminals operate independently, each terminal aims to maximise its own profit respectively. A buy-back contract enables the terminals to exchange permits and buy-back the unused permits at an agreed price to coordinate the system.

By setting the parameters for the contract appropriately and making the number of exchanged permits the same as that under the centralised decision making mode, it is possible that the total profits of the two terminals independently operated can be the same as that under centralised system.

In this example, under the decentralised system, when the wholesale price $s = 152.51$ and the buy-back price $b = 120$, the permit exchange number $q = 83$, the maximum profits of terminal A and B are 32079.5 and 36832.4, respectively. The total profits under this condition is 68911.9. There is only a small difference of 0.18% between the maximum system profit under the centralised mode and that under decentralised decision making due to the rounding-up of permit exchange number. Therefore, the numerical case indicates that the system can be coordinated under the buy-back contract with the given set of parameters.

6 Conclusion

As an attempt to improve Truck Appointment System, the research designed a mechanism for the exchange of Tradable Truck Permits. We have considered two different collaboration modes: perfect collaboration and collaboration via contacts. We first formulated the case of perfect collaboration where all the terminals are practically deemed as a single company, and obtained the maximised profits and the optimal amount of permits to be exchanged. We then formulated the case of collaboration via contracts where each terminal makes decision independently on truck booking without the knowledge of the other terminal's truck appointments. We proved that a buy-back contract can coordinate the decision makings of terminals in the sense that the total profits generated under buy-back contract is the same as that of perfect collaboration. This has been further validated by the provided numerical example.

TAS is a widely deployed IT infrastructure to reduce the emission and congestion, which are two serious problems faced by many ports and local governments all over the world. However, lack of coordination of TAS is one of the major issues that jeopardise their efficiency. In recognition of the issue, our research has presented the concept of Tradable Truck Permit as well as a buy-back contract that has been proved to be the optimal mechanism to coordinate the decision making of terminals associated with the same port. It can be envisaged that our research will be useful to enhance the performance of TAS.

Our research is only a start point to promote the collaboration between TASs. There are many further research oppotunities in the field. For example, further research may focus on how government should issue truck permits. In our study, we consider the number of permits issued by government is given, and has not considered how government need to make the decision. Also, further study may consider how the permits exchange will affect road traffic.

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Figure(s)

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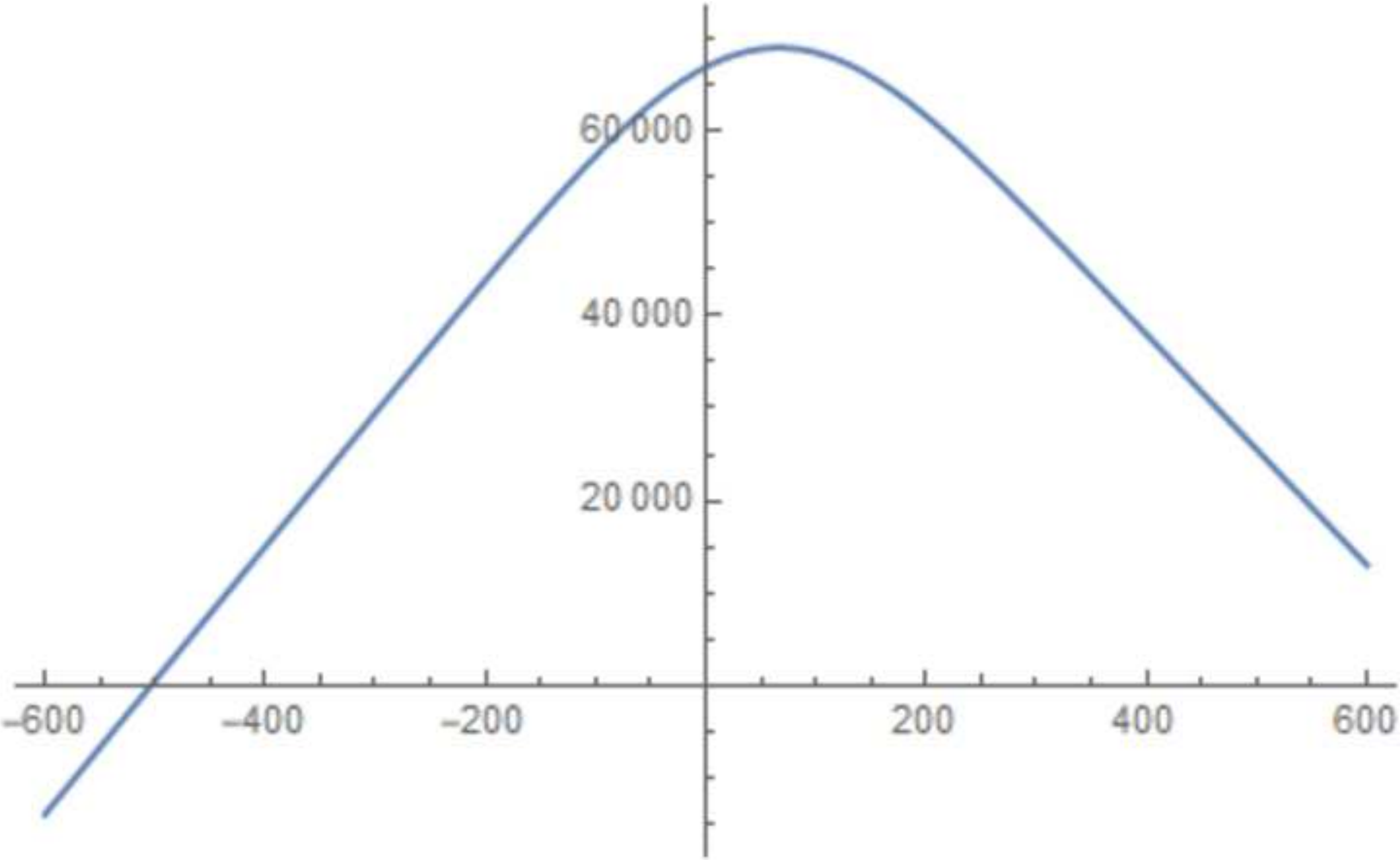

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