Chapter Three

Compliance decision in the presence of market power and banking

3.1. Introduction

In recent times the emissions permit market is a common mechanism to address the problem of global warming. However, the efficiency of emissions permit market is lost in the presence of market power (Hahn, 1984) and cheating among firms (Malik, 1990). The coexistence of twin imperfections (in market structure and in regulation) reinforces the critical role of the initial distribution of permits among firms (Egteren and Weber, 1996). However, Malik (2002) found desirability of some cheating in the presence of market power through an increase in the elasticity of permit demand. We want to see the effect of both the distortions (market and regulatory) in the two period set up, because multi-period models are more common in emissions trading market. We have recently studied the efficiency and effectiveness of the permit trading in the in a finite period model with market power and cheating (Sawhney and Mitra, 2011).

In the literature of enforcement mechanism of emissions permit market, the concept of restoration rate\(^1\) has gained importance to guarantee compliance in a perfect competitive set up (Hovi and Areklett, 2004; Restiani and Betz, 2010). However, there is a complex interaction between the restoration rate (increasing compliance decision) and market power (affecting permit price) (Godal and Klassen, 2006). Up to now there is no theoretical model studying this interaction as per our knowledge. Thus, this thesis formulates a theoretical model of profit maximising firms to see whether the presence of a restoration rate alters efficiency and effectiveness of the permit trading market in the presence of two distortions (market and regulatory) in an inter-temporal permit trading market. In the process, the model extends the recent works of Sawhney and Mitra (2011) and Godal and Klaassen (2006).

A simple two-period model is sufficient to discuss the key ideas of the paper. We will be considering only banking because a number of inter-temporal trading mechanisms prohibit

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\(^1\) The restoration rate is the rate at which permit is subtracted in the next period for the amount of permit falling short in any period.
borrowing because there is no guarantee that borrowed emissions will be abated in the future\(^2\).

### 3.2. Model set up without restoration rate

We consider a tradable permit market in which \( n \) firms participate. Among those one firm has the market power (either monopoly or monopsony) to manipulate the permit price. The dominant firm is represented by the first firm \( i = 1 \), and the competitive fringe firms by remaining firms \( i = 2, ..., n \). Both types of firms can be either compliant or noncompliant. All firms are assumed to be risk neutral.

The regulator decides upon a fixed stock of permits \( \bar{L} = \bar{L}_1 + \bar{L}_2 \) for the two periods, on the basis of an environmental objective. It is expected that \( \bar{L}_2 < \bar{L}_1 \), which is one of the reasons for the economists to support banking facility and to oppose the borrowing flexibility to the firms. The regulator distributes this predetermined stock of permits among the firms, and the initial endowment is denoted as \( l_{it}^0 \) for \( i^{th} \) firm in the time \( t \). However, firms are required to hold permits \( l_{it} \) to cover their emissions \( e_{it} \). Thus, the former (permit holding) can be thought as declared emission whereas the latter is actual emission.

With regulatory enforcement being imperfect, there is scope for cheating among firms. A firm’s actual emission may well exceed its declared emission in any period and we denote this as violation in that period. Thus \( v_{it} = Max \left( e_{it} - l_{it}, 0 \right) \), i.e. by definition \( v_{it} \geq 0 \). Since the firms are rational, declared emission cannot be greater than actual emission, but in any case if it is so, then by definition violation is zero. While the firms know about their actual emission, regulator knows only about the declared emission (based on their permit holding) and would only come to know about the actual emission when it audits the firm. The probability of firm \( i \) being audited is denoted by \( \beta_{it} \left( v_{it} \right) \), which is considered to be an increasing function of violation in that period with \( \beta_{it} \geq 0, \beta_{it}'' > 0 \) for \( v_{it} \geq 0 \), and with

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\(^2\) For example, a change in the ownership of a firm may make it difficult to ensure that borrowed emissions will be compensated by greater emission reductions. Furthermore, a country may change its policy with regard to participation in international agreements: if a country withdraws, there will be no obligation to abate the amount of emissions that it borrowed in previous periods. These concerns about borrowing are reflected in the US emissions trading system for sulfur dioxide permits, which allows only banking (EPA 2003), and California’s Low-Emission Vehicle Program, which also allows manufacturers of passenger cars only to bank, not to borrow, hydrocarbon emissions permits (California Air Resource Board 2003). Likewise, as mentioned, at the international level, the Kyoto Protocol allows banking of emissions permits between periods, but not borrowing (Hagem and Westkog, 2009).
If violation is detected, a fine is attached whose magnitude depends upon the extent of the violation, \( F_{it}(v_{it}) \), which is also an increasing function of violation in that period with \( F'_{it} > 0 \), \( F''_{it} > 0 \) for \( v_{it} \geq 0 \), and with \( F_{it}(0) = 0 \).

Firm’s final decision of emission \( e_{it} \) depends on the profit maximisation from the production of its output. Following Egteren and Weber (1996), the firm’s optimal profit for a given level of emission is

\[
B_{it}(e_{it}) \equiv \max_{q_{it}} \left[ r_{it}q_{it} - C_{it}(q_{it}, e_{it}) \right]
\]

Where, \( r_{it} \) is the price of the firm’s output \( q_{it} \) and \( C_{it}(q_{it}, e_{it}) \) captures costs of production. It is further assumed that the benefit function \( B \) is strictly concave in emissions so that \( B'_i > 0 \) and \( B''_i < 0 \).

Assuming a unique permit price \( P_t \), a firm \( i \) engage in permit trade with other firms, buying \( y_{it} > 0 \) (or selling, in case \( y_{it} < 0 \)) amount of permits. Firms also engage in inter-temporal trade in permits. \( l^0_{i1} - l_{i1} + y_{i1} \) is the banked amount from period 1 to 2 and the permit holding in period 2 becomes \( l_{i2} = l^0_{i2} + (l^0_{i1} - l_{i1} + y_{i1}) + y_{i2} \). If the borrowing is prohibited in the period 1, then the non-borrowing condition is represented by \( l^0_{i1} - l_{i1} + y_{i1} \geq 0 \). Since banking does not make sense in the period 2, thus the condition becomes \( l^0_{i2} - l_{i2} + (l^0_{i1} - l_{i1} + y_{i1}) + y_{i2} = 0 \).

Since in this model, emission, permit trading and violations are the three decision variables, thus we write the two conditions in these three decision variables using the relation \( v_{it} = e_{it} - l_{it} \), as:

\[
l^0_{i1} - e_{i1} + v_{i1} + y_{i1} \geq 0 \tag{1}
\]
\[
l^0_{i2} - e_{i2} + v_{i2} + (l^0_{i1} - e_{i1} + v_{i1} + y_{i1}) + y_{i2} = 0 \tag{2}
\]

While the fringe firms take permit prices as given, the dominant firm determines the price \( P_t(y_{1t}) \) in the permit market while maximising its profit subject to non-borrowing constraints. \( P_t(y_{1t}) \) is such that \( y_{1t} + \sum_{t=2}^{n} y_{it} = 0 \) for \( t = 1,2 \), and \( P'_t(y_{1t}) < 0 \), and \( P''_t(y_{1t}) > 0 \).
3.2.1. Optimisation of the competitive fringe firms

A price-taking fringe firm chooses its emission level, permit trading and violations level to maximise its profit subject to non-borrowing constraints. A typical fringe firm’s choice problem is to

\[
\text{maximise } \sum_{i,t} [B_{i1}(e_{i1}) - P_1 y_{i1} - \beta_{i1}(v_{i1})F_{i1}(v_{i1}) + \delta(B_{i2}(e_{i2}) - P_2 y_{i2} - \beta_{i2}(v_{i2})F_{i2}(v_{i2})] \\
\]

Subject to (1) and (2), where \( \delta \) is the discounting factor. Thus the Lagrange function becomes

\[
L = [B_{i1}(e_{i1}) - P_1 y_{i1} - \beta_{i1}(v_{i1})F_{i1}(v_{i1}) + \delta(B_{i2}(e_{i2}) - P_2 y_{i2} - \beta_{i2}(v_{i2})F_{i2}(v_{i2})] \\
+ \lambda_1[l_{i1}^0 - e_{i1} + v_{i1} + y_{i1}] \\
+ \alpha_i[l_{i2}^0 - e_{i2} + v_{i2} + (l_{i1}^0 - e_{i1} + v_{i1} + y_{i1}) + y_{i2}] \\
\]

Where, \( \lambda_i \) and \( \alpha_i \) are the two Lagrange multipliers associated with the non-borrowing constraints in two periods. The Kuhn-Tucker conditions for the above problem are-

\[
\frac{\partial L}{\partial e_{i1}} = B_{i1}'(e_{i1}) - \lambda_i - \alpha_i = 0 \\
\frac{\partial L}{\partial e_{i2}} = \delta B_{i2}'(e_{i2}) - \alpha_i = 0 \\
\frac{\partial L}{\partial y_{i1}} = -P_1 + \lambda_i + \alpha_i = 0 \\
\frac{\partial L}{\partial y_{i2}} = -\delta P_2 + \alpha_i = 0 \\
\frac{\partial L}{\partial v_{i1}} = -\beta_{i1}'(v_{i1})F_{i1}(v_{i1}) - \beta_{i1}(v_{i1})F_{i1}'(v_{i1}) + \lambda_i + \alpha_i = 0 \\
\frac{\partial L}{\partial v_{i2}} = \delta[-\beta_{i2}'(v_{i2})F_{i2}(v_{i2}) - \beta_{i2}(v_{i2})F_{i2}'(v_{i2})] + \alpha_i = 0 \\
\frac{\partial L}{\partial \lambda} = l_{i1}^0 - e_{i1} + v_{i1} + y_{i1} \geq 0 \\
\frac{\partial L}{\partial \alpha} = l_{i2}^0 - e_{i2} + v_{i2} + (l_{i1}^0 - e_{i1} + v_{i1} + y_{i1}) + y_{i2} = 0 \\
\]
The first order conditions yield equilibrium conditions for individual periods as:

\[ B_{it}^i(e_{it}^*) = P_t = \beta_{it}'(v_{it}^*)F_{it}(v_{it}^*) + \beta_{it}(v_{it}^*)F_{it}'(v_{it}^*) = \lambda_i + \alpha_i \]  \hfill (J)

and

\[ B_{i2}^i(e_{i2}^*) = P_2 = \beta_{i2}'(v_{i2}^*)F_{i2}(v_{i2}^*) + \beta_{i2}(v_{i2}^*)F_{i2}'(v_{i2}^*) = \frac{\alpha_i}{\delta} \]  \hfill (K)

and two periods taken together as:

\[
B_{i1}^i(e_{i1}^*) - \delta B_{i2}^i(e_{i2}^*) = P_1 - \delta P_2 = \\
= [\beta_{i1}'(v_{i1}^*)F_{i1}(v_{i1}^*) + \beta_{i1}(v_{i1}^*)F_{i1}'(v_{i1}^*)] \\
- \delta[\beta_{i2}'(v_{i2}^*)F_{i2}(v_{i2}^*) + \beta_{i2}(v_{i2}^*)F_{i2}'(v_{i2}^*)] = \lambda_i \]  \hfill (L)

The above conditions give the equilibrium levels (denoted with *) of emission, permit purchase and violation levels.

3.2.2. Fringe firm’s permits demand

From (J) and (K) we can say that in any period fringe firm’s equilibrium condition condition is:

\[ B_{it}^i(e_{it}^*) = P_t = \beta_{it}'(v_{it}^*)F_{it}(v_{it}^*) + \beta_{it}(v_{it}^*)F_{it}'(v_{it}^*) \]

Differentiating the above equilibrium condition totally we get:

\[ B_{it}''(e_{it}^*)d_eit^* = dp_t = (\beta_{it}''F_{it} + 2\beta_{it}'F_{it}' + \beta_{it}F_{it}'')dv_{it}^* \]

It implies that the emissions fall with an increase in permit price but violations increase, for a fringe firm:

\[
\frac{de_{it}^*}{dp_t} = \frac{1}{B_{it}'(e_{it}^*)} < 0 \]

\[
\frac{dv_{it}^*}{dp_t} = \frac{1}{(\beta_{it}''F_{it} + 2\beta_{it}'F_{it}' + \beta_{it}F_{it}'')} > 0 \]

Since we have \( y_{it}^* = e_{it}^* - v_{it}^* - l_{it}^0 \), we derive the fringe firm’s permit demand as:
With an increase in permit price, here the fringe firm can choose to reduce emission and cheat more (both of which become cheaper options, ceteris paribus) until equilibrium is restored. Thus price sensitivity of permit demand is higher in this model with non-compliance compared to the price sensitivity in a model with no cheating (in the latter $\frac{dy_{it}^*}{dP_t} = \frac{1}{B_{it}''(e_{it}^*)} < 0$). It implies that the price elasticity of permit demand of the fringe firm, $\varepsilon_d = \frac{dy_{it}^*}{dP_t} \cdot \frac{P_t}{y_{it}^*}$ is greater here compared to a full-compliance model (similar to Malik, 2002).

### 3.2.3. Optimisation of the dominant firm

A typical dominant firm’s choice problem is to:

$$\text{maximise } e_{1t}, y_{1t}, v_{1t} \left[ B_{11}(e_{11}) - P_1(y_{11}) \cdot y_{11} - \beta_{11}(v_{11}) F_{11}(v_{11}) + \delta \{ B_{12}(e_{12}) - P_2(y_{12}) \cdot y_{12} - \beta_{12}(v_{12}) F_{12}(v_{12}) \} \right]$$

Subject to (1) and (2), where $\delta$ is the discounting factor. Thus the Lagrange function becomes

$$\mathcal{L} = \left[ B_{11}(e_{11}) - P_1(y_{11}) \cdot y_{11} - \beta_{11}(v_{11}) F_{11}(v_{11}) \\
+ \delta \{ B_{12}(e_{12}) - P_2(y_{12}) \cdot y_{12} - \beta_{12}(v_{12}) F_{12}(v_{12}) \} \\
+ \lambda_1 [ l_{11}^0 - e_{11} + v_{11} + y_{11} ] \\
+ \lambda_2 [ l_{12}^0 - e_{12} + v_{12} + (l_{11}^0 - e_{11} + v_{11} + y_{11}) + y_{12} ]$$

Where, $\lambda_1$ and $\alpha_1$ are the two Lagrange multipliers associated with the non-borrowing constraints in two periods. The Kuhn-Tucker conditions for the above problem are:

$$\frac{\partial \mathcal{L}}{\partial e_{11}} = B_{11}'(e_{11}) - \lambda_1 - \alpha_1 = 0 \quad (A')$$

$$\frac{\partial \mathcal{L}}{\partial e_{12}} = \delta B_{12}'(e_{12}) - \alpha_1 = 0 \quad (B')$$

$$\frac{\partial \mathcal{L}}{\partial y_{11}} = -P_1' y_{11} - P_1 + \lambda_1 + \alpha_1 = 0 \quad (C')$$

Chapter Three | 67
\[
\frac{\partial L}{\partial y_{12}} = \delta (-p'_{22} y_{12} - p_2) + \alpha_1 = 0 \tag{D'}
\]

\[
\frac{\partial L}{\partial v_{11}} = -\beta_{11}'(v_{11})F_{11}(v_{11}) - \beta_{11}(v_{11})F'_{11}(v_{11}) + \lambda_1 + \alpha_1 = 0 \tag{E'}
\]

\[
\frac{\partial L}{\partial v_{12}} = \delta [\beta_{12}'(v_{12})F_{12}(v_{12}) - \beta_{12}(v_{12})F'_{12}(v_{12})] + \alpha_1 = 0 \tag{F'}
\]

\[
\frac{\partial L}{\partial \lambda} = l_{11}^0 - e_{11} + v_{11} + y_{11} \geq 0 \tag{G'}
\]

\[
\frac{\partial L}{\partial \alpha} = l_{12}^0 - e_{12} + v_{12} + (l_{11}^0 - e_{11} + v_{11} + y_{11}) + y_{12} = 0 \tag{H'}
\]

\[
\lambda_1 \cdot \frac{\partial L}{\partial \lambda} = 0 \tag{I'}
\]

The first order conditions yield equilibrium conditions for individual periods as:

\[
B_{11}'(e_{11}^*) = p'_1 y_{11}^* + p_1 = \beta_{11}'(v_{11}^*)F_{11}(v_{11}^*) + \beta_{11}(v_{11}^*)F'_{11}(v_{11}^*) = \lambda_1 + \alpha_1 \tag{J'}
\]

and \(B_{12}'(e_{12}^*) = p'_2 y_{12}^* + p_2 = \beta_{12}'(v_{12}^*)F_{12}(v_{12}^*) + \beta_{12}(v_{12}^*)F'_{12}(v_{12}^*) = \frac{\alpha_1}{\delta} \tag{K'}\)

and two periods taken together as:

\[
B_{11}'(e_{11}^*) - \delta B_{12}'(e_{12}^*) = [p'_1 y_{11}^* + p_1] - \delta [p'_2 y_{12}^* + p_2] = [\beta_{11}'(v_{11}^*)F_{11}(v_{11}^*) + \beta_{11}(v_{11}^*)F'_{11}(v_{11}^*)] - \delta [\beta_{12}'(v_{12}^*)F_{12}(v_{12}^*) + \beta_{12}(v_{12}^*)F'_{12}(v_{12}^*)] = \lambda_1 \tag{L'}
\]

**Market equilibrium:** assuming an interior solution exists, from conditions \((J), (K) \) and \((J'), \tag{K'}\), the market equilibrium is characterised by:

\[
P_t = B_{1t}'(e_{1t}^*) - p'_t y_{1t}^* = B_{1t}'(e_{1t}^*) = [\beta_{1t}'(v_{1t}^*)F_{1t}(v_{1t}^*) + \beta_{1t}(v_{1t}^*)F'_{1t}(v_{1t}^*)] - p'_t y_{1t}^* = [\beta_{1t}'(v_{1t}^*)F_{1t}(v_{1t}^*) + \beta_{1t}(v_{1t}^*)F'_{1t}(v_{1t}^*)] \tag{4}
\]
3.2.4. Efficiency of the model: equimarginal principle between dominant and fringe firms

From the market equilibrium (4) we see that the equimarginal principle for efficiency of the permit market is ensured in this model only when the dominant firm does not engage in trade, i.e. when $y_{1t}^* = 0$ a la Hahn (1984). The degree of inefficiency, i.e. the difference in the marginal conditions of the dominant firm and a typical fringe firm is represented by $\frac{p_t'y_{1t}^*}{p_t}$:

$$B_t'(e_{1t}^*) = B_t'(e_{it}^*) \left(1 + \frac{p_t'y_{1t}^*}{p_t}\right)$$

and

$$[\beta_t'(v_{1t}^*)F_t'(v_{1t}^*) + \beta_{it}(v_{it}^*)F_t'(v_{it}^*)] = [\beta_t'(v_{it}^*)F_t'(v_{it}^*) + \beta_{it}(v_{it}^*)F_t'(v_{it}^*)]\left(1 + \frac{p_t'y_{1t}^*}{p_t}\right)$$

Now, $\frac{p_t'y_{1t}^*}{p_t}$ is the inverse of the price elasticity of demand for permits of dominant firm. This result is similar to that of Chevalier (2008), except that due to the presence of cheating in this set up we cannot equate the dominant firm’s permit trade to the emissions in the system without bringing in violations.

Although, efficiency is ensured when permit purchase of the dominant firm is zero in this model (both with or without restoration rate), however, due to the possibility of cheating, zero permit trade does not necessarily imply that initial allocation of permit to the dominant firm is equal to the optimal holding at any period of the two, i.e. $y_{1t}^* = e_{1t}^* - v_{1t}^* - l_0^t = 0$ can exist along with $v_{1t}^* = e_{1t}^* - l_0^t > 0$. In that situation, the equimarginal principle can ensure efficiency but the as long as violations are greater than zero the effectiveness of the cap-and-trade program is not guaranteed.

3.2.5. Effectiveness of the model: The compliance decision

The emission cap in the system is the total number of permits allocated across firms in the two period, i.e. $\tilde{L} = \tilde{L}_1 + \tilde{L}_2 = \sum_{i=1}^n \tilde{l}_{i1}^0 + \sum_{i=1}^n \tilde{l}_{i2}^0$. We interpret effectiveness of the cap-and-trade system as zero violations of firms in both the periods i.e. when $v_{1t}^*$ and $v_{it}^*$ are zero for $t = 1, 2$. The conditions for compliance implies that, in equilibrium the marginal expected penalty is greater or equal to the marginal cost of emission permit as well as marginal benefit.
from emitting for the firms, at zero violation level. Since $F_{it}(0) = 0$, for compliant fringe firms we get the condition as follows:

$$B_i'(e_{it}^*) = P_t \leq \beta_{it}(0)F_{it}(0) \quad \text{for } i = 2,3,\ldots, n \text{ and } t = 1,2$$

The sufficient condition for non-compliance:

$$\beta_{it}(0)F_{it}(0) < P_t = B_i'(e_{it}^*) \quad (5)$$

It is evident that as in Egtern and Weber (1996), the compliance decision of the fringe firm $i$ is independent of the initial allocation of permit $l_{it}^0$, in both $t = 1,2$.

However, the sufficient conditions for non-compliance for the dominant firm are:

$$\beta_{11}(0)F_{11}(0) < P_1 + P_1'\{e_{11}^* - l_{11}^0\} = B_{11}'(e_{11}^*) \quad \text{and} \quad \beta_{12}(0)F_{12}(0) < P_2 + P_2'\{e_{12}^* - l_{12}^0\} = B_{12}'(e_{12}^*) \quad (6)$$

Thus compliance decision of dominant firm depends on the initial allocations in contrast to condition of fringe firm.

### 3.2.6. Higher probability of detection for a net seller dominant firm

From the equilibrium conditions for compliance we have the sufficient condition for a fringe firm to cheat as $\beta_{it}(0)F_{it}(0) < P_t$ for $i = 2,3,\ldots, n$ and for the dominant firm to cheat as $\beta_{1t}(0)F_{1t}(0) < P_t + P_t'y_{1t}^*$ for $t = 1,2$. The sufficient condition for cheating for the dominant firm means that implications are different for the dominant firm when it is a net buyer versus a net seller of permits. In case the dominant firm is a net buyer of permits (i.e. $y_{1t}^* = e_{1t}^* - l_{1t}^0 > 0$), the term $P_t'y_{1t}^*$ is negative, thus the sufficient condition for non-compliance implies that $P_t \gg \beta_{1t}(0)F_{1t}(0)$. However, when the dominant firm is a net seller, $P_t'y_{1t}^*$ is positive, so it is possible to have either $P_t < \beta_{1t}(0)F_{1t}(0)$ or $P_t > \beta_{1t}(0)F_{1t}(0)$ as long as the total sum of the two terms ensure the inequality of $\beta_{1t}(0)F_{1t}(0) < P_t + P_t'y_{1t}^*$ to hold.

In the special case where the penalty functions of the fringe and the dominant firms are the same, the above asymmetry can give rise to a case where the following inequality holds:

$$P_t < \beta_{it}(0)F_{it}(0) = \beta_{1t}(0)F_{1t}(0) < P_t + P_t'y_{1t}^* \quad (7)$$
such that the fringe firms have zero violation, but the net seller dominant firm is cheating as long as the market-power effect $P_t' y_{it}^*$ is large enough to ensure the above. Thus it is more likely for the regulator to choose a higher probability of detection and associated penalty for the net seller dominant firm compared to fringe firms, in order to offset this market power effect.

3.2.7. Relationship between firms’ violations

It is interesting to track the relationship between the non-compliance behaviours of the two types of firms. From dominant firm’s optimality condition we have

$$P_t' y_{it}^* + P_t = [\beta_{1t}(v_{1t}^*)F_{1t}(v_{1t}^*) + \beta_{1t}(v_{1t}^*)F_{1t}'(v_{1t}^*)]$$

Differentiating totally:

$$(P_t' y_{it}^* + 2P_t')dy_{it}^* = (\beta_{1t}''F_{1t} + 2\beta_{1t}'F_{1t}' + \beta_{1t}F_{1t}''')dv_{it}^*$$

$$\frac{dy_{it}^*}{dv_{it}^*} = \frac{(\beta_{1t}''F_{1t} + 2\beta_{1t}'F_{1t}' + \beta_{1t}F_{1t}'')}{(P_t'' y_{it}^* + 2P_t')}$$

From the market equilibrium (4) we have the relationship between the marginal expected penalties of the two types of firms as:

$$[\beta_{1t}(v_{1t}^*)F_{1t}(v_{1t}^*) + \beta_{1t}(v_{1t}^*)F_{1t}'(v_{1t}^*)] - P_t'y_{it}^*$$

$$= [\beta_{it}'(v_{it}^*)F_{it}(v_{it}^*) + \beta_{it}(v_{it}^*)F_{it}'(v_{it}^*)]$$

Differentiating the above equation completely, we get

$$(\beta_{1t}''F_{1t} + 2\beta_{1t}'F_{1t}' + \beta_{1t}F_{1t}'')dv_{it}^* - (P_t'' \cdot y_{1t}^* + P_t')dy_{1t}^*$$

$$= (\beta_{it}''F_{it} + 2\beta_{it}'F_{it}' + \beta_{it}F_{it}'')dv_{it}^*$$

Rearranging the above equation and using the value of $\frac{dy_{it}^*}{dv_{it}^*}$ we get

$$\frac{dv_{it}^*}{dv_{it}^*} = \frac{(\beta_{1t}''F_{1t} + 2\beta_{1t}'F_{1t}' + \beta_{1t}F_{1t}'')}{(\beta_{it}''F_{it} + 2\beta_{it}'F_{it}' + \beta_{it}F_{it}'')}
\frac{(P_t'' y_{1t}^* + P_t')}{(P_t'' y_{1t}^* + 2P_t')}$$

After simple manipulation of the above equation we get:
\[
\frac{dv_{1t}^*}{dv_{1t}} = \frac{(\beta''_{1t}F_{1t} + 2\beta'_{1t}F'_{1t} + \beta_{1t}F''_{1t})}{(\beta''_{it}F_{it} + 2\beta'_{it}F'_{it} + \beta_{it}F''_{it})} \cdot \left[ \frac{P_t'}{(P''_{1t}y_{1t}^* + 2P_t')} \right]
\]

or more simply,

\[
\frac{dv_{1t}^*}{dv_{1t}} = \frac{S_{1t}}{S_{it}} \cdot \left[ \frac{P_t'}{(P''_{1t}y_{1t}^* + 2P_t')} \right] = \frac{S_{1t}}{S_{it}} \cdot \left[ \frac{1}{\eta_t + 2} \right]
\]

Where \( S \) denotes the change in marginal penalty for the firms, with \( S_{1t} = (\beta''_{1t}F_{1t} + 2\beta'_{1t}F'_{1t} + \beta_{1t}F''_{1t}) > 0 \) and \( S_{it} = (\beta''_{it}F_{it} + 2\beta'_{it}F'_{it} + \beta_{it}F''_{it}) > 0 \); and \( \eta_t = \frac{p''_{it}y_{it}^*}{p_t'} \)

characterises the curvature of the dominant firm’s permit demand (elasticity of slope of its permit demand) and change in price distortion element. Recalling that \( p_t'(y_{1t}) < 0 \) and \( p_t''(y_{1t}) > 0 \), such that \( \eta_t \) will be negative when dominant firm is a net buyer of permits, and will be positive when the dominant firm is a net seller.

This implies that the violation of the fringe firm would move together with violation of the dominant firm, i.e. \( \frac{dv_{1t}^*}{dv_{1t}} > 0 \) increasing the total violation in the system, when \( (\eta_t + 2) > 0 \). This will be true when the dominant firm is a net seller, and also true when the dominant firm is a net buyer as long as \( \eta_t > -2 \). On the other hand, the violations of the fringe and the dominant firm will offset each other in the model, i.e. \( \frac{dv_{1t}^*}{dv_{1t}} < 0 \) when \( \eta_t < -2 \). The latter can hold only in the case of the dominant firm being a net buyer of permits in the market, with a high elasticity of the slope of the permit demand. In the special case, where the dominant firm has a linear permit demand curve, we get \( \eta_t = 0 \) and \( \frac{dv_{1t}^*}{dv_{1t}} = \frac{S_{1t}}{2S_{it}} > 0 \), with the result that violation of the fringe and dominant firm reinforce each other.

3.2.8. Initial permit endowment of dominant firm and cheating

Over time we expect the regulator to reduce the allocation of permits (as the cap is reduced over time), i.e. \( \bar{L}_2 < \bar{L}_1 \) and \( \bar{L}_{12} < \bar{l}_{11} \). It is thus interesting to examine the effect of the change in initial permit endowment on the violation of the dominant firm. From dominant firm’s optimality condition we have

\[
P_t'y_{1t}^* + P_t = [\beta_{1t}'(v_{1t}^*)F_{1t}(v_{1t}^*) + \beta_{1t}(v_{1t}^*)F'_{1t}(v_{1t}^*)]
\]
Differentiating totally and arranging terms, we get:

$$dy_{1t}^* = \frac{S_{1t}}{(P'_t y_{1t}^* + 2P'_t)} dv_{1t}^*$$

Where $S_{1t} = (\beta''_{1t} F_{1t} + 2\beta'_{1t} F'_t + \beta_{1t} F''_{1t})$. Now, from dominant firm’s optimality condition we also have

$$B_{1t}(e_{1t}^*) = [\beta'_{1t}(v_{1t}^*)F_{1t}(v_{1t}^*) + \beta_{1t}(v_{1t}^*)F'_t(v_{1t}^*)]$$

Differentiating totally we get:

$$de_{1t}^* = \frac{S_{1t}}{B_{1t}} dv_{1t}^*$$

Differentiating totally the permit trade equation $y_{1t}^* = e_{1t}^* - v_{1t}^* - l_{1t}^0$ we get:

$$dy_{1t}^* = de_{1t}^* - dv_{1t}^* - dl_{1t}^0$$

Substituting the values of $dy_{1t}^*$ and $de_{1t}^*$ in the above equation, and arranging terms we get:

$$\frac{dv_{1t}^*}{dl_{1t}^0} = -S_{1t}^{-1} \left( \frac{1}{P''_t y_{1t}^* + 2P'_t} - \frac{1}{B''_{1t} + \frac{1}{S_{1t}}} \right)^{-1} \tag{9}$$

Where $S_{1t} = (\beta''_{1t} F_{1t} + 2\beta'_{1t} F'_t + \beta_{1t} F''_{1t}) > 0$, and $B''_{1t} < 0$. The terms within the brackets in the right hand side of the above equation are the inverse of change in the marginal cost of permits, inverse of change in profit due to emission and the inverse of the change in marginal penalty cost for the dominant firm. The violation of the dominant firm will decline as its initial permit allocation declines, as long combined effects from the three is negative, such that $\frac{dv_{1t}^*}{dl_{1t}^0} > 0$. The necessary and sufficient conditions are:

$$\frac{1}{P''_t y_{1t}^* + 2P'_t} < 0, \text{ and } \left| \frac{1}{P''_t y_{1t}^* + 2P'_t} \right| > -\frac{1}{B''_{1t}} + \frac{1}{S_{1t}}$$

Which implies:

$$\eta_t > -2, \text{ and } \left| \frac{1}{(\eta_t + 2)P'_t} \right| > -\frac{1}{B''_{1t}} + \frac{1}{S_{1t}} \tag{10}$$

Thus, when the change in marginal benefit due to emission and marginal expected penalty of the dominant firm are relatively high compared to the magnitude of change in price distortion...
element, $\frac{dv_{i1}^*}{dt_{i1}} > 0$ will hold and the dominant firm’s violation will move in the same direction with respect to its permit endowment.

### 3.3. Introducing restoration rate in the model

We define restoration rate quite similar to as Restiani and Betz (2010). However, we have the probability of being caught in our model. Thus, only if a firm is found non-compliant in period 1, then the regulator deducts $\rho$ (restoration rate) times the audited violation of the first period from the second period’s initial endowment. The intuition behind this restoration rate in the presence of violation is to reduce the ill effect of cheating on the overall cap (provided the cheating is being caught). In presence of a restoration rate, instead of (2) the banking-borrowing condition in the second period becomes:

$$l_{i2}^0 - \rho \beta_{i1}(v_{i1}) \cdot v_{i1} - e_{i2} + v_{i2} + (l_{i1}^0 - e_{i1} + v_{i1} + y_{i1}) + y_{i2} = 0$$  \hspace{1cm} (11)

### 3.3.1. Optimisation of the competitive fringe firms

In the presence of a restoration rate a typical fringe firm’s maximisation problem changes slightly from our earlier set up. Here the firm maximises the same profit function subject to (1) and (11) instead of (1) and (2). For comparison purpose if we keep the Lagrange multiplier attached with the second constraint to be same as $\alpha_i$, then all other things remaining same only (E) changes to be:

$$\frac{\partial L}{\partial v_{i1}} = -\beta'_{i1}(v_{i1})F_{i1}(v_{i1}) - \beta_{i1}(v_{i1})F'_{i1}(v_{i1}) + \lambda_i + \alpha_i[1 - \rho \beta'_{i1}(v_{i1}) \cdot v_{i1} - \rho \beta_{i1}(v_{i1})]$$

$$= 0$$ \hspace{1cm} (E)

Thus (K) being unchanged (J) and (L) change to the followings:

$$B'_{i1}(e_{i1}^*) = P_1 = \beta'_{i1}(v_{i1}^*)F_{i1}(v_{i1}^*) + \beta_{i1}(v_{i1}^*)F'_{i1}(v_{i1}^*) + \alpha_i\rho[\beta'_{i1}(v_{i1}) \cdot v_{i1} + \beta_{i1}(v_{i1})]$$

$$= \lambda_i + \alpha_i$$ \hspace{1cm} (J)

$$B'_{i1}(e_{i1}^*) - \delta B'_{i2}(e_{i2}^*) = P_1 - \delta P_2$$

$$= [\beta'_{i1}(v_{i1}^*)F_{i1}(v_{i1}^*) + \beta_{i1}(v_{i1}^*)F'_{i1}(v_{i1}^*)] + \alpha_i\rho[\beta'_{i1}(v_{i1}) \cdot v_{i1} + \beta_{i1}(v_{i1})]$$

$$- \delta[\beta'_{i2}(v_{i2}^*)F_{i2}(v_{i2}^*) + \beta_{i2}(v_{i2}^*)F'_{i2}(v_{i2}^*)] = \lambda_i$$ \hspace{1cm} (L)
3.3.2. Fringe firm’s permit demand

With a restoration rate the permit demand of the fringe firm is not same in both the periods. For period 2 the results will be same as earlier, for period 1 we differentiate totally the following part of \((f)\)

\[
B_{i1}'(e_{i1}^*) = P_1 = \beta_{i1}'(v_{i1}^*)F_{i1}(v_{i1}^*) + \beta_{i1}(v_{i1}^*)F_{i1}'(v_{i1}^*) + \alpha_i \rho[\beta_{i1}'(v_{i1}) \cdot v_{i1} + \beta_{i1}(v_{i1})]
\]

and get:

\[
B_{i1}''(e_{i1}^*)de_{i1}^* = dP_1 = [\beta_{i1}''F_{i1} + 2\beta_{i1}'F_{i1}' + \beta_{i1}F_{i1}'' + \alpha_i \rho(\beta_{i1}' \cdot v_{i1}^* + 2\beta_{i1}')]dv_{i1}^*
\]

Thus, while the change in permit demand is unchanged in period 2, for period 1 it is given by:

\[
\frac{dy_{i1}^*}{dP_1} = \frac{1}{B_{i1}''(e_{i1}^*)} - \frac{1}{(\beta_{i1}''F_{i1} + 2\beta_{i1}'F_{i1}' + \beta_{i1}F_{i1}'' + \alpha_i \rho(\beta_{i1}' \cdot v_{i1}^* + 2\beta_{i1}'))} < 0 \tag{12}
\]

And for period 2 the change in permit demand is:

\[
\frac{dy_{i2}^*}{dP_2} = \frac{1}{B_{i2}''(e_{i2}^*)} - \frac{1}{(\beta_{i2}''F_{i2} + 2\beta_{i2}'F_{i2}' + \beta_{i2}F_{i2}'' + \alpha_i \rho(\beta_{i2}' \cdot v_{i2}^* + 2\beta_{i2}'))} < 0 \tag{13}
\]

Since \(\alpha_i \rho(\beta_{i1}' \cdot v_{i1}^* + 2\beta_{i1}')\) is non-negative, thus comparing (12) and (13) we see that price sensitivity is less in the first period compared to the second period due to the presence of a restoration rate. In general, in a multi period (more than two periods) model, the price sensitivity as well as price elasticity of permit demand of the fringe firm is less in all the periods, except the terminal period.

3.3.3. Optimisation of the dominant firm

Following similar logic of restoration rate, in case of the dominant firm, \((E')\), \((f')\) and \((L')\) become the followings:

\[
\frac{\partial L}{\partial v_{i1}} = -\beta_{i1}'(v_{i1})F_{i1}(v_{i1}) - \beta_{i1}(v_{i1})F_{i1}'(v_{i1}) + \lambda_1 + \alpha_i [1 - \beta_{i1}'(v_{i1}) \cdot v_{i1} - \rho \beta_{i1}(v_{i1})] = 0 \tag{E'}
\]
\[ B'_{11}(e_{11}^*) = P'_1 y_{11}^* + p_1 \]
\[ = \beta'_{11}(v_{11}^*) F_{11}(v_{11}^*) + \beta_{11}(v_{11}^*) F'_{11}(v_{11}^*) + \alpha_1 \rho [\beta'_{11}(v_{11}^*) \cdot v_{11} + \beta_{11}(v_{11}^*)] \]
\[ = \lambda_1 + \alpha_1 \quad (L') \]

\[ B'_{11}(e_{11}^*) - \delta B'_{12}(e_{12}^*) = [P'_1 y_{11}^* + p_1] - \delta [P'_2 y_{12}^* + p_2] \]
\[ = [\beta'_{11}(v_{11}^*) F_{11}(v_{11}^*) + \beta_{11}(v_{11}^*) F'_{11}(v_{11}^*) + \alpha_1 \rho [\beta'_{11}(v_{11}^*) \cdot v_{11} + \beta_{11}(v_{11}^*)] \]
\[ = \lambda_1 \quad (L') \]

3.3.4. Efficiency of the model: equimarginal principle between dominant and fringe firms

With the new conditions of fringe and dominant firm, the market equilibrium is separate in the two periods. For period 1 it is:

\[ P_1 = B'_1(e_{11}^*) - P'_1 y_{11}^* = B'_1(e_{11}^*) \]
\[ = [\beta'_{11}(v_{11}^*) F_{11}(v_{11}^*) + \beta_{11}(v_{11}^*) F'_{11}(v_{11}^*) + \alpha_1 \rho [\beta'_{11}(v_{11}^*) \cdot v_{11} + \beta_{11}(v_{11}^*)] \]
\[ = \lambda_1 + \alpha_1 \quad (L') \]

and for period 2 it is:

\[ P_2 = B'_2(e_{12}^*) - P'_2 y_{12}^* = B'_2(e_{12}^*) \]
\[ = [\beta'_{12}(v_{12}^*) F_{12}(v_{12}^*) + \beta_{12}(v_{12}^*) F'_{12}(v_{12}^*)] - \]
\[ P'_2 y_{12}^* = [\beta'_{12}(v_{12}^*) F_{12}(v_{12}^*) + \beta_{12}(v_{12}^*) F'_{12}(v_{12}^*)] \]

Comparing (4), (14) and (15) we see that only the marginal expected penalty for both the fringe and dominant firm changes due to the introduction of the restoration rate keeping the efficiency condition (of zero trade of permits for the dominant firm ) to be unchanged.

However, with the restoration rate, the degree of inefficiency i.e. the difference in the marginal conditions of the dominant firm and a typical fringe firm (represented by \( \frac{P'_1 y_{11}^*}{p_1} \)) is different in both the period. In period 1 the degree of inefficiency is \( \frac{P'_1(e_{11}^* - l_{11}'^0)}{p_1} \), whereas in period 2 it is \( \frac{P'_2(e_{12}^* - l_{12}'^0 \cdot \rho \beta_{11}(v_{11}) \cdot v_{11})}{p_2} \) instead of \( \frac{P'_2(e_{12}^* - l_{12}'^0)}{p_2} \). With positive violation in the
first period, the degree of inefficiency is small in the second period compared to the first period.

### 3.3.5. Effectiveness of the model: The compliance decision

From the market equilibrium with restoration rate (14) and (15) we see that the sufficient condition for non-compliance is the same for the fringe firm in period 2, but changes in period 1 as:

\[ \beta_{i1}(0)F'_{i1}(0) + \alpha_i \rho \beta_{i1}(0) < P_1 = B'_{i1}(e_{i1}^+) \]  

(16)

Similarly, the sufficient condition for cheating for the dominant firm in the first period is:

\[ \beta_{11}(0)F'_{11}(0) + \alpha_1 \rho \beta_{11}(0) < P_1 + P'_1(e_{11}^+ - l_{11}^0) = B'_{11}(e_{11}^+) \]  

(17)

Since all the three elements of the new additive term is positive, therefore with the introduction of the restoration rate the marginal expected penalty of violation increases in the first period for the fringe firms as well as the dominant firm. Comparing (5), (6) and (16), (17) we see that the cheating of both types of firms reduce in the first period with an introduction of restoration rate, similar to Godar and Klassen (2006), Restiani and Betz (2010).

### 3.3.6. Higher probability of detection for a net seller dominant firm

With the presence of a restoration rate, the special situation can still exist, where the regulator decides to have a higher probability of detection or higher penalty for the dominant seller. Only the condition (7) is slightly different in the two periods as:

\[ P_1 < \beta_{i1}(0)F'_{i1}(0) + \alpha_i \rho \beta_{i1}(0) = \beta_{11}(0)F'_{11}(0) + \alpha_1 \rho \beta_{11}(0) < P_1 + P'_1 y_{i1}^+ \]  

(18)

and

\[ P_2 < \beta_{i2}(0)F'_{i2}(0) = \beta_{12}(0)F'_{12}(0) < P_2 + P'_2 y_{i2}^+ \]  

(19)
3.3.7. Relationship between firms’ violations

In the presence of restoration rate $S_{1t}$ and $S_{2t}$ are different in both the periods in (8) as $S_{11} = (\beta_{11}''F_{11} + 2\beta_{11}'F_{11} + \beta_{11}''F_{11}) + \alpha_i \rho (\beta_{11}'' \cdot v_{11} + 2\beta_{11}') > 0, \ S_{11} = (\beta_{11}''F_{11} + 2\beta_{11}'F_{11} + \beta_{11}''F_{11}) + \alpha_i \rho (\beta_{11}'' \cdot v_{11} + 2\beta_{11}') > 0$, $S_{12} = (\beta_{12}''F_{12} + 2\beta_{12}'F_{12} + \beta_{12}''F_{12}) > 0$ and $S_{12} = (\beta_{12}''F_{12} + 2\beta_{12}'F_{12} + \beta_{12}''F_{12}) > 0$. However, since all the terms are positive, the conditions for the relationship between violations of two types of firms remain the same as in without the restoration rate.

3.3.8. Initial permit endowment of dominant firm and cheating

In the presence of restoration rate $S_{1t}$ is different in both the periods as $S_{11} = (\beta_{11}''F_{11} + 2\beta_{11}'F_{11} + \beta_{11}''F_{11}) + \alpha_i \rho (\beta_{11}'' \cdot v_{11} + 2\beta_{11}') > 0$, and $S_{12} = (\beta_{12}''F_{12} + 2\beta_{12}'F_{12} + \beta_{12}''F_{12}) > 0$ in (9). Since $\alpha_i \rho (\beta_{11}'' \cdot v_{11} + 2\beta_{11}')$ is nonnegative, therefore we see that $S_{11} > S_{12}$. Thus, condition (9) becomes different in both the periods as:

$$\eta_1 > -2, \text{ and } \left| \frac{1}{(\eta_1 + 2)P_1} \right| > -\frac{1}{B_{11}''} + \frac{1}{S_{11}}$$

(20)

and

$$\eta_2 > -2, \text{ and } \left| \frac{1}{(\eta_2 + 2)P_2} \right| > -\frac{1}{B_{12}''} + \frac{1}{S_{12}}$$

(21)

In the special case where the change in marginal benefit due to emission and magnitudes of changes in price distortion elements are the same in both the periods, (20) and (21) can give rise to a case where the following inequality holds:

$$-\frac{1}{B_{11}''} + \frac{1}{S_{11}} < \left| \frac{1}{(\eta_1 + 2)P_1} \right| = \left| \frac{1}{(\eta_2 + 2)P_2} \right| < -\frac{1}{B_{12}''} + \frac{1}{S_{12}}$$

(22)

Which implies that in some situations dominant firm’s violation might decline with a reduction of initial endowment in the first period but increase with that in the second period.
3.4. Conclusions

The current inter-temporal profit maximising model of firms extends the results of the established literature, and shows that the initial permit allocation to the dominant firm continues to play a significant role in both efficiency and effectiveness of the cap-and-trade system. The presence of cheating, however, makes the permit demand of firms more price-elastic compared to a model with no cheating. Moreover, the second order price sensitivity of the permit demand of the dominant firm plays a critical role in the compliance behaviour of the dominant firm. The paper analyses the relationship between violation of a fringe firm and the dominant firm, illustrating the asymmetrical implications for when the dominant firm is a buyer of permits versus a seller of permits. Since we expect the regulator to reduce initial permit allocations over time, we also examine the impact of an initial distribution on non-compliance behaviour of the dominant firm. The enforcement literature talks about restoration rate to increase compliance rate of the firms. This paper supports the existing result and further examines the effect of a restoration rate on the other above mentioned results. With the restoration rate the marginal expected penalty of both types of firm increase, which reduce the price elasticity of fringe firms and increase the degree of inefficiency except the terminal period. However, the condition for the efficiency of the model and the relationships between the violations of both types of firms are unchanged. In the presence of a restoration rate, there can exist situations where the violations of a dominant firm reduces with a reduction of initial endowment in the first period but increase with that of the second period.
Chapter 4

Sector specific emission trading: Implications of the incorporation of the aviation sector into EUETS

4.1 Introduction

The European Union is bound by international and domestic laws to reduce its GHG emissions to 20% below 1990 levels by 2020. As of 2009, aviation was the largest source of GHG emissions not yet covered by measures designed to reduce GHG emissions. As the EU did not foresee effective global measures emerging from cooperation under ICAO, as mandated under the 1997 Kyoto Protocol, the EU extended its ETS to control aviation emissions effective January 1, 2012 to all domestic and international flights – from or to anywhere in the world – that arrive at or depart from an EU airport (Leggett et al., 2012). Few other countries like Australia and New Zealand have also included aviation in their domestic programs, but not international flights to and from their countries, which is the unique and probably most debated issue of the aviation sector in EUETS. Some economists are afraid of the emergence of artificial stops outside EU territory (e.g. Switzerland, Turkey), or even the complete redirection of traffic flows, due to this policy (Vespermann and Wald, 2010). This probable route configuration might even result into an environmental phenomenon commonly known as carbon leakage\(^1\) through bypassing off the EU sky by international flights (both passenger and cargo) (The Ernst & Young & York Aviation study, 2008).

In the context of the inclusion of both domestic and international flights in the EUETS, this chapter extends the theoretical model of domestic network structure of aviation by Brueckner and Zhang (2010) in an international network structure scenario. Airlines can either operate a hub-and-spoke (HS) network or a fully connected / point to point (FC) network. In a three equidistant-node symmetric city framework of domestic aviation network structure Brueckner and Zhang (2010) found that it cannot be explicitly identified which network type

\(^1\)Carbon leakage is said to happen if due to any carbon emission reducing effort, CO2 emission increase as a result. Since CO2 is a global pollutant, so it does not matter where the emission is increasing finally.
is optimal. Moreover, they found the effects of emission charges on the profit maximising network structure (HS vs. FC) to be ambiguous. We extend their model set up in an international scenario where the two spoke points of the HS model for airlines lie outside EU whereas the hub lies inside EU to see the conditions for the shift of the existing preference for the HS to FC network in this context. The importance of this simple extension is that, if two spoke points lie outside the EU then a preference shift towards a FC network from a HS network would imply reduction of emission within the EU but simultaneous increase in the emission outside the EU.

Before going to the theoretical model, the next section presents the basic features of the aviation sector in EUETS.

4.2. Basic features of aviation in EUETS

In the year 2012, the total quantity of CO₂ allowances allocated to aircraft operators is planned to be 97% of their historical emissions in the years 2004-2006. This so called overall ‘cap’, however, is expected to be lowered by another 2% in 2013 (Scheelhaase, 2010). However, flights by aircraft with a maximum take-off weight (MTOW) of less than 5700 kg (Scheelhaase and Grimme, 2007), operators which have less than 243 flights per year or produce emission less than 10,000 tonnes per year, police, military, rescue, humanitarian flights will be excluded from the scheme (Hanus and Vittek, 2011). Also, exemptions will be available for operators with very low traffic levels on routes to, from and within EU. Under this mechanism many operators from developing countries with only limited air traffic links with the EU will be exempted (Ares, 2012).

Allowances will be distributed to individual airlines in proportion to tonne-kilometres flown within the reference years (the benchmark method)². The allocation methodology is to be same (i.e. harmonised) across all Member States. About 82% of the cap will be issued in the form of EU Aviation Allowances and allocated to airlines free of charge. A further 15% of the cap will be in the form of allowances that are to be auctioned, while the remaining 3% will be held for new entrants as a special reserve (Clements et al., 2011). Certified emissions

² benchmark = \( \frac{(1 - \text{quota of auctioned allowances}) \times (1 - \text{reduced quota}) \times \frac{\sum_{i=1}^{n} \text{average annual emission}_{2004-2006}}{\sum_{i=1}^{n} \text{revenue tonne kilometers of the monitoring year}}} \) (Scheelhaase et al., 2010)
reductions (CERs) and emission reduction units (ERUs) from the Clean Development Mechanism and the Joint Implementation of the Kyoto Protocol may be used up to an amount equalling 15% of an airline’s EUETS allocation in 2012. From 2013 onwards the usage of these credits is however unclear (Anger, 2010).

An open trading system is proposed – i.e. the airline sector can trade with all other sectors covered by the EUETS. However, this open trading is open on one side, i.e. only for buying from other sectors, but airlines cannot sell their allowances to the trading sectors other than the air transport sector itself. This is because the allowances that are issued for airlines under the EUETS are not considered within the Kyoto allowances nor included in the Kyoto targets (Anger, 2010; Anger and Kohler, 2010).

Allowances will be allowed to bank for the next accounting period. Excess emissions penalty shall be EUR 100 per tonne of emitted CO₂ equivalent, for which the operator has not surrendered allowances (Hanus and Vittek, 2011). Finally, to ensure consistent and robust enforcement throughout EU, as a last resort, Member States could ban an operator in the EU if it consistently fails to comply with the scheme (Ares, 2012).

4.3. Model

The model set up is same as Brueckner and Zhang (2010), however we have some modifications in the set up. While the three cities/airports in Brueckner and Zhang (2010) are assumed to be within EU, in our set up only one airport (the hub in HS network) is assumed to be located within EU whereas the two other airports are located outside EU. Otherwise, our analysis is also conducted in a three-node symmetric city layout with all the links equidistant and the three city pair markets assumed to have the same demand. The three cities (one in EU and the other two outside) are served by two competing international airlines denoted by \( i, (i = 1, 2) \), where one is a non-EU airline (airline 1) and the other is an EU airline (airline 2). Each of the airlines either use FC network to serve the three airports/cities or both use a HS network (asymmetric network choices are ruled out). Under the FC network, passengers in the three airports are carried by direct (non-stop) flights on three routes. For a HS network, with one airport serving as the hub (the airport located inside EU in our case), there are just two spoke routes, which connect the two non-hub airports to the hub. While
spoke passengers still take direct flights, passengers travelling between the two non-hub airports must take two flights and connect at the hub. The two non-hub airports located outside EU implies the direct route between them is outside the scope of permit costs.

### 4.3.1 Cost

Aircraft operating cost has three components – fuel cost, leasing cost and permit cost. The fuel cost depends on aircraft fuel efficiency, which is measured as fuel consumption per seat per flight hour and denoted by $e_i$ and aircraft seating capacity $s_i$ for airline. Let $r$ denote the unit price, then the fuel cost is simply $re_is_i$. Leasing cost per hour flown, denoted by $g_i(e_i,s_i) = \frac{\beta + \varepsilon s_i}{e_i}$, depends on $s_i$ and $e_i$, where $\beta$ and $\varepsilon$ are positive parameters. Since a lower $e$ implies a more fuel efficient plane which is more costly and a larger plane is also costlier, therefore we have $\frac{\partial g_i}{\partial e_i} < 0$ and $\frac{\partial g_i}{\partial s_i} > 0$. Economies of larger aircraft implies that $\frac{g_i}{s_i}$ is decreasing in $s_i$. Fuel efficiency is increasingly costly i.e. $g_i$ is convex in $e_i$. Since fuel efficiency is difficult to get in larger plane, we have $\frac{\partial g_i/\partial e_i}{\partial s_i} < 0$. Let $f_i$ be the flight frequency and $k$ be the hours per flight, which is an increasing function of distance travelled $d$.

Let $z$ denote the unit permit price and $x$ be the number of permits required per unit of fuel consumed, then the total permit cost is $zxe_is_if_i k(d)$. In this case the total cost becomes

$$TC_i = \left[ re_is_i + \frac{\beta + \varepsilon s_i}{e_i} + zxe_is_if_i \right] k(d) \tag{1}$$

However, before the imposition of the permit cost or in the case when permits are distributed on a free (grandfathering) basis the total cost is:

$$TC_i = \left[ re_is_i + \frac{\beta + \varepsilon s_i}{e_i} \right] f_i k(d) \tag{2}$$

---

3 This is the total cost when permits are distributed on a free (grandfathering) basis.
4.3.2. Demand

The two airlines are assumed to carry passenger volumes of \( q_1 \) and \( q_2 \). Each passenger makes one trip on either airline 1 or airline 2, so that the total number of passengers are fixed and normalised to 1 (i.e. \( q_1 + q_2 = 1 \)). ‘No travel’ option is ignored. \( q_i \) depends on fares charged by airlines denoted by \( p_i \) and on service qualities they provide. One element of service quality is flight frequency, which determines ‘frequency delay’ experienced by a passenger (the difference between passenger’s preferred time of departure and the nearest flight time). A passenger’s expected frequency delay is inversely proportional to the airlines flight frequency\( f_i \). The passenger’s cost of frequency delay on airline\( i \) can be written as \( \frac{Y}{f_i} \), where\( Y \) is a cost parameter common to all passengers. Another type of ‘stochastic delay’ arises through excess demand. Stochastic delay is denoted by \( l_i \) and mainly affected by airline’s load factor. The cost of this delay can be written as \( \lambda l_i \), where \( \lambda \) is a common cost parameter. Therefore, the cost of flying with airline \( i \) is the sum of fare and two delay costs

\[
\left[ p_i + \frac{Y}{f_i} + \lambda l_i \right].
\]

There is another important factor which acts towards the airline’s demand which is the brand loyalty. Brand loyalty appears as a negative cost for passengers preferring that airline and a positive cost for passengers preferring the other airline. Assuming that, this brand loyalty is uniformly distributed over \([-\alpha, \alpha]\), the number of passengers preferring airline \( i \) can be written as:

\[
q_i = \frac{1}{2} - \frac{1}{\alpha} \left( p_i - p_j + \frac{Y}{f_i} + \lambda l_i - \frac{Y}{f_j} - \lambda l_j \right), i \neq j
\]

Thus, an increase in flight frequency by any airline increases its demand while reducing the demand of the other airline. An increase in the load factor or the fare will have opposite effects. When all these variables are equal across two airlines, each airline faces a demand of \( \frac{1}{2} \).
4.3.3. HS vs. FC profits

Profit is denoted by \( \pi \), which is the difference between the revenue and the total cost, where revenue is the product of price and quantity. Thus for a single route the profit is:

\[
\pi_i = p_i q_i - TC_i
\]

Where, cost function will be either (1) or (2) depending on the presence or absence of permit-costs. When we talk about a network, the profit is some composition of this single route profit. Under the FC network, passengers in the three airports are carried by direct (non-stop) flights on three routes. Thus, In FC network occupied seats to the passengers total \((f_is_i,i)\) is equal to the demand \((q_i)\). With three equidistant points, the profit for a FC network is simply:

\[
\pi_{FCi} = 3p_i q_i - 3TC_i
\]

For a HS network, with one airport serving as the hub (the airport located inside EU in our case), there are just two spoke routes, which connect the two non-hub airports to the hub. While spoke passengers still take direct flights, passengers travelling between the two non-hub airports must take two flights and connect at the hub. Thus, occupied seats to the passengers total \((f_is_i,i)\) is equal to twice of the demand \((2q_i)\). Therefore although revenue is three times, cost is only two times. i.e.:

\[
\pi_{HSi} = 3p_i q_i - 2TC_i
\]

In the next sections we compare the route networks (HS vs. FC) between the initial situation without permit and the situation with permit.

4.4. Scenario 1: without emission permits

In this scenario, cost function (2) will be valid.

4.4.1. Hub and spoke (HS) network

The HS network catering passengers for three equidistant airports has 3 times revenue of a single route but cost will be two times only of the cost function (2):
Since both the spoke routes of the HS network carry both local and connecting passengers, thus \( f_{HSi} s_{HSi} l_{HSi} = 2q_{HSi} \) i.e. total number of seats (flight frequency multiplied by seating capacity multiplied by stochastic delay) equals twice the demand. Substituting for \( s_{HSi} = \frac{2q_{HSi}}{f_{HSi} l_{HSi}} \) and then collecting the terms involving \( q_{HSWPi} \) and putting the value for \( q_{HSi} \) we have:

\[
\pi_{HSi} = 3p_{HSi} q_{HSi} - 2 \left[ r e_{HSi} s_{HSi} + \frac{\beta + \varepsilon s_{HSi}}{e_{HSi}} \right] f_{HSi} k(d)
\]

(4) implies that part of profit depends on the demand and the other part is independent of it.

Airline \( i \) chooses \( p_{HSi}, e_{HSi}, l_{HSi}, f_{HSi} \) to maximise \( \pi_{HSi} \).

\[
\frac{\partial \pi_{HSi}}{\partial p_{HSi}} = 3q_{HSi} + \left( -\frac{1}{\alpha} \right) \left[ 3p_{HSi} - \frac{4r e_{HSi} k(d)}{l_{HSi}} - \frac{4\varepsilon k(d)}{e_{HSi} l_{HSi}} \right] = 0
\]

(5)

\[
\frac{\partial \pi_{HSi}}{\partial e_{HSi}} = \left[ - \frac{4r k(d)}{l_{HSi}} + \frac{4\varepsilon k(d)}{e_{HSi} l_{HSi}} \right] q_{HSi} + \frac{2f_{HSi} k(d)\beta}{e_{HSi}}
\]

(6)

\[
\frac{\partial \pi_{HSi}}{\partial f_{HSi}} = \left[ 3p_{HSi} - \frac{4r e_{HSi} k(d)}{l_{HSi}} - \frac{4\varepsilon k(d)}{e_{HSi} l_{HSi}} \right] \left( \frac{\gamma}{\alpha f_{HSi}^2} \right) - \frac{2k(d)\beta}{e_{HSi}} = 0
\]

(7)

\[
\frac{\partial \pi_{HSi}}{\partial l_{HSi}} = \left[ \frac{4r e_{HSi} k(d)}{l_{HSi}^2} + \frac{4\varepsilon k(d)}{e_{HSi}^2 l_{HSi}} \right] q_{HSi} + \left[ 3p_{HSi} - \frac{4r e_{HSi} k(d)}{l_{HSi}} - \frac{4\varepsilon k(d)}{e_{HSi} l_{HSi}} \right] \left( -\frac{\lambda}{\alpha} \right) = 0
\]

(8)

The above FOCs imply that the marginal effects of the variables on profit are via marginal revenues and marginal costs\(^4\). Given the symmetry of the model the equilibrium values of the choice variables will be symmetric across carriers. Thus, each airline’s equilibrium traffic will be equal \( \frac{1}{2} \), which provide the following results:

---

\(^4\) The SOC i.e. the positive definiteness of the Hessian matrix of profit is assumed to hold.
From (5) we have:

$$p_{HSi} = \frac{\alpha}{2} + \frac{4k(d)}{3l_{HSi}} \left[ re_{HSi} + \frac{\varepsilon}{e_{HSi}} \right]$$  (9)

From (6) we have:

$$e_{HSi}^2 = \frac{\varepsilon + \beta f_{HSi} l_{HSi}}{r}$$  (10)

From (5) and (7) we have:

$$f_{HSi}^2 = \frac{3e_{HSi} \gamma}{4k(d)\beta}$$  (11)

From (5) and (8) we have:

$$l_{HSi}^2 = \frac{4k(d)}{3\lambda} \left[ re_{HSi} + \frac{\varepsilon}{e_{HSi}} \right]$$  (12)

The equilibrium denoted by \((p_{HSi}^*, e_{HSi}^*, f_{HSi}^*, l_{HSi}^*)\) will be the solution to the equations (9) to (12). To solve the four simultaneous equations for the equilibrium values of the choice variables, we square both the sides of (10), put values of \(f_{HSi}^2\) and \(l_{HSi}^2\) from (11) and (12) and obtain the following:

$$e_{HSi}^* = \sqrt{\frac{1}{2r} \left( \frac{2\varepsilon + \frac{\beta y}{\lambda}}{\lambda} + \frac{\frac{\beta y}{\lambda} \left( 8\varepsilon + \frac{\beta y}{\lambda} \right)}{2r} \right)^{\frac{1}{2}}$$

Now, we get two positive values if \(\left( 2\varepsilon + \frac{\beta y}{\lambda} \right)^2 > \frac{\beta y}{\lambda} \left( 8\varepsilon + \frac{\beta y}{\lambda} \right)\), which boils down to \(4\varepsilon \left( \varepsilon - \frac{\beta y}{\lambda} \right) > 0\). Thus to ensure one unique real solution we assume \(\varepsilon < \frac{\beta y}{\lambda}\) to hold and get the solution as:

$$e_{HSi}^* = \sqrt{\frac{1}{2r} \left( \frac{2\varepsilon + \frac{\beta y}{\lambda}}{\lambda} + \frac{\frac{\beta y}{\lambda} \left( 8\varepsilon + \frac{\beta y}{\lambda} \right)}{2r} \right)^{\frac{1}{2}}}$$  (13)
4.4.2. Fully connected (FC) network

In this network system passengers travel all the routes directly. Thus revenue and cost both are three times that of any single route:

$$\pi_{FCi} = 3p_{FCi}q_{FCi} - 3\left[re_{FCi}s_{FCi} + \frac{\beta + \varepsilon s_{FCi}}{e_{FCi}}\right]f_{FCi}k(d)$$

Using $f_{FCi}s_{FCi}l_{FCi} = q_{FCi}$, i.e. total seats occupied is simply the demand of that route and then collecting the terms including $q_{FCi}$ we get:

$$i.e. \; \pi_{FCi} = 3\left[p_i - \frac{re_{FCi}k(d)}{l_{FCi}} - \frac{ek(d)}{e_{FCi}l_{FCi}}\right]$$

$$= \frac{1}{a}\left(p_{FCi} - p_{FCj} + \frac{y}{f_{FCi}} + \lambda l_{FCi} - \frac{y}{f_{FCj}} - \lambda l_{FCj}\right) - 3\frac{f_{FCi}k(d)\beta}{e_{FCi}} \tag{4'}$$

Airline $i$ chooses $p_{FCi}, e_{FCi}, l_{FCi}, f_{FCi}$ to maximise $\pi_{FCi}$. Proceeding in the similar manner we derive the following values of the choice variables:

$$p_{FCi} = \frac{\alpha}{2} + \frac{k(d)}{l_{FCi}}\left[re_{FCi} + \frac{\varepsilon}{e_{FCi}}\right] \tag{9'}$$

$$e_{FCi} = \frac{\varepsilon + 2\beta f_{FCi}l_{FCi}}{r} \tag{10'}$$

$$f_{FCi}^2 = \frac{e_{FCi}\gamma}{2k(d)\beta} \tag{11'}$$

$$l_{FCi}^2 = \frac{k(d)}{\lambda}\left[re_{FCi} + \frac{\varepsilon}{e_{FCi}}\right] \tag{12'}$$

In this case, the equilibrium denoted by $(p_{FCi}^*, e_{FCi}^*, f_{FCi}^*, l_{FCi}^*)$ will be the solution to the equations $(9')$ to $(12')$. To solve for all the equilibrium values of the choice variable we derive $e_{FCi}^*$ from $(10')$ and proceeding in the similar manner as done in the HS case, and assuming $\varepsilon < \frac{2\beta y}{\lambda}$ to ensure one unique real solution we get the solution as:

$$e_{FCi}^* = \left[\left(2\varepsilon + \frac{2\beta y}{\lambda}\right) + \sqrt{\frac{2\beta y}{\lambda} \left(8\varepsilon + \frac{2\beta y}{\lambda}\right)\frac{2r}{2\lambda}}\right]^{1/2} \tag{13'}$$
From (13) and (13’) it is seen that, \( e \) rises by less than a factor of \( \sqrt{2} \) from HS to FC network. \( \frac{e_{FCWPI}^*}{e_{HSWPI}^*} = \sqrt{2} \) provided \( \varepsilon = 0 \). Otherwise we have:

\[
e_{HSI}^* < e_{FCI}^* < \sqrt{2} e_{HSI}^*
\]

i.e. HS network has more fuel-efficient network than FC network. From (11), (11’) and (14) we have

\[
\frac{f_{FC}^2}{f_{HS}^2} = \frac{2 e_{FCI}^*}{3 e_{HSI}^*} < \frac{2}{3} \sqrt{2} < 1
\]

i.e. flight frequency is higher in HS network compared to FC network. These results are as in Brueckner and Zhang (2010).

4.4.3. Profit differential

Comparing (4) and (4’) we see that the profit differential is

\[
\pi_{HSI} - \pi_{FCI} = k(d) \left[ r \left( \frac{3 e_{FCI}}{2 l_{FCI}} - 2 \frac{e_{HSI}}{l_{HSI}} \right) + \varepsilon \left( \frac{3}{2} \frac{1}{e_{FCI} l_{FCI}} - 2 \frac{1}{e_{HSI} l_{HSI}} \right) \right]
\]

The sign of the profit differential depends on the magnitudes of the individual choice variables. Therefore, from the above interactions between the choice variables of two types of network we cannot conclude unambiguously which network is preferred to the other.

4.5. Scenario 2: With emission permits

In this scenario, cost function (1) will be valid. We write \( P \) in the subscript of the variables to denote that these pertain to the different network equilibria with emission permit.
4.5.1. Hub and spoke (HS) network

In this scenario both the spoke routes (through the hub in EU) are included in the EUETS, thus we have the cost function (1):

$$\pi_{HSP_i} = 3p_{HSP_i}q_{HSP_i} - 2\left[re_{HSP_i}s_i + \beta + \varepsilon s_{HSP_i} + zxe_{HSP_i}s_{HSP_i}\right]f_{HSP_i}k(d)$$

Again substituting for $s_{HSP_i} = \frac{2q_{HSP_i}}{f_{HSP_i}l_{HSP_i}}$ and then collecting the terms involving $q_i$ we have -

$$\pi_{HSP_i} = \left[3p_{HSP_i} - \frac{4re_{HSP_i}k(d)}{l_{HSP_i}} - \frac{4\varepsilon k(d)}{e_{HSP_i}l_{HSP_i}} - \frac{4zxe_{HSP_i}k(d)}{l_{HSP_i}}\right]q_{HSP_i} - \frac{2f_{HSP_i}k(d)\beta}{e_{HSP_i}}$$

Maximising (4a) with respect to $p_{HSP_i}, e_{HSP_i}, l_{HSP_i}, f_{HSP_i}$ similar to the previous case we get the following results:

$$p_{HSP_i} = \frac{\alpha}{2} + \frac{4k(d)}{3l_{HSP_i}} \left[re_{HSP_i} + \frac{\varepsilon}{e_{HSP_i}} + zxe_{HSP_i}\right]$$

$$e_{HSP_i}^2 = \frac{\varepsilon + \beta f_{HSP_i}l_{HSP_i}}{2(r + zx)}$$

$$f_{HSP_i}^2 = \frac{3e_{HSP_i}Y}{4k(d)\beta}$$

$$l_{HSP_i}^2 = \frac{4k(d)}{3\lambda} \left[re_{HSP_i} + \frac{\varepsilon}{e_{HSP_i}} + zxe_{HSP_i}\right]$$

The equilibrium denoted by $(p_{HSP_i}^*, e_{HSP_i}^*, f_{HSP_i}^*, l_{HSP_i}^*)$ will be the solution to the equations (9a) to (12a). To solve the four simultaneous equations for the equilibrium values of the choice variables, we square both the sides of (10a), put values of $f_{HSP_i}^2$ and $l_{HSP_i}^2$ from (11a) and (12a) and obtain the following:
Now, we get two positive values if \( (4\varepsilon + \frac{\beta \gamma}{\lambda})^2 > \frac{\beta \gamma}{\lambda} (24\varepsilon + \frac{\beta \gamma}{\lambda}) \), which boils down to \( \varepsilon > \frac{\beta \gamma}{\lambda} \). As before, to ensure one unique real solution we assume \( \varepsilon < \frac{\beta \gamma}{\lambda} \) to hold and get the solution as:

\[
e_{HSPi}^* = \left[ \frac{\left(4\varepsilon + \frac{\beta \gamma}{\lambda}\right) + \frac{\beta \gamma}{\lambda} \left(24\varepsilon + \frac{\beta \gamma}{\lambda}\right)}{8(r + zx)} \right]^{1/2}
\]

(13a)

### 4.5.2. Fully connected (FC) network

In this scenario two of the three direct routes which touches EU are included in EUETS, whereas, there is no permit cost for the third direct route. Thus, the total cost is

\[
2 \left[ r_{FCPi} e_{FCPi} s_{FCPi} + \frac{\beta + \varepsilon e_{FCPi}}{e_{FCPi}} + zx e_{FCPi} s_{FCPi} \right] f_{FCPi} k(d) + \left[ \frac{r e_{FCPi} s_{FCPi}}{e_{FCPi}} + \frac{\beta + \varepsilon e_{FCPi}}{e_{FCPi}} \right] f_{FCPi} k(d)
\]

The profit function in the FC model is the following:

\[
\pi_{FCPi} = 3p_{FCPi} q_{FCPi} - 2 \left[ r_{FCPi} e_{FCPi} s_{FCPi} + \frac{\beta + \varepsilon e_{FCPi}}{e_{FCPi}} + zx e_{FCPi} s_{FCPi} \right] f_{FCPi} k(d)
- \left[ \frac{r e_{FCPi} s_{FCPi}}{e_{FCPi}} + \frac{\beta + \varepsilon e_{FCPi}}{e_{FCPi}} \right] f_{FCPi} k(d)
\]

Again substituting \( s_{FCPi} = \frac{q_{FCPi}}{f_{FCPi} l_{FCPi}} \) and collecting all the terms with \( q_i \) we have:

\[
\Rightarrow \pi_{FCPi} = \left[ 3p_{FCPi} - \frac{3r e_{FCPi} k(d)}{f_{FCPi} l_{FCPi}} - \frac{3\varepsilon k(d)}{e_{FCPi} l_{FCPi}} - \frac{2 zx e_{FCPi} k(d)}{l_{FCPi}} \right] \frac{1}{2}
- \frac{1}{\alpha} \left( p_{FCPi} - p_{FCPj} + \frac{\gamma}{f_{FCPi}} + \lambda l_{FCPi} - \frac{\gamma}{f_{FCPj}} - \lambda l_{FCPj} \right) - \frac{3\beta f_{FCPi} k(d)}{e_{FCPi}} \quad (4a')
\]

Maximising \( (4a') \) with respect to \( p_{FCPi}, e_{FCPi}, l_{FCPi}, f_{FCPi} \) similar to the previous case we get:
In this case, the equilibrium denoted by \( p_{FCPi} \) will be the solution to the equilibriums \((9a')\) to \((12a')\).

To solve for all the equilibrium values of the choice variable we derive \( e_{FCP}^* \) from \((10a')\) and proceeding in the similar manner as done in the HS case, and assuming \( \varepsilon < \frac{2\beta y}{\lambda} \) to ensure one unique real solution we get the solution as:

\[
e_{FCP}^* = \left( \frac{2\varepsilon + \frac{2\beta y}{\lambda}}{2} + \sqrt{\frac{2\beta y}{\lambda} \left( \frac{8\varepsilon + \frac{2\beta y}{\lambda}}{2} \right)} \right)^{1/2}
\]

Comparing \((13a)\) and \((13a')\) we see that the ranking of the fuel efficiency is unclear for the two networks with the permits. This gives rise to the following proposition:

**Proposition 1:** Although the fuel efficiency is higher in hub and spoke network compared to the fully connected network without the permits, however, the ranking is unclear in the presence of the permits.
4.5.3. Profit differential

Comparing (4a) and (4a') with the equilibrium values we see that the profit differential is

$$\pi_{HS\pi} - \pi_{FCP\pi} = k(d) \left[ r \left( \frac{3}{2} \frac{e_{FC\pi}^*}{l_{FC\pi}^*} - \frac{2 e_{HS\pi}^*}{l_{HS\pi}^*} \right) + \epsilon \left( \frac{3}{2} \frac{1}{e_{FC\pi}^* l_{FC\pi}^*} - \frac{2}{e_{HS\pi}^* l_{HS\pi}^*} \right) ight]$$

$$- \beta \left( \frac{3 f_{FC\pi}^*}{e_{FC\pi}^*} - \frac{2 f_{HS\pi}^*}{e_{HS\pi}^*} \right)$$

$$- \left( \frac{z e_{FC\pi}^*}{l_{FC\pi}^*} - \frac{2 z e_{HS\pi}^*}{l_{HS\pi}^*} \right)$$

(16a)

In this case also sign of the profit differential depends on the magnitudes of the individual choice variables and from the above interactions between the choice variables of two types of network we cannot conclude unambiguously that which network is preferred to the other. However, we compare the profit differential without permit (\(\pi_{diff}\)) and the profit differential permit (\(\pi_{diffp}\)) from (16) and (16a):

$$\pi_{diff} - \pi_{diffp}$$

$$= k(d) \left[ r \left( \frac{3}{2} \left( e_{FC\pi}^* - \frac{e_{FC\pi}^*}{l_{FC\pi}^*} \right) - \frac{2 e_{HS\pi}^*}{l_{HS\pi}^*} \right) - 2 \left( \frac{1}{e_{HS\pi}^* l_{HS\pi}^*} - \frac{1}{e_{HS\pi}^* l_{HS\pi}^*} \right) \right]$$

$$+ \epsilon \left( \frac{3}{2} \left( \frac{1}{e_{FC\pi}^* l_{FC\pi}^*} - \frac{1}{e_{FC\pi}^* l_{FC\pi}^*} \right) - 2 \left( \frac{1}{e_{HS\pi}^* l_{HS\pi}^*} - \frac{1}{e_{HS\pi}^* l_{HS\pi}^*} \right) \right)$$

$$+ \beta \left( 3 \left( \frac{f_{FC\pi}^*}{e_{FC\pi}^*} - \frac{f_{FC\pi}^*}{e_{FC\pi}^*} \right) - 2 \left( \frac{f_{HS\pi}^*}{e_{HS\pi}^*} - \frac{f_{HS\pi}^*}{e_{HS\pi}^*} \right) \right)$$

$$+ z x \left( \frac{e_{FC\pi}^*}{l_{FC\pi}^*} - \frac{2 e_{HS\pi}^*}{l_{HS\pi}^*} \right)$$

(17)

If the above final expression (17) is positive (negative), which implies a (an) reduction (increase) in the profit differential after imposition of permit price then we find a bias towards the FC (HS) network.

With an increase in \(z\), the change in the profit differential \(\frac{\partial (\pi_{diff} - \pi_{diffp})}{\partial z}\) will depend upon the sign of \(\frac{e_{FC\pi}^*}{l_{FC\pi}^*} - \frac{2 e_{HS\pi}^*}{l_{HS\pi}^*}\), since \(x\) is given a positive parameter. Thus, with an increase in the permit price the condition for a bias towards a FC network is:
The above condition implies that if the ratio of the fuel efficiency in the FC network to the HS network is higher than twice the ratio of the load factor (FC to HS), then there will be a bias towards the FC network with an increase in the permit price. This leads to the following proposition:

\[
\frac{e_{FCi}^*}{l_{FCi}^*} - \frac{2e_{HSi}^*}{l_{HSi}^*} > 0
\]

\[
\Rightarrow \frac{e_{FCi}^*}{e_{HSi}^*} > 2 \frac{l_{FCi}^*}{l_{HSi}^*}
\]

Proposition 2: With an increase in the permit price there will be a bias towards the fully connected network if the ratio of the fuel efficiency in the FC network to the HS network is higher than twice the ratio of the load factor (FC to HS).

### 4.6. Conclusions

In the context of the inclusion of both domestic and international flights in the EUETS, this chapter extends the theoretical model of domestic network structure of aviation by Brueckner and Zhang (2010) in an international network structure scenario. Airlines can either operate a hub-and-spoke (HS) network or a fully connected / point to point (FC) network. In a three equidistant-node symmetric city framework of domestic aviation network structure Brueckner and Zhang (2010) found that it cannot be explicitly identified which network type is optimal. Moreover, they found the effects of emission charges on the profit maximising network structure (HS vs. FC) to be ambiguous. We extend their model set up in an international scenario where the two spoke points of the HS model for airlines lie outside EU whereas the hub lies inside EU.

As in Brueckner and Zhang (2010) we also found that the ranking the profits of the two networks is not unique. However, we found that in contrast to the higher fuel efficiency in the HS network compared to the FC network without the permits, the ranking is unclear in the presence of the permits. Although in our model we have assumed the permit price to be given, but in reality it is decided in the market and is expected to increase over the time. Thus
we checked the effect of an increase in the permit price on the profit differential and found that there will be a bias towards the fully connected network if the ratio of the fuel efficiency in the FC network to the HS network is higher than twice the ratio of the load factor (FC to HS). The way we have set up our model, the two spoke points are outside EU, so a direct route (under FC network) has no permit charges applied to it. Although HS network has its own incentive to economise through higher aircraft fuel efficiency, in our set up both the connecting routes (under HS network) has to incur permit charges. Thus, there is a trade off between the permit cost and efficiency gain under HS network when the two spoke points lie outside the EU.

The result derived from a simple extension of the network structure model of Brueckner and Zhang (2010) is important because, if two spoke points lie outside the EU then a preference shift towards a FC network from a HS network would imply reduction of emission within the EU but simultaneous increase in the emission outside the EU. Although our model set up assumes away any possibility of asymmetric routes of the two airlines, however, if the two spoke points lie outside EU, then in reality it might happen that only the non-EU airline will have direct flights between the two spoke points and the EU airline continue to have HS network. In that case the profit comparison of the HS and FC network will be only valid for the non-EU airline. In the extreme case, if the cost of travelling in the EU sky exceeds the revenue due to a high permit cost, then it might happen that only EU airline will be operating in the HS network and the non-EU airline will only have direct flights between the two spoke airports. This would lead to a carbon leakage via alternative routes and diversion of traffic, as indicated in the literature.