Emission Reduction through Regulating Indirect Sources
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EC.1. Proofs

In this section, we provide the proofs of the results presented in the paper.

Preliminaries: Without loss of generality, we normalize the total number of shipping orders to 1 (i.e., $\sum_{i=1}^{M} N_i = 1$) in all proofs. Accordingly, we can calculate the trucking company's profit functions as follows.

$$P^{\mathcal{T}} \doteq \int_0^{\bar{d}} (p_g - c_g)\cdot a_i(d)\cdot d f(d)\mathrm{d}d + \int_0^{\bar{d}} (p_e - c_e - I/L)\cdot(1-a_i(d))\cdot d\cdot f(d)\mathrm{d}d - m\cdot\int_0^{\bar{d}} a_i(d)\cdot f(d)\mathrm{d}d, \quad \text{(A1)}$$

$$P^{\mathcal{W}} \doteq \int_0^{\bar{d}} (p_g - c_g)\cdot a_i(d)\cdot d f(d)\mathrm{d}d + \int_0^{\bar{d}} (p_e - c_e - I/L)\cdot(1-a_i(d))\cdot d f(d)\mathrm{d}d, \quad \text{(A2)}$$

$$P^{\mathcal{WT}} \doteq \int_0^{\bar{d}} (p_g - c_g)\cdot a_i(d)\cdot d f(d)\mathrm{d}d + \int_0^{\bar{d}} (p_e - c_e - \frac{I-s}{L})\cdot(1-a_i(d))\cdot d f(d)\mathrm{d}d, \quad \text{(A3)}$$

where the subsidy level s under policy $\mathcal{WT}$ is given by $s = \min\left\{\frac{L\cdot m\cdot\int_0^{\bar{d}} a_i(d)\cdot f(d)\mathrm{d}d}{\int_0^{\bar{d}}(1-a_i(d))\cdot d\cdot f(d)\mathrm{d}d}, I\right\}$.

Proof of Lemma 1. We conduct backward induction to solve the equilibrium outcome under policy $\mathcal{T}$. First, given any $d\in[0,\bar{d}]$, the rental decision of warehouse i that minimizes its cost $C_i^{\mathcal{T}}$ is given by $a_i(d)=0$ if $p_e \le p_g$ and $a_i(d)=1$ if $p_e > p_g$. Correspondingly, the trucking company's profit equals

$$P^{\mathcal{T}}(p_e) = \begin{cases} P_1^{\mathcal{T}}(p_e) \doteq \int_0^{\bar{d}}(p_e - c_e - I/L) d f(d)\mathrm{d}d = (p_e - c_e - I/L)\cdot\frac{\bar{d}}{2}, & \text{if } p_e \le p_g \\ P_2^{\mathcal{T}} \doteq \int_0^{\bar{d}}\left[(p_g - c_g)d - m\right] f(d)\mathrm{d}d = (p_g - c_g)\cdot\frac{\bar{d}}{2} - m, & \text{if } p_e > p_g\,. \end{cases} \quad \text{(A4)}$$

Case (i): If $0 < m < \frac{\bar{d}}{2}\cdot\Delta_c$, it can be calculated that $P_1^{\mathcal{T}}(p_e) < P_2^{\mathcal{T}}$ $\forall p_e \le p_g$ given that $\Delta_c > 0$. Hence, it is optimal for the trucking company to set $p_e^{\mathcal{T}} > p_g$. Accordingly, all warehouses adopt diesel trucks for their trips.

Case (ii): If $m \ge \frac{\bar{d}}{2}\cdot\Delta_c$, it can be calculated that $\max_{p_e\le p_g} P_1^{\mathcal{T}}(p_e) \ge P_1^{\mathcal{T}}(p_e)$, where the maximum of $P_1^{\mathcal{T}}(p_e)$ is achieved when $p_e = p_g$. Hence, it is optimal for the trucking company to set $p_e^{\mathcal{T}} = p_g$. Accordingly, all warehouses adopt electric trucks for their trips. This completes the proof of Lemma 1. □

Proof of Lemma 2. We apply the same backward induction procedure used in the proof of Lemma 1. Specifically, under policy $\mathcal{W}$, for a shipping order with traveling distance d, warehouse i incurs a rental cost of $p_e d$ for using an electric truck, and $p_g d + m$ for using a diesel truck. Hence, the optimal rental decision for warehouse i is given by $a_i(d)=0$ if $0 < d \le \frac{m}{p_e - p_g}$ and $a_i(d)=1$ if $d > \frac{m}{p_e-p_g}$. Let t denote the distance threshold $\frac{m}{p_e-p_g}$ in the warehouses' optimal decision. Accordingly, the trucking company's profit equals

$$P^{\mathcal{W}}(p_e) = \begin{cases} \int_0^t (p_e - c_e - I/L)\, d f(d)\mathrm{d}d + \int_t^{\bar{d}}(p_g - c_g) d f(d)\mathrm{d}d, & \text{if } p_e > p_g + \frac{m}{\bar{d}} \\ \int_0^{\bar{d}} (p_e - c_e - I/L)\, d f(d)\mathrm{d}d, & \text{if } p_e \le p_g + \frac{m}{\bar{d}} \end{cases} \quad \text{(A5)}$$

It is straightforward to show that $P^{\mathcal{W}}(p_e)$ increases with p_e when $p_e \le p_g + \frac{m}{\bar{d}}$, and it remains continuous at $p_e = p_g + \frac{m}{\bar{d}}$. When $p_e > p_g + \frac{m}{\bar{d}}$, it can be calculated that $\frac{\partial P^{\mathcal{W}}}{\partial p_e} = \frac{m^2(p_g + 2\Delta_c - p_e)}{2\bar{d}(p_e - p_g)^3}$. Accordingly,

Case (i): if $0 < m < 2\bar{d}\cdot\Delta_c$, it can be shown that $P^{\mathcal{W}}$ is maximized when $p_e^{\mathcal{W}} = p_g + 2\Delta_c$. Plugging this optimal price into the warehouse decision, we obtain that the equilibrium t threshold, $t^{\mathcal{W}}$, equals $\frac{m}{2\Delta_c}$. Hence, warehouses adopt electric trucks if $0 < d \le \frac{m}{2\Delta_c}$ and diesel trucks otherwise.

Case (ii): If $m \ge 2\bar{d}\cdot\Delta_c$, $P^{\mathcal{W}}$ decreases in $p_e \in (p_g + \frac{m}{\bar{d}}, \infty)$, and thus the optimal solution is $p_e^{\mathcal{W}} = p_g + \frac{m}{\bar{d}}$. In that case, $t^{\mathcal{W}} = \bar{d}$, and warehouses adopt electric trucks for all trips. This completes the proof of Lemma 2. □

Proofs of Proposition 1 and Proposition 2. These two propositions directly follow from the equilibrium characterization shown in the proofs of Lemmas 1 and 2. Specifically, we can calculate the following.

- Under the direct source rule, by Lemma 1,
  —if $0 < m < \frac{\bar{d}}{2}\cdot\Delta_c$, $G^{\mathcal{T}} = 0$, $C^{\mathcal{T}} = \sum_{i=1}^{M} C_i^{\mathcal{T}} = p_g\cdot\frac{\bar{d}}{2}$, $P^{\mathcal{T}} = (p_g - c_g)\cdot\frac{\bar{d}}{2} - m$, and $B^{\mathcal{T}} = C^{\mathcal{T}} - P^{\mathcal{T}} = c_g\cdot\frac{\bar{d}}{2} + m$.
  —if $m \ge \frac{\bar{d}}{2}\cdot\Delta_c$, $G^{\mathcal{T}} = 1$, $C^{\mathcal{T}} = p_g\cdot\frac{\bar{d}}{2}$, $P^{\mathcal{T}} = \left(p_g - c_e - \frac{I}{L}\right)\cdot\frac{\bar{d}}{2}$, and $B^{\mathcal{T}} = C^{\mathcal{T}} - P^{\mathcal{T}} = \left(c_e + \frac{I}{L}\right)\cdot\frac{\bar{d}}{2}$.

- Under the indirect source rule, by Lemma 2,

—if $0<m<2\bar{d}\cdot\Delta_c$, $G^{\mathcal{W}}=(t^{\mathcal{W}})^2/\bar{d}^2=\left(\frac{m}{2\Delta_c}\right)^2/\bar{d}^2$, $C^{\mathcal{W}}=\sum_{i=1}^{M}C_i^{\mathcal{W}}=m-\frac{m^2}{4\bar{d}\cdot\Delta_c}+p_g\cdot\frac{\bar{d}}{2}$, $P^{\mathcal{W}}=\frac{m^2}{8\bar{d}\cdot\Delta_c}+(p_g-c_g)\cdot\frac{\bar{d}}{2}$, and $B^{\mathcal{W}}=C^{\mathcal{W}}-P^{\mathcal{W}}=m-\frac{3m^2}{8\bar{d}\cdot\Delta_c}+c_g\cdot\frac{\bar{d}}{2}$.

—if $m\geq 2\bar{d}\cdot\Delta_c$, $G^{\mathcal{W}}=1$, $C^{\mathcal{W}}=p_g\cdot\frac{\bar{d}}{2}+m$, $P^{\mathcal{W}}=\left(p_g+\frac{m}{\bar{d}}-c_e-\frac{I}{L}\right)\cdot\frac{\bar{d}}{2}$, and $B^{\mathcal{W}}=C^{\mathcal{W}}-P^{\mathcal{W}}=\left(c_e+\frac{I}{L}\right)\cdot\frac{\bar{d}}{2}$.

Comparing the above values leads to Proposition 1 and Proposition 2. □.

Proof of Lemma 3. Since the subsidy does not affect warehouses' cost function, the warehouses' optimal rental decision under policy $\mathcal{WT}$ is the same as that under policy $\mathcal{W}$ as shown in the proof of Lemma 2. Accordingly, the trucking company's profit function under policy $\mathcal{WT}$ can be then expressed as:

$$P^{\mathcal{WT}}(p_e)=\begin{cases}\int_0^t(p_e-c_e)\,df(d)\mathrm{d}d+\int_t^{\bar{d}}(p_g-c_g)\,df(d)\mathrm{d}d-\frac{I-s}{L}\int_0^t df(d)\mathrm{d}d, & \text{if } p_e>p_g+\frac{m}{\bar{d}}\\ \int_0^{\bar{d}}(p_e-c_e-I/L)df(d)\mathrm{d}d, & \text{if } p_e\leq p_g+\frac{m}{\bar{d}}\end{cases}, \tag{A6}$$

where the subsidy per electric truck is defined as $s=\min\left\{I,\frac{mL\cdot\int_{\frac{m}{p_e-p_g}}^{\bar{d}}f(d)\mathrm{d}d}{\int_0^{\frac{m}{p_e-p_g}}df(d)\mathrm{d}d}\right\}$. It is straightforward to show that $P^{\mathcal{WT}}(p_e)$ increases with p_e when $p_e\leq p_g+\frac{m}{\bar{d}}$, and it remains continuous at $p_e=p_g+\frac{m}{\bar{d}}$. Next, we analyze the monotonicity of $P^{\mathcal{WT}}(p_e)$ over the interval $p_e>p_g+\frac{m}{\bar{d}}$. For analytical convenience, we write p_e as a function of t, i.e., $p_e=p_g+\frac{m}{t}$ and plug it into the formula of $P^{\mathcal{WT}}(p_e)$. We denote the resulting function as $P^{\mathcal{WT}}(t)$. The interval $p_e>p_g+\frac{m}{\bar{d}}$ corresponds to $t\in(0,\bar{d})$. In the rest of this proof, we analyze the monotonicity of $P^{\mathcal{WT}}(t)$ where $t\in(0,\bar{d})$. To do so, it can be calculated that the subsidy $s=I$ if $0<t\leq\tilde{t}$ and $s=\frac{2mL\left(\bar{d}-t\right)}{t^2}$ if $\tilde{t}<t\leq\bar{d}$, where $\tilde{t}=\bar{d}\cdot\frac{2L}{\sqrt{L^2+\frac{2L\bar{d}\cdot I}{m}}+L}$ which can be shown to reside in $(0,\bar{d})$. That is, when $t=\tilde{t}$, the collected mitigation fees exactly offset the trucking company's investment costs, resulting in zero actual truck investment expenditure under policy $\mathcal{WT}$. Accordingly, we analyze the following two cases.

Case (i): If $0<t\leq\tilde{t}$, we plug $s=I$ into the first piece of the equation (A6) and calculate that $P^{\mathcal{WT}}(t)=\frac{m\cdot t+\left(c_g-c_e\right)t^2+\left(p_g-c_g\right)\bar{d}^2}{2\bar{d}}$. In this case, $P^{\mathcal{WT}}(t)$ increases over the interval $t\in(0,\tilde{t}]$.

Case (ii): If $\tilde{t}<t<\bar{d}$, we plug $s=\frac{2mL\left(\bar{d}-t\right)}{t^2}$ into the first piece of the equation (A6) and calculate that $P^{\mathcal{WT}}(t)=\frac{-\Delta_c\cdot t^2-m\cdot t+\left(p_g-c_g\right)\bar{d}^2+2m\bar{d}}{2\bar{d}}$. It can be calculated that $P^{\mathcal{WT}}(t)$ decreases over the interval $t\in(\tilde{t},\bar{d}]$.

Combining the aforementioned cases, we conclude that the trucking company achieves the maximum profit at $t=\tilde{t}$ or equivalently $p_e=p_g+\frac{m}{\tilde{t}}$ which is the equilibrium price. Plugging this price back into the warehouses' decisions, we obtain that the equilibrium distance threshold is $t^{\mathcal{WT}}=\tilde{t}$; trips below this threshold choose to adopt electric trucks, while those above it use diesel trucks. This completes the proof of Lemma 3. □

Proof of Proposition 3. We first compare the equilibrium price, electric truck adoption rate, and warehouses' cost under policies $\mathcal{W}$ and $\mathcal{WT}$. Based on Lemmas 2 and 3, it can be shown that under each policy $r=\mathcal{W},\mathcal{WT}$, $p_e^r=p_g+\frac{m}{t^r}$, $G^r=(t^r)^2/\bar{d}^2$ and $C^r=p_g\cdot\frac{\bar{d}}{2}-\frac{m\cdot t^r}{2\bar{d}}+m$, where t^r is the distance threshold that defines warehouses' rental decision in equilibrium under policy r. Since we have obtained that $t^{\mathcal{W}}=\frac{m}{2\Delta_c}$ if $0\leq m<2\bar{d}\cdot\Delta_c$ and $t^{\mathcal{W}}=\bar{d}$ if $m\geq 2\bar{d}\cdot\Delta_c$ (see the proof of Lemma 2), and $t^{\mathcal{WT}}=\bar{d}\cdot\frac{2L}{\sqrt{L^2+\frac{2L\bar{d}\cdot I}{m}}+L}$ (see the proof of Lemma 3), we can calculate that $t^{\mathcal{WT}}>t^{\mathcal{W}}$ if and only if $m<\frac{8\bar{d}\Delta_c^2}{I/L+4\Delta_c}$ and $t^{\mathcal{WT}}<t^{\mathcal{W}}$ if and only if $m>\frac{8\bar{d}\Delta_c^2}{I/L+4\Delta_c}$. Accordingly, we have:

- Since G^r is increasing in t^r, $G^{\mathcal{WT}}>G^{\mathcal{W}}$ if and only if $t^{\mathcal{WT}}>t^{\mathcal{W}}$ and in turn, if and only if $m<\frac{8\bar{d}\Delta_c^2}{I/L+4\Delta_c}$.
- Since both p_e^r and C^r are decreasing in t^r, it follows that $p_e^{\mathcal{WT}}<p_e^{\mathcal{W}}$ and $C^{\mathcal{WT}}<C^{\mathcal{W}}$ if and only if $t^{\mathcal{WT}}>t^{\mathcal{W}}$, which in turn implies $m<\frac{8\bar{d}\Delta_c^2}{I/L+4\Delta_c}$.

We then compare the trucking company's equilibrium profit. Under policy $\mathcal{WT}$, it can be calculated that $P^{\mathcal{WT}}=\left(p_g+\frac{m}{t^{\mathcal{WT}}}-c_e\right)\cdot\left[(t^{\mathcal{WT}})^2/\bar{d}^2\right]\cdot\frac{\bar{d}}{2}+(p_g-c_g)\left[1-\left(t^{\mathcal{WT}}\right)^2/\bar{d}^2\right]\cdot\frac{\bar{d}}{2}$. Compare this equation with $P^{\mathcal{W}}$ (presented in the proof of Proposition 2), it can be shown that $P^{\mathcal{WT}}=P^{\mathcal{WT}}|_{t=t^{\mathcal{WT}}}>P^{\mathcal{WT}}|_{t=t^{\mathcal{W}}}>P^{\mathcal{W}}|_{t=t^{\mathcal{W}}}=P^{\mathcal{W}}$.

Finally, we compare industry burden under the two policies. By definition, $B^{\mathcal{W}} = \int_0^{t^{\mathcal{W}}} \left(c_e + \frac{I}{L}\right) df(d)\mathrm{d}d + \int_{t^{\mathcal{W}}}^{\bar{d}} (c_g \cdot d + m)\, f(d)\,\mathrm{d}d$ and $B^{\mathcal{WT}} = \int_0^{t^{\mathcal{WT}}} c_e \cdot df(d)\,\mathrm{d}d + \int_{t^{\mathcal{WT}}}^{\bar{d}} (c_g \cdot d + m)\, f(d)\,\mathrm{d}d$. We consider two cases as follows.

Case (i): Assume $t^{\mathcal{WT}} \geq t^{\mathcal{W}}$. In this case, define $\mathcal{F}_1(t) \doteq \int_0^t c_e \cdot df(d)\,\mathrm{d}d + \int_t^{\bar{d}} c_g \cdot df(d)\,\mathrm{d}d$. Then we can show that

$$B^{\mathcal{W}} - B^{\mathcal{WT}} = \left[\mathcal{F}_1(t^{\mathcal{W}}) - \mathcal{F}_1(t^{\mathcal{WT}})\right] + \int_{t^{\mathcal{W}}}^{t^{\mathcal{WT}}} mf(d)\mathrm{d}d + \int_0^{t^{\mathcal{W}}} \frac{I}{L} \cdot df(d)\mathrm{d}d.$$

Because it can be shown that $\mathcal{F}_1(t)$ decreases in $t \in (0, \bar{d})$, we have $B^{\mathcal{W}} - B^{\mathcal{WT}} > 0$ when $t^{\mathcal{WT}} \geq t^{\mathcal{W}}$.

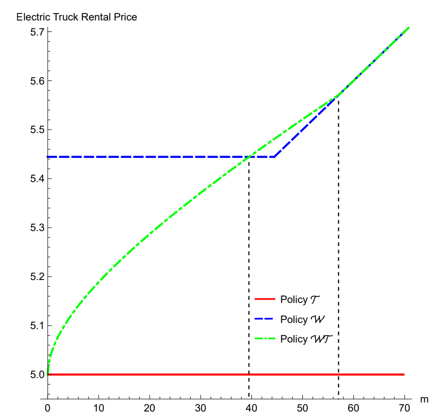
Case (ii): Assume $t^{\mathcal{WT}} < t^{\mathcal{W}}$. Since we have $\int_0^{t^{\mathcal{WT}}} \frac{I}{L} \cdot df(d)\,\mathrm{d}d = \int_{t^{\mathcal{WT}}}^{\bar{d}} m \cdot f(d)\,\mathrm{d}d$ under policy $\mathcal{WT}$ (i.e., subsidy funding is fully used), we can rewrite $B^{\mathcal{WT}}$ as $B^{\mathcal{WT}} = \int_0^{t^{\mathcal{WT}}} (c_e + \frac{I}{L}) \cdot df(d)\,\mathrm{d}d + \int_{t^{\mathcal{WT}}}^{\bar{d}} c_g \cdot df(d)\,\mathrm{d}d$. In this case, define $\mathcal{F}_2(t) = \int_0^t (c_e + \frac{I}{L}) \cdot df(d)\,\mathrm{d}d + \int_t^{\bar{d}} c_g \cdot f(d)\,\mathrm{d}d$. Then we can show that

$$B^{\mathcal{W}} - B^{\mathcal{WT}} = \mathcal{F}_2(t^{\mathcal{W}}) - \mathcal{F}_2(t^{\mathcal{WT}}) + \int_{t^{\mathcal{WT}}}^{\bar{d}} m \cdot f(d)\,\mathrm{d}d.$$

Because it can be shown that $\mathcal{F}_2(t)$ increases in $t \in (0, \bar{d})$, we have $B^{\mathcal{W}} - B^{\mathcal{WT}} > 0$ when $t^{\mathcal{WT}} < t^{\mathcal{W}}$ in this case too. This completes the proof of Proposition 3. $\square$

Proof of Lemma 4. We first characterize the Nash equilibrium of the competition model.

Figure A1: **Clearing price of electric truck rentals in the competition model (for $K = 5, p_g = 5, c_g = 2, c_e = 0.5, I/L = 4.3, \bar{d} = 100$)**



Lemma A1. *Consider a competitive scenario with $K \geq 2$ trucking companies.*

(i) Under the direct source rule, $Q_j^{\mathcal{T}} = 0$ $\forall j \in \mathcal{K}$ if $0 < m < \frac{\bar{d}}{2} \cdot \Delta_c^K$, and $Q_j^{\mathcal{T}} = \frac{\bar{d}}{2K}$ $\forall j \in \mathcal{K}$ if $m \geq \frac{\bar{d}}{2} \cdot \Delta_c^K$.

(ii) Under the indirect source rule (without subsidies), $Q_j^{\mathcal{W}} = \frac{m^2(2K-1)^2}{8\bar{d}K \cdot (\Delta_c^K)^2}$ $\forall j \in \mathcal{K}$ if $0 < m < \frac{2\bar{d}}{2K-1} \cdot \Delta_c^K$, and $Q_j^{\mathcal{W}} = \frac{\bar{d}}{2K}$ $\forall j \in \mathcal{K}$ if $m \geq \frac{2\bar{d}}{2K-1} \cdot \Delta_c^K$.

(iii) Under the indirect source rule with subsidies, $Q_j^{\mathcal{WT}} = \frac{(2K-1)^2 m^2 + 16m(K-1)\bar{d} \cdot \Delta_c^K - (2K-1)\sqrt{(2K-1)^2 m^4 + 32m^3(K-1)\bar{d} \cdot \Delta_c^K}}{16K\bar{d} \cdot \left(\Delta_c^K\right)^2}$ $\forall j \in \mathcal{K}$ if $0 < m < \frac{2\bar{d}}{2K-3} \cdot \Delta_c^K$, and $Q_j^{\mathcal{WT}} = \frac{\bar{d}}{2K}$ $\forall j \in \mathcal{K}$ if $m \geq \frac{2\bar{d}}{2K-3} \cdot \Delta_c^K$.

We prove Lemma A1 as follows.

- First consider the direct source rule.

—**Policy $\mathcal{T}$- Case (i):** Assume $0 < m < \frac{\bar{d}}{2} \cdot \Delta_c^K$. For any trucking company $j \in \mathcal{K}$, given $Q_l^{\mathcal{T}} = 0$ $\forall l \neq j$, there are two feasible quantities for j (given that its profit function is defined when the total supply Q is either 0 or $\sum_{i=1}^M n_i$.)

$*$ $Q_j^{\mathcal{T}} = 0$, which gives rise to a total supply of $Q = 0$ electric trucks. The corresponding market clearing price is $p_e^{\mathcal{T}}(Q) > p_g$. Plugging it into the trucking company's profit function in equation (7) in the paper, we obtain $P_j^{\mathcal{T}}(Q_j, Q_{-j}) = (p_g - c_g) \cdot \frac{1}{K} \cdot \sum_{i=1}^M n_i - m \cdot \frac{1}{K}$.

$*$ $Q_j^{\mathcal{T}} = \sum_{i=1}^M n_i$, which gives rise to a total supply of $Q = \sum_{i=1}^M n_i$. The corresponding market clearing price is $p_e^{\mathcal{T}}(Q) = p_g$. Plugging it into the trucking company's profit function in equation (7) in the paper, we obtain $P_j^{\mathcal{T}}(Q_j, Q_{-j}) = (p_g - c_e - I/L) \cdot \sum_{i=1}^M n_i$.

When $0 < m < \frac{\bar{d}}{2} \cdot \Delta_c^K$, it can be calculated that trucking company's profit is higher under $Q_j^{\mathcal{T}} = 0$ than under $Q_j^{\mathcal{T}} = \sum_{i=1}^M n_i$ assuming a uniform distance distribution. Hence, $Q_j^{\mathcal{T}} = 0$ is the Nash equilibrium in this case.

—**Policy $\mathcal{T}$ - Case (ii):** Assume $m \geq \frac{\bar{d}}{2} \cdot \Delta_c^K$. For any trucking company $j \in \mathcal{K}$, given $Q_l^{\mathcal{T}} = \frac{\bar{d}}{2K}$ $\forall l \neq j$, the only feasible quantity for company j to ensure a well-defined market clearing price $p_e^{\mathcal{T}}(Q) = p_g$ is $Q_j = \frac{\bar{d}}{2K}$ (such that $Q = \sum_{i=1}^M n_i$). Accordingly, trucking company j's profit function is $P_j^{\mathcal{T}}(Q_j, Q_{-j}) = (p_g - c_e - I/L)Q_j + (p_g - c_g) \cdot \frac{1}{K} \cdot \left[\frac{\bar{d}}{2} - \left(\frac{\bar{d}(K-1)}{2K} + Q_j\right)\right] - m \cdot \frac{1}{K} \cdot \left[\frac{\bar{d}}{2} - \left(\frac{\bar{d}(K-1)}{2K} + Q_j\right)\right] / \left(\frac{\bar{d}}{2}\right)$ which can be shown to increase in $Q_j \in (0, \frac{\bar{d}}{2K}]$. Thus, if $m > \frac{\bar{d}}{2} \cdot \Delta_c$, $Q_j^{\mathcal{T}} = \frac{\bar{d}}{2K}$ $\forall j \in \mathcal{K}$ constitutes a Nash equilibrium.

• Next consider the indirect source rule without subsidies. We can derive the trucking company's profit under this policy in three steps. First, as shown in the proof of Lemma 2, given the rental prices p_e and p_g, a shipping order with distance $d \le \frac{m}{p_e - p_g}$ will use electric trucks, while orders with distance $d > \frac{m}{p_e - p_g}$ will use diesel trucks. Second, we solve for the p_e solution that satisfies $Q = \int_0^{\frac{m}{p_e - p_g}} df(d)\mathrm{d}d$ to obtain the market clearing price $p_e^{\mathcal{W}}(Q) = p_g + m/\sqrt{2\bar{d}\cdot Q}$. Third, we plug in the market clearing price into the trucking company's profit function and obtain $P_j^{\mathcal{W}}(Q_j) = (p_g + m/\sqrt{2\bar{d}\cdot Q} - c_e - \frac{I}{L})Q_j + (p_g - c_g)\cdot \frac{1}{K}\cdot(\bar{d}/2 - Q)$. We then analyze the maximum of this function.

—**Policy $\mathcal{W}$ - Case (i):** Assume $m < \frac{2\bar{d}}{2K-1}\cdot \Delta_c^K$. For any trucking company $j \in \mathcal{K}$, given $Q_l^{\mathcal{W}} = \frac{m^2(2K-1)^2}{8\bar{d}K\cdot(\Delta_c^K)^2}$ $\forall l \neq j$, j's feasible quantity decision region is the interval $[0, \sum_{i=1}^M n_i - (K-1)\cdot \frac{m^2(2K-1)^2}{8\bar{d}K\cdot(\Delta_c^K)^2}]$. Furthermore, given $Q_{-j}^{\mathcal{W}} = \frac{m^2(2K-1)^2}{8\bar{d}K\cdot(\Delta_c^K)^2}\cdot(K-1)$, it can be verified that $\frac{\partial P_j^{\mathcal{W}}}{\partial Q_j} = 0$ when $Q_j = \frac{m^2(2K-1)^2}{8\bar{d}K\cdot(\Delta_c^K)^2}$. It can be shown that this value resides in the feasible quantity decision region formulated above when $m < \frac{2\bar{d}}{2K-1}\cdot\Delta_c^K$. Since this holds for all $j\in\mathcal{K}$, $Q_j^{\mathcal{W}} = \frac{m^2(2K-1)^2}{8\bar{d}K\cdot(\Delta_c^K)^2}$ $\forall j \in \mathcal{K}$ is a Nash equilibrium by definition.

—**Policy $\mathcal{W}$ - Case (ii):** Assume $m \ge \frac{2\bar{d}}{2K-1}\cdot\Delta_c^K$. For any trucking company $j\in\mathcal{K}$, given $Q_l^{\mathcal{W}} = \frac{\bar{d}}{2K}$ $\forall l \neq j$, j's feasible quantity decision region is the interval $[0, \sum_{i=1}^M n_i - (K-1)\cdot\frac{\bar{d}}{2K}]$. It can be verified that when $m \ge \frac{2\bar{d}}{2K-1}\cdot\Delta_c^K$, the function $P_j^{\mathcal{W}}$ increases in $Q_j \in [0, \frac{\bar{d}}{2K}]$. Since this holds for all $j\in\mathcal{K}$, $Q_j^{\mathcal{W}} = \frac{\bar{d}}{2K}$ $\forall j\in\mathcal{K}$ is a Nash equilibrium.

• The proof of the equilibrium outcome under the indirect source rule with subsidies is similar to that under the indirect source rule without subsidies, and is omitted for brevity. This completes the proof of Lemma A1.

Back to the proof of Lemma 4, it can be observed from the proof of Lemma A1 that in Case (i), examined under any policy r, the equilibrium total supply is strictly smaller than the total demand for trucks $\sum_{i=1}^M n_i$, indicating that $G^r < 1$ under the condition that corresponds to that case. In contrast, equilibrium total supply equals $\sum_{i=1}^M n_i$, i.e., $G^r = 1$ in Case (ii). This completes the proofs of Lemma 4. □

Proof of Proposition 4. The result follows directly from Lemma 4, and the proof is omitted for brevity. □

Proof of Proposition 5. Recall from Lemma 1-3 that under the uniform distribution, warehouses' rental decision follows a threshold policy based on the trip distance. We find this remains the case yet the thresholds t^r and accordingly the equilibrium price p_e^r are different under the generalized distribution $f(d)$, which we characterize as follows.

LEMMA A2. *Consider the distance distribution $f(d) = k\cdot(d - \bar{d}/2) + 1/\bar{d}$ where $k > 0$.*

(i) Under the direct source rule, the distance threshold in equilibrium is $t^{\mathcal{T}} = \begin{cases} 0, & 0 < m < \frac{\bar{d}}{12}(6+\bar{d}^2k)\cdot\Delta_c \\ \bar{d}, & m \ge \frac{\bar{d}}{12}(6+\bar{d}^2k)\cdot\Delta_c \end{cases}$. *The equilibrium rental price of electric trucks is* $p_e^{\mathcal{T}} \begin{cases} > p_g, & 0 < m < \frac{\bar{d}}{12}(6+\bar{d}^2k)\cdot\Delta_c \\ = p_g, & m \ge \frac{\bar{d}}{12}(6+\bar{d}^2k)\cdot\Delta_c \end{cases}$.

(ii) Under the indirect source rule without subsidies, the distance threshold in equilibrium is $t^{\mathcal{W}} = \begin{cases} t_{inte}^{\mathcal{W}}, & 0 \le m < \frac{6\bar{d}\Delta_c(2+\bar{d}^2k)}{6+5\bar{d}^2k} \\ \bar{d}, & m \ge \frac{6\bar{d}\Delta_c(2+\bar{d}^2k)}{6+5\bar{d}^2k} \end{cases}$, *where* $t_{inte}^{\mathcal{W}} = \frac{3(2-\bar{d}^2k)}{\sqrt{(4\bar{d}k)^2 + \frac{3\Delta_c(2-\bar{d}^2k)}{m}\left(\frac{3\Delta_c(2-\bar{d}^2k)}{m} + 4\bar{d}k\right)} - 4\bar{d}k + \frac{3\Delta_c(2-\bar{d}^2k)}{m}}$, *and* $p_e^{\mathcal{W}} = p_g + \frac{m}{t^{\mathcal{W}}}$.

(iii) Under the indirect source rule with subsidies, the distance threshold in equilibrium $t^{\mathcal{WT}}$ is determined by the t solution to the equation $\frac{t^2\left(6-\bar{d}k(3\bar{d}-4t)\right)}{(\bar{d}-t)(2+\bar{d}kt)} = \frac{6mL}{I}$ *for any $m > 0$, and* $p_e^{\mathcal{WT}} = p_g + \frac{m}{t^{\mathcal{WT}}}$.

The proof of Lemma A2 is similar to those of Lemma 1-3 previously presented and thus is omitted for brevity in this appendix. Instead, the proof of Lemma A2 is available in EC.4 on SSRN (link).

We use Lemma A2 to prove Proposition 5. First, since electric truck adoption G^r increases in the distance threshold t^r under policies $r = \mathcal{T}, \mathcal{W}, \mathcal{WT}$, it follows that $G^{\mathcal{W}} > G^{\mathcal{T}}$ if and only if $m < \frac{\bar{d}}{12}\left(6+\bar{d}^2k\right)\cdot\Delta_c$. It is easy to show that $\frac{\bar{d}}{12}\left(6+\bar{d}^2k\right)\cdot\Delta_c > \frac{\bar{d}}{2}\cdot\Delta_c$ (which is the threshold identified in Proposition 1) given $k > 0$.

Next, we compare $t^{\mathcal{W}}$ with $t^{\mathcal{WT}}$. Since it can be shown that $t_{inte}^{\mathcal{W}}$ decreases Δ_c and the equilibrium subsidy $s^{\mathcal{WT}} = I$, it follows that $\lim_{m\to 0^+} t^{\mathcal{WT}} > \lim_{m\to 0^+} t^{\mathcal{W}}$. Moreover, because $t^{\mathcal{W}} = \bar{d}$ when $m \ge \frac{6\bar{d}\Delta_c(2+\bar{d}^2k)}{6+5\bar{d}^2k}$ and $\lim_{m\to\infty} t_1^{\mathcal{WT}} = \bar{d}$, there must exist a threshold $\hat{m}_{incr} \in \big(0, \frac{6\bar{d}\Delta_c(2+\bar{d}^2k)}{6+5\bar{d}^2k}\big)$ such that $t^{\mathcal{WT}} > t^{\mathcal{W}}$ if and only if $m < \hat{m}_{incr}$. We then compare the threshold $\hat{m}_{incr}$ with that under the uniform distribution, denoted by $\hat{m}_{unif} \doteq \frac{8\bar{d}\Delta_c^2}{I/L+4\Delta_c}$. We also denote $\rho \doteq \frac{I/L}{\Delta_c}$.

Case (i): When $\frac{6}{5\bar{d}^2} < k \le \frac{2}{\bar{d}^2}$ and $1 < \rho \le \frac{8\bar{d}^2k}{3(2+\bar{d}^2k)}$, we have $\frac{6\bar{d}\Delta_c(2+\bar{d}^2k)}{6+5\bar{d}^2k} \le \frac{8\bar{d}\Delta_c^2}{I/L+4\Delta_c}$ and $\hat{m}_{incr} < \hat{m}_{unif}$ holds.

Case (ii): When either (i) $0 < k \le \frac{6}{5\bar{d}^2}$, or (ii) $\frac{6}{5\bar{d}^2} < k \le \frac{2}{\bar{d}^2}$ and $\rho = \frac{I/L}{\Delta_c} > \frac{8\bar{d}^2k}{3(2+\bar{d}^2k)}$, we have $\frac{6\bar{d}\Delta_c(2+\bar{d}^2k)}{6+5\bar{d}^2k} > \frac{8\bar{d}\Delta_c^2}{I/L+4\Delta_c}$. In that case, we can show the following:

$$\hat{m}_{incr} < \hat{m}_{unif} \Leftrightarrow^1 t^{\mathcal{WT}}(m = \hat{m}_{unif}) < t^{\mathcal{W}}(m = \hat{m}_{unif}) \Leftrightarrow^2 \frac{6L\cdot\hat{m}_{unif}}{I} < \frac{(t^{\mathcal{W}})^2\left(6 - \bar{d}k\left(3\bar{d} - 4t^{\mathcal{W}}\right)\right)}{\left(\bar{d} - t^{\mathcal{W}}\right)\left(2 + \bar{d}kt^{\mathcal{W}}\right)}\Big|_{m=\hat{m}_{unif}} \Leftrightarrow^3 h(\rho) > 0. \tag{A7}$$

The last function in (A7) is $h(\rho) \doteq \frac{(4+\rho)\rho\left(48+2\bar{d}^2k(4-3\rho)+12\rho+\Gamma\right)\left(\bar{d}^2k(44+3\rho)-6(4+\rho)+\Gamma\right)^2}{144\bar{d}^2k(4+\rho)\left(6(4+\rho)+\bar{d}^2k(4+9\rho)-\Gamma\right)\left(72+18\rho+\bar{d}^2k(44+3\rho)+\Gamma\right)} - 1$, where $\Gamma \doteq \sqrt{36(4+\rho)^2 - 12(4+\rho)(3\rho-4)\bar{d}^2k + (784+3\rho(3\rho-8))\left(\bar{d}^2k\right)^2}$. In (A7), the first iff "$\Leftrightarrow^1$" is derived from the fact that $t^{\mathcal{WT}}(m) > t^{\mathcal{W}}(m)$ if and only if $m < \hat{m}_{incr}$. The second iff "$\Leftrightarrow^2$" is derived based on Lemma A2(iii), where it is shown that $t = t^{\mathcal{WT}}$ satisfies the equation $\frac{6Lm}{I} = \frac{t^2\left(6-\bar{d}k(3\bar{d}-4t)\right)}{(\bar{d}-t)(2+\bar{d}kt)}$ of which the right-hand side decreases in $t \in (0, \bar{d})$. The third iff "$\Leftrightarrow^3$" is derived by algebraic transformation which is omitted for brevity.

Hence, we focus on analyzing when $h(\rho) > 0$ holds in the rest of this proof. To do so, we first verify that $h(\rho)$ strictly decreases in $\rho \in (1, \infty)$. Specifically, we can derive that: (1) $\lim_{\rho\to 1} h(\rho) = \frac{\left(60+2\bar{d}^2k+\mathbb{K}\right)\left(-30+47\bar{d}^2k+\mathbb{K}\right)^2}{144\bar{d}^2k\left(30+13\bar{d}^2k-\mathbb{K}\right)\left(90+47\bar{d}^2k+\mathbb{K}\right)} - 1 > 0$ when $0 < k \le \frac{6}{5\bar{d}^2}$, where $\mathbb{K} = \sqrt{900 + 60\bar{d}^2k + 769\left(\bar{d}^2k\right)^2}$; (2) $h(\rho) \to \infty$ as $\rho \to \frac{8\bar{d}^2k}{3(2+\bar{d}^2k)}$ when $\frac{6}{5\bar{d}^2} < k < \frac{2}{\bar{d}^2}$; and (3) $\lim_{\rho\to\infty} h(\rho) = -1 < 0$. Therefore, there exists a threshold $\hat{\rho}_1$ such that $h(\rho) > 0$ if and only if $\rho < \hat{\rho}_1$, where the threshold $\hat{\rho}_1$ increases in k. Moreover, observe that given $\rho = \frac{I/L}{\Delta_c}$, we can write $\frac{I/L}{c_g - c_e} = 1 + \frac{1}{\rho - 1}$, which implies that the condition of $\rho < \hat{\rho}_1$ is equivalent to $\frac{I/L}{c_g - c_e} > t_1$ for some threshold t_1 that decreases in k.

Combining the above two cases completes the proof of Proposition 5-(ii). □

EC.2. Additional Results and Extensions

In this section, we present the additional analyses and results that are briefly discussed in the paper. All proofs of the results can be found in EC.5. on SSRN (link).

EC.2.1. Overall Environmental Benefit Assessment

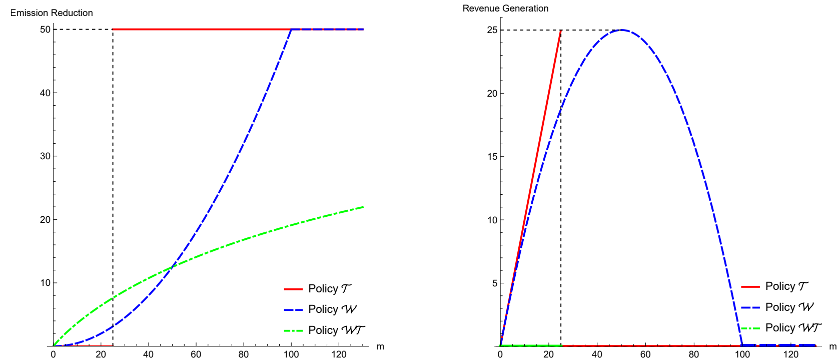
In this subsection, we analyze the overall environmental benefits with the following two environmental benefit components taken into account under the three policies considered.

- Emission reduction: We measure this benefit by the total number of electric trucks adopted in equilibrium, formulated by $E^r = \sum_{i=1}^{M} e_i$ under policies $r = \mathcal{T}, \mathcal{W}, \mathcal{WT}$.
- Environmental benefit from fee revenue: Without loss of generality, we normalize the unit environmental benefit per dollar spent on other initiatives to 1. Hence, this part of the environmental benefit is simply formulated as the total mitigation fee collected in equilibrium, formulated by $F^r = m \cdot \sum_{i=1}^{M} \tau_i^g$.

We first analyze these two components separately. As discussed in §4.1.1, since mitigation fee is collected from diesel truck usage, which generates fee revenue but comes at the expense of electric truck adoption. Figure A2 well illustrates this tradeoff. Specifically, when the mitigation fee m is relatively low, the direct source rule, i.e., policy $\mathcal{T}$, generates higher fee revenue than the indirect source rule, i.e., policy $\mathcal{W}$, but is less effective in promoting electric truck adoption. As the mitigation fee m increases, policy $\mathcal{T}$ achieves full adoption of electric trucks first, but the fee revenue drops to zero. In contrast, policy $\mathcal{W}$ continues to generate fee revenue while maintaining moderate level of electric truck adoption. The indirect rule without subsidies, i.e., policy $\mathcal{WT}$ does not generate fee revenue as the mitigation fee is fully used as electric truck subsidies in equilibrium.

Second, we analyze how the government may balance these two types of benefits, and furthermore, given government's balancing efforts, how the three policies compare in terms of their overall environmental benefit potential. To

Figure A2 Benefit comparison (for $c_e = 0.5, c_g = 2, L = 3000, I = 6000, p_g = 5, \bar{d} = 100$)

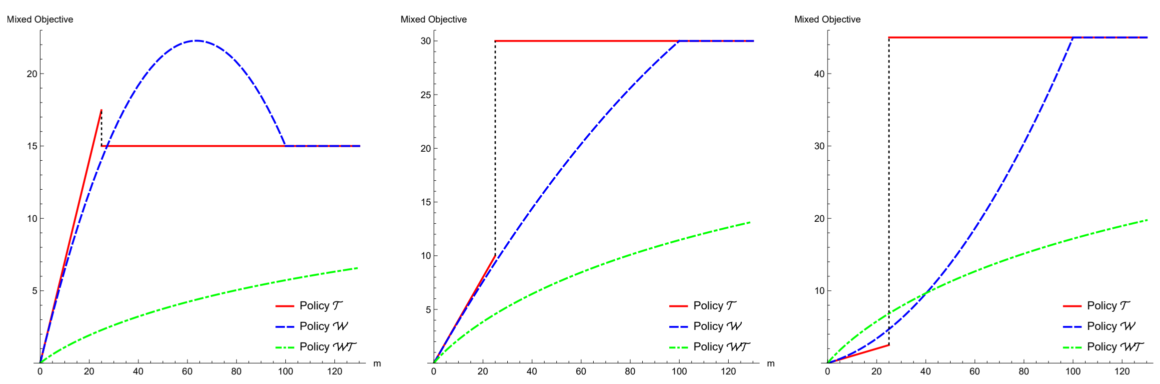


(a) Emission Reduction (b) Fee Revenue Generation

this end, we consider the weighted average between the two types of benefits as the government's objective, formulated by $W = \theta \times E^r + (1-\theta) \times F^r$, where $\theta \in [0,1]$. A higher θ reflects a stronger government focus on reducing emissions, while a lower value of θ indicates a greater emphasis on revenue generation (e.g., when there exist other programs that may lead to high environmental benefit per dollar spent). We consider W as a function of the mitigation fee m, and add a decision stage at the beginning of the model studied in the paper, where the government chooses m to maximize $W(m)$ before the trucking company sets the rental prices and warehouses choose the type of trucks to use. It can be shown that under policies $\mathcal{T}$ and $\mathcal{W}$, $\forall \theta \in [0,1]$, $W(m)$ achieves its maximum value under a certain mitigation fee level (due to the tradeoff between the two benefit components previously discussed). Accordingly, let $W^{*r} \doteq \max_m W(m)$ and m^{*r} denote the maximum weighted average environmental benefit that can be achieved and the corresponding optimal mitigation fee level, respectively, under the policies $r = \mathcal{T}, \mathcal{W}$. However, under policy $\mathcal{WT}$, no fee revenue is generated, and accordingly W, which equals emission reduction, increases in m because the electric truck adoption does so according to Lemma 3 in the paper. Hence, we use $W^{*\mathcal{WT}} \doteq \lim_{m\to\infty} W(m)$ to denote the supremum of W under this policy.

Proposition A1. *When $0 \le \theta < \frac{2\Delta_c}{1+2\Delta_c}$, $W^{*\mathcal{W}} > W^{*\mathcal{T}} > W^{*\mathcal{WT}}$. Otherwise, $W^{*\mathcal{W}} = W^{*\mathcal{T}} > W^{*\mathcal{WT}}$. Furthermore, for any $\theta \in [0,1]$, $m^{*\mathcal{W}} > m^{*\mathcal{T}}$.*

Figure A3 Weighted average benefit comparison (for $c_e = 0.5, c_g = 2, L = 3000, I = 6000, p_g = 5, \bar{d} = 100$)



(a) $\theta = 0.3$ (b) $\theta = 0.6$ (c) $\theta = 0.9$

Proposition A1 provides three insights. First, between the direct and indirect source rules, Proposition A1 indicates that when the government places greater emphasis on fee revenue generation, the indirect source rule (i.e., policy $\mathcal{W}$) can achieve a strictly higher environmental benefit overall than the direct source rule (i.e., policy $\mathcal{T}$), as illustrated by Figure A3(a), due to its greater flexibility in balancing emission reduction and fee revenue generation. Otherwise, the two policies have the same potential for overall environmental benefit (see Figure A3 (b)-(c)). Nevertheless, the optimal mitigation fee under policy $\mathcal{W}$ is consistently higher than that under policy $\mathcal{T}$, implying that the indirect approach may impose a greater burden on the industry in equilibrium. As such, the government must also carefully evaluate this potential trade-off to ensure that its environmental objectives are achieved without exerting excessive burden on industrial development. Finally, comparing policies $\mathcal{T}$ and $\mathcal{W}$ with the indirect source rule with subsidies (i.e., policy $\mathcal{WT}$), Proposition A1 shows that the maximum overall environmental benefits under the former two are higher than that under policy $\mathcal{WT}$, indicating that using the mitigation fee to subsidize electric truck investments (or usage) may not be a preferred approach if the government has more decision freedom in setting the mitigation fee. Otherwise, if the mitigation fee needs to be set low, policy $\mathcal{WT}$ can still lead to the best environmental outcome among the three policies considered (as illustrated by Figure A3(c)).

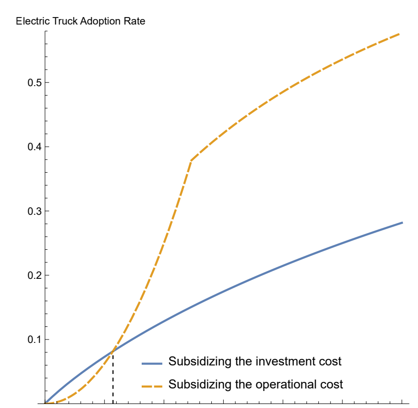
EC.2.2. Subsidizing Electric Truck Charging Infrastructure

In this subsection, we analyze the indirect source rule that subsidizes electric truck charging infrastructure. We capture the impact of this type of subsidy on the operations of the trucking company by a reduction (denoted by s_e) of the trucking company's unit operational cost of electric trucks c_e. Accordingly, the trucking company's profit function is modified as $\sum_{i=1}^{M}\left[(p_g-c_g)\cdot g_i+(p_e-c_e-(I-s_e)/L)\cdot e_i\right]$, where $s_e \doteq \min\left\{c_e, \left(m\cdot\sum_{i=1}^{M}\tau_i^g\right)\Big/\left(\sum_{i=1}^{M}e_i\right)\right\}$. The second term in the formula of s_e calculates the ratio between the total mitigation fee collected and the total distances traveled by electric truck. To interpret this ratio, note that assuming the total operational cost reduction for electric trucks is proportional to the subsidy funding which is the total mitigation fee collected, then the ratio is essentially the average cost reduction for a unit distance traveled. This cost reduction is also capped by c_e. For clarity, we denote this policy by $\mathcal{WT}'$ to differentiate it from the $\mathcal{WT}$ policy analyzed in the paper

We solve the modified model under the policy $\mathcal{WT}'$ and show that the equilibrium outcome is structurally similar to that under the policy $\mathcal{WT}$ (see Lemma 3 in the paper). The main difference is that when the investment cost of electric trucks is too high, operational cost reduction may not be as effective as investment subsidy in incentivizing trucking company to reduce electric truck rental price in order to increase demand. Accordingly, it can occur in equilibrium under the policy $\mathcal{WT}'$ that the a portion of the mitigation fee collection remains unused when the mitigation fee m is low. We refer the interested reader to the full online appendix on SSRN (link) for the detailed technical illustration.

Based on the equilibrium outcome, we perform two analyses. First, we compare the equilibrium outcome under the policy $\mathcal{WT}'$ with the indirect source rule without subsidies, i.e., policy $\mathcal{W}$. The goal is to analyze if our results in §4.2 of the paper, which are derived based on investment subsidies, continue to hold under charging infrastructure subsides. The next proposition shows this is indeed the case.

Figure A4: **Subsidy comparison (for** $c_e=0.5, c_g=1.8, L=3000, I=6000, p_g=5, \bar{d}=100$)



PROPOSITION A2. *Under the indirect source rule with subsidies targeting charging infrastructure:*

(i) *The electric truck adoption rate is strictly higher than that in the absence of subsidies (i.e., $G^{\mathcal{WT}'} > G^{\mathcal{W}}$) if and only if $m < 8\bar{d}\Delta_c^2/(c_e+4\Delta_c)$.*

(ii) *The electric truck rental price and the aggregate daily costs among all warehouses are strictly lower than those in the absence of subsidies (i.e., $p_e^{\mathcal{WT}'} < p_e^{\mathcal{W}}$ and $\sum_{i=1}^{M} C_i^{\mathcal{WT}'} < \sum_{i=1}^{M} C_i^{\mathcal{W}}$) if and only if $m < 8\bar{d}\Delta_c^2/(c_e+4\Delta_c)$.*

(iii) *The trucking company's daily profit and the overall industry burden are strictly higher and lower, respectively, than those in the absence of subsidies, i.e., $P^{\mathcal{WT}'} > P^{\mathcal{W}}$ and $B^{\mathcal{WT}'} < B^{\mathcal{W}}$.*

Second, we compare the environmental effectiveness of the two types of subsidies (i.e., investment versus charging infrastructure subsidies) by comparing the electric truck adoption rate in equilibrium under policies $\mathcal{WT}$ and $\mathcal{WT}'$.

Proposition A3. *When $c_g < I/L$, $G^{\mathcal{WT}'} > G^{\mathcal{WT}}$ if and only if $m > \frac{8\bar{d}(I/L-c_g)^2}{5\cdot(I/L)-4c_g}$, and $G^{\mathcal{WT}'} < G^{\mathcal{WT}}$ if and only if $m < \frac{8\bar{d}(I/L-c_g)^2}{5\cdot(I/L)-4c_g}$. When $c_g \geq I/L$, $G^{\mathcal{WT}'} > G^{\mathcal{WT}}$ if and only if $c_e < I/L$, and $G^{\mathcal{WT}'} < G^{\mathcal{WT}}$ if and only if $c_e > I/L$.*

Proposition A3 shows that the relative effectiveness of subsidizing electric truck investment or charging infrastructure in promoting adoption depends on truck costs and the mitigation fee. When the investment cost of electric trucks is large (specifically, when $I/L > c_g$), the relative effectiveness of the two subsidy schemes depends on the mitigation fee m. When m is relatively low, charging infrastructure subsidies do not fully utilize the available funds in equilibrium as previously explained, and thereby are less effective in promoting electric truck adoption compared to investment subsidies. However, as the mitigation fee increases, subsidizing charging infrastructure can better support longer electric truck trips (due to the reduction of unit operational cost), eventually outperforming investment subsidies. This result is illustrated in Figure A4. Nevertheless, when the investment cost of electric trucks becomes low (specifically, when $c_g \geq I/L$), all mitigation fees are fully utilized in equilibrium under either subsidy scheme. In this case, Proposition A3 indicates that subsidizing/reducing the smaller cost components between investment and operational costs of the electric trucks turns out to be more effective in promoting adoption.

EC.2.3. Competition between Asymmetric Trucking Companies

In this subsection, we consider a competitive scenario with trucking companies with asymmetric costs. For tractability, we focus on a duopoly setting with two competing trucking companies $j = 1, 2$. Without loss of generality, we assume $0 < I_1/L_1 < I_2/L_2$. We demonstrate that the key insights derived from the symmetric case presented in §5.1 of the paper continue to hold qualitatively in this context, as summarized in the following proposition.

Proposition A4. *In a competitive scenario with an asymmetric duopoly of trucking companies where $0 < I_1/L_1 < I_2/L_2$, let $\Delta_{cj} \doteq p_g - c_g - 2(p_g - c_e - I_j/L_j)$ for $j = 1, 2$ and assuming $\Delta_{c2} < 2\Delta_{c1}$.*
(i) *$G^{\mathcal{W}} > G^{\mathcal{T}}$ if and only if $m < \frac{\bar{d}}{2}\cdot\Delta_{c1}$;*
(ii) *$G^{\mathcal{W}} > G^{\mathcal{WT}}$ holds when $\frac{\bar{d}}{3}\cdot(\Delta_{c1}+\Delta_{c2}) < m < \bar{d}\cdot(\Delta_{c1}+\Delta_{c2})$.*

Proposition A4 parallels Proposition 4 in the paper to show that competition promotes the effectiveness of the indirect source approach, and makes subsidizing (using the mitigation fee collected) less likely to backfire. Specifically, when the degree of asymmetry is sufficiently small, the equilibrium outcome degenerates to the case of $N = 2$ analyzed in §5.1 of the paper. Furthermore, assuming I_2/L_2 (i.e., the cost efficiency of the higher-cost firm) is unchanged, a decrease in the cost of the other firm—which leads to greater cost asymmetry—would narrow the relative advantage of the indirect source rule over the direct source rule. This is because under the direct source rule, it can be shown that the industry's adoption of electric trucks depends solely on the cost of the lower-cost firm. As this cost decreases, direct regulation on the trucking sector becomes increasingly effective in promoting electric truck adoption. On the other hand, under the indirect source rule, subsidies are less likely to backfire, as the lower investment cost of company 1 facilitates faster full adoption of electric trucks through the subsidy mechanism.

EC.2.4. Impact of Alternative Distance Distributions: Additional Results for §5.2

We provide the full details of the results discussed in §5.2 regarding the impact of a linearly decreasing $f(d)$ on policy comparisons. First, Proposition A5 pertains to the case when the linear probability density function decreases slowly, i.e., when $|k|$ is small, specifically within the range of $k \in [-6/(5\bar{d}^2), 0)$. This suggests that the decline in the likelihood of longer truck trips is relatively gradual.

Proposition A5. *Consider* $f(d) = k \cdot (d - \bar{d}/2) + 1/\bar{d}$ *where* $k \in [-6/(5\bar{d}^2), 0)$.

(i) *The mitigation fee threshold below which* $G^{\mathcal{W}} > G^{\mathcal{T}}$ *holds is lower than that under the uniform distribution.*

(ii) *There exists* $t_2 > 1$ *such that the mitigation fee threshold below which* $G^{\mathcal{WT}} > G^{\mathcal{W}}$ *holds is higher than that under the uniform distribution if and only if* $\frac{I/L}{c_g - c_e} > t_2$. *Moreover,* t_2 *decreases in* k.

Proposition A5 is essentially opposite to Proposition 5 where $f(d)$ increases. It indicates that in regions where the likelihood of long truck trips diminishes slowly over distance, the indirect source rule outperforms the direct source rule for a smaller range of mitigation fees. Furthermore, the provision of subsidies becomes more likely to enhance electric truck adoption, particularly when the investment and operational costs of electric trucks are high.

Next, we consider the case where the linear probability density function decreases rapidly, i.e., when $|k|$ is large. We first present the following lemma that characterizes two unique equilibrium structural features in this case.

Lemma A3. *Consider the distance distribution* $f(d) = k \cdot (d - \bar{d}/2) + 1/\bar{d}$ *where* $k < -6/(5\bar{d}^2)$. *For any* $m > 0$, *under policy* $r = \mathcal{W}, \mathcal{WT}$, *there exists a distance threshold* $t^r \in (0, \bar{d})$ *such that each warehouse* $i \in \mathcal{M}$ *adopts diesel trucks (i.e.,* $a_i^r(d) = 1$*) if* $d > t^r$, *and adopts electric trucks (i.e.,* $a_i^r(d) = 0$*) otherwise in equilibrium. Furthermore, there exists a threshold* $\hat{m}_1$ *such that* $t^{\mathcal{WT}}$ *increases and decreases in* m *when* $m < \hat{m}_1$ *and* $m \geq \hat{m}_1$, *respectively.*

Lemma A3 shares similarities with Lemmas 2 and 3 but has two fundamental differences. First, the distance threshold under the indirect source rule (without subsidies) satisfies $t^{\mathcal{W}} < \bar{d}$, indicating that only partial electric truck adoption can be achieved when $f(d)$ decreases rapidly in d. In contrast, under the uniform distribution, full adoption can be achieved (see Lemma 2). This difference emerges because when longer truck trips are less frequent, reducing the rental price of electric trucks increases their adoption rate with diminishing returns. Meanwhile, reducing the rental price sacrifices the trucking company's profit margin from serving shorter trips with electric trucks. This tradeoff motivates the trucking company to forgo potential electric truck demand from long trips.

Second, surprisingly, we discover that the tradeoff between profit margin and demand can even compel the trucking company to relinquish existing electric truck demand, particularly when the mitigation fee m is sufficiently large under the indirect source rule with subsidies. This occurs because the margin is boosted under electric truck investment subsidies, leading to a stronger influence in the trucking company's decision-making process. As a result, the threshold $t^{\mathcal{WT}}$ may decrease in m, indicating that a higher mitigation fee can effectively reduce the electric truck adoption rate under policy $\mathcal{WT}$ (see Figure A5(a)). Consequently, more mitigation fees are anticipated to be imposed on the warehouses, increasing their cost burden. Moreover, fewer electric truck investments are made, potentially causing the total mitigation fee to surpass the total subsidy payment (which cannot exceed the investment cost incurred). In such a scenario, investment subsidy provision under the indirect source rule may actually lead to a heavier industry cost burden than the direct source rule, especially when the mitigation fee reaches a significant level (see Figure A5(b)). This contrasts the results in the uniform distribution case.

The next two propositions summarize the implications of Lemma A3 on the comparison of the environmental and economic performance of the three policies under consideration when $f(d)$ decreases rapdily.

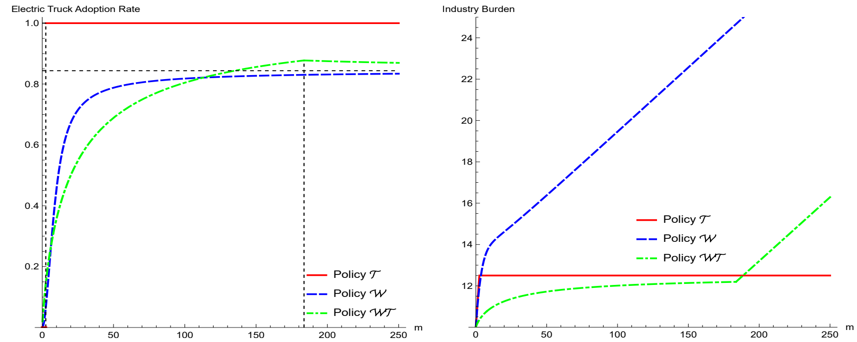
Proposition A6. *Consider* $f(d) = k \cdot (d - \bar{d}/2) + 1/\bar{d}$ *where* $k < -6/(5\bar{d}^2)$. *Comparing the direct source rule and the indirect source rule indicates that:*

(i) *The electric truck adoption rates under the two policies satisfy* $G^{\mathcal{W}} > G^{\mathcal{T}}$ *if and only if* $m < \bar{d}/12 \cdot (6 + \bar{d}^2 k) \cdot \Delta_c$.

(ii) *There exists a threshold* $\hat{m}_2$ *on the mitigation fee such that the overall industry burden under the two policies satisfies* $B^{\mathcal{W}} < B^{\mathcal{T}}$ *if and only if* $m < \hat{m}_2$. *Moreover,* $\hat{m}_2$ *increases in* k.

Proposition A6 suggests that when $f(d)$ decreases more rapidly with distance (i.e., the likelihood of longer truck trips declines quickly), the advantage of the indirect source rule weakens relative to the direct source rule. In other words, the direct source rule is more likely to outperform the indirect source rule in promoting the adoption of electric trucks, as illustrated in the comparison between policy $\mathcal{T}$ and policy $\mathcal{W}$ in Figure A5(a).

Figure A5 **The equilibrium outcome under $f(d)=\frac{2}{\bar{d}}\left(1-\frac{d}{\bar{d}}\right)$ (for $c_e=0.5, c_g=2, L=3000, I=6000, p_g=5, \bar{d}=15$)**



(a) Electric truck adoption rate (b) Industry cost burden

Proposition A7. *Consider $f(d)=k\cdot(d-\bar{d}/2)+1/\bar{d}$ where $k<-6/(5\bar{d}^2)$. When comparing the indirect source rule with subsidies and without subsidies, there exist two thresholds $\hat{k}\in\left(-2/(\bar{d}^2),-6/(5\bar{d}^2)\right)$ and $t_3>1$ (where t_3 increases in k) such that the electric truck adoption rates under the two policies satisfy the following:*

(i) *When $k<\hat{k}$ and $\frac{I/L}{c_g-c_e}>t_3$, $G^{\mathcal{WT}}>G^{\mathcal{W}}$ holds for any $m>0$.*

(ii) *When $k\geq\hat{k}$ or $\frac{I/L}{c_g-c_e}\in(1,t_3]$, there exist two thresholds $\hat{m}_3<\hat{m}_4$ for the mitigation fee such that $G^{\mathcal{WT}}<G^{\mathcal{W}}$ if and only if $\hat{m}_3<m<\hat{m}_4$.*

Further, the overall industry burden under the two policies satisfies $B^{\mathcal{WT}}<B^{\mathcal{W}}$ for any $m>0$.

Proposition A7 is directionally consistent with Proposition A5(ii) in the sense that it shows electric truck investment subsidies can improve adoption under a decreasing density function $f(d)$. Moreover, Proposition A7 underscores that this effect is amplified in two ways as $f(d)$ decreases more rapidly. First, according to Proposition A7(i), investment subsidies always improve the electric truck adoption rate under the indirect source rule when $f(d)$ decreases rapidly, especially when the investment and operational costs of electric trucks are high. Second, Proposition A7(ii) indicates that even when the investment and operational costs of electric trucks decrease, investment subsidies can still improve adoption under a fast decreasing $f(d)$ when the mitigation fee is substantial (as illustrated in the comparison between policies $\mathcal{W}$ and $\mathcal{WT}$ in Figure A5(a)). This contrasts the scenario of the slowly decreasing $f(d)$ where subsidies can become counterproductive when the mitigation fee is substantial.

We also considered nonlinear distance distributions and can demonstrate that our main insights derived from the linear distributions still hold qualitatively. Notably, we find that the equilibrium results are primarily determined by the tail behavior of the distribution. For example, when the probability density function $f(d)$ first increases and then decreases with d, the resulting outcomes closely resemble those under a decreasing function. The detailed equilibrium results under the above distributions are available in the full online appendix on SSRN (link).

EC.2.5. Warehouses partially pass on mitigation fees to downstream customers

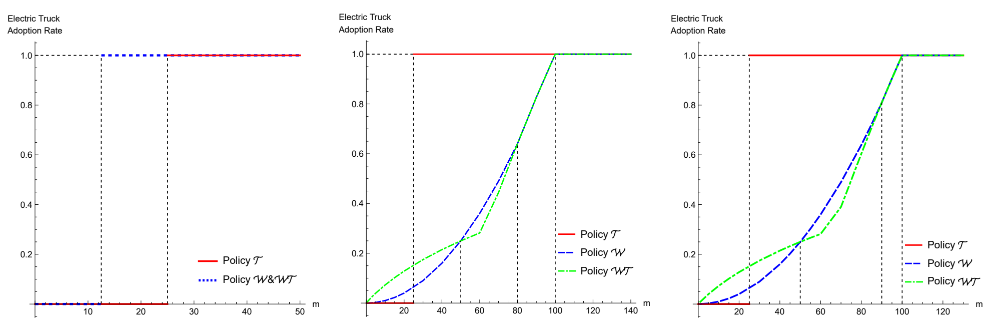
In this subsection, we consider a scenario in which warehouses can choose to pass on a proportion, modeled by $\lambda\in[0,1]$, of the mitigation fee to their downstream clients. We assume that given λ, warehouses' total demand is reduced by a percentage of $\zeta\cdot\lambda m$, where $\zeta>0$ captures the price sensitivity of downstream clients to the part of the mitigation fee they need to absorb (i.e., λm). For simplicity, we assume that λ is an industry level decision from the warehouse sector in response to the mitigation fee. That is, we do not delve into competition between warehouses using λ as a competitive lever. (In fact, if λ becomes a competitive lever, given the highly fragmented warehousing industry in the status quo, λ likely becomes zero in equilibrium which is the case analyzed in the main model.)

We modify the sequence of events of the model as follows. After the trucking company sets the electric truck rental price, the warehouse industry (or their representative body, such as the Warehouse Logistics Association) determines the optimal pass-through rate λ that maximizes the total daily profit over all warehouses. Assuming each truck trip generates a revenue of $R>0$ for the warehouses, this total profit can be formulated by $\left(\sum_{i=1}^M N_i(1-\zeta\cdot\lambda m)\right)\cdot\left(R\cdot\sum_{i=1}^M n_i - \sum_{i=1}^M C_i^r\right)$ under each policy r. Then, each warehouse determines its truck rental decision based on p_e and λ that are determined in the previous stages. We note that our main model can be regarded as an extreme case where ζ is very large so that it is always suboptimal to pass any mitigation fee to the clients (i.e., optimal λ is zero).

The modified model turns out to be analytically intractable. As such, we conduct extensive numerical analyses, which give rise to two main insights, illustrated by Figure A6. First, it can be observed that when ζ is sufficiently small (i.e., when warehouses' clients are insensitive to costs), policies $\mathcal{W}$ and $\mathcal{WT}$ lead to identical outcomes in terms of the equilibrium rental price and adoption rate of electric trucks. This is because in that case, if the mitigation fee m is low, warehouses opt to pass the entire mitigation fee to downstream clients ($\lambda^*=1$), resulting in all truck trips being fulfilled by diesel trucks. Conversely, if m is high, we have $\lambda^*=0$, and all trips are fulfilled by electric trucks.

When ζ is large, i.e., when warehouses' clients are cost sensitive and thus warehouses are more cautious in passing mitigation fee onto them, we observe that policy $\mathcal{WT}$ can lead to a higher electric truck adoption rate but only when the mitigation fee is sufficiently small. In fact, for intermediate values of m, policy $\mathcal{W}$ achieves a higher electric truck adoption rate compared to policy $\mathcal{WT}$. As ζ increases, this range of mitigation fee (i.e., the one under which policy $\mathcal{W}$ outperforms policy $\mathcal{WT}$) is enlarged. When ζ is sufficiently large, the comparative outcome becomes the same as that shown in Proposition 3 of the paper, indicating the robustness of the insights from the main model.

Figure A6 **The electric truck adoption rate under the three policies when warehouses can partially pass on the mitigation fees (for $c_e=0.5, c_g=2, L=3000, I=6000, p_g=5, \bar{d}=100, R=300$)**



(a) $\zeta=0.01$ (b) $\zeta=0.1$ (c) $\zeta=0.2$

EC.2.6. Partial Use of Mitigation Fees as Subsidies

In this subsection, we consider a generalized setting where the government allocates a proportion $\eta\in[0,1]$ of the collected mitigation fees to subsidize the trucking company. Accordingly, the policies $\mathcal{W}$ and $\mathcal{WT}$ studied in the paper represent the special case where $\eta=0$ and $\eta=1$, respectively. The only model modification needed is to multiply the second term in the formulation of the average subsidy s in the paper by η, that is, $s\doteq\min\left\{I,\left(\eta\cdot L\cdot m\cdot\sum_{i=1}^M\tau_i^g\right)\Big/\left(\sum_{i=1}^M e_i\right)\right\}$. We show that this generalization does not affect our insights. Specifically, the key insight from the paper regarding the use of subsidies is that between policies $\mathcal{W}$ and $\mathcal{WT}$ (i.e., when η increases from 0 to 1), the electric truck adoption rate goes up/down when the mitigation fee is small/large. In what follows, we generalize this result. Let us denote the equilibrium electric truck adoption rate under policy $\mathcal{WT}$ given η portion of mitigation fee used as subsidies by $G_\eta^{\mathcal{WT}}$.

Proposition A8. *Consider the indirect source rule with subsidies with $\eta_1<1/2<\eta_2$ portion of the mitigation fee used as subsidies. There exists a mitigation fee threshold $\tilde{m}_\eta$ such that $G_{\eta_1}^{\mathcal{WT}}<G_{\eta_2}^{\mathcal{WT}}$ if and only if $m<\tilde{m}_\eta$.*

EC.2.7. Indirect Source Rule with Fixed Subsidies

In this subsection, we explore an alterantive subsidy approach where the investment subsidy given out per truck is predetermined before the implementation of the policy and fixed at a certain level. This entails a modification of the sequence of events as follows. First, the government calculates a fixed subsidy $\hat{s}$ and announces it to the public. Second, the trucking company determines the electric truck rental price p_e to maximize its profit function, which stays the same as in the main model if we replace s by $\hat{s}$ in equation (5) in the paper. Third, warehouses choose the types of trucks to rent accordingly. Note that in this model, the trucking company's price and the warehouses' truck rental decisions all depend on $\hat{s}$. Accordingly, the amount of mitigation fee collected, $m \cdot \sum_{i=1}^{M} (\tau_i^g)^r$ (where $(\tau_i^g)^r$ is obtained by plugging in the equilibrium truck rental decision a_i^r into the formulation of τ_i^g introduced in §3.3.1), and the number of electric trucks used $\sum_{i=1}^{M} e_i^r$ in equilibrium are all functions of $\hat{s}$. In the first stage of the model, the government solves the subsidy level $\hat{s}$ to make sure that the total subsidy given equals the mitigation fee collected, i.e., $\hat{s} \cdot \sum_{i=1}^{M} e_i^r(\hat{s}) = m \cdot \sum_{i=1}^{M} (\tau_i^g)^r(\hat{s})$.

We solve this model and show that the fixed subsidy in equilibrium depends on the cost differential between the two types of trucks and the mitigation fee.

Proposition A9. *Under the indirect source rule with fixed subsidies, assuming* $0 < m < \min\left\{2\bar{d}^2 \cdot \Delta_c, \frac{2\bar{d} \cdot \Delta_c}{(2\bar{d}-1)^2}\right\}$, *the fixed subsidy in equilibrium is given by* $\hat{s} = \frac{L\left(16\bar{d}^3 \cdot \Delta_c - (4\bar{d}-1)m - \sqrt{m^2(4\bar{d}-1)^2 + 32\bar{d}^3 \cdot \Delta_c \cdot m}\right)}{16\bar{d}^3}$, *and we have* $\frac{\partial \hat{s}}{\partial m} < 0$ *and* $\frac{\partial \hat{s}}{\partial \Delta_c} > 0$.

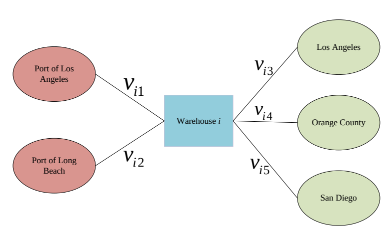
Under the indirect source rule, a predetermined fixed subsidy can effectively deter the trucking company from strategically raising the rental price of electric trucks in order to preserve some level of diesel truck usage, thereby avoiding adverse incentives. It is worth noting that the government can credibly commit to an effective ex-ante subsidy level in equilibrium only when the mitigation fee per diesel truck trip m is not too high. This is because as the mitigation fee increases, more electric trucks are adopted, while fewer diesel truck trips pay the mitigation fee, leading to a gradual decline in the per-truck subsidy level for electric trucks. When the mitigation fee is overly high (i.e., $m \geq 2\bar{d} \cdot \Delta_c$), the warehouses choose to adopt electric trucks for all their orders, in which case the predetermined subsidy for electric trucks becomes zero.

EC.3. Supplementary Details in the Case Study

EC.3.1. Numerical Example Construction

Warehouse locations: Rule 2305 applies to the existing and new warehouses within the South Coast Air Basin (including the non-desert regions of Los Angeles, Riverside, and San Bernardino counties, and all of Orange County) with at least 100,000 square feet of indoor floor space and at least 50,000 square feet for warehousing activities. This amounts to 3,320 warehouses subject to Rule 2305,[8] whose locations are illustrated in Figure A8. These warehouses are mostly concentrated in 22 major economic zones commonly referred to as the "submarkets".[9] The relative locations of these submarkets capture the main geographic features

Figure A7: **Five shipping routes for each sample warehouse in the case study**



[8] https://www.aqmd.gov/docs/default-source/planning/fbmsm-docs/pr-2305_sr_2nd-draft_4-7-21_clean.pdf?sfvrsn=8. Page 145-171

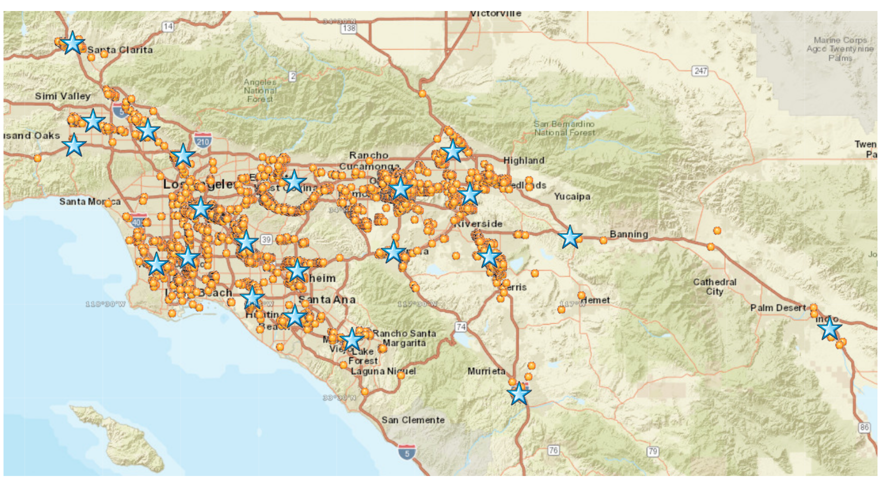
[9] https://scag.ca.gov/sites/main/files/file-attachments/comprehensive_regional_goods_movement_plan_and_implementation_strategy_-_reigonal_warehousing_needs_assessment_final_report.pdf. Table 5.1

associated with warehouse operations in the Southern California region. Hence, for a representative study, we consider a sample warehouse location in each submarket so the number of warehouses is $M = 22$ in the numerical example. In particular, we pick locations that are approximately in the center of the warehouse clusters of the corresponding submarkets. These locations are shown in Table A1 and marked by stars in Figure A8.

Table A1 Submarkets, warehouse clusters and sample warehouse locations in Southern California

County	Submarket	Warehouse cluster area	Representative address
LA	South Bay	Torrance	1540 W 190th St, Torrance, CA, 90501
	I-710	Compton	660 W Artesia Blvd, Compton, CA, 90220
	I-605	Santa Fe Springs	13530 Rosecrans Ave, Santa Fe Springs, CA, 90670
	Central LA	central LA	2615 S Bonnie Beach Pl, Los Angeles, CA, 90058
	San Gabriel	Covina	222 N Vincent Ave, West Covina, CA, 91790
	I-5	Burbank	3000 Winona Ave, Burbank, CA, 91504
	North LA	Glendale	4561 Colorado Blvd, Los Angeles, CA, 90039
Ventura	SR-126	SR-126	26121 Avenue Hall, Valencia, CA, 91355
	SR-118	SR-118	18537 Parthenia St, Northridge, CA, 91324
	I-110	I-110	21240 Burbank Blvd, Woodland Hills, CA, 91367
Orange	North Orange	Fullerton-Anaheim	1000 N Edward Ct, Anaheim, CA, 92806
	West Orange	Garden Grove	12570 Knott St, Garden Grove, CA, 92841
	South Orange	Lake Forest	25392 Commercentre Dr, Lake Forest, CA, 92630
	Orange airport	Santa Ana	2400 S Garnsey St, Santa Ana, CA, 92707
Riverside	West Riverside	Corona	450 N Sheridan St, Corona, CA, 92878
	March JPA	I-215	14950 Meridian Pkwy, March Air Reserve Base, CA, 92518
	Pass	Banning I-10	415 Nicholas Rd, Beaumont, CA, 92223
	Coachella	Coachella	85810 Peter Rabbit Ln, Coachella, CA, 92236
	SW Riverside	Tamecula	27565 Diaz Rd, Temecula, CA, 92590
San Bernardino	Westend	Ontario	1000 Sarah Pl, Ontario, CA, 91761
	East SB Valley	Fontana - SB	1501 E Cooley Dr, Colton, CA, 92324
	High desert	Muscoy	3196 N Locust Ave, Rialto, CA, 92377

Figure A8 Locations of warehouses subject to Rule 2305. Sample warehouse locations that represent the 22 submarkets are highlighted by stars.



Shipping orders: We assume that the sample warehouses provide shipping services to and from five logistics hotspots in Southern California, i.e., $N_i = 5$ for each warehouse $i = 1, 2, ..., 22$ in the numerical example. These five locations include (i) the two largest ports in the U.S., i.e., the Ports of Los Angeles and Long Beach,[10] labeled as $j = 1, 2$, and (ii) the three major residential regions: the city of Los Angeles, Orange Country and the city of San Diego, which represent main consumer markets and are labeled as $j = 3, 4, 5$. See Figure A7 for an illustration. For

[10] https://lao.ca.gov/Publications/Report/4618

Table A2 Submarket warehouse space and distances of sample truck trips

Submarket	Warehouse space (sq)	Distances (miles)				
		LA Port	Long beach port	Los Angeles	Orange County	San Diego
South Bay	55,222,927	12.0	13.2	24.6	39.4	116.0
I-710	21,339,348	15.0	10.6	30.3	35.7	114.0
I-605	55,174,480	23.1	21.6	32.3	25.6	104.0
Central LA	78,121,132	22.2	20.8	21.4	36.4	115.0
San Gabriel	74,710,961	36.3	34.9	37.1	40.9	119.0
I-5	20,674,648	39.2	39.1	11.8	54.2	133.0
North LA	5,453,221	34.0	33.9	13.0	48.9	127.0
SR-126	2,409,068	60.6	62.0	30.2	77.7	156.0
SR-118	8,934,654	46.3	47.7	15.9	68.7	150.0
I-110	10,540,581	45.6	47.1	15.2	68.0	147.0
North Orange	12,018,265	33.1	31.7	52.4	18.4	96.9
West Orange	6,844,239	22.1	20.7	43.9	20.3	98.9
South Orange	1,649,100	44.4	42.9	66.2	4.4	81.3
Orange airport	13,976,430	34.1	32.7	55.9	11.5	88.9
West Riverside	199,602,848	51.0	49.5	64.5	25.2	96.9
March JPA	70,449,164	70.6	69.1	79.2	44.8	89.1
Pass	9,107,191	90.0	88.6	97.4	64.2	99.3
Coachella	31,716,876	143.0	142.0	149.0	118.0	135.0
SW Riverside	39,726,019	87.7	86.3	100.0	61.9	60.1
Westend	214,731,986	61.4	60.0	61.7	39.0	109.0
East SB Valley	170,088,812	71.5	70.1	74.4	45.8	103.0
High desert	38,501,561	71.1	69.7	65.0	51.8	116.0

(ii), we consider the center of these areas as representative locations.[11] We calculate the distances (in miles) between each sample warehouse i and each of these five hotspots j, and set them as the d_{ij} parameters in the numerical example. See Table A2. We note that this is different from the model definition where the distance is expressed in the number of days of the trip. However, this does not affect our results because the cost parameters in this case study, which are introduced later, are also defined as per mile estimates as they are typically quoted in practice.

We estimate the volume parameter v_{ij} as follows. First, we adopt the total warehouse space data at the submarket level, which are available in a 2010 survey on industrial space in Southern California conducted by the Southern California Association of Governments.[12] We then note that there is explosive warehouse development in the Inland Empire (i.e., San Bernadino and Riverside counties) between 2010 and 2021 when Rule 2305 was enacted. The Warehouse CITY mapping tool developed by the Robert Redford Conservancy for Southern California Sustainability estimated that the total warehouse space in that region increased by about 157% during that time.[13] Changes of warehouse space in other counties were very small in comparison.[14] Hence, we increase the 2010 total warehouse space data in the submarkets in Inland Empire by 157% and keep those in other counties unchanged for our case study. We assume that the total shipping volume V_i of the sample warehouse in a submarket is proportional to the warehouse space in that submarket. This assumption reflects practice where warehouses typically provide shipping services for goods stored therein and is consistent with existing estimation approaches.[15]

[11] The center of the city of Los Angeles is 2600 Franklin Canyon Drive, Beverly Hills according to https://losangelesexplorersguild.com/2021/03/16/center-of-los-angeles/. The center of the Orange County is the Great Park according to https://www.cityofirvine.org/irvine-gives/orange-county-great-park. The center of San Diego city is 397 Broadway according to Google map.

[12] https://scag.ca.gov/sites/main/files/file-attachments/comprehensive_regional_goods_movement_plan_and_implementation_strategy_-_reigonal_warehousing_needs_assessment_final_report.pdf. Occupied space in Table 5.1

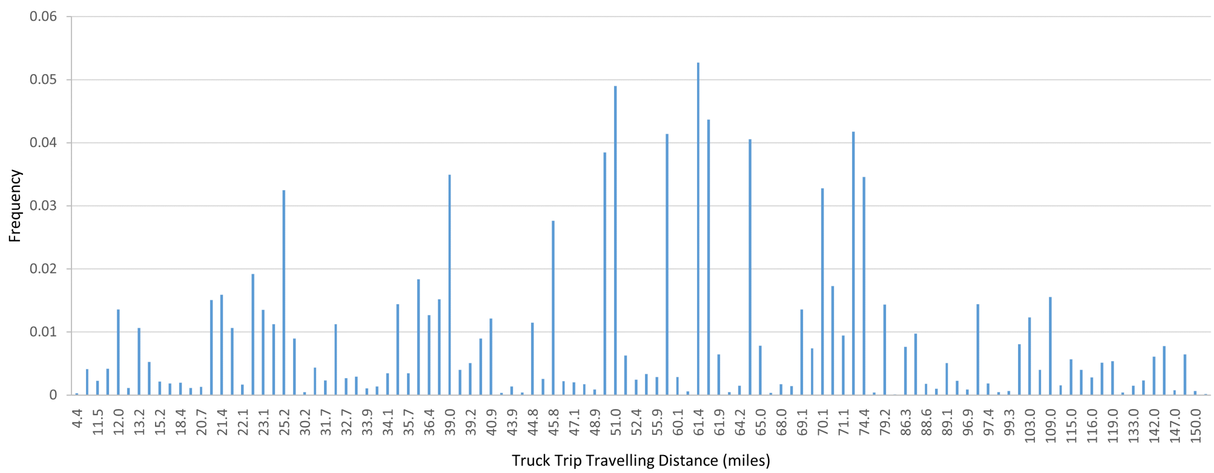
[13] The tool is available at https://www.pitzer.edu/redfordconservancy/mapping-data-visualization/. It shows that the area occupied by warehouses in the Inland Empire in 2010 is 406,043,081 square feet. It increases to 1,041,229,079 square feet in 2021.

[14] For example, according to Warehouse CITY mapping tool, the number of warehouses in Los Angeles has increased by 6% between 2010 to 2025 (including warehouses approved and to be completed by 2025). That in major warehouse clusters in the Orange County (e.g., Anaheim, Orange, Santa Ana, Irvine and Lake Forest) has increased by 2%.

[15] For example, it is estimated that 0.67 truck trips occur per 1,000 square feet of warehouse floor space. See https://www.latimes.com/california/story/2023-02-05/warehouses-big-rigs-fill-inland-empire-streets

Second, to partition the total shipping volume V_i between the five routes considered, we note that in practice, warehouses often serve as waypoints between local markets and hubs. For example, imported goods are transported from hubs into warehouses, and are then picked up and sent to local cites. The direction is reversed for exports. Assuming the entire volume V_i are transported this way, we obtain $v_{i1} + v_{i2} = v_{i3} + v_{i4} + v_{i5} = V_i$. Furthermore, based on the average number of containers processed by the two ports each year,[16] we can estimate the relative proportion of volumes shipped between the sample warehouse i and the two ports and calculate that $v_{i1} = 0.56V_i$ and $v_{i2} = 0.44V_i$. Similarly, we use the relative population proportions of the three residential areas (i.e., 3.967 million (Los Angeles), 3.176 million (Orange County), 1.41 million (San Diego)) to estimate the proportions of the total volume between warehouse i to the corresponding markets, that is, $v_{i3} = 0.464V_i$, $v_{i4} = 0.371V_i$ and $v_{i5} = 0.165V_i$.

Figure A9 Frequency distribution of distances in the case study



Frequency distribution of distances: We apply the (v_{ij}, d_{ij}) numbers estimated above to come up with the frequency distribution of distances. The distribution is shown in Figure A9, which shows that the distances in our numerical example range from 4.4 miles to 156 miles, with an average of 56.87 miles.

Truck investment and operational costs: We consider two major components of the operational cost of diesel semi-trucks: fuel cost and maintenance cost. The average fuel efficiency of diesel semi-trucks is 7 miles per gallon.[17] The maintenance cost of a diesel semi-truck is approximately 15 cents per mile.[18] We adopt the diesel price as of August 2023, which is \$5.518 per gallon.[19] Therefore, we estimate the operating cost of a diesel semi-truck to be $c_g =$ 5.518 (dollar per gallon)/7 (miles per gallon)+ 0.15 (dollar per mile) $\approx$ 0.94 dollars/mile. A typical daily rental price of a diesel semi-truck is about 200 dollars per day[20] plus the operating costs such as fuel, maintenance and driver wages. We ignore driver wages because there is no evidence that different wages are paid for driving diesel versus electric trucks. Based on the typical daily range of a semi-truck which is about 250 miles,[21] we can estimate the per mile rental price of diesel semi-truck to be $p_g = 200$ (dollars per day)/250 (miles per day)$+c_g = 1.74$ dollars/mile.

[16] See https://www.portoflosangeles.org/business/statistics/container-statistics for the port volume of the LA port and https://www.portoflosangeles.org/business/statistics/container-statistics for that of the Long Beach port.

[17] https://haletrailer.com/blog/semi-truck-fuel-efficiency/

[18] https://theicct.org/cost-electric-semi-feb22/

[19] https://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=pet&s=emd_epd2d_pte_sca_dpg&f=m

[20] The rental price depends on the type of semi-trucks rented. We use \$200 because this appears to be a common price point for different types of semi-trucks. https://pricecomparisonadvisor.com/highway-trucks/how-much-does-it-cost-to-rent-new-semi-truck/

[21] https://theicct.org/cost-electric-semi-feb22/

Current heavy-duty electric truck batteries typically use about 2 kWh/mile,[22] which amounts to a cost of \$0.34 per mile based on the average electricity price in the U.S which is \$0.17 per kWh as of August 2023.[23] In addition, the maintenance costs of battery electric semi-trucks are estimated to be 15%-45% lower than their diesel truck counterpart.[24] We take the middle value of this estimated range, that is, 30%, and calculate that the unit operating cost for electric trucks is $c_e = 0.34 + 0.15 \times (1 - 30\%) \approx 0.45$ dollars/mile. As for the electric truck investment cost, recent press releases suggest that the purchase price of an electric semi-truck is between \$400,000 and \$500,000.[25] We take the middle value of this range and set $I = \$450,000$. The lifespan of an electric semi-truck is estimated to be six years,[26] which is equivalent to $L = 6$ (years)$\times$ 52 (weeks) $\times$ 6 (days) $\times$ 250 (miles) = 468,000 miles. Accordingly, we can calculate the amortized investment cost per unit distance to be $I/L \approx 0.96$ dollars/mile. We note that the above estimates are based on the current electric semi-truck technology, which is rapidly evolving. We discuss the implications of such technology changes on our results in the case analysis as well.

Mitigation fee under Rule 2305: We calculate the unit mitigation fee per class 8 truck trip as follows. According to regulation,[27] a class 8 truck trip to a warehouse adds $2.5 \times 0.0025 = 0.00625$ WAIRE (Warehouse Action and Investments to Reduce Emission) points to that warehouse's legal obligation under the full implementation of Rule 2305. Warehouses can fulfill this obligation through payment of a mitigation fee in the amount of \$1,000 for each WAIRE Point. This amounts to $0.00625 \times 1000 = \$6.25$ per class 8 truck trip. Moreover, the warehouse should also pay an administrative fee equal to 6.25% of the mitigation fee it pays.[28] Hence, the total fee paid by a warehouse for a class 8 truck trip equals $6.25 \times (1 + 6.25\%) \approx \$6.64$.

EC.3.2. Additional Results

The case study allows us to illustrates our analytical results in the context of the implementation of Rule 2305. For example, Figure 2(a) indicates that in this case study, the regulation of direct sources of truck emissions may prove to be significantly more effective than regulating indirect sources when the mitigation fee reaches \$26.73 per class 8 truck trip, which is roughly four times the current level. In instances where regulating direct sources is impractical, Figure 2(a) also suggests that eliminating electric truck investment subsidies under Rule 2305 could enhance the adoption rate as the mitigation fee increases to \$44.97 per class 8 truck trip.

Incorporating truck distance changes due to warehouse expansion in the Inland Empire area into our numerical example results in changes of the above thresholds that are consistent with the results in Proposition 5. Specifically, the condition under which the indirect source rule achieves greater adoption than the direct source rule is $m < \$28.05$, which is less stringent than its counterpart under the status quo, indicating enhanced effectiveness of the indirect source rule. However, provision of the subsidy on electric truck investment may become more likely to backfire, as our calculations show that the indirect source rule with subsidies results in a lower adoption rate than without subsidies when the mitigation fee exceeds \$41.25, a scenario more likely to occur than under the current conditions. The policy implication here is that the local government should closely monitor warehouse expansion in the Inland Empire and adjust the subsidy policy under the indirect source rule accordingly.

[22] https://omev.se/2019/09/26/analysis-of-advanced-battery-electric-long-haul-trucks/

[23] https://www.bls.gov/regions/midwest/data/averageenergyprices_selectedareas_table.htm

[24] https://theicct.org/cost-electric-semi-feb22/

[25] https://theicct.org/cost-electric-semi-feb22/

[26] https://schneiderjobs.com/blog/how-long-is-semi-truck

[27] https://www.aqmd.gov/docs/default-source/rule-book/reg-xxiii/r2305.pdf

[28] https://www.aqmd.gov/docs/default-source/planning/reg-iii/r316_2021.pdf?sfvrsn=8