Incentivizing the Adoption of Electric Vehicles in City Logistics: Pricing, Driving Range, and Usage Decisions under Time Window Policies[a, b]

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June, September, and December 2021

Accepted December 2021

To appear in *International Journal of Production Economics*

[a]The authors are grateful to the Editor (Professor T.C.E. Cheng) and two anonymous reviewers for their insightful comments that helped improve this paper.

[b]Acknowledgement: The first author (Yongling Gao) was supported by the Humanities and Social Science Research Project of Ministry of Education of China (17YJC630027) and the National Social Science Fund of China (18BGL217). The second author (Mingming Leng) was supported by the General Research Fund (GRF) of the Hong Kong Research Grants Council under Research Project No. LU13500020.

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Abstract

In the presence of time window policies for electric vehicles (EVs) and internal combustion engine vehicles (ICVs), a logistics service provider (LSP) may renew her fleet by partially replacing existing ICVs with either only EVs (strategy E) or a mix of EVs and new ICVs (strategy H). In this paper, we investigate the LSP's choice between strategies E and H and the impacts of these time window policies on the LSP's EV usage rate and the social welfare. We analyze a two-echelon supply chain involving an EV manufacturer and an LSP or two competing LSPs and perform game analyses. The EV manufacturer determines the driving range and sale price of EVs and the LSP makes her EV usage rate and service pricing decisions. We find that strategy H is not always more profitable than strategy E, which depends on the unit operating cost for new ICVs and the portion of demand fulfilled by new vehicles. If they are sufficiently high or both of them are sufficiently low, then the LSP should opt for strategy E. A wider time window for EVs can encourage the monopolistic LSP's EV usage rate, whereas a narrower time window for ICVs can encourage (discourage) this LSP's EV usage rate if the demand potential for her service is sufficiently large (small). In addition, the per mile environmental impact of using EVs also influences the impacts of time window factors for EVs and ICVs on the social welfare.

Key words: supply chain management; electric vehicles; logistics service providers; time windows; driving range.

1 Introduction

1.1 Background and Motivations

Recent years have witnessed an increasing interest in deploying electric vehicles (EVs) in city logistics (Pelletier, Jabali, and Laporte 2016). Such vehicles may lower motor noise and emissions, thus making more environmental benefits than traditional internal combustion (engine) vehicles (ICVs). Some large companies in the USA (including large fleet operators like Wal-Mart, Amazon, UPS, and DHL) have signed the Business for Social Responsibility's Sustainable Fuel Buyers' Principles, aiming at accelerating the transition to more sustainable vehicle technologies. In 2020, EVs accounted for 18 percent of the DHL's last-mile delivery fleet. DHL has committed that, by 2030, this figure would be 60% by operating more than 80,000 EVs (DHL 2021). Similarly, FedEx has made its commitment that all of its pickup and delivery vehicle purchases would be EVs by 2030 (FedEx 2021). The large fleet operators, such as La Poste in France, British Gas in the UK, the SF Express, and the online retailer JD.com in China, have committed to prioritizing electric options when renewing their fleets.

To promote EVs in competition with long-serving ICVs, the manufacturers should make proper decisions on the driving range and sale price of EVs, which is important because of the following facts. High (low) driving ranges imply less (more) charging frequencies and fewer (more) chances for EVs to contrast unfavorably with ICVs, but may increase (decrease) battery costs and affect the sale price and demand for EVs. Automakers have developed customized EV models to increase their attractiveness. For example, Rivian (an EV startup in the USA) has received an order from Amazon to offer 100,000 customized EVs (Kolodny 2021). GM has launched a new business unit to provide purpose-built EVs for delivery (LaReau 2021). In addition, the Chinese startup Nio has introduced a battery as a service business model in which EV users can sign up for different battery sizes (Baldwin 2020).

A time window is an interval in time at which vehicles are permitted to enter certain areas of the city (Quak and De Koster 2009 and Akyol and De Koster 2013). Wider time windows for EVs compared to ICVs have been implemented in a number of cities—such as Rome, Bologna, Milan, and Florence in Italia, 's-Hertogenbosch (a Dutch city), as well as Chengdu, Tianjin, and Xi'an in China—with an aim to motivate fleet managers to adopt EVs (Franceschetti et al. 2017). For example, fuel trucks are not allowed to enter the 3rd ring road of the Chengdu city during certain hours of each day, whereas EVs are free of these restrictions, which has motivated the online retailer JD.com to adopt the EV for fast delivery (National Business Daily 2016). JD.com pays great attention to the driving range, loading capacity, and right of way of EVs (Qiu 2017). By October 2020, the SF Express had used more than 16,000 new energy logistics vehicles in 180 Chinese cities; and, in China, the proportion of cities with preferential policies for such vehicles had accounted for 70% (EV Partner 2020). By implementing a mixed policy involving more convenient time windows for EVs (compared to ICVs) and operational subsidies for EVs, the Chinese city of Shenzhen has achieved the adoption of 70,417 electric freight vehicles by the end of 2019 (Wang et al. 2020). The tendency to impose increasingly restrictive regulations for less green vehicles has incentivized companies to adopt EVs for their fleet renewals (Taefi et al. 2016).

1.2 Research Questions and Major Findings

According to our discussions above, we analyze a two-echelon supply chain consisting of an EV manufacturer and an LSP who currently owns a logistics fleet and is deciding to purchase either only EVs (under a pure EV strategy, i.e., "strategy E") or a mix of EVs and new ICVs (under a hybrid replacement strategy, i.e., "strategy H") to replace a portion of her old vehicles. We aim to address three streams of research questions for EV promotion in logistics industry.

1. Which replacement strategy (i.e., strategy E or strategy H) can generate a higher profit for the LSP?
2. What are the impacts of time window regulations for EVs and ICVs on the LSP's EV usage rate (i.e., the percentage of miles traveled by EVs per day)?

3. Whether and when can a wider time window for EVs or a narrower time window for ICVs increase the social welfare? Does the impact differ if there are two LSPs competing for customers in a market? These two questions are important to governments.

To address these questions, we investigate a sequential game, in which the EV manufacturer first determines the driving range and sale price of EVs, and the LSP then decides on her EV usage rate and service price. We solve the game to find Stackelberg equilibrium and discuss our analytical results in the monopoly and duopoly settings.

We obtain some key insights for EV promotion in the logistics industry. For example, we find that whether strategy E is more profitable to the LSP than strategy H depends on the unit operating cost for new ICVs and the portion of demand fulfilled by new vehicles. A wider time window for EVs can help increase the EV usage rate, whereas a narrower time window for ICVs may not necessarily increase the EV usage rate, which relies on the demand potential for the LSP's service. The above insights hold for the monopoly case but may not be true when two LSPs compete for customers. The impacts of time windows for EVs and ICVs on the social welfare in the monopoly and duopoly cases are dependent on how they influence the demand fulfilled by EVs and the per mile environmental impact of using EVs. If such environmental impact is sufficiently low (high), then the government should change time windows to increase (decrease) the demand fulfilled by EVs, which can help raise the social welfare.

1.3 Major Contributions and Paper Structure

As in practice, the time window policies for EVs and ICVs and the charging time of EVs are important factors in the LSP's EV usage decision and the EV manufacturer's decisions. However, to the best of our knowledge, these factors have not been jointly considered in any extant publication. We can thus conclude that our paper is a seminal one contributing to the impacts of these factors on (i) the EV manufacturer's decisions on the driving range and EV price, (ii) the LSP's decisions on the EV usage rate and logistics service fee, and (iii) the social welfare. We compare the partial replacement strategies E and H with respect to the LSP's profit and social welfare. In addition, our findings expose the impacts of time window policies for EVs and ICVs on the EV usage rate and social welfare. These contribute to the literature and may help the LSPs, EV manufacturers, and governments.

The remainder of this paper is organized as follows. Section 2 presents a literature review. Section 3 introduces preliminary discussions for the EV manufacturer and the LSP. In Section 4, we conduct a game-theoretic analysis for the EV supply chain and perform sensitivity analyses. In Section 5, we investigate impacts of time window factors for EVs and ICVs and the LSP's replacement strategies on the social welfare. In Section 6, we obtain our analytic results with duopoly LSPs. This paper ends with a summary of major results in Section 7. We relegate our proofs and supplementary discussions to online Appendices.

2 Literature Review

We review relevant and representative publications in this section. To better present our review, we classify all the publications into two streams: (1) the delivery fleet renewal with EV adoptions for a single firm and (2) the analyses of EV supply chains.

2.1 The Delivery Fleet Renewal with EV Adoptions for a Single Firm

The deployment of EVs as a way to implement the green distribution practice has received increasing attention (Pelletier, Jabali, and Laporte 2016). Following a fleet renewal project of La Poste, Kleindorfer et al. (2012) obtained an optimal timing decision for the EV acquisition under cost uncertainty, and Neboian and Spinler (2015) analyzed an option of breaching a vehicle-leasing contract. Wang et al. (2013) developed a model for a firm's dynamic capacity adjustment with competing technologies (i.e., ICVs and diesel-electric hybrid vehicle trucks), and applied their model to Coca-Cola Enterprises' fleet renewal decisions. The fleet renewal problem with EVs has been analyzed in a fruitful and growing literature, which includes, e.g., Feng and Figliozzi (2013), Ansaripoor, Oliveira, and Liret (2014), Ahani, Arantes, and Melo (2016), Ansaripoor, Oliveira, and Liret (2016), Ansaripoor and Oliveira (2018), and Schiffer et al. (2021).

These studies provided academics and practitioners with a variety of models and algorithms to solve fleet replacement problems. However, these studies mainly focused on the LSP's decisions, which is different from our EV supply chain context. Our paper is relevant to Franceschetti et al. (2017) who investigated an LSP's strategical fleet composition, area partitioning, and routing strategy problem, and used the maximum within-area route duration as a constraint to account for time access restrictions. Different from Franceschetti et al. (2017), we estimate the impacts of time windows for EVs and ICVs on their expected service capacities, and analyze the EV manufacturer's decisions on the driving range and sale price of EVs as well as the LSP's service pricing and usage rate decisions.

2.2 The Analyses of EV Supply Chains

In the literature regarding the EV supply chain analysis, researchers widely used game-theoretic models to investigate a government's subsidies, which include (i) a fixed subsidy scheme (Huang et al. 2013), (ii) a price-discount subsidy scheme (Luo et al. 2014), (iii) the optimal subsidy with demand uncertainty (Cohen, Lobel, and Perakis 2016), (iv) subsidies and price discount rates for EV buyers (Shao, Yang, and Zhang 2017), (v) linear and fixed subsidies (Fu, Chen, and Hu 2018), (vi) the subsidy partition ratio (Gu, Ieromonachou, and Zhou 2019), (vii) risk aversion (Deng, Li, and Wang 2020), and (viii) subsidies for the driving range (Gao and Leng 2021). To find subsidy or tariff decisions, Fan et al. (2020) analyzed the optimal pricing strategies for the manufacturers of imported and domestic EVs. Chakraborty, Kumar, and Bhaskar (2021) analyzed a combination of a subsidy for EVs and a green tax for ICVs, and investigated their impacts on the sales of EVs and ICVs as well as social welfare. In addition, Fan, Huang, and Wang (2021) studied vertical cooperation and pricing strategies in a supply chain involving a battery supplier and two EV manufacturers.

According to our review above, we summarize major relevant publications in Table 1 in which we present decision variables, a government's policies, driving range, and charging situations. We find that most of extant publications relevant to EV supply chains do not explicitly account for the time window policies.

Literature	Decision variables	A government's policies	Driving range	Charging situations
Huang et al. (2013)	Wholesale and retail prices of ICVs and EVs	Subsidy		
Luo et al. (2014)	Wholesale and retail prices of EVs	Subsidy		
Cohen, Lobel, and Perakis (2016)	Subsidy, price, and quantity	Subsidy		
Shao, Yang, and Zhang (2017)	Subsidy, price discount rate, and prices of EVs and ICVs	Subsidy		
Fu, Chen, and Hu (2018)	Wholesale and retail prices and order quantity for EVs	Subsidy		
Wang and Deng (2019)	Wholesale and selling prices, and distance between charging stations	Subsidy		√
Gu, Ieromonachou, and Zhou (2019)	Subsidy partition ratio	Subsidy		
Chen and Fan (2020)	EV price and wholesale price and driving range of battery	Subsidy	√	
Fan et al. (2020)	Subsidy, tariff, and EV price	Subsidy, tariff		
Fan, Chen, and Zhao (2021)	EV price and battery price	Subsidy	√	
Gao and Leng (2021)	Subsidies and prices of EVs and ICVs	Subsidy	√	
Chakraborty, Kumar, and Bhaskar (2021)	Subsidy, green tax, and prices of EVs and ICVs	Subsidy, tax		
Kumar, Chakraborty, and Mandal (2021)	Effort in charging infrastructure and prices of EVs and ICVs	Subsidy		√
Yoo, Choi, and Sheu (2021)	Subsidy, EV price, service fee, and number of charging stations	Subsidy		√
Yu et al. (2021)	Numbers of charging stations built by the government and the firm, EV price, subsidy	Subsidy		√
Kuppusamy, Magazine and Rao (2021)	Numbers of EVs and ICVs and contract fee	-	√	√
Our paper differs from the above	The driving range, EV price, usage rate of EVs, and logistics service fee	Time window policies for EVs and ICVs	√	√

Table 1: Comparision between this paper and major relevant EV supply chain analysis publications.

A number of publications (e.g., Lin 2014, Kontou, Yin, and Lin 2015, Li et al. 2016, and Kontou et al. 2017) have studied the optimal driving range decision. These studies focused on how the optimal driving range decision affects the expected battery cost or social welfare rather than the EV supply chain. Our paper is related to a stream of the EV supply chain literature regarding the driving range. For example, in a supply chain with a battery supplier and an EV manufacturer, Chen and Fan (2020) found optimal decisions on the wholesale price, retail price, and driving range, whereas Fan, Chen, and Zhao (2021) analyzed battery outsourcing and product choice strategies, considering two types of driving ranges. Gao and Leng (2021) investigated the competition between an EV manufacturer and an ICV manufacturer under a government's subsidy scheme. Different from this stream of publications, we investigate an EV supply chain with an EV manufacturer and an LSP.

Our paper is also related to the EV supply chain literature that considered the charging environment. Wang and Deng (2019) studied charging station investments by the manufacturer or the dealer. Kumar, Chakraborty, and Mandal (2021) examined the scenario that the EV manufacturer or the government develops the charging infrastructure. Yoo, Choi, and Sheu (2021) investigated a supply chain consisting of an EV manufacturer, an ICV manufacturer, a charging service provider, and a government under four charging infrastructure investment modes. Yu et al. (2021) studied the EV price, the number of charging stations built by a government, and the number of charging stations constructed by an automobile maker, in the presence of the government's per station and purchase subsidies. Nonetheless, these publications have not considered the driving range. Although Kuppusamy, Magazine, and Rao (2021) examined both the driving range and recharging time, they focused on an EV supply chain consisting of an infrastructure service provider and a set of taxicab companies. Our paper differs from Kuppusamy, Magazine and Rao (2021) by involving an EV manufacturer's decisions on the driving range and sale price under time window policies.

3 Preliminaries

We consider a two-echelon supply chain consisting of an EV manufacturer and an LSP who decides to replace a portion of old ICVs in her fleet with new vehicles to serve customers in a market. As in the current practice of fleet renewal in city logistics, the LSP has two possible *partial* replacement strategies to replace a part of her old ICVs: (i) purchase only EVs (i.e., strategy E); and (ii) buy a mix of EVs and new ICVs (i.e., strategy H). If the LSP decides to choose strategy i ($i = E, H$), then she needs to determine her EV usage rate u_i (i.e., the proportion of demand in terms of daily miles fulfilled by EVs under strategy i) and logistics service fee f_i which is charged to customers in a market. The EV manufacturer makes decisions on price p_{1i} and driving range r_i which means the maximal running distance of a fully-charged EV in each charging cycle and acts as a performance indicator for EVs (Lin 2014). Table 2 summarizes key notations in this paper.

Parameters			
i	the LSP's replacement strategy, $i = E, H$	j	$j = 0, 1, 2$ denote an old ICV, an EV, and a new ICV, respectively
α_1	the time window factor for EVs		
α_2	the time window factor for ICVs	c_j	the unit operating cost for j
$v_1(r_i)$	the production cost for an EV under strategy i	$\hat{\gamma}_j$	the per mile environmental impact of using j
$\bar{t}_C$	the average charge time during operations	q_{0i}	the quantity of kept ICVs in the fleet under strategy i
t_C	the time for a full charge of an EV	q_{1i}	the order quantity for EVs under strategy i
N	the total number of working days	q_2	the order quantity for new ICVs under strategy H
ρ_i	the number of charging cycles of the EV under strategy i	q_{Ri}	the number of old ICVs replaced by new vehicles under strategy i
a	the demand potential for the LSP's service	ε_0	the salvage value of a replaced ICV
b	the demand sensitivity to the service fee	δ	the probability of recharging the EV during operations
ϕ	the proportion of the demand fulfilled by new vehicles under strategy H	ξ_j	$\xi_j \equiv 1 - \mu_j$, where μ_j denotes the value preservation rate of vehicle $j = 1, 2$
s	the average driving speed	τ	the unit depreciation of old ICVs
Decision variables			
r_i	the driving range of an EV under strategy i	p_{1i}	the sale price of an EV under strategy i
u_i	the usage rate of EVs under strategy i	f_i	the logistics service fee under strategy i
Object functions			
$\pi_i(r_i, p_{1i})$	the EV manufacturer's profit under strategy i	$\Pi_i(u_i, f_i)$	the LSP's profit under strategy i

Table 2: The list of key notations.

3.1 The EV Manufacturer's Profit Function

The EV manufacturer produces each EV with a cost $v_1(r_i)$ and sells EVs to the LSP with a price p_{1i}. He needs to determine the driving range for each EV (i.e., r_i) and the price (i.e., p_{1i}) under the LSP's strategy i ($i = E, H$). According to Lin (2014) and Kontou et al. (2017), each EV's production cost under strategy i can be estimated as

$$v_1(r_i) = c_{BD} + (r_i e(r_i) c_{BT}(r_i))/h_{BT}, \tag{1}$$

where c_{BD} denotes the r_i-independent body cost for an EV, $e(r_i)$ represents the theoretical energy consumption rate (kwh/mile), $c_{BT}(r_i)$ is the unit battery cost (\$/kwh), and h_{BT} is a battery utilization parameter (i.e., the ratio of the available capacity to the total capacity). When the EV becomes heavier as a result of its bigger battery, the energy consumption rate $e(r_i)$ naturally increases. The unit battery cost $c_{BT}(r_i)$ naturally decreases if the battery size increases. Here, $r_i e(r_i)$ means the usable capacity of an EV (kwh), and the second term in the right side of (1) represents the battery cost. In addition, each EV's production cost under strategy i (i.e., $v_1(r_i)$) increases with r_i. The parameters in (1) are given such that $\partial v_1(r_i)/\partial r_i > 0$, which is reasonable because the EV's production cost with a longer driving range is usually higher.

We calculate the EV manufacturer's profit as

$$\pi_i(r_i, p_{1i}) = q_{1i}(p_{1i} - v_1(r_i)), \text{ for } i = E, H, \tag{2}$$

where q_{1i} is the LSP's purchase quantity for EVs, and is calculated as in the subsequent section.

3.2 The LSP's Vehicle Replacements under Time Window Policies

To meet customer demand, the LSP needs to evaluate her fleet's service capacity in miles per day. Let α_1 and α_2 denote the time window factor for EVs and that for ICVs, respectively. For a day, the time window factor for EVs (ICVs) represents the extent to which EVs (ICVs) are allowed to access the city center in certain times of the day. Obviously, a wider time window for EVs (ICVs) results in greater total working hours of each EV (ICV). We begin by estimating the service capacity of any new or old ICV, which is measured as the number of miles for the ICV to run in a working day. In the LSP's fleet, T means the total available working hours per day. Hence, the service capacity of an ICV is calculated as $Q_0 \equiv \alpha_2 T s$, where s denotes the average driving speed.

We next estimate the service capacity of an EV, which is measured as the number of miles for the EV to run per day. Multiplying the number of charging cycles for the EV (denoted by ρ_i) and the driving range r_i, we compute the expected service capacity of the EV as

$$Q_1(r_i) = \rho_i r_i, \text{ for } i = E, H. \tag{3}$$

As ρ_i plays an important role in (3), we should estimate its value, which depends on the total working hours of the EV per day. Similar to the total working hours of an ICV, the total working hours of the EV per day is computed as $\alpha_1 T$, which consists of (i) the running hours of the EV per day (i.e., T_W) and (ii) the total charging time during operations (i.e., T_C), i.e., $\alpha_1 T = T_W + T_C$. The running hours of the EV per day can be obtained as $T_W = \rho_i r_i / s$, where $\rho_i r_i$ denotes the expected service capacity of the EV. The LSP may recharge the EV during operations or may do it outside operations. Letting $\delta \in [0, 1]$ denote the probability of recharging the EV during operations, we calculate the expected charging number for the EV during operations as $\delta\rho_i$. Then, we find the total charging time during operations T_C as the expected charging number during operations (i.e., $\delta\rho_i$) times the time for a full charge of an EV (i.e., t_C). That is, $T_C = \rho_i \delta t_C$. It thus follows that the total working hours of the EV per day is

$$\alpha_1 T = \frac{\rho_i r_i}{s} + \rho_i \delta t_C. \tag{4}$$

The number of charging cycles for an EV (i.e., ρ_i) affects both T_W and T_C. According to (4), we obtain ρ_i as

$$\rho_i = \frac{\alpha_1 T}{\bar{t}_C + r_i / s}, \text{ for } i = E, H, \tag{5}$$

where $\bar{t}_C \equiv \delta t_C$ means the average charging time during operations. Note that ρ_i in (5) may not be an integer.

One may note that the LSP may not incur any loss from charging EVs if one or both of the following issues occur: first, it is sufficient to recharge EVs overnight or in between shifts, or outside the time windows for EVs. Secondly, the charging time during operations is negligibly short if drivers can change batteries quickly. Nonetheless, we learn from the Rocky Mountain Institute's report in 2019[2], Kuppusamy, Magazine, and Rao's discussions (2017), and Morganti and Browne's results (2018) that in today's society, recharging during operations may still be necessary in city operations. For generality, we consider both the case of recharging during operations and the case of no recharging during operations. In reality, there may be no need to charge an EV during operations, which corresponds to the case of $\delta = 0$. When an EV is charged during its operations, the value of δ is positive. For example, for the case of $\delta = 0.5$, the fraction of times that the LSP recharges the EV during operations is 50%. The above indicates that our model describes all possible situations and can thus viewed as a general one.

The expected service capacity of the EV is

$$Q_1(r_i) = \frac{\alpha_1 T r_i}{\delta t_C + r_i / s}, \text{ for } i = E, H. \tag{6}$$

The function in (6) possesses the following practical properties. First, when the probability of recharging the EV during operations (i.e., δ) approaches zero or the driving range of EVs (i.e., r_i) is sufficiently high, the service capacity function $Q_1(r_i)$ is approximately equal to $\alpha_1 T s$, which is similar to the service capacity of an ICV in the function form. Secondly, the service capacity of an EV is increasing in the time window factor for EVs. When the time window factor equals zero, the service capacity is reduced to zero. Thirdly, the service capacity function accounts for the driving range, the average charging time during operations, and the time window policies for EVs, which are all the major factors influencing the EV promotion in city logistics.

Traffic incentives granted to EV users are made locally in a number of countries, such as Netherlands, Sweden, UK, Germany, France, China, Canada, and US (Song and Potoglou 2020). This allows local governments to implement traffic incentives for EVs with more flexibility based on their specific local needs. For example, the city of Shenzhen in China provides road access priorities for EVs, which allow EVs to operate on certain routes and at certain times whereas ICVs are prohibited on those roads and at those times. The only exception is that electric logistics vehicles are not permitted to access certain portions of Shennan Boulevard every day from 7:30 a.m. to 9:00 p.m. to avoid a high traffic congestion (Crow et al. 2019).

Next, we calculate the LSP's order quantity q_{1i} for EVs under strategy i $(i = E, H)$. In reality, a higher service fee usually discourages customer demand. Therefore, the aggregate demand for the LSP's logistics service (with both EVs and traditional ICVs) under strategy i $(i = E, H)$ is dependent on service fee f_i. We accordingly use a demand function $d_i(f_i)$ (measured in miles per day) as $d_i(f_i) = a - bf_i$, where a denotes the demand potential for the LSP's service and b is a parameter reflecting the demand sensitivity to the service fee. Such a linear demand function has been widely used to analyze relevant problems. Using total demand $d_i(f_i)$, the LSP's usage rate u_i, and expected service capacity of an EV (per day) $Q_1(r_i)$, we obtain the LSP's order quantity for EVs as

$$q_{1i} = \frac{u_i d_i(f_i)}{Q_1(r_i)} = z(r_i) u_i d_i(f_i), \text{ for } i = E, H. \tag{7}$$

According to our results in (6), we can rewrite the LSP's order quantity for EVs in (7) as $q_{1i} = z(r_i)u_i d_i(f_i)$, where $z(r_i) \equiv 1/Q_1(r_i) = W_1 + \eta/r_i$ with $W_1 \equiv 1/(\alpha_1 T s)$ and $\eta \equiv \delta t_C/(\alpha_1 T)$.

The LSP keeps q_{0i} $(i = E, H)$ old vehicles in the fleet. Under strategy E, the number of old ICVs to be used by the LSP is $q_{0E} \equiv (1 - u_E)d_E(f_E)/Q_0$. Letting $W_0 \equiv 1/Q_0$, which reflects a multiplicative inverse of the service capacity of an ICV, we have $q_{0E} = W_0(1 - u_E)d_E(f_E)$. Under strategy H, the LSP purchases new vehicles including EVs and new ICVs to fullfill the proportion of demand ϕ. Obviously, $\phi > u_H$. The number of old ICVs to be still used in the LSP's fleet under strategy H is $q_{0H} = W_0(1 - \phi)d_H(f_H)$. The LSP's order quantity for new ICVs under strategy H is

$$q_2 = \frac{(\phi - u_H)d_H(f_H)}{Q_0} = W_0(\phi - u_H)d_H(f_H). \tag{8}$$

Since the ICV and the EV may differ in their capacities, the number of old, replaced ICVs may be different from that of new vehicles (which is calculated above). We let q_{RE} denote the number of old ICVs replaced by EVs under strategy E, and use q_{RH} to represent the number of old ICVs replaced by EVs and new ICVs under H. We compute q_{RE} and q_{RH} as

$$q_{RE} = \frac{u_E d_E(f_E)}{Q_0} = W_0 u_E d_E(f_E) \text{ and } q_{RH} = \frac{\phi d_H(f_H)}{Q_0} = \phi W_0 d_H(f_H). \tag{9}$$

According to the above discussion, the LSP determines demand allocation and the corresponding fleet composition under strategies E and H. In the former, the LSP buys q_{1E} units of EVs to meet demand $u_E d_E(f_E)$ and uses q_{0E} units of old vehicles to meet demand $(1-u_E)d_E(f_E)$, respectively. In the latter, the LSP purchases both EVs and new ICVs. Specifically, she buys q_{1H} units of EVs and q_2 units of new ICVs to satisfy demands $u_H d_H(f_H)$ and $(\phi - u_H)d_H(f_H)$, respectively. She also uses q_{0H} units of old vehicles to meet demand $(1-\phi)d_H(f_H)$ under strategy H.

Using these vehicle quantities, we can calculate the LSP's depreciation costs for EVs (denoted by the subscript 1), old ICVs (denoted by the subscript 0), and new ICVs (denoted by the subscript 2). Let μ_1 and μ_2 represent value preservation rates of an EV and a new ICV in the end of time horizon. The depreciation of three types of vehicles is analyzed as follows. First, the LSP's perceived salvage value for an EV is $\mu_1 p_{1i}$. The depreciation value of EVs under strategy i is $q_{1i}\xi_1 p_{1i}$, where $\xi_1 = 1-\mu_1$ and p_{1i} denotes the sale price of an EV. Second, the market value of old ICVs decreases with their ages. The depreciation value of old ICVs under strategy i is $q_{0i}\tau$, where τ denotes the depreciation of an old ICV. Third, the depreciation of new ICVs is $q_2\xi_2 p_2$, where $\xi_2 = 1-\mu_2$ and p_2 denotes the sale price of an ICV. In addition, since the LSP resells some old ICVs, she obtains the salvage value of those ICVs $q_{Ri}\varepsilon_0$ under strategy i, where ε_0 represents the salvage value of a replaced ICV. For a summary of our above results, see Table 3.

Strategy		E	H	Remarks
EV	Unit service capacity	$Q_1(r_E) = \rho_E r_E$	$Q_1(r_H) = \rho_H r_H$	$\rho_i = \frac{\alpha_1 T}{\delta t_C + r_i/s}$, for $i = E, H$.
	The demand to be satisfied by EVs	$u_E d_E(f_E)$	$u_H d_H(f_H)$	—
	Order quantity	$q_{1E} = z(r_E) u_E d_E(f_E)$	$q_{1H} = z(r_H) u_H d_H(f_H)$	$z(r_i) = 1/Q_1(r_i)$
	Depreciation of EVs	$q_{1E}\xi_1 p_{1E}$	$q_{1H}\xi_1 p_{1H}$	$\xi_1 = 1-\mu_1$
Old ICV	Unit service capacity	$Q_0 = \alpha_2 Ts$	$Q_0 = \alpha_2 Ts$	—
	The demand to be satisfied by kept ICVs	$(1-u_E)\, d_E(f_E)$	$(1-\phi) d_H(f_H)$	—
	Number of kept ICVs	$q_{0E} = W_0(1-u_E)\, d_E(f_E)$	$q_{0H} = W_0(1-\phi) d_H(f_H)$	$W_0 = 1/Q_0$
	Depreciation of kept ICVs	$q_{0E}\tau$	$q_{0H}\tau$	
	Number of replaced ICVs	$q_{RE} = W_0 u_E d_E(f_E)$	$q_{RH} = W_0 \phi d_H(f_H)$	—
	Total salvage value of replaced ICVs	$q_{RE}\varepsilon_0$	$q_{RH}\varepsilon_0$	—
New ICV	Unit service capacity	Q_0	Q_0	—
	The demand to be satisfied by new ICVs	—	$(\phi - u_H) d_H(f_H)$	—
	Order quantity	—	$q_2 = W_0(\phi - u_H) d_H(f_H)$	—
	Depreciation of new ICVs	—	$q_2\xi_2 p_2$	$\xi_2 = 1-\mu_2$

Table 3: The analytic results for the LSP's vehicle replacements under strategies E and H.

4 Supply Chain Analysis with a Monopolistic Logistics Service Provider

Under strategies E and H, we analyze the two-echelon supply chain to find the EV manufacturer's and the LSP's decisions in Stackelberg equilibrium, and derive the conditions for the monopolistic

LSP's optimal replacement strategy. We then investigate the impacts of time window factors on the Stackelberg equilibrium under each strategy.

4.1 The Sequential Game Analysis

As the "leader" in the game, the EV manufacturer first announces his EV pricing and driving range decisions (i.e., p_{1i} and r_i, $i = E, H$). His profit function is defined in (2). Then, as the "follower" in the game, the LSP determines her EV usage rate u_i and logistics service fee f_i. Under strategy E, we develop the LSP's profit function as

$$\Pi_E(u_E, f_E) = N(f_E - c_E)d_E(f_E) - q_{1E}\xi_1 p_{1E} - q_{0E}\tau + q_{RE}\varepsilon_0 - \frac{M}{2}u_E^2, \tag{10}$$

where N is the total number of working days, $Nf_E d_E(f_E)$ and $Nc_E d_E(f_E)$ denote the LSP's total revenue and operating cost, and c_E is the LSP's operating cost per mile. Since the LSP's service fee is determined based on her usage rate and cost structure, we write the LSP's operating cost per mile in (10) as $c_E = u_E c_1 + (1 - u_E)c_0$, where c_1 and c_0 denote the unit operating costs for EVs and kept ICVs, respectively. According to our definitions, the first term in (10) is the total revenue minus the total operating cost, the second term (i.e.,$q_{1E}\xi_1 p_{1E}$) and third term (i.e., $q_{0E}\tau$) mean the depreciation of EVs and that of kept ICVs as defined in Table 3, and the fourth term (i.e., $q_{RE}\varepsilon_0$) is the LSP's total resale value from disposing of old ICVs. There is a fixed cost of using EVs. Following the cost of greening in Banker, Khosla, and Sinha (1998) and Ghosh and Shah (2015), we compute this fixed cost as $Mu_i^2/2$, for $i = E, H$, where M is the fixed cost of greening. This quadratic function indicates increasing marginal cost of usage rates.

Under strategy H, the LSP's profit is

$$\Pi_H(u_H, f_H) = N(f_H - c_H)d_H(f_H) - q_{1H}\xi_1 p_{1H} - q_{0H}\tau - q_2\xi_2 p_2 + q_{RH}\varepsilon_0 - \frac{M}{2}u_H^2, \tag{11}$$

where $c_H = u_H c_1 + (\phi - u_H)c_2 + (1 - \phi)c_0$ (in which c_2 is the unit operating cost for new ICVs) means the LSP's operating cost per mile under strategy H. The term $q_2\xi_2 p_2$ in (11) denotes the depreciation of new ICVs.

Letting $G_E \equiv W_0\tau + Nc_0$, $\lambda_E \equiv N(c_0 - c_1) + W_0\varepsilon_0 + \tau W_0 - z(r_E)\xi_1 p_{1E}$, $G_H \equiv N[\phi c_2 + (1-\phi)c_0] + W_0(1-\phi)\tau + \phi W_0\xi_2 p_2 - \phi W_0\varepsilon_0$, and $\lambda_H \equiv W_0\xi_2 p_2 + N(c_2 - c_1) - z(r_H)\xi_1 p_{1H}$, we can rewrite the LSP's profit functions under strategies E and H as

$$\begin{cases} \Pi_E(u_E, f_E) = (Nf_E + \lambda_E u_E - G_E)(a - bf_E) - Mu_E^2/2, \\ \Pi_H(u_H, f_H) = (Nf_H + \lambda_H u_H - G_H)(a - bf_H) - Mu_H^2/2. \end{cases}$$

Proposition 1 *When $Na - bG_i > 0$, $\lambda_i > 0$, and $M > [b\lambda_i(Na - bG_i) + b^2\lambda_i^2]/(2bN)$, for $i = E, H$, we find that, in Stackelberg equilibrium, the LSP's optimal usage rate of EVs and logistics service fee are*

$$u_i^* = \frac{\lambda_i b\,(Na - bG_i)}{2bNM - b^2\lambda_i^2} \text{ and } f_i^* = \frac{M\,(Na + bG_i) - ab\lambda_i^2}{2bNM - b^2\lambda_i^2}, \text{ for } i = E, H;$$

and the EV manufacturer's optimal driving range and EV price are (r_i^*, p_{1i}^*) (for $i = E, H$), where the optimal driving range r_i^* is the unique solution of the following equation:

$$\frac{\bar{t}_C v_1(r_i)}{r_i^2} - \frac{\partial v_1(r_i)}{\partial r_i}\left(\frac{1}{s} + \frac{\bar{t}_C}{r_i}\right) = 0,$$

and the optimal EV price p_{1i}^* is the unique solution of the equation

$$2bNM\lambda_i - b^2\lambda_i^3 - z(r_i)\xi_1\left(p_{1i} - v_1(r_i)\right)\left(2bNM + 3b^2\lambda_i^2\right) = 0.$$

Proposition 1 reveals that the EV manufacturer's optimal driving range in Stackelberg equilibrium is independent of whether the LSP uses strategy E or H, i.e., $r^* \equiv r_E^* = r_H^*$. This occurs because the optimal driving range for the EV manufacturer does not involve the terms including the optimal EV price, which is in accordance with previous studies (e.g., Lin 2014, Kontou, Yin, and Lin 2015, and Li et al. 2016) on the optimal driving range of EVs from a cost minimization perspective. In addition, the optimal range is independent of the time window factors for EVs and ICVs (i.e., α_1 and α_2) but dependent on the average charging time during operations $\bar{t}_C$.

We also learn from Proposition 1 that the EV price, the usage rate of EVs, and the logistics service fee are all dependent on which strategy the LSP uses for her fleet replacement. Moreover, different from the driving range of EVs, these decisions are influenced by the time window factors for EVs and ICVs. It thus follows that the factors α_1 and α_2 play an important role in determining the profit allocation between the two supply chain members, although they do not influence the EV manufacturer's driving range decision.

Corollary 1 *The optimal driving range is increasing in the average charging time during operations.*

In practice, the development of longer range vehicles and the construction of faster charging infrastructure are complementary, because they both affect the expected service capacity of an EV (Funke, Plötz and Wietschel 2019). Corollary 1 indicates that, when the average charging time during operations decreases, the EV manufacturer should reduce the driving range of EVs to maximize his profit. This means that the EV manufacturer should consider the probability of recharging the EV during operations and the time for a full charge of an EV to determine the optimal driving range.

Corollary 2 *The impacts of the unit operating cost for old ICVs (i.e., c_0), the unit operating cost for EVs (i.e., c_1), and that for new ICVs (i.e., c_2) on the EV manufacturer's optimal EV price p_{1i}^*, the optimal driving range r^*, the LSP's optimal usage rate of EVs u_i^*, and the logistics service fee f_i^* are obtained as shown in Table 4, where $\Upsilon_i \equiv 4N^2M^2 - 12NMb\lambda_i^2 - 3b^2\lambda_i^4$, $i = E, H$; $A_{0F} \equiv bG_E/N + F_E$ with $F_i \equiv (2bNM - t_i^2)y_i/(Nl_it_i)$, $t_i \equiv b\lambda_i$, $l_i \equiv (2NM + 3b\lambda_i^2)^2$, and $y_i \equiv 4N^2M^2 + 3b^2\lambda_i^4$ for $i = E, H$; $A_{0U} \equiv bG_E/N + U_E$ with $U_i \equiv 2(2bNM - t_i^2)y_it_i/[Nl_i(2bNM + t_i^2)]$; $A_{2F} = bG_H/N + \phi F_H$; $A_{2U} = bG_H/N + \phi U_H$; $A_{0F} > A_{0U}$, and $A_{2F} > A_{2U}$.*

	r^*	p^*_{1i} (for $i = E, H$)	f^*_E	u^*_E	f^*_H	u^*_H
c_1	–	$\begin{cases} \uparrow, & \text{if } sgn(\Upsilon_i) = -1, \\ -, & \text{if } sgn(\Upsilon_i) = 0, \\ \downarrow, & \text{otherwise.} \end{cases}$	$\uparrow$	$\downarrow$	$\uparrow$	$\downarrow$
c_0	–	$\begin{cases} \downarrow, & \text{if } sgn(\Upsilon_E) = -1, \\ -, & \text{if } sgn(\Upsilon_E) = 0, \\ \uparrow, & \text{otherwise.} \end{cases}$	$\begin{cases} \uparrow, & \text{if } a < A_{0F}, \\ \downarrow, & \text{if } a \geq A_{0F}. \end{cases}$	$\begin{cases} \uparrow, & \text{if } a \geq A_{0U}, \\ \downarrow, & \text{if } a < A_{0U}. \end{cases}$	$\uparrow$	$\downarrow$
c_2	–	$\begin{cases} \downarrow, & \text{if } sgn(\Upsilon_H) = -1, \\ -, & \text{if } sgn(\Upsilon_H) = 0, \\ \uparrow, & \text{otherwise.} \end{cases}$	–	–	$\begin{cases} \uparrow, & \text{if } a < A_{2F}, \\ \downarrow, & \text{if } a \geq A_{2F}. \end{cases}$	$\begin{cases} \uparrow, & \text{if } a \geq A_{2U}, \\ \downarrow, & \text{if } a < A_{2U}. \end{cases}$

Table 4: The impacts of the parameter c_j on the optimal EV prices, the optimal driving ranges, the optimal logistics service fees, and the optimal usage rates. Note that the marks "↓," "↑," and "—" indicate that the optimal decisions are decreasing in, increasing in, and independent of the corresponding parameter, respectively. Moreover, $sgn(\Upsilon_i)$ means the sign of Υ_i.

Corollary 2 indicates that a lower unit operating cost for EVs (i.e., c_1) can increase the usage rates of EVs under strategies E and H. In practice, the city of Shenzhen in China has implemented the operational subsidy for EVs since 2018 to decrease their unit operating costs, which has already helped increase their usage rates. The total operational subsidy for an EV over three years should not exceed ¥75,000 if the EV belongs to a fleet of a sufficiently large scale and can meet the criteria about the miles traveled, vehicle type, and battery quality. This operational subsidy policy has a notable impact on the EV utilization, as the proportion of EVs that satisfies the requirement for the subsidy's mileage increased from 18.6% in 2018 to 44.2% in 2019 (Wang et al. 2020). As the value of c_1 is smaller, the EV manufacturer should raise the EV price under strategy i (i.e., p^*_{1i}) if $\Upsilon_i \geq 0$ but reduce p^*_{1i} if $\Upsilon_i < 0$. When the value of c_1 decreases, the LSP should lower her service fee f^*_i.

A government may charge gasoline fuel taxes for a per kilometer usage of ICVs (Jenn, Azevedo, and Fischbeck 2015). This causes an increase in the unit operating costs for old ICVs (i.e., c_0) and new ICVs (i.e., c_2). This may impact the EV usage rate, which depends on the LSP's replacement strategies and the demand potential for her service. As the value of c_0 increases, the LSP should increase her service fee under strategy H. This results in a decrease in the service demand $d_H(f^*_H)$, thereby reducing the LSP's motivation to use EVs and decreasing the usage rate of EVs u^*_H.

The demand potential for the LSP's service (i.e., a) implies the effect of c_0 (c_2) on her EV usage rate u^*_E under strategy E (u^*_H under strategy H). Note that the demand for the LSP's service is increasing in a, $A_{0F} > A_{0U}$, and $A_{2F} > A_{2U}$. If a is sufficiently high such that $a \geq A_{0F}$ ($a \geq A_{2F}$), then the LSP can increase u^*_E (u^*_H) and decrease her service fee f^*_E under strategy E (f^*_H under strategy H) due to a higher value of c_0 (c_2). As the value of c_0 (c_2) rises, the LSP can reduce u^*_E $\left(u^*_H\right)$ if $a < A_{0U}$ ($a < A_{2U}$), because a sufficiently low demand for the LSP's service discourages her from using EVs. As a response, the LSP should increase f^*_E (f^*_H) with c_0 (c_2). When the value of a is greater than A_{0U} (A_{2U}) but smaller than A_{0F} (A_{2F}), the LSP should increase u^*_E (u^*_H) and f^*_E (f^*_H) as a response to a higher value of c_0 (c_2). As EVs compete with old (new) ICVs under strategy E (H), we find that when the value of c_0 (c_2) is higher, the EV manufacturer should increase the EV price p^*_{1E} (p^*_{1H}) if $\Upsilon_E > 0$ ($\Upsilon_H > 0$) but reduce p^*_{1E} (p^*_{1H}) if $\Upsilon_E \leq 0$ ($\Upsilon_H \leq 0$).

4.2 The LSP's Partial Replacement Strategy

We examine the LSP's partial replacement strategies, for which we let $\hat{c}_2 \equiv c_0+W_0(\tau+\varepsilon_0-\xi_2 p_2)/N$ and $\hat{\phi} \equiv (Nc_0+W_0\tau)/[N(\hat{c}_2 - c_2)] + [\sqrt{2(2bNM-t_H^2)\Pi_E(u_E^*, f_E^*)/M} - Na]/[bN(\hat{c}_2 - c_2)]$.

Proposition 2 *If $c_2 = \hat{c}_2$, or, $\phi = \hat{\phi}$ and $c_2 \neq \hat{c}_2$, then the LSP's profits under strategies E and H are the same. If $c_2 < \hat{c}_2$ and $\phi < \hat{\phi}$, or, $c_2 > \hat{c}_2$ and $\phi > \hat{\phi}$, then the LSP prefers strategy E to strategy H. Otherwise, the LSP prefers strategy H to strategy E.*

The LSP determines her replacement strategy mainly based on the unit operating cost for new ICVs (i.e., c_2) and the portion of demand fulfilled by new vehicles under strategy H (i.e., ϕ). Note the LSP's profit under strategy E $\Pi_E(u_E^*, f_E^*)$ is not affected by c_2 and ϕ. When c_2 is sufficiently high such that $c_2 > \hat{c}_2$, the LSP selects strategy H (strategy E) if she chooses a sufficiently low (high) portion of demand fulfilled by new vehicles $\phi < \hat{\phi}$ ($\phi > \hat{\phi}$). When c_2 is sufficiently low such that $c_2 < \hat{c}_2$ and ϕ is sufficiently large such that $\phi > \hat{\phi}$ (sufficiently low such that $\phi < \hat{\phi}$), the LSP's profit under strategy H $\Pi_H(u_H^*, f_H^*)$ is higher (lower) than that under strategy E. When c_2 equals to $\hat{c}_2$, $\Pi_H(u_H^*, f_H^*)$ is equal to $\Pi_E(u_E^*, f_E^*)$, because the EV price and the usage rate of EVs become indifferent to the LSP's replacement strategies. When c_2 is not equal to $\hat{c}_2$, the LSP can also obtain the same profits under the two strategies if $\phi = \hat{\phi}$. The thresholds $\hat{c}_2$ and $\hat{\phi}$ can help the LSP estimate her profitability under strategy H in comparison to that under strategy E.

We provide a numerical example that offers more insights into the results derived in Proposition 2. Consider a period of six years, e.g., from 2022 to 2027. At the end of 2021, the LSP disposes of a number of old ICVs, purchases new vehicles, and uses them for the next six years. According to Redmer (2009) and Taefi, Stütz, and Fink (2017), suppose the salvage value from disposing an old ICV ε_0 is \$9,783.62 and value preservation rates of an EV and an ICV are 0.25 and 0.33. Depreciation of an old ICV τ is $\$3,510.3$ (Ansaripoor and Oliveira 2018). In line with Cagliano et al. (2017), the monthly working days are 22 days. The total number of working days is $N = 1,584$. In addition, the LSP's fixed cost of greening is $M = \$5$ million, and the proportion of the demand fulfilled by new vehicles under strategy H is $\phi = 0.9$. The demand potential is $a = 20,000$ miles, and the demand sensitivity to the logistics service fee is $b = 4,000$. According to Redmer (2009) and Feng and Figliozzi (2013), we set the unit operating costs for old ICVs, EVs, and new ICVs as $c_0 = \$0.7386$/mile, $c_1 = \$0.2486$/mile, and $c_2 = \$0.633$/mile, respectively. The vehicle body cost is $\$12,000$; and similar to Kontou et al. (2017), the battery cost for an EV is given as $r_i e(r_i) c_{BT}(r_i)/0.9$, where $e(r_i) = 0.2839 + 0.0004r_i$ and $c_{BT}(r_i) = 181.8 - 0.309r_i$ (BloombergNEF 2020). We set the probability of recharging the EV during operations as $\delta = 0.5$. The time for a full charge of an EV is 3.5 hours and the sale price of an ICV p_2 is \$55,661 (Taefi, Stütz, and Fink 2017). Following Franceschetti et al. (2017) who described the vehicle speed and time window policies in the Dutch city of 's-Hertogenbosch, we set the average driving speed in miles per hour s is 30 mile/hour, $\alpha_1 = 1$, $\alpha_2 = 0.5$, and $T = 14$ hours. We refer to these parameter values as the base case.

We plot Figure 1 to depict the influences of unit operating cost for new ICVs (i.e., c_2) on the EV manufacturer's and the LSP's profits. Under strategy E, since the LSP buys EVs only, c_2 does not affect the LSP's and the EV manufacturer's profits. When the value of c_2 increases from \$0.5/mile to \$0.75/mile, the LSP's profit decreases because strategy H's advantage is weakened, whereas $\hat{\phi}$ varies but remains smaller than ϕ. Consequently, when c_2 is smaller (greater) than $\hat{c}_2$, the LSP should opt for strategy H (E). When $c_2 = \hat{c}_2$, both the LSP and the EV manufacturer obtain an identical profit under these two strategies, which occurs because $p^*_{1H} = p^*_{1E}$ and $q^*_{1H} = q^*_{1E}$. As shown in Figure 1, the EV manufacturer gains a higher profit from the LSP's strategy E (H) when c_2 is sufficiently low (high), because the price and order quantity for EVs under strategy E are greater (smaller) than those under strategy H.

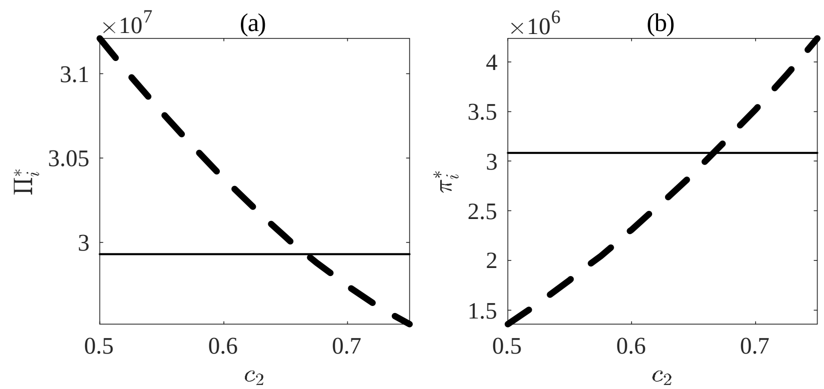

Figure 1: The LSP's and the EV manufacturer's profits when the unit operating cost of new ICVs varies. Note that the solid and dashed lines represent the results under strategies E and H, respectively.

4.3 Sensitivity Analyses and Managerial Insights

We perform sensitivity analyses to investigate the impacts of time window factors on decisions of the EV manufacturer and the LSP. Then, we use the parameter values given in Section 4.2 to conduct numerical experiments.

Proposition 3 *As the time window factor for EVs increases, the LSP's optimal service fee f^*_i ($i = E, H$) decreases, whereas the LSP's optimal EV usage rate u^*_i and profit $\Pi_i(u^*_i, f^*_i)$ as well as the EV manufacturer's profit $\pi_i(r^*_i, p^*_{1i})$ increase. Moreover, the elasticity of the EV price (i.e., p^*_{1i}) with respect to the time window factor for EVs is smaller than one, i.e., $(\partial p^*_{1i}/p^*_{1i})/(\partial \alpha_1/\alpha_1) < 1$.*

We learn from Proposition 3 that a wider time window for EVs can help increase the usage rate of EVs and decrease the LSP's service fee because of greater service capacities of EVs, leading both the LSP and the EV manufacturer to achieve a higher profit. These results are independent of which replacement strategy the LSP uses. The change of the EV price is inelastic to the time window factor for EVs, which implies that the time window for EVs influences the EV manufacturer's pricing decision less proportionally because of competition. The EV manufacturer may increase or decrease her product price with α_1. Therefore, we examine their relations numerically.

Time windows for EVs and ICVs might be the same in many cities. Therefore, when α_k ($k = 1, 2$) increases from 0.5 to 1, the corresponding percentage changes in u_i, f_i, p_{1i}, Π_i, and π_i are computed by $\Delta u_i(\alpha_k) \equiv (u_i(\alpha_k) - u_i(\alpha_k = 0.5))/u_i(\alpha_k = 0.5)$, $\Delta f_i(\alpha_k) \equiv (f_i(\alpha_k) - f_i(\alpha_k = 0.5))/f_i(\alpha_k = 0.5)$, $\Delta p_{1i}(\alpha_k) \equiv (p_{1i}(\alpha_k) - p_{1i}(\alpha_k = 0.5))/p_{1i}(\alpha_k = 0.5)$, $\Delta\Pi_i(\alpha_k) \equiv (\Pi_i(\alpha_k) - \Pi_i(\alpha_k = 0.5))/\Pi_i(\alpha_k = 0.5)$, and $\Delta\pi_i(\alpha_k) \equiv (\pi_i(\alpha_k) - \pi_i(\alpha_k = 0.5))/\pi_i(\alpha_k = 0.5)$, where $i = E, H$. Figures 2(a), (d), and (e) expose that a greater time window for EVs results in an increase in usage rates of EVs as well as the LSP's and the EV manufacturer's profits, which is the same as shown in Proposition 3. We learn from Figures 2(b) and 2(c) that a greater time window factor for EVs reduces the logistics service fees and raises the EV prices under both strategies. The time window factor for EVs significantly affects the EV manufacturer's pricing decision with a limitation. When the value of α_1 increases from 0.5 to 1, the percentage increase in the EV price is smaller than 81%. This result is consistent with Proposition 3. These observations also hold for another case in online Appendix B.

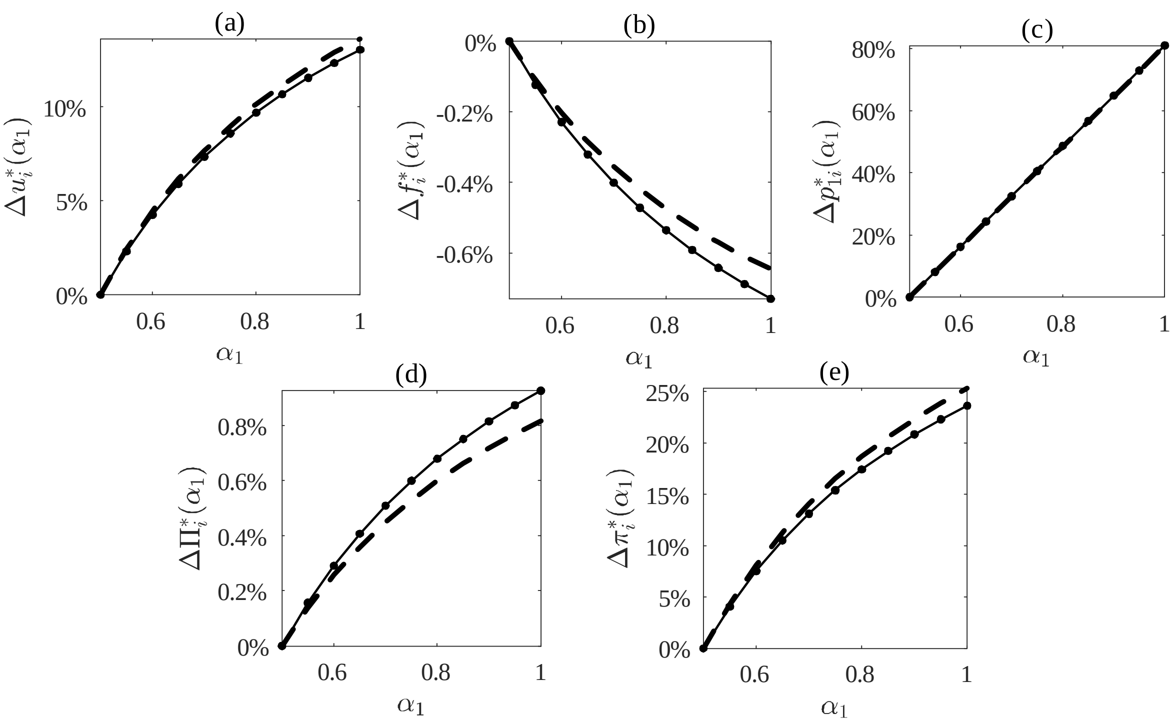

Figure 2: The impacts of time window factor for EVs on the percentage changes in the optimal usage rate of EVs (as shown in (a)), the optimal logistics service fee (as shown in (b)), the optimal EV price (as shown in (c)), and the LSP's and the EV manufacturer's profits (as shown in (d) and (e)). Note that the solid and dashed lines indicate the results under strategies E and H, respectively.

Proposition 4 *We draw the following results.*

1. *An increase in the time window factor for ICVs can decrease (increase) the LSP's optimal EV usage rate* u_i^* *if* $a > A_{iU}$ ($a \leq A_{iU}$) *and increase (decrease) the LSP's service fee* f_i^* *if* $a > A_{iF}$ ($a \leq A_{iF}$), *where* $A_{iU} \equiv bG_i/N + \kappa_i U_i$, $\kappa_E \equiv \tau/(\varepsilon_0+\tau)$, $\kappa_H \equiv -\tilde{G}/(\xi_2 p_2)$, $\tilde{G} \equiv \phi\varepsilon_0 - (1-\phi)\tau - \xi_2\phi p_2$, $A_{iF} \equiv bG_i/N + \kappa_i F_i$, U_i *and* F_i *are defined as in Corollary 2.*
2. *The sign of* $\partial p_{1i}^*/\partial\alpha_2$ *is the same as the sign of* $-\Upsilon_i$, *and* $\partial p_{1i}^*/\partial\alpha_2 > -P_{1i}$, *for* $i = E, H$, *where* Υ_i *is defined as in Corollary 2,* $P_{1E} \equiv W_0(\varepsilon_0+\tau)/(z(r^*)\xi_1\alpha_2)$, *and* $P_{1H} \equiv W_0\xi_2 p_2/(z(r^*)\xi_1\alpha_2)$.
3. *A higher value of time window factor for ICVs can decrease (increase) the LSP's profit* $\Pi_i(u_i^*, f_i^*)$ *if* $a > A_{iL}$ ($a \leq A_{iL}$) *and also decrease (increase) the EV manufacturer's profit* $\pi_i(r_i^*, p_{1i}^*)$ *if* $a > A_{iM}$ ($a \leq A_{iM}$), *where* $A_{iL} \equiv bG_i/N + 2\kappa_i F_i$, *and* $A_{iM} \equiv bG_i/N + 2\kappa_i t_i(2bNM - t_i^2)/[N(2bNM + 3t_i^2)]$, $i = E, H$.

The time window factor for ICVs (i.e., α_2) affects the usage rates of EVs under strategies E and H in a similar manner, which depends on the demand potential for the LSP's service (i.e., a). Specifically, the LSP with a sufficiently high demand potential for her service (e.g., $a > A_{iU}$) can increase the EV usage rate, when the government implements a narrower time window for ICVs (e.g., a smaller value of α_2). The above may help explain why some large fleets were among early firms that adopted EVs in the presence of increasingly restrictive regulations for ICVs (Taefi et al. 2016). This occurs mainly because a sufficient demand potential can help offset the effect of the fixed cost for choosing EVs. Consequently, when the value of α_2 decreases, the LSP can decrease (increase) her service fee if $a > A_{iF}$ ($a \leq A_{iF}$) and obtain a higher (lower) profit if $a > A_{iL}$ ($a \leq A_{iL}$). The above also indicates that the government should consider the demand potential for the LSP's service in evaluating the impacts of a more strict time window for ICVs on the LSP's decisions and profits.

A more stringent time window for ICVs can increase (decrease) the EV manufacturer's profit if a is larger (smaller) than A_{iM}. The sign of Υ_i determines the impacts of α_2 and the unit operating cost for EVs (e.g., c_1) on the EV price (e.g., p_{1i}^*). As the value of α_2 decreases, the EV manufacturer can increase (decrease) the EV price under strategy i if $\Upsilon_i \geq 0$ ($\Upsilon_i < 0$). Proposition 4 shows that there exists a lower bound about the proportional response of the EV price to changes in the value of α_2 under each strategy. If the EV manufacturer chooses to decrease the EV price as a response to a one-unit reduction in the value of α_2, then the decrease in EV price p_{1i}^* should be greater than $-P_{1i}$. This ensures that the EV manufacturer cannot overreact to the change in the time window factor for ICVs.

We plot Figure 3 to show the impacts of the time window factor for ICVs on the optimal decisions and the LSP's and the EV manufacturer's profits. According to Figures 3(a) and 3(e), as the value of α_2 increases from 0.5 to 1, the LSP decreases her EV usage rate because of $a > A_{iU}$, which results in a decrease in the EV manufacturer's profit when $a > A_{iM}$. Similar observations can be also found for an alternative case in online Appendix B.

A greater time window factor for ICVs can reduce the LSP's profit under strategy E when $a > A_{EL}$ but increase the profit under strategy H when $a < A_{HL}$, according to Figure 3(d). This

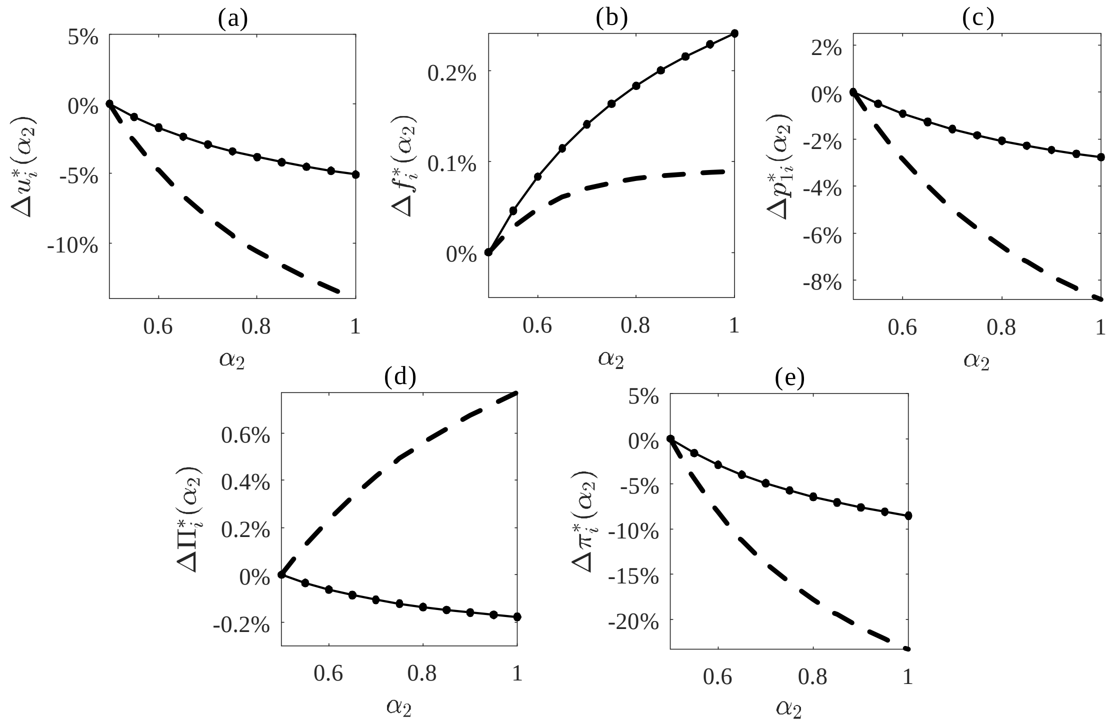

Figure 3: The impacts of time window factor for ICVs on the percentage changes in the optimal usage rate of EVs (as shown in (a)), the optimal logistics service fee (as shown in (b)), the optimal EV price (as shown in (c)), and the LSP's and the EV manufacturer's profits (as shown in (d) and (e), respectively). Note that the solid and dashed lines represent the results under strategies E and H, respectively.

exposes that the impact of α_2 on $\Delta\Pi_i(\alpha_2)$ depends on the LSP's replacement strategies. A greater time window factor for ICVs can result in a percentage increase in the logistics service fee under strategy i (i.e., f_i^*), because $a > A_{iF}$, as shown by Figure 3(b). However, it can cause a percentage decrease in f_i^* in an alternative case in online Appendix B, because $a < A_{iF}$. Figure 3 also indicates that a greater time window factor for ICVs can encourage the LSP to choose strategy H, because this strategy can generate a higher percentage increase in the LSP's profit than that under strategy E. We summarize our major analytical results as in Table A (see Appendix C).

5 The Social Welfare with a Monopolistic Logistics Service Provider and Policy Implications

A practical question for the government is about the impacts of time window policies and the LSP's replacement strategies on the social welfare. The total social welfare under strategy i ($i = E, H$), denoted by SW_i with a monopolistic LSP, accounts for the LSP's profit $\Pi_i(u_i, f_i)$, the EV manufacturer's profit $\pi_i(r_i, p_{1i})$, consumer surplus CS_i, and environment impact I_i. It is computed as

$$SW_i = \Pi_i(u_i^*, f_i^*)+\pi_i(r_i^*, p_{1i}^*) + CS_i - I_i. \tag{12}$$

As Cohen, Lobel, and Perakis (2016) argued, the consumer surplus for the monopoly case CS_i in (12) can be calculated as the (maximum) total amount that consumers are willing to pay for the LSP's logistics service minus the total amount that they actually pay (i.e., the market price), i.e.,

$$CS_i = \int_{f_i}^{f_i^{\max}} d_i(f_i)df_i = \int_{f_i}^{\frac{a}{b}} (a - bf_i)df_i = \frac{(a-bf_i)^2}{2b}, \text{ for } i = E, H, \tag{13}$$

where $f_i^{\max}$ is the maximum value of the logistics service fee charged by the LSP, and corresponds to the fee that yields zero demand, that is, $f_i^{\max}$ is calculated by solving $d_i(f_i) = a - bf_i = 0$ for f_i.

We account for production and use stages of EVs and ICVs to calculate the total environmental impact of each replacement strategy (Agrawal and Bellos 2016). Let γ_j denote the environmental impact of producing a vehicle j, where $j = 0, 1, 2$. The environmental impact of vehicle production is dependent on the value of γ_j ($j = 0, 1, 2$) and the corresponding vehicle quantity. Although EVs generate a negligibly small emission, they are not vehicles with zero impact on the environment, because, for example, the electricity used by EVs may be produced by burning natural gas or coal. Let $\hat{\gamma}_0$, $\hat{\gamma}_1$, and $\hat{\gamma}_2$ represent the per mile environmental impacts of using old ICVs, EVs, and new ICVs, respectively. The environmental impact of vehicle usage is contingent on the per mile environmental impact (i.e., $\hat{\gamma}_j$, $j = 0, 1, 2$), the total working days in the time horizon (i.e., N), and the miles traveled per day.

Using the above, we compute the total environmental impact of strategy i in the monopoly case as

$$\begin{cases} I_E \equiv q_{0E}\gamma_0 + q_{1E}\gamma_1 + N(1-u_E^*)d_E(f_E^*)\hat{\gamma}_0 + Nu_E^* d_E(f_E^*)\hat{\gamma}_1, \\ I_H \equiv \tilde{I}_H + N(\phi - u_H^*)d_H(f_H^*)\hat{\gamma}_2, \end{cases} \tag{14}$$

where $\tilde{I}_H \equiv q_{0H}\gamma_0 + q_{1H}\gamma_1 + q_2\gamma_2 + N(1-\phi)d_H(f_H^*)\hat{\gamma}_0 + Nu_H^* d_H(f_H^*)\hat{\gamma}_1$, q_{0i} ($i = E, H$), q_{1i} ($i = E, H$), and q_2 in (14) are the numbers of old ICVs, EVs, and new ICVs, respectively, as given in Section 3.2.

The LSP's strategy E can be viewed as the case that the government completely bans on the procurement of new ICVs, whereas strategy H corresponds to the case the LSP is allowed to buy both EVs and new ICVs.

Remark 1 If the per mile environmental impact of a new ICV (i.e., $\hat{\gamma}_2$) is greater (smaller) than $\hat{\gamma}_{2HE}$, then strategy E generates a higher (lower) social welfare than strategy H. That is, $SW_E > SW_H$ ($SW_E \leq SW_H$), if $\hat{\gamma}_2 > \hat{\gamma}_{2HE}$ ($\hat{\gamma}_2 \leq \hat{\gamma}_{2HE}$), where $\hat{\gamma}_{2HE} \equiv \Gamma/[N(\phi - u_H^*)d_H(f_H^*)]$ and $\Gamma \equiv \Pi_H(u_H^*, f_H^*) + \pi_H(r_H^*, p_{1H}^*) + CS_H - (\Pi_E(u_E^*, f_E^*)+\pi_E(r_E^*, p_{1E}^*) + CS_E - I_E) - \tilde{I}_H$.

Remark 1 reveals that strategy E may not increase the social welfare. When the use of new ICVs has a sufficiently large environmental impact such that $\hat{\gamma}_2 > \hat{\gamma}_{2HE}$, the social welfare is higher under strategy E than that under strategy H. If the per mile environmental impact of using new

ICVs is sufficiently small, then the government should encourage the LSP to implement strategy H.

Proposition 5 *The social welfare is increasing (decreasing) in the time window factor for EVs, if the per mile environmental impact of using EVs is smaller (greater) than Λ_{i1}. In addition, if $\omega_{i2} > 0$ and $\hat{\gamma}_1 < \Lambda_{i2}$ or if $\omega_{i2} < 0$ and $\hat{\gamma}_1 > \Lambda_{i2}$, then the social welfare is increasing in the time window factor for ICVs (i.e., α_2). Otherwise, the social welfare is decreasing in α_2.*

Note that, in the above expression,

$$\Lambda_{ik} \equiv \left(\frac{\partial \Pi_i(u_i^*, f_i^*)}{\partial \alpha_k} + \frac{\partial \pi_i(r_i^*, p_{1i}^*)}{\partial \alpha_k} + \frac{\partial CS_i}{\partial \alpha_k} - B_{ik}\right) \Big/ (N\omega_{ik}), \text{ for } i = E, H \text{ and } k = 1, 2,$$

where (1) $\omega_{i1} \equiv \partial(u_i^* d_i(f_i^*))/\partial\alpha_1$, $\omega_{i2} \equiv \partial(u_i^* d_i(f_i^*))/\partial\alpha_2$; (2) $B_{E1} \equiv \Psi_0\zeta_{E1} + \omega_{E1}(z(r^*)\gamma_1 - \Psi_0) - z(r^*)u_E^* d_E(f_E^*)\gamma_1/\alpha_1$ with $\Psi_0 \equiv \gamma_0 W_0 + N\hat{\gamma}_0$ and $\zeta_{ik} \equiv \partial d_i(f_i^*)/\partial\alpha_k$, $B_{H1} \equiv \varphi\zeta_{H1} + \omega_{H1}(z(r^*)\gamma_1 - \Psi_2) - z(r^*)u_H^* d_H(f_H^*)\gamma_1/\alpha_1$ with $\Psi_2 \equiv \gamma_2 W_0 + N\hat{\gamma}_2$ and $\varphi \equiv (1-\phi)\Psi_0 + \phi\Psi_2$; (3) $B_{E2} \equiv \Psi_0\zeta_{E2} + \omega_{E2}(z(r^*)\gamma_1 - \Psi_0) - W_0(1 - u_E^*)d_E(f_E^*)\gamma_0/\alpha_2$, $B_{H2} \equiv \varphi\zeta_{H2} + \omega_{H2}(z(r^*)\gamma_1 - \Psi_2) - W_0[(1-\phi)\gamma_0 + (\phi - u_H^*)\gamma_2]d_H(f_H^*)/\alpha_2$.

When the use of EVs has a sufficiently small environmental impact such that $\hat{\gamma}_1 < \Lambda_{i1}$, a wider time window for EVs can raise the social welfare for the monopoly case (i.e., SW_i, for $i = E, H$). However, if $\hat{\gamma}_1 > \Lambda_{i1}$, then SW_i is decreasing in the time window factor for EVs. That is, when there is a monopolistic LSP, we find that, if the EV's influence on the environment is small, then the government should broaden the time window to encourage the use of EVs. Otherwise, the government should enforce a shorter time window for EVs.

The impact of the time window factor for ICVs (i.e., α_2) on SW_i ($i = E, H$) depends on its influence on the demand fulfilled by EVs (i.e., ω_{i2}) and the per mile environmental impact of using EVs (i.e., $\hat{\gamma}_1$). When $\hat{\gamma}_1 < \Lambda_{i2}$, a greater usage rate of EVs results in an increase in SW_i, which indicates that the government should implement a wider (narrower) time window for ICVs if $\omega_{i2} > 0$ ($\omega_{i2} < 0$). If $\hat{\gamma}_1 > \Lambda_{i2}$, the government should discourage the use of EVs by rolling out a wider (narrower) time window for ICVs if $\omega_{i2} < 0$ ($\omega_{i2} > 0$). Thus, the time window factor for EVs and that for ICVs have different impacts on SW_i, because of their different effects on the usage rate of EVs.

6 Supply Chain Analysis with Duopoly Logistics Service Providers

We investigate the decision-making problems for a two-echelon supply chain with an EV manufacturer and two competing LSPs (i.e., X and Y), who purchase the vehicles from the EV manufacturer and provide the logistics service to customers in a market. Each LSP determines her usage rate of EVs and logistics service fee. The demand faced by LSP m ($m = X, Y$) is dependent on her own service fee f_{im}, as well as LSP n's ($n = X, Y$ and $n \neq m$) service fee f_{in}. Similar to Banker, Khosla, and Sinha (1998) and Zhu and He (2017), we construct the demand function for LSP m as

$$d_{im}(f_{im}; f_{in}) \equiv a_m - bf_{im} + \beta f_{in}, \text{ for } m, n = X, Y \text{ and } m \neq n, \; i = E, H, \tag{15}$$

where a_m is the demand potential for LSP m's service, the parameter b represents the demand sensitivity to LSP m's logistics service fee under strategy i, and β denotes the demand sensitivity to LSP n's logistics service fee under strategy i. For simplicity, we subsequently use the short notation d_{im} for the demand in (15).

Under strategy E, LSP m's weighted unit operating cost is $c_{Em} \equiv u_{Em}c_1 + (1 - u_{Em})c_0$. When adopting strategy E, LSP m uses q_{1Em} units of EVs and q_{0Em} units of old ICVs in her fleet, and also disposes q_{REm} units of her old ICVs. We can obtain these vehicle quantities by substituting d_{im} and u_{im} into the functions in (7)-(9). Similar to Section 4.1, we compute LSP m's profit functions under strategies E and H as

$$\begin{cases} \Pi^D_{Em}(u_{Em}, f_{Em}) = Nd_{Em}(f_{Em} - c_{Em}) - q_{1Em}\xi_1 p_{1E} - q_{0Em}\tau + q_{REm}\varepsilon_0 - \frac{M}{2}u^2_{Em}, \\ \Pi^D_{Hm}(u_{Hm}, f_{Hm}) = Nd_{Hm}(f_{Hm} - c_{Hm}) - q_{1Hm}\xi_1 p_{1H} - q_{2Hm}\xi_2 p_2 - q_{0Hm}\tau + q_{RHm}\varepsilon_0 - \frac{M}{2}u^2_{Hm}, \end{cases} \tag{16}$$

respectively, where $c_{Hm} \equiv u_{Hm}c_1 + (\phi - u_{Hm})c_2 + (1 - \phi)c_0$.

The EV manufacturer's profit function under strategy i ($i = E, H$) in the duopoly case is $\pi^D_i(r_i, p_{1i}) = (q_{1im} + q_{1in})(p_{1i} - v_1(r_i))$. As in the monopolistic LSP case, the EV manufacturer first determines the driving range and sale price of EVs, and the two LSPs "simultaneously" choose their usage rates of EVs and then determine their logistics service fees using (16).

Proposition 6 *For the duopoly case, LSP m's ($m = X, Y$) optimal usage rate of EVs and logistics service fee under strategy i ($i = E, H$) are obtained as*

$$u^{D*}_{im} = \frac{R_{i1}\left(R_{i2}L_{im} - 2\beta b^2\lambda_i R_{i1}L_{in}\right)}{R_{i5}} \text{ and } f^{D*}_{im} = \frac{R_{i5}K_{im} - b\lambda_i R_{i1}(2bR_{i3}L_{im} + R_{i4}\beta L_{in})}{NR_{i5}(4b^2 - \beta^2)},$$

where $m, n = X, Y$ and $m \neq n$, $R_{i1} \equiv \lambda_i(2b^2 - \beta^2)$, $R_{i2} \equiv MN(4b^2 - \beta^2)^2 - 2bR^2_{i1}$, $R_{i3} \equiv R_{i2} - \beta^2 b\lambda_i R_{i1}$, $R_{i4} \equiv R_{i2} - 4b^3\lambda_i R_{i1}$, $R_{i5} \equiv R^2_{i2} - 4\beta^2 b^4\lambda^2_i R^2_{i1}$, $K_{im} \equiv 2bNa_m + \beta Na_n + b(2b + \beta)G_i$, and $L_{im} \equiv (a_m N - bG_i)(4b^2 - \beta^2) + \beta K_{in}$.

The EV manufacturer's optimal driving range and EV price under strategy i ($i = E, H$) are found as follows: the optimal driving range r^{D*} can be uniquely obtained by solving the following equation for r_i:

$$\frac{\bar{t}_C v_1(r_i)}{r^2_i} - \frac{\partial v_1(r_i)}{\partial r_i}\left(\frac{1}{s} + \frac{\bar{t}_C}{r_i}\right) = 0.$$

The optimal EV price p^{D*}_{1i} can be uniquely obtained by solving the following equation for p_{1i}: $u^{D*}_{im} \times d_{im} + u^{D*}_{in} \times d_{in} - z(r^{D*}) \times \xi_1 \times [p_{1i} - v_1(r^{D*})] \times (\chi_{im} + \chi_{in}) = 0$, where $\chi_{im} \equiv \partial(u^{D*}_{im}d_{im})/\partial\lambda_i$ and $\chi_{in} \equiv \partial(u^{D*}_{in}d_{in})/\partial\lambda_i$.

The EV manufacturer's optimal driving range r^{D*} in the duopoly case is identical to that in the monopoly case, i.e., $r^{D*} = r^*$. The optimal range is based on the trade-off between the battery cost and service capacity of an EV, and it is dependent on the average charging time during operations $\bar{t}_C$ but is independent of the time window factors for EVs and ICVs (i.e., α_1 and α_2). The competition between the LSPs induces the two firms to change their pricing and EV usage rate decisions. As a result, the EV price is more complex than that in the monopoly case. Therefore, the impacts of time window factors for EVs and ICVs and their unit operating costs on the optimal decisions cannot be determined, which differs from those in the monopoly case. For the duopoly case, the social welfare is

$$SW_i^D = \sum_m \Pi_{im}^D(u_{im}^{D*}, f_{im}^{D*}) + \pi_i^D(r^*, p_{1i}^{D*}) + \sum_m CS_{im}^D - I_i^D, \text{ for } m = X, Y. \tag{17}$$

Using (13), we compute LSP m's consumer surplus as $CS_{im}^D = (a - bf_{im}^{D*})^2/(2b)$. The total environmental impact for the duopoly case (i.e., I_i^D) is $I_E^D \equiv (q_{0Em} + q_{0En})\gamma_0 + (q_{1Em} + q_{1En})\gamma_1 + N\hat{\gamma}_0[d_{Em}(1-u_{Em}^{D*}) + d_{En}(1-u_{En}^{D*})] + N\hat{\gamma}_1(u_{Em}^{D*}d_{Em} + u_{En}^{D*}d_{En})$ and $I_H^D \equiv (q_{0Hm}+q_{0Hn})\gamma_0 + (q_{1Hm} + q_{1Hn})\gamma_1 + (q_{2m}+q_{2n})\gamma_2 + N\hat{\gamma}_0(1-\phi)(d_{Hm}+d_{Hn}) + N\hat{\gamma}_1(u_{Hm}^{D*}d_{Hm} + u_{Hn}^{D*}d_{Hn}) + N\hat{\gamma}_2[(\phi - u_{Hm}^{D*})d_{Hm} + (\phi - u_{Hn}^{D*})d_{Hn}]$. Similar to the monopoly case, strategy E may not increase the social welfare in the duopoly case. Strategy E results in a higher (lower) social welfare than strategy H, if the per mile environmental impact of using new ICVs is sufficiently large (small).

We next examine the impacts of time window factors for EVs and ICVs on the social welfare in (17). Let $\omega_{ikm} \equiv \partial(u_{im}^{D*}d_{im})/\partial\alpha_k$, for $i = E, H$, $k = 1, 2$, and $m = X, Y$. We let $\omega_{ikm} \neq 0$ to focus on non-trivial results which indicate that the changes in these parameters affect the demand fulfilled by EVs. For the duopoly case, the impact of the time window factor (i.e., α_k) on the social welfare is non-monotonic, which depends on the factor's influence on the EV usage rate (i.e., $\sum_m \omega_{ikm}$) and the per mile environmental impact of using EVs (i.e., $\hat{\gamma}_1$). When $\hat{\gamma}_1$ is sufficiently low such that $\hat{\gamma}_1 < \Lambda_{ik}^D$, an increase in the value of α_k can help improve the EV usage rate, thereby generating an increase in SW_i^D, whereas it reduces SW_i^D due to the lower EV usage rate, where Λ_{ik}^D is defined as in online Appendix D. When $\hat{\gamma}_1$ is sufficiently large, the social welfare increases (decreases) with α_k due to a decrease (an increase) in the EV usage rate. Similar to the monopoly case, the impact of the time window factor for ICVs (i.e., α_2) on the social welfare in the duopoly case is moderated by its influence on the demand satisfied by EVs and $\hat{\gamma}_1$. Different from the results in the monopoly case, the time window factor for EVs (i.e., α_1) affects the demand fulfilled by EVs in a non-monotonic manner. Thus, for the duopoly case, the impact of α_1 on the social welfare is dependent on its effect on the demand.

7 Summary and Concluding Remarks

In today's city logistics, an LSP may acquire only EVs (strategy E) or a mix of EVs and ICVs (strategy H) to replace a portion of her existing ICVs, in the presence of time window policies for EVs and ICVs. In this paper, we consider a two-echelon supply chain consisting of (i) an EV manufacturer who determines the driving range and sale price of EVs and (ii) an LSP who makes her decisions on the usage rate of EVs and service fee. We construct a sequential game and obtain the two firms' decisions in Stackelberg equilibrium. We also investigate the social welfare and extend our game theoretic analysis to a duopoly case in which two LSPs compete for customers in a market.

We find that strategy E may be more profitable than strategy H for the LSP. The LSP should adopt strategy E if the unit operating cost for new ICVs and the portion of demand fulfilled by new vehicles are sufficiently high or both of them are sufficiently low. Otherwise, the LSP is likely to choose strategy H. As reported in practice, some firms (e.g., FedEx) have committed that they would not buy any new ICV in the future. Our findings help the LSP understand under what conditions the firm should ban the purchase of new ICVs.

Our analysis can be deemed as an early attempt to understand the impacts of time window regulations for EVs and ICVs and their operating costs on the EV adoption. A wider time window for EVs or a lower unit operating cost for EVs can induce the LSP to increase the EV usage rates under strategies E and H. Our finding may explain why, for EVs, a mixed policy involving both a wider time window (compared to ICVs) and the operational subsidies for EVs has caused a considerable EV adoption in the logistics industry of Shenzhen in China. When the demand potential for her service is sufficiently high, the LSP may increase her EV usage rate, if the unit operating cost for used (new) ICVs increases under strategy E (strategy H), or if the time window for ICVs becomes narrower under both strategies. Otherwise, the LSP may decrease her usage rate. The above insights apply to the monopoly case and may not hold for the duopoly case due to their competition. These findings also indicate that the government should consider the demand potential for the LSP's service in evaluating the narrower time window for ICVs or a higher fee for the ICV usage per kilometer.

We then examine the effects of time window factors for EVs and ICVs on the social welfare. When the per mile environmental impact of using EVs is sufficiently low (high), a wider time window for EVs makes an increase (a decrease) in the social welfare in the monopoly case, and it increases the social welfare if it can promote (prevent) the EV usage rate in the duopoly case. The above insights hold under strategies E and H. The narrower time window for ICVs increases the social welfare if it increases (decreases) the EV usage rate and the per mile environmental impact of using EVs is sufficiently low (high). It decreases the social welfare, otherwise. The impact holds under both strategies for the monopoly and duopoly cases.

Our results reveal the following managerial insights that may be useful, and interesting, to practitioners. To motivate the LSP to adopt strategy E rather than strategy H, the government can induce the LSP to (i) choose a sufficiently high (low) portion of demand fulfilled by new vehicles and (ii) incur a sufficiently high (low) unit operating cost for new ICVs. Our results can help the government better understand the implications regarding its incentive policies for EVs (i.e., wider time windows and greater operational subsidies) and its disincentive policies for ICVs (i.e., narrower time windows and higher per kilometer fees). The government needs to note that the impacts of those disincentive policies for ICVs on the usage rate of EVs may depend on the LSP's partial replacement strategy and the demand potential for her service. If this demand potential is sufficiently large (small), a narrower time window for ICVs or a higher per kilometer fee can increase (decrease) the LSP's EV usage rate. This may help explain why some large fleet operators were among early enterprises that deployed EVs for deliveries. The LSP can increase her EV usage rate for the case of a wider time window for EVs or a lower unit operating cost for EVs, but may change her usage rate decisions if two competing LSPs exist. To impose a more convenient (strict) time window for EVs (ICVs), the government needs to ensure (i) a sufficiently small per mile environmental impact of the EV usage and (ii) an increase in the usage rate of EVs from the perspective of social welfare maximization.

In this paper, we focus on the role of time window policies in EV adoption. Besides these policies, it may be interesting to investigate the impacts of some other non-financial incentives on the EV supply chain, which include, for example, access permits in high-pollution days and low emission zone (LEZ) policies. LEZ policies specify certain geographical areas in cities that may only be accessed by vehicles that meet predefined emissions criteria. Such policies have been widely implemented in practice (Malina and Scheffler 2015). Furthermore, the EV adoption in logistics fleets are dependent on social and attitudinal factors (Mohammed, Niesten and Gagliardi 2020). In the future, we may incorporate these behavioral factors in fostering the penetration of EVs.

Notes

[1] The authors are grateful to the Editor (Professor T.C.E. Cheng) and two anonymous reviewers for their insightful comments that helped improve this paper.

[2] `https://www.rmi-china.com/static/upfile/news/nfiles/dianzhuangyouhua.pdf` (Last accessed December 30, 2021)

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Appendix A Proofs

Proof of Proposition 1. We first find the LSP's optimal (best-response) service fee decision under strategy E. The LSP's profit under this strategy is $\Pi_E(u_E, f_E) = (Nf_E + \lambda_E u_E - G_E)(a - bf_E) - Mu_E^2/2$, where $G_E = W_0\tau + Nc_0$ and $\lambda_E = N(c_0 - c_1) + W_0\varepsilon_0 + \tau W_0 - z(r_E)\xi_1 p_{1E}$ with $\xi_1 = 1 - \mu_1$. The first- and second-order derivatives of $\Pi_E(u_E, f_E)$ w.r.t. f_E are

$$\frac{\partial \Pi_E(u_E, f_E)}{\partial f_E} = N(a - bf_E) - b(Nf_E + \lambda_E u_E - G_E) \text{ and } \frac{\partial^2 \Pi_E(u_E, f_E)}{\partial f_E^2} = -2bN < 0.$$

Therefore, the optimal logistics service fee under strategy E is $f_E = (aN + bG_E - b\lambda_E u_E)/(2bN)$. Then, we can rewrite our optimization problem for the LSP as follows:

$$\max_{u_E} \Pi_E(u_E, f_E) = \frac{1}{4bN}(Na - bG_E + b\lambda_E u_E)^2 - \frac{M}{2}u_E^2.$$

Since $\partial \Pi_E(u_E, f_E)/\partial u_E = 0$, the LSP's optimal usage rate is $u_E^* = b\lambda_E(aN - bG_E)/(2bNM - b^2\lambda_E^2)$; and thus, the optimal logistics service fee is $f_E^* = [M(aN + bG_E) - ab\lambda_E^2]/(2bNM - b^2\lambda_E^2)$.

Substituting u_E^* and f_E^* into $d_E(f_E^*)$ yields $d_E(f_E^*) = bM(aN - bG_E)/(2bNM - b^2\lambda_E^2)$. When $aN - bG_E > 0$, $M > [b\lambda_E(aN - bG_E) + b^2\lambda_E^2]/(2bN)$, and $\lambda_E > 0$, we find that $u_E^* \in [0, 1]$ and $d_E(f_E^*) > 0$. Note that $z(r_E) = W_1 + \eta/r_E$. Substituting q_{1E} and v_1 into $\pi_E(r_E, p_{1E})$, we can rewrite the EV manufacturer's profit $\pi_E(r_E, p_{1E})$ as

$$\max_{r_E, p_{1E}} \pi_E(r_E, p_{1E}) = \frac{z(r_E)\lambda_E(p_{1E} - v_1(r_E))}{(2bNM - b^2\lambda_E^2)^2} Mb^2(aN - bG_E)^2.$$

Taking the first-order derivative of $\pi_E(r_E, p_{1E})$ w.r.t. p_{1E} gives

$$\frac{\partial \pi_E(r_E, p_{1E})}{\partial p_{1E}} = Mb^2(aN - bG_E)^2 z(r_E) \frac{\lambda_E(2bNM - b^2\lambda_E^2) - z(r_E)\xi_1(2bNM + 3b^2\lambda_E^2)(p_{1E} - v_1(r_E))}{(2bNM - b^2\lambda_E^2)^3}.$$

The optimal EV price under strategy E is the solution of the equation that $2bNM\lambda_E - b^2\lambda_E^3 - z(r_E)\xi_1(p_{1E} - v_1(r_E))(2bNM + 3b^2\lambda_E^2) = 0$. The second-order derivative of $\pi_E(r_E, p_{1E})$ w.r.t. p_{1E} is $\partial^2\pi_E(r_E, p_{1E})/\partial p_{1E}^2 < 0$. Recalling that $z(r_E)\xi_1(p_{1E} - v_1(r_E))(2bNM + 3b^2\lambda_E^2) = 2bNM\lambda_E - b^2\lambda_E^3$, we compute the first-order derivative of $\pi_E(r_E, p_{1E})$ w.r.t. r_E as

$$\frac{\partial \pi_E(r_E, p_{1E})}{\partial r_E} = \frac{Mb^2(aN - bG_E)^2\lambda_E}{(2bNM - b^2\lambda_E^2)^2 r_E^2}\left(\eta v_1(r_E) - z(r_E)r_E^2\frac{\partial v_1(r_E)}{\partial r_E}\right).$$

That is, the optimal range r_E^* is the solution of the equation that $\eta v_1(r_E)/r_E^2 - z(r_E)\partial v_1(r_E)/\partial r_E = 0$. We also find that $\partial^2\pi_E(r_E, p_{1E})/(\partial r_E \partial p_{1E}) = 0$, and

$$\frac{\partial^2 \pi_E(r_E, p_{1E})}{\partial r_E^2} = \frac{-Mb^2\lambda_E(aN - bG_E)^2}{(2bNM - b^2\lambda_E^2)^2} A_v(r_E),$$

where $A_v(r_E) = z(r_E)\partial^2 v_1(r_E)/\partial r_E^2 + 2\eta v_1(r_E)/r_E^3 - 2\eta\partial v_1(r_E)/\partial r_E/r_E^2$. When $A_v(r_E) > 0$, we know that $\partial^2\pi_E(r_E, p_{1E})/\partial r_E^2 < 0$. As a result, the Hessian matrix of $\pi_E(r_E, p_{1E})$ at the optimal solution (r_E^*, p_{1E}^*) is negatively definite.

For strategy H, we write

$$\Pi_H(u_H, f_H) = (Nf_H - G_H + \lambda_H u_H)(a - bf_H) - \frac{M}{2}u_H^2,$$

where $G_H = N[\phi c_2 + (1-\phi)c_0] + W_0(1-\phi)\tau + \phi W_0\xi_2 p_2 - \phi W_0\varepsilon_0$ and $\lambda_H = W_0\xi_2 p_2 + N(c_2 - c_1)$ $-z(r_H)\xi_1 p_{1H}$. As $\partial^2\Pi_H(u_H, f_H)/\partial f_H^2 = -2bN < 0$, we solve the first-order condition to find the LSP's optimal service fee under strategy H as

$$f_H = \frac{Na + bG_H - b\lambda_H u_H}{2bN}.$$

Substituting f_H into $\Pi_H(u_H, f_H)$ gives $\Pi_H(u_H, f_H) = (Na - bG_H + b\lambda_H u_H)^2/(4bN) - Mu_H^2/2$. The LSP's optimal usage rate decision under strategy H is then found as

$$u_H^*(r_H, p_{1H}) = \frac{b\lambda_H(Na - bG_H)}{2bNM - b^2\lambda_H^2}.$$

We have $f_H^* = [M(Na + bG_H) - ab\lambda_H^2]/(2bNM - b^2\lambda_H^2)$ and $d_H(f_H^*) = bM(Na - bG_H)/(2bNM - b^2\lambda_H^2)$. When $\lambda_H > 0$, $Na - bG_H > 0$, and $M > [b\lambda_H(Na - bG_H) + b^2\lambda_H^2]/(2bN)$, we find that $d_H(f_H^*) > 0$ and $u_H^* \in [0, 1]$.

The EV manufacturer's optimization problem under strategy H is

$$\max_{r_H, p_{1H}} \pi_H(r_H, p_{1H}) = b^2 M(Na - bG_H)^2 \frac{\lambda_H z(r_H)(p_{1H} - v_1(r_H))}{(2bNM - b^2\lambda_H^2)^2}.$$

The first-order conditions of $\pi_H(r_H, p_{1H})$ w.r.t. p_{1H} and r_H are

$$\begin{aligned}\frac{\partial\pi_H(r_H, p_{1H})}{\partial p_{1H}} &= \frac{b^2 M(Na - bG_H)^2 z(r_H)}{(2bNM - b^2\lambda_H^2)^3}[(2bNM - b^2\lambda_H^2)\lambda_H - \xi_1 z(r_H) \\ &\quad \times (2bNM + 3b^2\lambda_H^2)(p_{1H} - v_1(r_H))],\end{aligned}$$

and

$$\frac{\partial\pi_H(r_H, p_{1H})}{\partial r_H} = \frac{b^2 M(Na - bG_H)^2\lambda_H}{(2bNM - b^2\lambda_H^2)^2 r_H^2}\left[\eta v_1(r_H) - z(r_H)r_H^2\frac{\partial v_1(r_H)}{\partial r_H}\right].$$

It follows that $r_H^* = r_E^*$. The optimal EV price p_{1H}^* is the solution of the equation that $(2bNM - b^2\lambda_H^2)\lambda_H - \xi_1 z(r_H)(2bNM + 3b^2\lambda_H^2)(p_{1H} - v_1(r_H)) = 0$. Note that $\partial^2\pi_H(r_H, p_{1H})/\partial r_H^2 = -A_v(r_H)\lambda_H b^2 M(Na - bG_H)^2/(2bNM - b^2\lambda_H^2)^2$. When

$$A_v(r_H) = z(r_H)\frac{\partial^2 v_1(r_H)}{\partial r_H^2} + 2\eta\frac{v_1(r_H)}{r_H^3} - \frac{2\eta}{r_H^2}\frac{\partial v_1(r_H)}{\partial r_H} > 0,$$

we know that $\partial^2\pi_H(r_H, p_{1H})/\partial r_H^2 < 0$. We find that $\partial^2\pi_H(r_H, p_{1H})/\partial p_{1H}^2 < 0$. Thus, the Hessian matrix of $\pi_H(r_H, p_{1H})$ at the optimal solution (r_H^*, p_{1H}^*) is negatively definite. This proposition is thus proved. ■

Proof of Corollary 1. We rewrite $\eta v_1(r_i)/r_i^2 - z(r_i)\partial v_1(r_i)/\partial r_i = 0$ and find $v_1(r_i) = (W_1 r_i^2/\eta + r_i)\partial v_1(r_i)/\partial r_i > r_i \partial v_1(r_i)/\partial r_i$, where $W_1 = 1/(\alpha_1 T s)$, $\eta = \tau_C/(\alpha_1 T)$, and $\bar{t}_C = \delta t_C$. As $A_v(r_i) > 0$, the first-order derivative of r_i w.r.t. $\bar{t}_C$ is

$$\frac{\partial r_i}{\partial \bar{t}_C} = \frac{v_1(r_i) - r_i \partial v_1(r_i)/\partial r_i}{\alpha_1 T r_i^2 A_v(r_i)} > 0.$$

■

Proof of Corollary 2. As $t_i = b\lambda_i$, for $i = E, H$, we compute the first-order derivative of p_{1i}^* w.r.t. λ_i as $\partial p_{1i}^*/\partial \lambda_i = \Upsilon_i b^2/[\xi_1 z(r_i)(2bNM + 3t_i^2)^2]$, where $\Upsilon_i = 4N^2M^2 - 12b\lambda_i^2 NM - 3b^2\lambda_i^4$ for $i = E, H$. The first-order derivatives of p_{1E}^* w.r.t. c_0 and p_{1i}^* w.r.t. c_1 are $\partial p_{1E}^*/\partial c_0 = \Upsilon_E N/(2z(r^*)\xi_1 y_E)$ and $\partial p_{1i}^*/\partial c_1 = -\Upsilon_i N/(2z(r^*)\xi_1 y_i)$, where $y_i = 4N^2M^2 + 3b^2\lambda_i^4$, $i = E, H$. The first-order derivative of p_{1H}^* w.r.t. c_2 is $\partial p_{1H}^*/\partial c_2 = N\Upsilon_H/(2z(r^*)\xi_1 y_H)$.

According to the proof of Proposition 1, we have $t_i = b\lambda_i > 0$ and $\lambda_i > 0$, where $\lambda_E = N(c_0 - c_1) + W_0\varepsilon_0 + \tau W_0 - z(r_E)\xi_1 p_{1E}^*$ and $\lambda_H = W_0\xi_2 p_2 + N(c_2 - c_1) - z(r_H)\xi_1 p_{1H}^*$. We find that $\partial\lambda_E/\partial c_0 = N l_E/(2y_E)$, $\partial\lambda_i/\partial c_1 = -N l_i/(2y_i) < 0$, and $\partial\lambda_H/\partial c_2 = N l_H/(2y_H)$, where $l_i = (2NM + 3b\lambda_i^2)^2$, $i = E, H$. The first-order derivative of f_i^* w.r.t. c_j is

$$\frac{\partial f_i}{\partial c_j} = \frac{Mb\left(2bNM - t_i^2\right)\partial G_i/\partial c_j - 2b^2\lambda_i M\left(aN - bG_i\right)\partial\lambda_i/\partial c_j}{\left(2bNM - t_i^2\right)^2},$$

where $j = 0, 1, 2$, $\partial G_E/\partial c_0 = N$ (where $G_E = W_0\tau + Nc_0$), $\partial G_H/\partial c_0 = N(1-\phi)$ (where $G_H = N[\phi c_2 + (1-\phi)c_0] + W_0(1-\phi)\tau + \phi\xi_2 W_0 p_2 - \phi W_0\varepsilon_0$), and $\partial G_H/\partial c_2 = N\phi$. The first-order derivative of f_E^* w.r.t. c_0 is

$$\frac{\partial f_E^*}{\partial c_0} = bMN\frac{\left(2bNM - t_E^2\right)y_E - t_E l_E\left(aN - bG_E\right)}{\left(2bNM - t_E^2\right)^2 y_E}.$$

We then obtain $\partial f_E^*/\partial c_0 > 0$ if $a < A_{0F}$, and $\partial f_E^*/\partial c_0 \le 0$ if $a \ge A_{0F}$, where A_{0F} is defined as in this corollary, $A_{0F} > bG_E/N$. We compute the first-order derivative of f_E^* w.r.t. c_1 as

$$\frac{\partial f_E^*}{\partial c_1} = \frac{-2bMt_E\left(aN - bG_E\right)}{\left(2bNM - t_E^2\right)^2}\frac{\partial\lambda_E}{\partial c_1} > 0.$$

The first-order derivatives of f_H^* w.r.t. c_0, c_1, and c_2 are

$$\frac{\partial f_H^*}{\partial c_0} = \frac{MbN(1-\phi)}{2bNM - t_H^2} > 0,\ \frac{\partial f_H^*}{\partial c_1} = \frac{-2b^2\lambda_H M\left(aN - bG_H\right)}{\left(2bNM - t_H^2\right)^2}\frac{\partial\lambda_H}{\partial c_1} > 0,$$

and

$$\frac{\partial f_H^*}{\partial c_2} = MbN\frac{\left(2bNM - t_H^2\right)\phi y_H - \left(aN - bG_H\right)t_H l_H}{\left(2bNM - t_H^2\right)^2 y_H}.$$

If $a < A_{2F}$, then $\partial f_H^*/\partial c_2 > 0$. If $a \geq A_{2F}$, then $\partial f_H^*/\partial c_2 \leq 0$, where A_{2F} is defined as in this corollary, $A_{2F} > bG_H/N$. The first-order derivative of u_i^* w.r.t. c_j is

$$\frac{\partial u_i^*}{\partial c_j} = b\frac{-t_i\left(2bNM - t_i^2\right)\partial G_i/\partial c_j + \left(2bNM + t_i^2\right)\left(aN - bG_i\right)\partial \lambda_i/\partial c_j}{\left(2bNM - t_i^2\right)^2}.$$

The first-order derivative of u_E^* w.r.t. c_0 is

$$\frac{\partial u_E^*}{\partial c_0} = Nb\frac{\left(2bNM + t_E^2\right)\left(aN - bG_E\right)l_E - 2y_E t_E\left(2bNM - t_E^2\right)}{2y_E\left(2bNM - t_E^2\right)^2}.$$

It follows that $\partial u_E^*/\partial c_0 > 0$ if $a > A_{0U}$, and $\partial u_E^*/\partial c_0 \leq 0$ if $a \leq A_{0U}$, where A_{0U} is defined as in this corollary, $A_{0U} > bG_E/N$. The first-order derivative of u_E^* w.r.t. c_1 is

$$\frac{\partial u_E^*}{\partial c_1} = b\frac{\left(2bNM + t_E^2\right)\left(aN - bG_E\right)}{\left(2bNM - t_E^2\right)^2}\frac{\partial \lambda_E}{\partial c_1} < 0.$$

The first-order derivatives of u_H^* w.r.t. c_0, c_1, and c_2 are

$$\frac{\partial u_H^*}{\partial c_0} = \frac{-N(1-\phi)b^2\lambda_H}{2bNM - t_H^2} < 0,\ \frac{\partial u_H^*}{\partial c_1} = \frac{b\left(2bNM + t_H^2\right)\left(aN - bG_H\right)}{\left(2bNM - t_H^2\right)^2}\frac{\partial \lambda_H}{\partial c_1} < 0,$$

and

$$\frac{\partial u_H^*}{\partial c_2} = Nb\frac{\left(aN - bG_H\right)\left(2bNM + t_H^2\right)l_H - 2\phi t_H y_H\left(2bNM - t_H^2\right)}{2y_H\left(2bNM - t_H^2\right)^2}.$$

We learn from that $\partial u_H^*/\partial c_2 > 0$ if $a > A_{2U}$, and $\partial u_H^*/\partial c_2 \leq 0$ if $a \leq A_{2U}$, where A_{2U} is defined as in this corollary, $A_{2U} > bG_H/N$. The difference between A_{0F} and A_{0U} is $A_{0F} - A_{0U} = (2bNM - t_E^2)^2 y_E/[Nl_E t_E(2bNM + t_E^2)] > 0$. As $A_{2F} - A_{2U} = \phi y_H(2bNM - t_H^2)^2/[Nl_H t_H(2bNM + t_H^2)] > 0$, we have $A_{0F} > A_{0U}$ and $A_{2F} > A_{2U}$. ■

Proof of Proposition 2. We learn that $\Pi_i(u_i^*, f_i^*) = M(aN - bG_i)^2/[2(2bNM - b^2\lambda_i^2)]$, where $i = E,\ H$, $G_E{=}W_0\tau{+}Nc_0$, $G_H = N[\phi c_2 + (1{-}\phi)c_0] + W_0(1-\phi)\tau + \phi W_0\xi_2 p_2 - \phi W_0\varepsilon_0$, $\lambda_E = N(c_0{-}c_1) + W_0\varepsilon_0{+}\tau W_0{-}z(r_E)\xi_1 p_{1E}$, and $\lambda_H = \xi_2 W_0 p_2 + N(c_2 - c_1){-}z(r_H)\xi_1 p_{1H}$. When

$$c_2 = \hat{c}_2 = c_0 + W_0(\tau + \varepsilon_0 - \xi_2 p_2)/N,$$

we find that $G_E = G_H$, $\lambda_E = \lambda_H$, and $\partial G_H/\partial\phi = 0$. Note that $r_E^* = r_H^*$ and p_{1i}^* is the solution of the equation $2bNM\lambda_i - b^2\lambda_i^3{-}z(r_i)\xi_1(p_{1i} - v_1(r_i))(2bNM + 3b^2\lambda_i^2) = 0$. Since the coefficients of this equation are the same under strategies E and H, we find that $p_{1E}^* = p_{1H}^*$ when $c_2 = \hat{c}_2$. In this case, $u_E^* = u_H^*$, $f_E^* = f_H^*$, and $q_{1E}^* = q_{1H}^*$ if $c_2 = \hat{c}_2$.

When $c_2 = \hat{c}_2$, $\Pi_E(u_E^*, f_E^*) = \Pi_H(u_H^*, f_H^*)$ and $\pi_E(r_E^*, p_{1E}^*) = \pi_H(r_H^*, p_{1H}^*)$. This occurs because the coefficients of strategy H including ϕ and c_2, and p_2 do not affect the LSP's profit under strategy H when $c_2 = \hat{c}_2$. When $c_2 \neq \hat{c}_2$, the equation $\Pi_H(u_H^*, f_H^*) = \Pi_E(u_E^*, f_E^*)$ is equivalent to

$$\hat{\phi} = (Nc_0 + W_0\tau)/[N(\hat{c}_2 - c_2)] + [\sqrt{2(2bNM - t_H^2)\Pi_E(u_E^*, f_E^*)/M} - Na]/[bN(\hat{c}_2 - c_2)].$$

Since G_E, t_E, and λ_H do not include ϕ, we find that $\Pi_H(u_H^*, f_H^*) \geq \Pi_E(u_E^*, f_E^*)$ when $c_2 < \hat{c}_2$ and $\phi > \hat{\phi}$, or, $c_2 > \hat{c}_2$ and $\phi < \hat{\phi}$. It thus follows that $\Pi_H(u_H^*, f_H^*) < \Pi_E(u_E^*, f_E^*)$ when $c_2 < \hat{c}_2$ and $\phi < \hat{\phi}$, or, $c_2 > \hat{c}_2$ and $\phi > \hat{\phi}$. ■

Proof of Proposition 3. Noting that $r_E^* = r_H^* = r^*$, we learn from Proposition 1 that p_{1i}^* satisfies the equation $2bNMt_i - t_i^3 - b\xi z(r^*)(p_{1i}^* - v_1(r^*))\left(2bNM + 3t_i^2\right) = 0$. Then,

$$\frac{\partial p_{1i}^*}{\partial \alpha_1} - \frac{p_{1i}^*}{\alpha_1} = \frac{-\left(2bNM + 3t_i^2\right) v_1(r^*)}{\alpha_1[4bNM - 6t_i b\xi_1 z\left(r^*\right)\left(p_{1i}^* - v_1(r^*)\right)]},$$

where

$$4bNM - 6t_i b\xi_1 z(r^*)(p_{1i}^* - v_1(r^*)) = \frac{2(4b^2N^2M^2 + 3t_i^4)}{2bNM + 3t_i^2} > 0.$$

Therefore, $(\partial p_{1i}^*/p_{1i}^*)/(\partial\alpha_1/\alpha_1) < 1$. We have

$$\frac{\partial \lambda_i}{\partial \alpha_1} = \frac{z(r^*)\xi_1 v_1(r^*) l_i}{2\alpha_1 y_i} > 0.$$

The first-order derivatives of u_i^* and $d_i(f_i^*)$ w.r.t. α_1 are computed as

$$\frac{\partial u_i^*}{\partial \alpha_1} = b\left(aN - bG_i\right)\frac{2bNM + t_i^2}{\left(2bNM - t_i^2\right)^2}\frac{\partial \lambda_i}{\partial \alpha_1} > 0,$$

and

$$\frac{\partial d_i(f_i^*)}{\partial \alpha_1} = \frac{2b^3M\lambda_i\left(Na - bG_i\right)}{\left(2bNM - t_i^2\right)^2}\frac{\partial \lambda_i}{\partial \alpha_1} > 0.$$

The first-order derivative of f_i^* w.r.t. α_1 is

$$\frac{\partial f_i^*}{\partial \alpha_1} = -\frac{2b^2\lambda_i M\left(aN - bG_i\right)}{\left(2bNM - t_i^2\right)^2}\frac{\partial \lambda_i}{\partial \alpha_1} < 0.$$

The first-order derivative of $\Pi_i(u_i^*, f_i^*)$ (which equals $M(aN - bG_i)^2/[2(2bNM - t_i^2)]$) w.r.t. α_1 is

$$\frac{\partial \Pi_i(u_i^*, f_i^*)}{\partial \alpha_1} = \frac{b^2\lambda_i M\left(aN - bG_i\right)^2}{\left(2bNM - t_i^2\right)^2}\frac{\partial \lambda_i}{\partial \alpha_1} > 0.$$

Noting that $\pi_i(r^*, p_{1i}^*) = Mb^2\lambda_i z(r^*)(p_1 - v_1(r^*))(aN - bG_i)^2/(2bNM - t_i^2)^2$, we compute

$$\frac{\partial \pi_i(r^*, p_{1i}^*)}{\partial \alpha_1} = b^2 M \frac{\lambda_i v_1(r^*) z(r^*) (Na - bG_i)^2}{\alpha_1 \left(2bNM - t_i^2\right)^2} > 0.$$

■

Proof of Proposition 4. Under strategy E, $\partial\lambda_E/\partial\alpha_2 = -z(r_E^*)\xi_1\partial p_{1E}^*/\partial\alpha_2 - W_0(\varepsilon_0 + \tau)/\alpha_2$. The first-order derivative of p_{1E}^* w.r.t. α_2 is

$$\frac{\partial p_{1E}^*}{\partial \alpha_2} + \frac{W_0 (\varepsilon_0 + \tau)}{z(r^*)\xi_1\alpha_2} = \frac{W_0(\varepsilon_0+\tau) l_E}{2z(r^*)\xi_1\alpha_2 y_E} > 0,$$

where $\partial p_{1E}^*/\partial\alpha_2 > -P_{1E}$, $P_{1E} = W_0(\varepsilon_0+\tau)/[z(r^*)\xi_1\alpha_2]$. Then, we find $\partial t_E/\partial\alpha_2 = -b[z(r^*)\xi_1\partial p_{1E}^*/\partial\alpha_2 + W_0(\varepsilon_0+\tau)/\alpha_2] < 0$ and

$$\frac{dp_{1E}^*}{d\alpha_2} = \frac{-W_0(\varepsilon_0+\tau)\Upsilon_E}{2z(r_E^*)\xi_1\alpha_2 y_E},$$

where $\Upsilon_E = 4N^2M^2 - 12bNM\lambda_E^2 - 3b^2\lambda_E^4$. Then, the first-order derivative of λ_E w.r.t. α_2 is

$$\frac{\partial \lambda_E}{\partial \alpha_2} = \frac{-W_0(\varepsilon_0+\tau) l_E}{2\alpha_2 y_E} < 0,$$

where $l_E = (2NM + 3b\lambda_E^2)^2$ and $y_E = 4N^2M^2 + 3b^2\lambda_E^4$. Noting that $G_E = W_0\tau + Nc_0$, $W_0 = 1/(\alpha_2 Ts)$, and $u_E = t_E(aN - bG_E)/(2bNM - t_E^2)$, we find that $\partial G_E/\partial\alpha_2 = -\tau W_0/\alpha_2$. We compute the first-order derivatives of u_E^* and d_E w.r.t. α_2 as

$$\frac{\partial u_E^*}{\partial \alpha_2} = bW_0 \frac{2y_E\tau t_E\left(2bNM - t_E^2\right) - (\varepsilon_0+\tau) l_E (aN - bG_E)\left(2bNM + t_E^2\right)}{2\alpha_2 y_E\left(2bNM - t_E^2\right)^2},$$

and

$$\frac{\partial d_E(f_E^*)}{\partial \alpha_2} = b^2 MW_0 \frac{\tau y_E\left(2bNM - t_E^2\right) - t_E(aN - bG_E)(\varepsilon_0+\tau) l_E}{\alpha_2 y_E\left(2bNM - t_E^2\right)^2}.$$

If $a \le A_{EU}$ (where A_{EU} is defined as in this proposition), then $\partial u_E^*/\partial\alpha_2 \ge 0$; and if $a > A_{EU}$, then $\partial u_E^*/\partial\alpha_2 < 0$. We also find $\partial d_E^*(f_E^*)/\partial\alpha_2 \ge 0$ if $a \le A_{ED}$, and $\partial d_E^*(f_E^*)/\partial\alpha_2 < 0$ if $a > A_{ED}$, where $A_{ED} \equiv bG_E/N + \tau y_E\left(2bNM - t_E^2\right)/[t_E(\varepsilon_0+\tau) l_E N]$.

We compute the first-order derivative of f_E^* w.r.t. α_2 as

$$\frac{\partial f_E^*}{\partial \alpha_2} = \frac{W_0 bM}{\alpha_2} \frac{t_E l_E(\varepsilon_0+\tau)(Na - bG_E) - \tau y_E\left(2bNM - t_E^2\right)}{y_E\left(2bNM - t_E^2\right)^2},$$

which is non-positive if $a \le A_{EF}$ (where A_{EF} is defined as in this proposition) but is positive if $a > A_{EF}$.

The first-order derivatives of $\Pi_E(u_E^*, f_E^*)$ and $\pi_E(r_E^*, p_{1E}^*)$ w.r.t. α_2 are

$$\frac{\partial \Pi_E(u_E^*, f_E^*)}{\partial \alpha_2} = \frac{bMW_0\left(aN - bG_E\right)}{\alpha_2\left(2bNM - t_E^2\right)^2}\left[\tau\left(2bNM - t_E^2\right) - \frac{\left(\varepsilon_0+\tau\right)\left(aN - bG_E\right)}{2y_E}t_E l_E\right],$$

and

$$\frac{\partial \pi_E(r_E^*, p_{1E}^*)}{\partial \alpha_2} = \frac{2\tau t_E\left(2bNM - t_E^2\right) - \left(\varepsilon_0+\tau\right)\left(2bNM + 3t_E^2\right)\left(Na - bG_E\right)}{\left(2bNM - t_E^2\right)^3\alpha_2} \times W_0 z(r_E^*) M b^2\left(Na - bG_E\right)\left(p_{1E}^* - v_1(r_E^*)\right).$$

It follows that $\partial \Pi_E(u_E^*, f_E^*)/\partial \alpha_2 \geq 0$ if $a \leq A_{EL}$ and $\partial \Pi_E(u_E^*, f_E^*)/\partial \alpha_2 < 0$ if $a > A_{EL}$. In addition, $\partial \pi_E(r_E^*, p_{1E}^*)/\partial \alpha_2 \geq 0$ if $a \leq A_{EM}$, and $\partial \pi_E(r_E^*, p_{1E}^*)/\partial \alpha_2 < 0$ if $a > A_{EM}$. Here, A_{EL} and A_{EM} are defined as in this proposition. Recalling $t_H = b\lambda_H$, we compute the first-order derivative of p_{1H}^* w.r.t. α_2 as

$$\frac{\partial p_{1H}^*}{\partial \alpha_2} + \frac{W_0\xi_2 p_2}{\alpha_2 z\left(r^*\right)\xi_1} = \frac{W_0\xi_2 p_2 l_H}{2\alpha_2 z\left(r^*\right)\xi_1 y_H} > 0,$$

which means that $\partial p_{1H}^*/\partial \alpha_2 > -P_{1H}$, where $P_{1H} = W_0\xi_2 p_2/[\alpha_2 z(r^*)\xi_1]$. Moreover, as $\Upsilon_H = 4N^2M^2 - 12b\lambda_H^2 NM - 3b^2\lambda_H^4$, we have

$$\frac{dp_{1H}^*}{d\alpha_2} = \frac{-W_0\xi_2 p_2\Upsilon_H}{2z(r_H^*)\xi_1\alpha_2 y_H} \text{ and } \frac{\partial \lambda_H}{\partial \alpha_2} = -\frac{W_0\xi_2 p_2 l_H}{2\alpha_2 y_H} < 0.$$

Recalling that $G_H = N[\phi c_2 + (1-\phi)c_0] + W_0(1-\phi)\tau + \phi W_0\xi_2 p_2 - \phi W_0\varepsilon_0$, we have $\partial G_H/\partial \alpha_2 = W_0\tilde{G}/\alpha_2$, where $\tilde{G} = \phi\varepsilon_0 - (1-\phi)\tau - \phi\xi_2 p_2$. The first-order derivatives of u_H^* and $d_H(f_H^*)$ w.r.t. α_2 are

$$\frac{\partial u_H^*}{\partial \alpha_2} = -bW_0\frac{\xi_2 p_2 l_H\left(2bNM + t_H^2\right)\left(Na - bG_H\right) + 2y_H t_H\tilde{G}\left(2bNM - t_H^2\right)}{2y_H\alpha_2\left(2bNM - t_H^2\right)^2},$$

and

$$\frac{\partial d_H(f_H^*)}{\partial \alpha_2} = -b^2MW_0\frac{\xi_2 p_2 l_H t_H\left(Na - bG_H\right) + y_H\tilde{G}\left(2bNM - t_H^2\right)}{y_H\alpha_2\left(2bNM - t_H^2\right)^2}.$$

We find that $\partial u_H^*/\partial \alpha_2 \geq 0$ if $a \leq A_{HU}$, and $\partial u_H^*/\partial \alpha_2 < 0$ if $a > A_{HU}$, where A_{HU} is defined as in this proposition. We also have $\partial d_H(f_H^*)/\partial \alpha_2 \geq 0$ ($\partial d_H(f_H^*)/\partial \alpha_2 < 0$) if $a \leq A_{HD}$ ($a > A_{HD}$), where $A_{HD} \equiv bG_H/N - y_H\tilde{G}(2bNM - t_H^2)/(N\xi_2 p_2 l_H t_H)$. The first-order derivative of f_H^* w.r.t. α_2 is

$$\frac{\partial f_H^*}{\partial \alpha_2} = W_0Mb\frac{y_H\tilde{G}\left(2bNM - t_H^2\right) + \xi_2 p_2 l_H t_H\left(Na - bG_H\right)}{y_H\alpha_2\left(2bNM - t_H^2\right)^2}.$$

Therefore, $\partial f_H^*/\partial \alpha_2 \leq 0$ ($\partial f_H^*/\partial \alpha_2 > 0$), if $a \leq A_{HF}$ ($a > A_{HF}$), where A_{HF} is defined as in this proposition.

The first-order derivatives of $\pi_H(r^*, p_{1H}^*)$ and $\Pi_H(u_H^*, f_H^*)$ w.r.t. α_2 are

$$\frac{\partial \Pi_H(u_H^*, f_H^*)}{\partial \alpha_2} = -bM\left(Na - bG_H\right)W_0 \frac{2y_H\tilde{G}\left(2bNM - t_H^2\right) + \xi_2 p_2 l_H t_H\left(Na - bG_H\right)}{2\alpha_2 y_H\left(2bNM - t_H^2\right)^2},$$

and

$$\begin{aligned}\frac{\partial \pi_H(r^*, p_{1H}^*)}{\partial \alpha_2} = &\frac{-2t_H\tilde{G}(2bNM - t_H^2) - \xi_2 p_2(2bNM + 3t_H^2)\left(Na - bG_H\right)}{(2bNM - t_H^2)^3\alpha_2} \\ &\times W_0 z\left(r^*\right)Mb^2(p_{1H}^* - v_1(r^*))(Na - bG_H).\end{aligned}$$

Then, $\partial \Pi_H(u_H^*, f_H^*)/\partial \alpha_2 \geq 0$ ($\partial \Pi_H(u_H^*, f_H^*)/\partial \alpha_2 < 0$), if $a \leq A_{HL}$ ($a > A_{HL}$), where A_{HL} and A_{HM} are defined as in this proposition. Moreover, $\partial \pi_H(r^*, p_{1H}^*)/\partial \alpha_2 \geq 0$, if $a \leq A_{HM}$; but, $\partial \pi_H(r^*, p_{1H}^*)/\partial \alpha_2 < 0$, if $a > A_{HM}$. ■

Proof of Remark 1. The social welfare under strategy i is $SW_i = \Pi_i(u_i^*, f_i^*) + \pi_i(r_i^*, p_{1i}^*) + CS_i - I_i$, where $i = E,\ H$. Let

$$\begin{aligned}\Gamma = &\Pi_H(u_H^*, f_H^*) + \pi_H(r_H^*, p_{1H}^*) + CS_H - SW_E \\ &- \left[q_{0H}\gamma_0 + q_{1H}\gamma_1 + q_2\gamma_2 + N(1-\phi)d_H(f_H^*)\hat{\gamma}_0 + Nu_H^* d_H(f_H^*)\hat{\gamma}_1\right].\end{aligned}$$

The difference between SW_H and SW_E is $SW_H - SW_E = \Gamma - N(\phi - u_H^*)d_H(f_H^*)\hat{\gamma}_2$. If $\hat{\gamma}_2 > \hat{\gamma}_{2HE}$, then $SW_E > SW_H$; If $\hat{\gamma}_2 \leq \hat{\gamma}_{2HE}$, then $SW_E \leq SW_H$, where $\hat{\gamma}_{2HE} = \Gamma/[N(\phi - u_H^*)d_H(f_H^*)]$. ■

Proof of Proposition 5. The total environmental impacts in the monopoly case under strategies E and H can be written as

$$I_E = \left(W_0\gamma_0 + N\hat{\gamma}_0\right)d_E(f_E^*) + \left[z(r^*)\gamma_1 - W_0\gamma_0 + N\hat{\gamma}_1 - N\hat{\gamma}_0\right]u_E^* d_E(f_E^*),$$

and

$$I_H = \left[(1-\phi)\left(W_0\gamma_0 + N\hat{\gamma}_0\right) + \phi\left(\gamma_2 W_0 + N\hat{\gamma}_2\right)\right]d_H(f_H^*) + \left[z(r^*)\gamma_1 - W_0\gamma_2 + N\hat{\gamma}_1 - N\hat{\gamma}_2\right]u_H^* d_H(f_H^*).$$

Note $\omega_{i1} = \partial(u_i^* d_i(f_i^*))/\partial \alpha_1 = d_i(f_i^*)\partial u_i^*/\partial \alpha_1 + u_i^*\partial d_i(f_i^*)/\partial \alpha_1 > 0$, where $\partial u_i^*/\partial \alpha_1$ and $\partial d_i(f_i^*)/\partial \alpha_1$ are defined as in the proof of Proposition 3. The first-order derivative of I_E w.r.t. α_1 is $\partial I_i/\partial \alpha_1 = B_{i1} + N\omega_{i1}\hat{\gamma}_1$, where B_{E1} and B_{H1} are defined as in this proposition, $\partial \Pi_i(u_i^*, f_i^*)/\partial \alpha_1$ and $\partial \pi_i(r^*, p_{1i}^*)/\partial \alpha_1$ are defined as in the proof of Proposition 3.

As $CS_i = d_i(f_i^*)^2/2b$, we get $\partial CS_i/\partial \alpha_k = d_i(f_i^*)\partial d_i(f_i^*)/\partial \alpha_k/b$, where $k = 1,\ 2$. The first-order derivative of the social welfare SW_i w.r.t. α_1 is

$$\frac{\partial SW_i}{\partial \alpha_1} = \frac{\partial \Pi_i(u_i^*, f_i^*)}{\partial \alpha_1} + \frac{\partial \pi_i(r^*, p_{1i}^*)}{\partial \alpha_1} + \frac{\partial CS_i}{\partial \alpha_1} - B_{i1} - N\omega_{i1}\hat{\gamma}_1.$$

Therefore, $\partial SW_i/\partial \alpha_1 > 0$ if $\hat{\gamma}_1 < \Lambda_{i1}$ (where Λ_{i1} is defined as in this proposition) and $\partial SW_i/\partial \alpha_1 \leq$

0 if $\hat{\gamma}_1 \geq \Lambda_{i1}$.

Note $\omega_{i2} = \partial(u_i^* d_i(f_i^*))/\partial\alpha_2 = d_i(f_i^*)\partial u_i^*/\partial\alpha_2 + u_i^*\partial d_i(f_i^*)/\partial\alpha_2$, where $\partial u_E^*/\partial\alpha_2$, $\partial d_E(f_E^*)/\partial\alpha_2$, $\partial u_H^*/\partial\alpha_2$, and $\partial d_H(f_H^*)/\partial\alpha_2$ are all defined as in the proof of Proposition 4. We calculate the first-order derivative of I_i w.r.t. α_2 as $\partial I_i/\partial\alpha_2 = B_{i2} + N\omega_{i2}\hat{\gamma}_1$, where B_{E2} and B_{H2} are defined as in this proposition; and, $\partial\Pi_E(u_E^*, f_E^*)/\partial\alpha_2$, $\partial\Pi_H(u_H^*, f_H^*)/\partial\alpha_2$, $\partial\pi_E(r^*, p_{1E}^*)/\partial\alpha_2$, and $\partial\pi_H(r^*, p_{1H}^*)/\partial\alpha_2$ are all defined as in the proof of Proposition 4. The first-order derivative of SW_i w.r.t. α_2 is

$$\frac{\partial SW_i}{\partial\alpha_2} = \frac{\partial\Pi_i(u_i^*, f_i^*)}{\partial\alpha_2} + \frac{\partial\pi_i(r^*, p_{1i}^*)}{\partial\alpha_2} + \frac{\partial CS_i}{\partial\alpha_2} - B_{i2} - N\omega_{i2}\hat{\gamma}_2.$$

If $\omega_{i2} > 0$ and $\hat{\gamma}_1 < \Lambda_{i2}$ (where Λ_{i2} is defined as in this proposition) or if $\omega_{i2} < 0$ and $\hat{\gamma}_1 > \Lambda_{i2}$, then $\partial SW_i/\partial\alpha_2 > 0$. Otherwise, $\partial SW_i/\partial\alpha_2 \leq 0$. ■

Appendix B Parameters and Numerical Experiments in an Alternative Case

In the alternative case, we set c_0 = \$0.7/mile, c_1 = \$0.6/mile, c_2 = \$0.8/mile, and use the other parameter values as in the case in the main body of this paper. The impacts of time window factors in the alternative case is illustrated in Figures A and B.

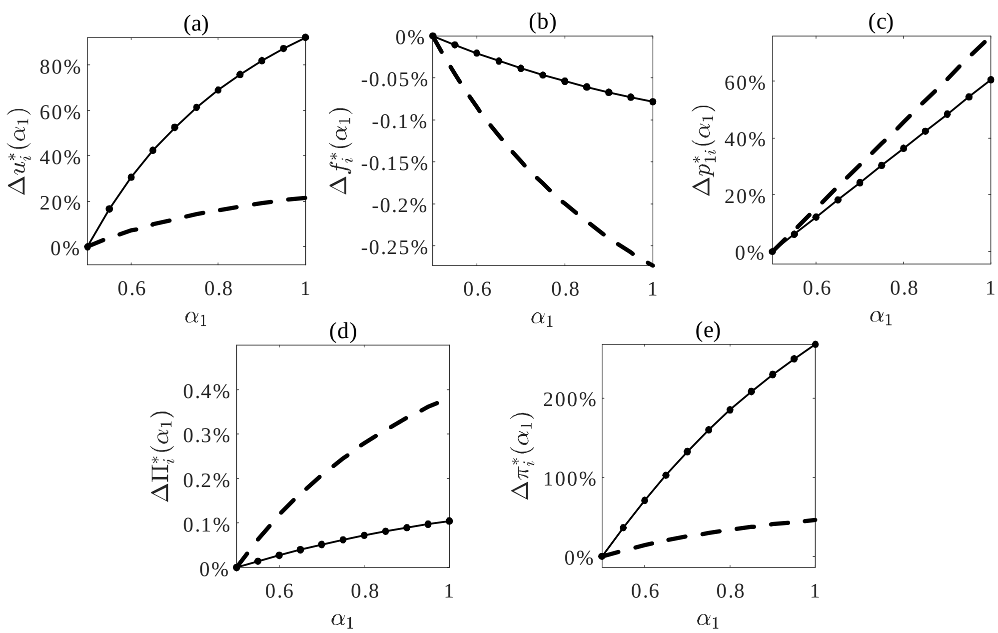

Figure A: The impacts of time window factor for EVs on the percentage changes in the optimal usage rate of EVs (as shown in (a)), the optimal logistics service fee (as shown in (b)), the optimal EV price (as shown in (c)), and the LSP's and the EV manufacturer's profits (as shown in (d) and (e)). Note that the solid and dashed lines indicate the results under strategies E and H, respectively.

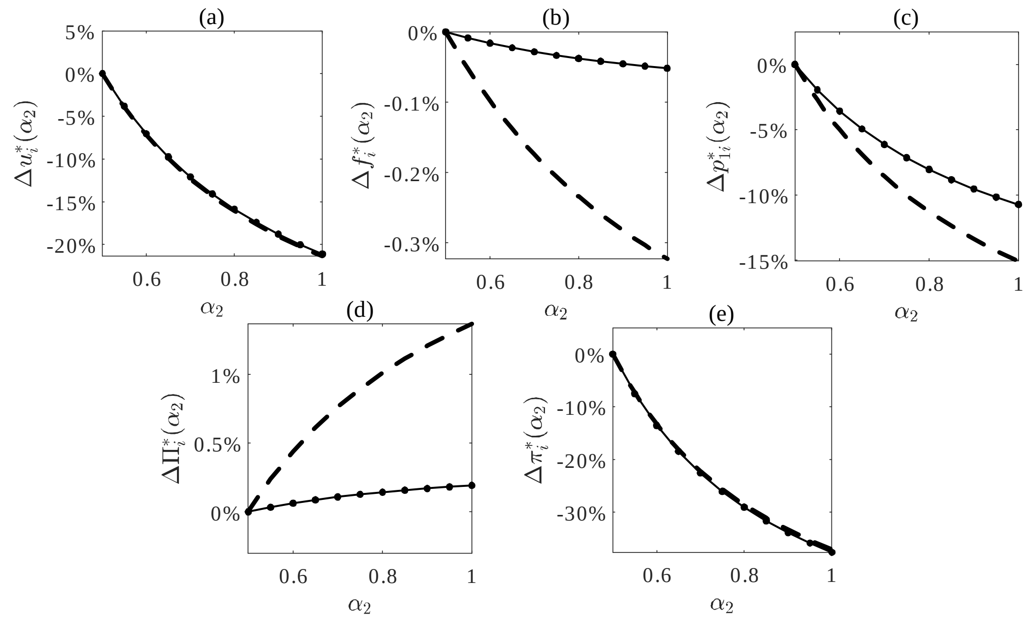

Figure B: The impacts of time window factor for ICVs on the percentage changes in the optimal usage rate of EVs (as shown in (a)), the optimal logistics service fee (as shown in (b)), the optimal EV price (as shown in (c)), and the LSP's and the EV manufacturer's profits (as shown in (d) and (e)). Note that the solid and dashed lines indicate the results under strategies E and H, respectively.

Appendix C A Summary of Major Analytical Results

We summarize our major analytical results in Table A. From this table, we find that a greater time window for EVs can increase the LSP's EV usage rate, decrease her optimal service fee, and cause an increase in the LSP's and the EV manufacturer's profits. When the demand potential for the LSP's service is sufficiently large (small), a smaller time window for ICVs can increase (decrease) the LSP's EV usage rate, her profit as well as the EV manufacturer's profit, but it can decrease (increase) the LSP's optimal service fee. These insights hold under strategies E and H.

	r^*	p_{1i}^* $(i = E, H)$	f_i^*	u_i^*	$\Pi_i(u_i^*, f_i^*)$	$\pi_i(r_i^*, p_{1i}^*)$
α_1	–	↑↓	↓	↑	↑	↑
α_2	–	$\begin{cases} \uparrow, & \text{if } sgn(\Upsilon_i) = -1, \\ -, & \text{if } sgn(\Upsilon_i) = 0, \\ \downarrow, & \text{otherwise.} \end{cases}$	$\begin{cases} \uparrow, & \text{if } a > A_{iF}, \\ \downarrow, & \text{otherwise.} \end{cases}$	$\begin{cases} \downarrow, & \text{if } a > A_{iU}, \\ \uparrow, & \text{otherwise.} \end{cases}$	$\begin{cases} \downarrow, & \text{if } a > A_{iL}, \\ \uparrow, & \text{otherwise.} \end{cases}$	$\begin{cases} \downarrow, & \text{if } a > A_{iM}, \\ \uparrow, & \text{otherwise.} \end{cases}$

Table A: The impacts of the parameters α_1 and α_2 on the optimal EV prices, the optimal driving ranges, the optimal logistics service fees, and the optimal usage rates. Note that the marks "↓," "↑," "↓↑," and "—" indicate that the optimal decisions, or profits are decreasing in, increasing in, may be increasing or may be decreasing in, independent of the corresponding parameter, respectively.

Appendix D Mathematical Arguments for Section 6

Under strategy i, the LSP m's profit $\Pi_{im}^{D}(u_{im}, f_{im})$ yields $\Pi_{im}^{D}(u_{im}, f_{im}) = (Nf_{im} - G_i + u_{im}\lambda_i)(a_m - bf_{im} + \beta f_{in}) - Mu_{im}^2/2$. Since $\partial^2\Pi_{im}^{D}(u_{im}, f_{im})/\partial(f_{im})^2 = -2bN < 0$, we solve the first-order condition to find LSP m's ($m = X, Y$) service fee as

$$f_{im} = \frac{b\left(G_i - u_{im}\lambda_i\right) + a_m N}{2Nb} + \frac{\beta f_{in}}{2b}.$$

Therefore, the LSP n's service fee is $f_{in} = [b(G_i - u_{in}\lambda_i) + a_n N]/(2bN) + \beta f_{im}/(2b)$. Substituting f_{in} into f_{im} gives

$$f_{im}\left(u_{im}, u_{in}\right) = \frac{K_{im} - b\lambda_i\left(2bu_{im} + \beta u_{in}\right)}{N\left(4b^2 - \beta^2\right)} \text{ and } f_{in}\left(u_{im}, u_{in}\right) = \frac{K_{in} - b\lambda_i\left(2bu_{in} + \beta u_{im}\right)}{N\left(4b^2 - \beta^2\right)},$$

where $K_{im} = 2bNa_m + \beta Na_n + b(2b + \beta)G_i$, $K_{in} = 2bNa_n + \beta Na_m + b(2b + \beta)G_i$, $i = E, H$.

Letting $L_{im} = (a_m N - bG_i)(4b^2 - \beta^2) + \beta K_{in}$, $R_{i1} = \lambda_i(2b^2 - \beta^2)$, and $R_{i2} = MN(4b^2 - \beta^2)^2 - 2bR_{i1}^2$, we use the first-order condition to obtain

$$u_{im}\left(u_{in}\right) = \frac{R_{i1}}{R_{i2}}\left(L_{im} - 2b^2\lambda_i\beta u_{in}\right) \text{ and } u_{in}\left(u_{im}\right) = \frac{R_{i1}}{R_{i2}}\left(L_{in} - 2b^2\lambda_i\beta u_{im}\right).$$

Substituting u_{in} into u_{im} yields

$$u_{im}^{D*} = \frac{R_{i1}\left(R_{i2}L_{im} - 2\beta b^2\lambda_i R_{i1}L_{in}\right)}{R_{i2}^2 - 4\beta^2 b^4\lambda_i^2 R_{i1}^2}.$$

The LSP m's optimal service fee under strategy i is

$$f_{im}^{D*} = \frac{R_{i5}K_{im} - b\lambda_i R_{i1}\left(2bR_{i3}L_{im} + \beta L_{in}R_{i4}\right)}{NR_{i5}\left(4b^2 - \beta^2\right)},$$

where $R_{i3} = R_{i2} - \beta^2 b\lambda_i R_{i1}$, $R_{i4} = R_{i2} - 4b^3\lambda_i R_{i1}$, $R_{i5} = R_{i2}^2 - 4\beta^2 b^4\lambda_i^2 R_{i1}^2$.

As the "leader" in the sequential game, the EV manufacturer determines the driving range and the EV price before the LSP makes her decisions. The manufacturer's profit in the duopoly case is $\pi_i^D(r_i, p_{1i}) = (u_{im}d_{im} + u_{in}d_{in})z(r_i)(p_{1i} - v_1(r_i))$. Its first-order derivatives w.r.t. r_i and p_{1i} are

$$\begin{aligned}\frac{\partial\pi_i^D(r_i, p_{1i})}{\partial r_i} &= \frac{\partial\lambda_i}{\partial r_i}\left(\chi_{im} + \chi_{in}\right)z(r_i)\left(p_{1i} - v_1\left(r_i\right)\right) \\ &\quad + \left(u_{im}d_{im} + u_{in}d_{in}\right)\left[\frac{\partial z(r_i)}{\partial r_i}\left(p_{1i} - v_1\left(r_i\right)\right) - z(r_i)\frac{\partial v_1\left(r_i\right)}{\partial r_i}\right] = 0,\end{aligned}$$

and

$$\frac{\partial\pi_i^D(r_i, p_{1i})}{\partial p_{1i}} = \frac{\partial\lambda_i}{\partial p_{1i}}\left(\chi_{im} + \chi_{in}\right)\left(p_{1i} - v_1\left(r_i\right)\right)z(r_i) + (u_{im}d_{im} + u_{in}d_{in})z(r_i) = 0,$$

where $\chi_{im} = \partial(u_{im}d_{im})/\partial\lambda_i$ and $\chi_{in} = \partial(u_{in}d_{in})/\partial\lambda_i$. We find that $u_{im}d_{im} + u_{in}d_{in} = -(\chi_{im} +$

$\chi_{in})(p_{1i} - v_1(r))\partial\lambda_i/\partial p_{1i}$. Therefore, r_i^{D*} satisfies the equation:

$$z(r_i^{D*})\partial v_1(r_i^{D*})/\partial r_i^{D*} - \eta v_1(r_i^{D*})/r_i^{D*2} = 0;$$

as a result, $r_i^{D*} = r^*$. Moreover, p_{1i}^{D*} satisfies the equation that $u_{im}d_{im} + u_{in}d_{in} - z(r_i^{D*})\xi_1(\chi_{im} + \chi_{in})(p_{1i}^{D*} - v_1(r_i^{D*})) = 0$. Assume $\partial^2\Pi_{im}^D(u_{im}^D, f_{im}^D)/\partial u_{im}^{D2} = 2b\lambda_i^2(2b^2-\beta^2)^2/[N(4b^2-\beta^2)^2] - M < 0$. Thus, when $\partial^2\pi_i^D/\partial r_i^2 < 0$, $\partial^2\pi_i^D/\partial p_{1i}^2 < 0$, and $\partial^2\pi_i^D/\partial r_i^2 \times \partial^2\pi_i^D/\partial p_{1i}^2 - [\partial^2\pi_i^D/(\partial r_i \partial p_{1i})]^2 > 0$, the Hessian matrix of π_i^D at the optimal solution (r_i^{D*}, p_{1i}^{D*}) is negatively definite.

Next, we define the parameter $\chi_{im} = \partial(u_{im}^* d_{im})/\partial\lambda_i$. Note $f_{im}^{D*} = [K_{im} - b\lambda_i\left(2bu_{im}^{D*} + \beta u_{in}^{D*}\right)]/[N\left(4b^2 - \beta^2\right)]$ and $f_{in}^{D*} = [K_{in} - b\lambda_i\left(2bu_{in}^{D*} + \beta u_{im}^{D*}\right)]/[N\left(4b^2 - \beta^2\right)]$. According to $d_{im} = a_m - bf_{im} + \beta f_{in}$, we have

$$u_{im}^{D*}d_{im} = u_{im}^{D*}\frac{\left[N\left(4b^2 - \beta^2\right)a_m + \beta K_{in} - bK_{im}\right] + b\lambda_i\left[\left(2b^2 - \beta^2\right)R_{i2}u_{im}^{D*} + 2b^3\beta^2 R_{i6}\lambda_i u_{im}^{D*} - b\beta R_{i6}L_{in}\right]}{N\left(4b^2 - \beta^2\right)},$$

where $R_{i6} \equiv R_{i1}/R_{i2}$. The first-order derivative of u_{im}^{D*} w.r.t. λ_i is

$$\frac{\partial u_{im}^{D*}}{\partial\lambda_i} = \frac{\left(R_{i2}L_{Em} - 4\beta b^2\lambda_i R_{i1}L_{in}\right)\left(2b^2 - \beta^2\right) - 4b\lambda_i\left(2b^2 - \beta^2\right)^2 R_{i1}L_{im} - 2\beta b^2 R_{i1}^2 L_{in}}{R_{i5}^2}.$$

The first-order derivative of R_{i6} w.r.t. λ_i is

$$\frac{\partial R_{i6}}{\partial\lambda_i} = \left(2b^2 - \beta^2\right)\frac{MN\left(4b^2 - \beta^2\right)^2 - 2bR_{i1}^2 + 4b\lambda_i\left(2b^2 - \beta^2\right)R_{i1}}{R_{i2}^2}.$$

Defining

$$R_{im7} \equiv \frac{bu_{im}^{D*}}{N\left(4b^2 - \beta^2\right)}\left\{\left[\left(2b^2 - \beta^2\right)R_{i2} + 4b^3\beta^2 R_{i6}\lambda_i - 4b\lambda_i^2\left(2b^2 - \beta^2\right)^3\right]u_{im}^{D*} - b\beta R_{i6}L_{in}\right\},$$

we have the first-order of $u_{im}^{D*}d_{im}$ w.r.t. λ_i as

$$\begin{aligned}\chi_{im} = \frac{\partial(u_{im}^{D*}d_{im})}{\partial\lambda_i} &= \left\{\frac{R_{im8} + 2b\lambda_i\left[\left(2b^2 - \beta^2\right)R_{i2} + 2b^3\beta^2\lambda_i R_{i6}\right]u_{im}^{D*}}{N\left(4b^2 - \beta^2\right)}\right\}\frac{\partial u_{im}^{D*}}{\partial\lambda_i} \\ &+ R_{im7} + \frac{b^2\beta\lambda_i(2b^2\beta\lambda_i u_{im}^{D*2} - L_{in}u_{im}^{D*})}{N\left(4b^2 - \beta^2\right)}\frac{\partial R_{i6}}{\partial\lambda_i},\end{aligned}$$

where $R_{im8} \equiv N\left(4b^2 - \beta^2\right)a_m + \beta K_{in} - bK_{im} - b^2\lambda_i\beta R_{i6}L_{in}$. Similarly, we can obtain $\chi_{in} = \partial(u_{in}^{D*}d_{in})/\partial\lambda_i$.

For the duopoly case, the social welfare is

$$SW_i^D = \textstyle\sum_m \Pi_{im}^D(u_{im}^{D*}, f_{im}^{D*}) + \pi_i^D(r^*, p_{1i}^{D*}) + \sum_m CS_{im}^D - I_i^D, \text{ for } m = X, Y.$$

Using (13), we compute the LSP m's consumer surplus as $CS_{im}^D = (a - bf_{im}^{D*})^2/(2b)$. The total environmental impact for the duopoly case (i.e., I_i^D) is $I_E^D \equiv (q_{0Em}+q_{0En})\gamma_0+(q_{1Em}+q_{1En})\gamma_1+N\hat{\gamma}_0[d_{Em}(1-u_{Em}^{D*})+d_{En}(1-u_{En}^{D*})]+N\hat{\gamma}_1(u_{Em}^{D*}d_{Em}+u_{En}^{D*}d_{En})$ and $I_H^D \equiv (q_{0Hm}+q_{0Hn})\gamma_0+(q_{1Hm}+q_{1Hn})\gamma_1+(q_{2m}+q_{2n})\gamma_2+N\hat{\gamma}_0(1-\phi)(d_{Hm}+d_{Hn})+N\hat{\gamma}_1(u_{Hm}^{D*}d_{Hm}+u_{Hn}^{D*}d_{Hn})+N[(\phi-u_{Hm}^{D*})d_{Hm}+(\phi-u_{Hn}^{D*})d_{Hn}]\hat{\gamma}_2$. The difference between SW_H^D and SW_E^D is

$$SW_H^D - SW_E^D = \Gamma^D - N[(\phi-u_{Hm}^{D*})d_{Hm}+(\phi-u_{Hn}^{D*})d_{Hn}]\hat{\gamma}_2.$$

If $\hat{\gamma}_2 > \hat{\gamma}_{2HE}^D$, then $SW_E^D > SW_H^D$; If $\hat{\gamma}_2 \leq \hat{\gamma}_{2HE}^D$, then $SW_E^D \leq SW_H^D$, where $\hat{\gamma}_{2HE}^D = \Gamma^D/[N(\phi-u_{Hm}^{D*})d_{Hm}+N(\phi-u_{Hn}^{D*})d_{Hn}]$, Γ^D is defined by

$$\begin{aligned}\Gamma^D = {} & \textstyle\sum_m \Pi_{Hm}^D(u_{Hm}^{D*}, f_{Hm}^{D*}) + \pi_H^D(r^*, p_{1H}^{D*}) + \sum_m CS_{Hm}^D - SW_E^D \\ & - [(q_{0Hm}+q_{0Hn})\gamma_0+(q_{1Hm}+q_{1Hn})\gamma_1+(q_{2m}+q_{2n})\gamma_2] \\ & - N\hat{\gamma}_0(1-\phi)(d_{Hm}+d_{Hn}) - N\hat{\gamma}_1(u_{Hm}^{D*}d_{Hm}+u_{Hn}^{D*}d_{Hn}).\end{aligned}$$

We consider the impacts of time window factors on the optimal decisions. Note that p_{1i}^{D*} satisfies the equation $u_{im}^{D*}d_{im}+u_{in}^{D*}d_{in}-z(r^*)\xi_1(\chi_{im}+\chi_{in})[p_{1i}^{D*}-v_1(r^*)]=0$. We find that the signs of $\partial p_{1i}^{D*}/\partial\alpha_1$ and $\partial p_{1i}^{D*}/\partial\alpha_2$ are uncertain, and $\partial\lambda_i/\partial\alpha_1 = -\xi_1 z(r^*)(\partial p_{1i}^{D*}/\partial\alpha_1 - p_{1i}^{D*}/\alpha_1)$. Note $\partial\lambda_i/\partial\alpha_2 = -z(r_i)\xi_1\partial p_{1i}^{D*}/\partial\alpha_2 - W_0\theta_i/\alpha_2$, where $\theta_E=\varepsilon_0+\tau$, $\theta_H=\xi_2 p_2$. Using the definitions of R_{i1}, R_{i2}, R_{i3}, and R_{i4}, for $i=E,H$, we have $\partial R_{i1}/\partial\lambda_i = 2b^2-\beta^2$, $\partial R_{i2}/\partial\lambda_i = -4b\lambda_i(2b^2-\beta^2)^2$, $\partial R_{i3}/\partial\lambda_i = 2b\lambda_i(2b^2-\beta^2)(\beta^2-4b^2)$, and $\partial R_{i4}/\partial\lambda_i = 4b\lambda_i(2b^2-\beta^2)(\beta^2-4b^2)$. As $\partial L_{im}/\partial\alpha_1 = \partial K_{im}/\partial\alpha_1 = 0$, we calculate $\partial u_{im}^{D*}/\partial\lambda_i$ as

$$\frac{\partial u_{im}^{D*}}{\partial\lambda_i} = \frac{Z_{1i}L_{im}-Z_{2i}L_{in}}{R_{i5}^2}\left(2b^2-\beta^2\right),$$

where $Z_{1i} \equiv MN(4b^2-\beta^2)^2R_{i5}-6bR_{i1}^2R_{i5}+8bR_{i1}^2R_{i2}(R_{i2}+2\beta^2b^3\lambda_i^2)$ and $Z_{2i} \equiv 6b^2\beta\lambda_iR_{i1}R_{i5}+16\beta\lambda_ib^3R_{i1}^3(R_{i2}+2\beta^2b^3\lambda_i^2)$. The first-order derivative of the logistics service fee f_{im}^{D*} w.r.t. λ_i is

$$\frac{\partial f_{im}^{D*}}{\partial\lambda_i} = \frac{-b}{N\left(4b^2-\beta^2\right)}\left[2bu_{im}^{D*}+\beta u_{in}^{D*}+\lambda_i\left(2b\frac{\partial u_{im}^{D*}}{\partial\lambda_i}+\beta\frac{\partial u_{in}^{D*}}{\partial\lambda_i}\right)\right].$$

The above indicates that the signs of $\partial u_{im}^{D*}/\partial\alpha_1$, $\partial f_{im}^{D*}/\partial\alpha_1$, $\partial u_{im}^{D*}/\partial\alpha_2$, and $\partial f_{im}^{D*}/\partial\alpha_2$ are uncertain. The environmental impacts for the duopoly case can be written as

$$I_E^D \equiv \Psi_0\left(d_{Em}+d_{En}\right)+\left(\gamma_1 z(r^*)-\Psi_0\right)\left(u_{Em}^{D*}d_{Em}+u_{En}^{D*}d_{En}\right)+N\hat{\gamma}_1\left(u_{Em}^{D*}d_{Em}+u_{En}^{D*}d_{En}\right),$$

and

$$I_H^D \equiv \varphi(d_{Hm}+d_{Hn})+\left(\gamma_1 z(r^*)-\Psi_2\right)\left(u_{Hm}^{D*}d_{Hm}+u_{Hn}^{D*}d_{Hn}\right)+N\hat{\gamma}_1\left(u_{Hm}^{D*}d_{Hm}+u_{Hn}^{D*}d_{Hn}\right),$$

where $\Psi_0=\gamma_0W_0+N\hat{\gamma}_0$, $\Psi_2=W_0\gamma_2+N\hat{\gamma}_2$, $\varphi=(1-\phi)\Psi_0+\phi\Psi_2$. The first-order derivative of the social welfare SW_i^D w.r.t. α_1 is

$$\frac{\partial SW_i^D}{\partial \alpha_1} = \sum_m \frac{\partial \Pi_{im}^D(u_{im}^{D*}, f_{im}^{D*})}{\partial \alpha_1} + \frac{\partial \pi_i^D(r^*, p_{1i}^{D*})}{\partial \alpha_1} + \sum_m \frac{\partial CS_{im}^D}{\partial \alpha_1} - \frac{\partial I_i^D}{\partial \alpha_1},$$

where $\partial I_i^D/\partial\alpha_1 = \sum_m B_{i1m} + N\hat{\gamma}_1 \sum_m \omega_{i1m}$, $B_{E1m} \equiv \Psi_0\zeta_{E1m} + (z(r^*)\gamma_1 - \Psi_0)\omega_{E1m} - \gamma_1 z(r^*)u_{Em}^{D*}d_{Em}/\alpha_1$, $B_{H1m} \equiv \varphi\zeta_{H1m} + (z(r^*)\gamma_1 - \Psi_2)\omega_{H1m} - \gamma_1 z(r^*)u_{Hm}^{D*}d_{Hm}/\alpha_1$, $\omega_{i1m} \equiv \partial(u_{im}^{D*}d_{im})/\partial\alpha_1$, and $\zeta_{i1m} \equiv \partial d_{im}/\partial\alpha_1$. The first-order derivative of the social welfare SW_i^D w.r.t. α_2 is

$$\frac{\partial SW_i^D}{\partial \alpha_2} = \sum_m \frac{\partial \Pi_{im}^D(u_{im}^{D*}, f_{im}^{D*})}{\partial \alpha_2} + \frac{\partial \pi_i^D(r^*, p_{1i}^{D*})}{\partial \alpha_2} + \sum_m \frac{\partial CS_{im}^D}{\partial \alpha_2} - \frac{\partial I_i^D}{\partial \alpha_2},$$

where $\partial I_i^D/\partial\alpha_2 = \sum_m B_{i2m} + N\hat{\gamma}_1 \sum_m \omega_{i2m}$, $B_{E2m} \equiv \Psi_0\zeta_{E2m} + (z(r^*)\gamma_1 - \Psi_0)\omega_{E2m} - W_0(1 - u_{Em}^{D*})d_{Em}\gamma_0/\alpha_2$, $B_{H2m} \equiv \varphi\zeta_{H2m} + (z(r^*)\gamma_1 - \Psi_2)\omega_{H2m} - W_0[(1-\phi)\gamma_0 + (\phi - u_{Hm}^{D*})\gamma_2]d_{Hm}/\alpha_2$, $\omega_{i2m} \equiv \partial(u_{im}^{D*}d_{im})/\partial\alpha_2$, and $\zeta_{i2m} \equiv \partial d_{im}/\partial\alpha_2$.

If $\sum_m \omega_{ikm} > 0$ and $\hat{\gamma}_1 < \Lambda_{ik}^D$ or if $\sum_m \omega_{ikm} < 0$ and $\hat{\gamma}_1 > \Lambda_{ik}^D$, $\partial SW_i^D/\partial\alpha_k > 0$. Otherwise, $\partial SW_i^D/\partial\alpha_k \leq 0$. Here, $\Lambda_{ik}^D \equiv [\sum_m \partial\Pi_{im}^D(u_{im}^{D*}, f_{im}^{D*})/\partial\alpha_k + \partial\pi_i^D(r^*, p_{1i}^{D*})/\partial\alpha_k + \sum_m \partial CS_{im}^D/\partial\alpha_k - \sum_m B_{ikm}]/(N\sum_m \omega_{ikm})$.