

Effectiveness of Discount Incentives in Carbon Reduction: Impact of Customer-Perceived Value Sacrificed for Green Hotels

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Supplementary Materials

Supplementary A. Derivations of the optimal decisions in Case-E.

The optimization problem of the hotel is given by

$$\text{Max } \pi_1 = \left(1 - \frac{p-d}{b}\right) (p - c - c_E) + \left(\frac{d}{1-b} - \frac{p-d}{b}\right) (v + c_E r_L - d) \quad (\text{S1})$$

$$\text{s.t.} \quad 1 - \frac{p-d}{b} \leq Q,$$

$$p(1-b) \leq d \leq 1-b,$$

$$p, d > 0.$$

By Equation (S1), we have $\frac{\partial^2 \pi_1}{\partial p^2} = -\frac{2}{b} < 0$; $\frac{\partial^2 \pi_1}{\partial d^2} = -\frac{2}{b(1-b)} < 0$; $\frac{\partial^2 \pi_1}{\partial p \partial d} = \frac{\partial^2 \pi_1}{\partial d \partial p} =$

$\frac{2}{b} > 0$. Thus, we have Hessian Matrix as follows:

$$H(\pi_1) = \begin{vmatrix} \frac{\partial^2 \pi_1}{\partial p^2} & \frac{\partial^2 \pi_1}{\partial p \partial d} \\ \frac{\partial^2 \pi_1}{\partial d \partial p} & \frac{\partial^2 \pi_1}{\partial d^2} \end{vmatrix} = \frac{4}{b(1-b)} > 0$$

As $H(\pi_1) < 0$, Hessian matrix is positive definite and thus the profit function of the

hotel is convex. Letting $\mathcal{L} = \left[\frac{d-p(1-b)}{b(1-b)}\right] [p - c + v - c_E(1 - r_L) - d] + \left(1 - \frac{d}{1-b}\right) (p - c - c_E) - \lambda_1 \left(1 - \frac{p-d}{b} - Q\right) - \lambda_2 (p(1-b) - d) - \lambda_3 (d - (1-b))$. Then,

the KKT conditions are given as below:

$$\begin{cases}
\frac{\partial \mathcal{L}}{\partial p} = \frac{-2p+2d+b+c_E(1-r_L)+c-v}{b} + \frac{\lambda_1}{b} - \lambda_2(1-b) \leq 0, \\
p \frac{\partial \mathcal{L}}{\partial p} = p \left[\frac{-2p+2d+b+c_E(1-r_L)+c-v}{b} + \frac{\lambda_1}{b} - \lambda_2(1-b) \right] = 0, \\
\frac{\partial \mathcal{L}}{\partial d} = \frac{2(p-d-pb)-c(1-b)-c_E(1-r_L-b)+v}{b(1-b)} - \frac{\lambda_1}{b} + \lambda_2 - \lambda_3 \leq 0, \\
d \frac{\partial \mathcal{L}}{\partial d} = d \left[\frac{2(p-d-pb)-c(1-b)-c_E(1-r_L-b)+v}{b(1-b)} - \frac{\lambda_1}{b} + \lambda_2 - \lambda_3 \right] = 0, \\
\begin{cases}
1 - \frac{p-d}{b} - Q \leq 0, \\
\lambda_1 \left(1 - \frac{p-d}{b} - Q \right) = 0, \\
p(1-b) - d \leq 0, \\
\lambda_2(p(1-b) - d) = 0, \\
d - (1-b) \leq 0, \\
\lambda_3(d - (1-b)) = 0,
\end{cases}
\end{cases}$$

$$0 < p^*, d^* < 1,$$

$$\lambda_1^*, \lambda_2^*, \lambda_3^* \geq 0.$$

1) Case 1: $\lambda_1 = \lambda_2 = \lambda_3 = 0$

We have $\frac{-2p+2d+b+c_E(1-r_L)+c-v}{b} = 0$, and $\frac{2(p-d-pb)-c(1-b)-c_E(1-r_L-b)+v}{b(1-b)} = 0$. Thus,

we obtain

$$\begin{aligned}
p^* &= \frac{1+c+c_E}{2}; \\
d^* &= \frac{1-b+c_E r_L+v}{2} \geq p^*(1-b) \Leftrightarrow \mathbf{b} \geq \mathbf{1} - \frac{c_E r_L+v}{c+c_E}; \\
Q &\geq 1 - \frac{p-d}{b} = \frac{b-c+v-c_E(1-r_L)}{2b}; \\
\pi_1^* &= \frac{[c+c_E(1-r_L)-v]^2 + b(c+c_E)[2(c_E r_L+v)-c-c_E] - b(1-b)[2(c+c_E)-1]}{4b(1-b)}; \\
D_{T,1} &= \frac{b-c+v-c_E(1-r_L)}{2b}; \\
D_{I,1} &= \frac{v-c(1-b)-c_E(1-b-r_L)}{2b(1-b)} > 0 \Leftrightarrow \mathbf{b} > \mathbf{1} - \frac{c_E r_L+v}{c+c_E}; \\
D_{N,1} &= \frac{1-b-v-c_E r_L}{2(1-b)} \geq 0 \Leftrightarrow \mathbf{b} \leq \mathbf{1} - \mathbf{v} - \mathbf{c}_E r_L \Leftrightarrow \mathbf{d}_1^{0*} \leq \mathbf{1} - \mathbf{b}. \\
E_{T,1} &= \frac{b(1-b-c_E r_L)-c(1-b)(1-r_L)+[v-c_E(1-r_L)](1-b-r_L)}{2b(1-b)}.
\end{aligned}$$

For Case-PE, we have $D_{N,1} > 0$ and $D_{I,1} > 0$, or equivalently, $1 - \frac{c_E r_L+v}{c+c_E} \leq b <$

$1 - v - c_E r_L$. For Case-FE, we have $D_{N,1} = 0$ and $D_{I,1} > 0$, or equivalently, $b =$

$$1 - v - c_E r_L > 1 - \frac{c_E r_L + v}{c + c_E}.$$

2) Case 2: $\lambda_1 = \lambda_2 = 0$, and $\lambda_3 > 0$

We have $\mathbf{d} - (\mathbf{1} - \mathbf{b}) = \mathbf{0}$ (i.e., it is Case-FE), $\frac{-2p+2d+b+c_E(1-r_L)+c-v}{b} = 0$, and

$$\frac{2(p-d-pb)-c(1-b)-c_E(1-r_L-b)+v}{b(1-b)} - \frac{\lambda_1}{b} - \lambda_3 = 0. \text{ Thus, we obtain}$$

$$\lambda_3^* = \frac{v+c_E r_L-(1-b)}{1-b} > 0 \Leftrightarrow \mathbf{b} > \mathbf{1} - \mathbf{v} - \mathbf{c}_E \mathbf{r}_L;$$

$$p^* = 1 - \frac{b-c+v-c_E(1-r_L)}{2};$$

$$d^* = 1 - b;$$

$$\mathbf{Q} \geq 1 - \frac{p-d}{b} = \frac{b-c+v-c_E(1-r_L)}{2b};$$

$$\pi_1^* = \frac{(b-c+v-c_E(1-r_L))^2}{4b};$$

$$D_{T,1} = \frac{b-c+v-c_E(1-r_L)}{2b};$$

$$D_{I,1} = \frac{b-c+v-c_E(1-r_L)}{2b};$$

$$D_{N,1} = 0;$$

$$E_{T,1} = \frac{(1-r_L)(b-c+v-c_E(1-r_L))}{2b}.$$

3) Case 3: $\lambda_1 = \lambda_3 = 0$, and $\lambda_2 > 0$

We have $p(1-b) - d = 0$, $\frac{-2p+2d+b+c_E(1-r_L)+c-v}{b} - \lambda_2(1-b) = 0$, and

$$\frac{2(p-d-pb)-c(1-b)-c_E(1-r_L-b)+v}{b(1-b)} + \lambda_2 = 0. \text{ Thus, we obtain}$$

$$\lambda_2^* = \frac{c(1-b)-v+c_E(1-r_L-b)}{b(1-b)} > 0 \Leftrightarrow \mathbf{b} < \mathbf{1} - \frac{\mathbf{v} + \mathbf{c}_E \mathbf{r}_L}{\mathbf{c} + \mathbf{c}_E};$$

$$p^* = \frac{1+c+c_E}{2};$$

$$d^* = \frac{(1-b)(1+c+c_E)}{2};$$

$$\mathbf{Q} \geq 1 - \frac{p-d}{b} = \frac{1-c-c_E}{2};$$

$$\pi_1^* = \frac{[1-(c+c_E)]^2}{4};$$

$$D_{T,1} = \frac{1-c-c_E}{2};$$

$$D_{I,1} = 0 \text{ (Contradictory with } D_{I,1} > 0);$$

$$D_{N,1} = \frac{1-c-c_E}{2};$$

$$E_{T,1} = \frac{1-c-c_E}{2}.$$

As there is contradiction, the above solution is not optimal.

4) Case 4: $\lambda_1 = 0$, $\lambda_2 > 0$, and $\lambda_3 > 0$

We have $p(1-b) - d = 0$, $d - (1-b) = 0$, $\frac{-2p+2d+b+c_E(1-r_L)+c-v}{b} - \lambda_2(1-b) = 0$, and $\frac{2(p-d-pb)-c(1-b)-c_E(1-r_L-b)+v}{b(1-b)} + \lambda_2 - \lambda_3 = 0$. Then, we have $\lambda_3^* = -\frac{1-c-c_E}{1-b} < 0$, which contradicts the condition that $\lambda_3 > 0$. Thus, it is not optimal.

5) Case 5: $\lambda_1 > 0$, and $\lambda_2 = \lambda_3 = 0$

We have $1 - \frac{p-d}{b} - Q = 0$, $\frac{-2p+2d+b+c_E(1-r_L)+c-v}{b} + \frac{\lambda_1}{b} = 0$, and $\frac{2(p-d-pb)-c(1-b)-c_E(1-r_L-b)+v}{b(1-b)} - \frac{\lambda_1}{b} = 0$. Thus, we obtain

$$\lambda_1^* = b - c + v - c_E(1 - r_L) - 2bQ > 0 \Leftrightarrow Q < \frac{b-c+v-c_E(1-r_L)}{2b};$$

$$p^* = \frac{[1+b(1-2Q)+c_E r_L+v]}{2};$$

$$d^* = \frac{1-b+c_E r_L+v}{2} \geq p_1^{O*}(1-b) \Leftrightarrow b \geq 1 - \frac{c_E r_L+v}{c+c_E};$$

$$\pi_1^* = \frac{1-b(1-2Q)^2-4Q(c+c_E)-2(1-2Q)(c_E r_L+v)}{4} + \frac{(c_E r_L+v)^2}{4[1-b]};$$

$$D_{T,1} = Q;$$

$$D_{I,1} = \frac{c_E r_L+v-(1-2Q)(1-b)}{2(1-b)} > 0 \Leftrightarrow Q > \frac{1-b-c_E r_L-v}{2(1-b)};$$

$$D_{N,1} = \frac{1-b-v-c_E r_L}{2(1-b)} \geq 0 \Leftrightarrow b \leq 1 - v - c_E r_L \Leftrightarrow d_1^{O*} \leq 1 - b.$$

$$E_{T,1} = Q(1 - r_L) + \frac{r_L[1-b-c_E r_L-v]}{2[1-b]}.$$

For Case-PE, we have $D_{N,1} > 0$ and $D_{I,1} > 0$, or equivalently, $1 - \frac{c_E r_L+v}{c+c_E} \leq b <$

$1 - v - c_E r_L$. For Case-FE, we have $D_{N,1} = 0$ and $D_{I,1} > 0$, or equivalently, $b =$

$$1 - v - c_E r_L > 1 - \frac{c_E r_L + v}{c + c_E}.$$

6) Case 6: $\lambda_1 > 0$, $\lambda_2 = 0$, and $\lambda_3 > 0$

We have $1 - \frac{p-d}{b} - Q = 0$, $d - (1 - b) = 0$ (i.e., it is Case-FE),

$$\frac{-2p+2d+b+c_E(1-r_L)+c-v}{b} + \frac{\lambda_1}{b} = 0, \text{ and } \frac{2(p-d-pb)-c(1-b)-c_E(1-r_L-b)+v}{b(1-b)} - \frac{\lambda_1}{b} - \lambda_3 = 0.$$

Consequently, we have

$$\lambda_1^* = b - c + v - c_E(1 - r_L) - 2bQ > 0 \Leftrightarrow Q < \frac{b-c+v-c_E(1-r_L)}{2b};$$

$$\lambda_3^* = \frac{v+c_E r_L-(1-b)}{1-b} > 0 \Leftrightarrow b > 1 - v - c_E r_L;$$

$$p^* = 1 - bQ;$$

$$d^* = 1 - b;$$

$$\pi_1^* = Q((1 - Q)b - c + v - c_E(1 - r_L));$$

$$D_{T,1} = Q;$$

$$D_{I,1} = Q;$$

$$D_{N,1} = 0;$$

$$E_{T,1} = (1 - r_L)Q.$$

7) Case 7: $\lambda_1 > 0$, $\lambda_2 > 0$, and $\lambda_3 = 0$

We have $1 - \frac{p-d}{b} - Q = 0$, $p(1 - b) - d = 0$, $\frac{2(p-d-pb)-c(1-b)-c_E(1-r_L-b)+v}{b(1-b)} -$

$\frac{\lambda_1}{b} + \lambda_2 = 0$, and $\frac{-2p+2d+b+c_E(1-r_L)+c-v}{b} + \frac{\lambda_1}{b} - \lambda_2(1 - b) = 0$. Then, we obtain

$$\lambda_1^* = 1 - c - c_E - 2Q > 0 \Leftrightarrow Q < \frac{1-c-c_E}{2};$$

$$\lambda_2^* = \frac{(1-2Q)(1-b)-c_E r_L-v}{b(1-b)} > 0 \Leftrightarrow Q < \frac{1-b-c_E r_L-v}{2(1-b)};$$

$$p^* = 1 - Q;$$

$$d^* = (1 - b)(1 - Q);$$

$$\pi_1^* = Q(1 - c - c_E - Q);$$

$$D_{T,1} = Q;$$

$$D_{I,1} = 0 \text{ (contradictory with } D_{I,1} > 0);$$

$$D_{N,1} = Q;$$

$$E_{T,1} = Q.$$

As there is contradiction, the above solution is not optimal.

8) Case 8: $\lambda_1 > 0$, $\lambda_2 > 0$, and $\lambda_3 > 0$

We have $1 - \frac{p-d}{b} - Q = 0$, $p(1-b) - d = 0$, and $d - (1-b) = 0$. Then, by $p(1-b) - d = 0$, we obtain $p = 1$. Finally, we have $1 - \frac{p-d}{b} - Q = -Q < 0$, which contradicts the condition that $Q > 0$.

(Q.E.D.)

Supplementary B. Derivations of the optimal decisions in Case-I

The optimization problem of the hotel is given by

$$\text{Max } \pi_2 = (1 - p)(p - c - c_E) \quad (\text{S2})$$

$$\text{s.t.} \quad 1 - p \leq Q,$$

$$d < p(1 - b),$$

$$p, d > 0.$$

As $\frac{\partial^2 \pi_2}{\partial p^2} = -2 < 0$, the profit function of the hotel is a convex function. Letting $\mathcal{L} =$

$(1 - p)(p - c - c_E) - \lambda_1(1 - p - Q)$, we have the KKT conditions as follows:

$$\frac{\partial \mathcal{L}}{\partial p} = -2p + 1 + c + c_E + \lambda_1 \leq 0,$$

$$p \frac{\partial \mathcal{L}}{\partial p} = p(-2p + 1 + c + c_E + \lambda_1) = 0,$$

$$1 - p - Q \leq 0,$$

$$\lambda_1(1 - p - Q) = 0,$$

$$0 < p^* < 1,$$

$$\lambda_1^* \geq 0.$$

1) Case 1: $\lambda_1 = 0$

We have $-2p + 1 + c + c_E = 0$ as $p > 0$. Then, we obtain

$$p^* = \frac{1+c+c_E}{2},$$

$$Q \geq 1 - p^* \Leftrightarrow Q \geq \frac{1-(c+c_E)}{2},$$

$$\pi_2^* = \frac{[1-(c+c_E)]^2}{4};$$

$$D_{T,2} = \frac{1-(c+c_E)}{2};$$

$$E_{T,2} = \frac{1-(c+c_E)}{2};$$

$$d^* \leq \frac{(1-b)(1+c+c_E)}{2}.$$

2) Case 2: $\lambda_1 > 0$

We have $1 - p - Q = 0$. Then, we obtain

$$p^* = 1 - Q;$$

$$\lambda_1 = 2(1 - Q) - 1 - c - c_E > 0 \Leftrightarrow \mathbf{Q} < \frac{1-(c+c_E)}{2};$$

$$\pi_2^* = Q[1 - Q - (c + c_E)];$$

$$D_{T,2} = Q;$$

$$E_{T,2} = Q;$$

$$d^* \leq (1 - b)(1 - Q).$$

(Q.E.D.)

Supplementary C. Derivations of the optimal decision results for $d > 1 - b > p(1 - b)$

As mentioned, only I-type customers exist for $\frac{d}{1-b} > 1$. Thus, by $\theta_i \sim \text{Uniform}(0,1)$, market demands of I-type customers, and total demand in this subcase are both given by Equation (S3).

$$D_T = D_{T,3} = D_I = D_{I,3} = \int_{\frac{p-d}{b}}^1 \theta_i d\theta_i = 1 - \frac{p-d}{b}. \quad (\text{S3})$$

As $p \in (0,1)$, $1 - b > p(1 - b)$ always holds. Then, by Equations (3) and (A3), the optimization problem of the hotel is given by

$$\text{Max } \pi_3 = \left(1 - \frac{p-d}{b}\right) (p - c - c_E + v + c_E r_L - d) \quad (\text{S4})$$

$$\text{s.t.} \quad 1 - \frac{p-d}{b} \leq Q,$$

$$d > 1 - b,$$

$$p, d > 0.$$

By Equation (S4), we have $\frac{\partial^2 \pi_3}{\partial p^2} = -\frac{2}{b} < 0$; $\frac{\partial^2 \pi_3}{\partial d^2} = -\frac{2}{b} < 0$; $\frac{\partial^2 \pi_1}{\partial p \partial d} = \frac{\partial^2 \pi_1}{\partial d \partial p} = \frac{2}{b} > 0$.

Thus, we have Hessian Matrix $H(\pi_1) = \begin{vmatrix} \frac{\partial^2 \pi_1}{\partial p^2} & \frac{\partial^2 \pi_1}{\partial p \partial d} \\ \frac{\partial^2 \pi_1}{\partial d \partial p} & \frac{\partial^2 \pi_1}{\partial d^2} \end{vmatrix} = 0$. This means that there is no

optimal solutions for this subcase.

(Q.E.D.)

Supplementary D. Proofs of the propositions

D1. Proof of Proposition 1

By Equations (1) and (2) in the main text, we have $\theta_i > p$ as $U_N > 0$; and $\theta_i > \frac{p-d}{b}$ as $U_I > 0$. In addition, by comparing U_N and U_I , we have $U_N \gtrless U_I$ if and only if $\theta_i \gtrless \frac{d}{1-b}$. Then, by comparing the above thresholds of θ_i , we obtain that $\frac{d}{1-b} \geq p \geq \frac{p-d}{b}$ if $d \geq p(1-b)$; and $\frac{p-d}{b} > p > \frac{d}{1-b}$ if $d < p(1-b)$. Consequently, we obtain Proposition 1. That is, **a)** if $d \geq p(1-b)$, customers with $\theta_i \in (\frac{p-d}{b}, \frac{d}{1-b}]$ will participate in hotel carbon reduction while those with $\theta_i > \frac{d}{1-b}$ will not; **b)** if $d < p(1-b)$, there is no customer participating in hotel carbon reduction, but those with $\theta_i \in (p, 1]$ will check in the hotel.

(Q.E.D.)

D2. Proof of Proposition 2(b)

$$\frac{\partial d_{PE}^{A*}}{\partial b} = \frac{\partial d_{PE}^{O*}}{\partial b} = -\frac{1}{2} < 0, \text{ and } \frac{\partial d_{FE}^{A*}}{\partial b} = \frac{\partial d_{FE}^{O*}}{\partial b} = -1 < 0.$$

(Q.E.D.)

D3. Proof of Proposition 3

Proof of Proposition 3(a). We have $\frac{\partial p_{PE}^{P*}}{\partial b} = \frac{1}{2} - Q$, where $Q < \bar{Q}_1$. $\bar{Q}_1 =$

$$\frac{b-c+v-c_E(1-r_L)}{2b} = \frac{1}{2} - \frac{c-v+c_E(1-r_L)}{2b} < \frac{1}{2}, \text{ as } c-v > 0 \text{ and } 0 < r_L < 1. \text{ Thus, we have}$$

$$Q < \bar{Q}_1 < \frac{1}{2}. \text{ Consequently, we obtain } \frac{\partial p_{PE}^{P*}}{\partial b} = \frac{1}{2} - Q > 0.$$

Proof of Proposition 3(b). We have $\frac{\partial p_{FE}^{O*}}{\partial b} = -\frac{1}{2} < 0$, and $\frac{\partial p_{FE}^{P*}}{\partial b} = -Q < 0$.

(Q.E.D.)

Supplementary E. Derivations of comparison results between Case-E and Case-I

E1. Profit comparison (Table 4)

Case-PE: $v + c_E r_L \leq 1 - b < \frac{c_E r_L + v}{c + c_E}$

$$\text{a) } \Delta\pi_{BS}^{PE} = \frac{[c + c_E(1 - r_L) - v]^2 + b(c + c_E)[2(c_E r_L + v) - c - c_E] - b(1 - b)[2(c + c_E) - 1]}{4b(1 - b)} - \frac{[1 - (c + c_E)]^2}{4} =$$

$$\frac{[v - c(1 - b) - c_E(1 - b - r_L)]^2}{4b(1 - b)} > 0, \text{ as } b > 1 - \frac{c_E r_L + v}{c + c_E} \text{ (see Appendix A for details).}$$

$$\text{b) } \Delta\pi_{GS}^{PE} = \frac{1 - b(1 - 2Q)^2 - 4Q(c + c_E) - 2(1 - 2Q)(c_E r_L + v)}{4} + \frac{(c_E r_L + v)^2}{4(1 - b)} - \frac{[1 - (c + c_E)]^2}{4} = 0 \quad \Leftrightarrow$$

$$Q = \bar{Q}_1 - \frac{\sqrt{\frac{[v - c(1 - b) - c_E(1 - b - r_L)]^2}{1 - b}}}{2b}, \text{ as } Q \leq \bar{Q}_1 \text{ in Situation 3. Thus, we have } \Delta\pi_{GS}^{PE} \geq$$

$$0 \text{ if and only } Q \geq \bar{Q}_1 - \frac{\sqrt{\frac{[v - c(1 - b) - c_E(1 - b - r_L)]^2}{1 - b}}}{2b} \text{ in this situation. Notably, we have}$$

$$\bar{Q}_1 - \frac{\sqrt{\frac{[v - c(1 - b) - c_E(1 - b - r_L)]^2}{1 - b}}}{2b} < \bar{Q}_2 \text{ as } b > 1 - \frac{c_E r_L + v}{c + c_E}. \text{ As } Q > \bar{Q}_2 \text{ in Situation 3,}$$

$$\text{we have } Q > \bar{Q}_1 - \frac{\sqrt{\frac{[v - c(1 - b) - c_E(1 - b - r_L)]^2}{1 - b}}}{2b} \text{ always holds. Hence, we have } \Delta\pi_{GS}^{PE} > 0.$$

$$\text{c) } \Delta\pi_{MS}^{PE} = \frac{1 - b(1 - 2Q)^2 - 4Q(c + c_E) - 2(1 - 2Q)(c_E r_L + v)}{4} + \frac{(c_E r_L + v)^2}{4(1 - b)} - Q[1 - Q - (c +$$

$$c_E)] = \frac{[v + c_E r_L - (1 - b)(1 - 2Q)]^2}{4(1 - b)} > 0 \text{ as } Q > \frac{1 - b - c_E r_L - v}{2(1 - b)} \text{ (see Case 5 in Appendix A}$$

for details).

Case-FE: $1 - b \leq v + c_E r_L$

$$\text{a) } \Delta\pi_{BS}^{FE} = \frac{[b - c + v - c_E(1 - r_L)]^2}{4b} - \frac{[1 - (c + c_E)]^2}{4} = \frac{1}{4} \left[\left(\frac{b - c + v - c_E(1 - r_L)}{\sqrt{b}} + (1 - c - c_E) \right) \left(\frac{b - c + v - c_E(1 - r_L)}{\sqrt{b}} - (1 - c - c_E) \right) \right].$$

As $b \geq 1 - v - c_E r_L$ for $d = 1 - b$, we have $b - c + v - c_E(1 - r_L) \geq 1 - c - c_E > 0$. Thus, we have $\frac{b - c + v - c_E(1 - r_L)}{\sqrt{b}} > (1 - c - c_E)$. Therefore, $\Delta\pi_{BS}^{FE} > 0$.

$$\text{b) } \Delta\pi_{MS}^{FE} = Q[(1 - Q)b - c + v - c_E(1 - r_L)] - \frac{[1 - (c + c_E)]^2}{4} = 0 \quad \Leftrightarrow \quad Q = \bar{Q}_1 -$$

$$\frac{\sqrt{[b - c + v - c_E(1 - r_L)]^2 - b[1 - (c + c_E)]^2}}{2b} \text{ as } Q \leq \bar{Q}_1 \text{ in MS, where } \bar{Q}_2 < Q \leq \bar{Q}_1. \text{ Thus, we}$$

have $\Delta\pi_{MS}^{FE} \geq 0$ if and only $Q \geq \bar{Q}_1 - \frac{\sqrt{[b-c+v-c_E(1-r_L)]^2 - b[1-(c+c_E)]^2}}{2b}$ in this

situation. $\bar{Q}_1 - \frac{\sqrt{[b-c+v-c_E(1-r_L)]^2 - b[1-(c+c_E)]^2}}{2b} - \bar{Q}_2 =$

$$\frac{v-c(1-b)-c_E(1-b-r_L)-\sqrt{[b-c+v-c_E(1-r_L)]^2 - b[1-(c+c_E)]^2}}{2b} \geq 0 \Leftrightarrow b \leq \frac{1+c-2v+c_E(1-2r_L)}{1+c+c_E}.$$

Then, we have $b > 1 - v - c_E r_L > \frac{1+c-2v+c_E(1-2r_L)}{1+c+c_E}$, as $1 - v - c_E r_L -$

$$\frac{1+c-2v+c_E(1-2r_L)}{1+c+c_E} = -\frac{(1-c-c_E)(v+c_E r_L)}{1+c+c_E} < 0. \quad \text{Thus, we have } \bar{Q}_1 -$$

$$\frac{\sqrt{[b-c+v-c_E(1-r_L)]^2 - b[1-(c+c_E)]^2}}{2b} < \bar{Q}_2. \quad \text{This means that } Q > \bar{Q}_1 -$$

$$\frac{\sqrt{[b-c+v-c_E(1-r_L)]^2 - b[1-(c+c_E)]^2}}{2b} \text{ in MS. Consequently, we have } \Delta\pi_{MS}^{FE} > 0.$$

c) $\Delta\pi_{GS}^{FE} = Q[(1-Q)b - c + v - c_E(1-r_L)] - Q[1-Q-(c+c_E)] = Q[v +$
 $c_E r_L - (1-b)(1-Q)] \geq 0 \Leftrightarrow Q \geq \frac{1-b-v-c_E r_L}{1-b}. \text{ As } b \geq 1 - v - c_E r_L,$
 $\frac{1-b-v-c_E r_L}{1-b} \leq 0. \text{ Thus, } Q > \frac{1-b-v-c_E r_L}{1-b} \text{ always holds in GS, as } Q > 0.$

Consequently, $\Delta\pi_{GS}^{FE} > 0$.

(Q.E.D.)

E2. Occupancy comparison (Table 5)

a) $\Delta D_{BS}^{PE} = \Delta D_{BS}^{FE} = \frac{b-c+v-c_E(1-r_L)}{2b} - \frac{1-(c+c_E)}{2} = \frac{v-c(1-b)-c_E(1-b-r_L)}{2b} > 0$, as $b >$
 $1 - \frac{c_E r_L + v}{c+c_E}$ (see Appendix A for details).

b) $\Delta D_{MS}^{PE} = \Delta D_{MS}^{FE} = Q - \frac{1-(c+c_E)}{2} > 0$, as $Q > \frac{1-(c+c_E)}{2} = \bar{Q}_2$ in MS.

c) $\Delta D_{GS}^{PE} = \Delta D_{GS}^{FE} = Q - Q = 0$.

(Q.E.D.)

E3. Price comparison (Table 6)

Case-PE: $v + c_E r_L < 1 - b \leq \frac{c_E r_L + v}{c+c_E}$

a) $\Delta p_{BS}^{PE} = \frac{1+c+c_E}{2} - \frac{1+c+c_E}{2} = 0$.

b) $\Delta p_{MS}^{PE} = \frac{[1+b(1-2Q)+c_E r_L+v]}{2} - \frac{1+c+c_E}{2} = \frac{[b(1-2Q)-c+v-c_E(1-r_L)]}{2} \geq 0 \Leftrightarrow Q \leq$

$$\frac{b-c+v-c_E(1-r_L)}{2b} = \bar{Q}_1. \text{ As } Q \leq \bar{Q}_1 \text{ in MS, we have } \Delta p_{MS}^{PE} \geq 0.$$

$$\text{c) } \Delta p_{GS}^{PE} = \frac{[1+b(1-2Q)+c_E r_L+v]}{2} - (1-Q) > 0 \Leftrightarrow Q > \frac{1-b-c_E r_L-v}{2(1-b)} > 0 \text{ (see Case 5}$$

in Appendix A for details).

Case-FE: $1-b \leq v+c_E r_L$

$$\text{a) } \Delta p_{BS}^{FE} = 1 - \frac{b-c+v-c_E(1-r_L)}{2} - \frac{1+c+c_E}{2} = \frac{1-b-v-c_E r_L}{2} \leq 0, \text{ as } b \geq 1-v-c_E r_L \text{ for}$$

$d = 1-b$ (see Appendix A for details).

$$\text{b) } \Delta p_{MS}^{FE} = 1 - bQ - \frac{1+c+c_E}{2} = \frac{1-c-c_E}{2} - bQ = 0 \Leftrightarrow Q = \frac{1-c-c_E}{2b}. \text{ As } b \geq 1-v-$$

$$c_E r_L \text{ for } d = 1-b, \text{ we have } \frac{1-c-c_E}{2b} - \frac{b-c+v-c_E(1-r_L)}{2b} = \frac{1-b-v-c_E r_L}{2b} \leq 0.$$

Furthermore, $\frac{1-c-c_E}{2b} - \frac{1-c-c_E}{2} > 0$ always holds as $0 < b < 1$. Therefore, we

have $\frac{1-c-c_E}{2} < \frac{1-c-c_E}{2b} \leq \frac{b-c+v-c_E(1-r_L)}{2b}$, i.e., $\bar{Q}_2 < \frac{1-c-c_E}{2b} \leq \bar{Q}_1$. Consequently,

we obtain that $\Delta p_{MS}^{FE} = \frac{1-c-c_E}{2} - bQ \geq 0 \Leftrightarrow Q \leq \frac{1-c-c_E}{2b}$ ($b \leq \frac{1-c-c_E}{2Q}$).

$$\text{c) } \Delta p_{GS}^{FE} = 1 - bQ - (1-Q) = Q(1-b) > 0 \text{ as } 0 < b < 1.$$

(Q.E.D.)

E4. Emission comparison results (Table 7)

Case-PE: $v+c_E r_L < 1-b \leq \frac{c_E r_L+v}{c+c_E}$

$$\text{a) } \Delta E_{BS}^{PE} = \frac{b(1-b-c_E r_L)-c(1-b)(1-r_L)+[v-c_E(1-r_L)](1-b-r_L)}{2b(1-b)} - \frac{1-(c+c_E)}{2} =$$

$$\frac{(1-b-r_L)[v-c(1-b)-c_E(1-b-r_L)]}{2b(1-b)}. \text{ As } b > 1 - \frac{c_E r_L+v}{c+c_E} \text{ (see Case 1 in Appendix A for}$$

details), we have $v-c(1-b)-c_E(1-b-r_L) > 0$. Thus, we have $\Delta E_{BS}^{PE} =$

$$\frac{(1-b-r_L)[v-c(1-b)-c_E(1-b-r_L)]}{2b(1-b)} \geq 0 \text{ if and only if } b \leq 1-r_L.$$

$$\text{b) } \Delta E_{MS}^{PE} = Q(1-r_L) + \frac{r_L(1-b-c_E r_L-v)}{2(1-b)} - \frac{1-(c+c_E)}{2} \geq 0 \Leftrightarrow Q \geq$$

$$\frac{(1-b)(1-c-c_E)-r_L(1-b-c_E r_L-v)}{2(1-b)(1-r_L)}. \text{ Let } \bar{Q}_3 = \frac{(1-b)(1-c-c_E)-r_L(1-b-c_E r_L-v)}{2(1-b)(1-r_L)}, \text{ and then, we}$$

have $\bar{Q}_3 - \bar{Q}_2 = \frac{r_L[v-c(1-b)-c_E(1-b-r_L)]}{2(1-b)(1-r_L)} > 0$, as $b > 1 - \frac{c_E r_L+v}{c+c_E}$. Thus, we have

$\bar{Q}_3 > \bar{Q}_2$. In addition, we have $\bar{Q}_3 - \bar{Q}_1 = \frac{[b-(1-r_L)][v-c(1-b)-c_E(1-b-r_L)]}{2b(1-b)(1-r_L)} \gtrless 0$ if

and only if $b \gtrless 1 - r_L$. Therefore, if $b \geq 1 - r_L$, we have $\bar{Q}_3 \geq \bar{Q}_1$ always holds

in Situation 3. Thus, we have $\Delta E_{MS}^{PE} \leq 0$, as $Q \leq \bar{Q}_1 \leq \bar{Q}_3$ in this situation.

Otherwise, if $b < 1 - r_L$, we have $\bar{Q}_2 < \bar{Q}_3 < \bar{Q}_1$. Thus, we have $\Delta E_{MS}^{PE} \gtrless 0$ if

and only if $Q \gtrless \bar{Q}_3$ in Situation 3.

$$\text{c) } \Delta E_{GS}^{PE} = Q(1 - r_L) + \frac{r_L(1-b-c_E r_L-v)}{2(1-b)} - Q = \frac{r_L[v+c_E r_L-(1-b)(1-2Q)]}{2(1-b)} \gtrless 0 \Leftrightarrow Q \gtrless \frac{1-b-c_E r_L-v}{2(1-b)}.$$

As $Q > \frac{1-b-c_E r_L-v}{2(1-b)}$ (see Case 5 in Appendix A for details), we have

$\Delta E_{GS}^{PE} < 0$ always holds.

Case-FE: $1 - b \leq v + c_E r_L$

$$\text{a) } \Delta E_{BS}^{FE} = (1 - r_L)\bar{Q}_1 - \frac{1-(c+c_E)}{2} = 0 \Leftrightarrow b = \frac{(1-r_L)[c-v+c_E(1-r_L)]}{c+c_E-r_L}.$$

Then,

if $r_L > c + c_E$,

we have $\Delta E_{BS}^{FE} \gtrless 0$ if and only if $b \gtrless \frac{(1-r_L)[c-v+c_E(1-r_L)]}{c+c_E-r_L}$; and have

$$\frac{(1-r_L)[c-v+c_E(1-r_L)]}{c+c_E-r_L} < 0 \text{ as } c > v \text{ and } 0 < r_L < 1. \text{ Thus, } b > \frac{(1-r_L)[c-v+c_E(1-r_L)]}{c+c_E-r_L}$$

always holds because $b > 0$. Consequently, we have $\Delta E_{BS}^{FE} < 0$.

If $r_L = c + c_E$,

$$\text{we have } (1 - r_L)\bar{Q}_1 - \frac{1-(c+c_E)}{2} = -\frac{[1-(c+c_E)][c-v+c_E(1-(c+c_E))]}{2b} < 0 \text{ as } c + c_E < 1$$

and $c > v$. Thus, we have $\Delta E_{BS}^{FE} < 0$ if $r_L = c + c_E$.

If $r_L < c + c_E$,

$$\text{we have } \Delta E_{BS}^{FE} \gtrless 0 \text{ if and only if } b \gtrless \frac{(1-r_L)[c-v+c_E(1-r_L)]}{c+c_E-r_L}.$$

Therefore, we have $\Delta E_{BS}^{FE} < 0$ if $r_L \geq c + c_E$; and $\Delta E_{BS}^{FE} \gtrless 0$ if and only if $b \gtrless$

$$\frac{(1-r_L)[c-v+c_E(1-r_L)]}{c+c_E-r_L}, \text{ for } r_L < c + c_E.$$

$$\text{b) } \Delta E_{GS}^{FE} = (1 - r_L)Q - Q = -r_L Q < 0, \text{ as } r_L > 0 \text{ and } Q > 0.$$

c) $\Delta E_{MS}^{FE} = (1 - r_L)Q - \frac{1-(c+c_E)}{2} \geq 0 \Leftrightarrow Q \geq \bar{Q}_4$, where $\bar{Q}_4 = \frac{1-(c+c_E)}{2(1-r_L)}$. As $0 <$

$1 - r_L < 1$, we have $\bar{Q}_4 > \bar{Q}_2$. By comparing \bar{Q}_4 and \bar{Q}_1 , we have $\bar{Q}_4 - \bar{Q}_1 = 0$

$$\Leftrightarrow b = \frac{(1-r_L)[c-v+c_E(1-r_L)]}{c+c_E-r_L}. \text{ Then,}$$

if $r_L > c + c_E$,

we have $\bar{Q}_4 \geq \bar{Q}_1$ if and only if $b \leq \frac{(1-r_L)[c-v+c_E(1-r_L)]}{c+c_E-r_L}$, where

$$\frac{(1-r_L)[c-v+c_E(1-r_L)]}{c+c_E-r_L} < 0. \text{ As } b > 0, b > \frac{(1-r_L)[c-v+c_E(1-r_L)]}{c+c_E-r_L} \text{ always holds, meaning}$$

that $\bar{Q}_4 < \bar{Q}_1$ is always true. Then, we have $\bar{Q}_2 < \bar{Q}_4 < \bar{Q}_1$. Thus, we have $\Delta E_{MS}^{FE} \geq$

0 if and only if $Q \geq \bar{Q}_4$.

If $r_L = c + c_E$,

We have $\bar{Q}_4 - \bar{Q}_1 = \frac{c-v+c_E(1-r_L)}{2b} > 0$ as $c > v$ and $0 < r_L < 1$. Thus, we have

$\bar{Q}_4 > \bar{Q}_1$. As $\bar{Q}_2 < Q \leq \bar{Q}_1$, $Q < \bar{Q}_4$ always holds in Situation 3, meaning that

$\Delta E_{MS}^{FE} < 0$ always holds.

If $r_L < c + c_E$,

We have $\bar{Q}_4 \geq \bar{Q}_1$ if and only if $b \geq \frac{(1-r_L)[c-v+c_E(1-r_L)]}{c+c_E-r_L}$. Thus, if $b \geq$

$\frac{(1-r_L)[c-v+c_E(1-r_L)]}{c+c_E-r_L}$, we have $\bar{Q}_4 \geq \bar{Q}_1$. Hence, $Q < \bar{Q}_4$ always holds as $\bar{Q}_2 < Q \leq$

\bar{Q}_1 in Situation 3, thereby having that $\Delta E_{MS}^{FE} < 0$. Otherwise, if $b <$

$\frac{(1-r_L)[c-v+c_E(1-r_L)]}{c+c_E-r_L}$, we have $\bar{Q}_2 < \bar{Q}_4 < \bar{Q}_1$, and thus $\Delta E_{MS}^{FE} \geq 0$ if and only if $Q \geq$

\bar{Q}_4 .

(Q.E.D.)