Optimal electric vehicle production strategy considering loss aversion, subsidy and battery recycling

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Abstract
This paper extends previous loss-averse newsvendor model by incorporating both subsidies and battery recycling to investigate how the optimal electric vehicle production strategy is influenced by loss aversion, subsidies, and battery recycling. The analytical solutions for our model are derived, together with numerical experiments evaluating the properties of our model.

Keywords: Battery Recycling, Loss Aversion, Subsidy

INTRODUCTION

Electric vehicles (EVs) produce no tailpipe emissions due to the fact that they have a battery instead of a gasoline tank, and an electric motor instead of an internal combustion engine. Replacing conventional vehicles with EVs can reduce greenhouse gas emissions, improve roadside air quality, and contribute to the environmental health. Therefore, as suggested by Smith (2009), the only long-term solution for the future of transport is the wider use of EVs. In fact, electric vehicles develop more and more rapidly in recent years. For example, the top 20 global sales of EVs, which include both pure electric vehicles and plug-in hybrids, sold 41680 EVs worldwide in June 2015 and sold 204265 EVs over the first six months of the year(Ling, 2015).

Though EV development is quickly, the lithium battery life is generally about 20 years. In fact, the performance of the lithium battery will decay after 3-5 years. Once the battery capacity is attenuated to below 80% of the initial capacity, the EVs mileage will be significantly reduced. Therefore, power batteries for EVs must be replaced after 3-5 years (Admin, 2016). Additionally, if the used batteries are not handled properly, they might do great harm to the environment. As is well known, the lithium-ion battery contains a large number of toxic heavy metals such as mercury, cadmium, lead and son on. Moreover, a 20 g cell phone lithium battery can contaminate the water of three standard swimming pools. If the waste batteries are left on the land, they will contaminate one square kilometer of land about 50 years (The first electric network, 2013). Besides, used batteries have values. Through dismantling, testing and classification, the used batteries can reduce 30-60% of the cost of power battery (Chinese electric vehicle network, 2014).

Recently, there have been various studies on recycling. Several related papers include Savaskan et al. (2004), who are the first to study the manufacturer's choice of reverse channel structures for collecting used products from consumers. Chuang et al. (2014) proposed closed-loop supply chain models for a high-tech product under alternative reverse channel and collection cost structures. Different from the above-mentioned studies, in this paper we focus on the influences of subsidy, loss aversion and battery recycling on EV production quantity.

Nowadays, the government encourages EV development by providing subsidies. There are many studies about the impact of subsidies on EVs. The optimal production quantity of the EVs increases with respect to the subsidy (Zhang, 2013). It is shown that the subsidy ceiling is more effective in influencing the optimal wholesale pricing decision of manufacturer with a higher unit production cost and the discount rate is more effective for the manufacturer with a lower unit production cost (Luo et al., 2014). Thus, we not only study the influences of subsidy and loss aversion on EV production quantity, but also study the influence of battery recycling on electric vehicle production quantity.

A most popular theoretical assumption on newsvendor model is that the decision maker is risk neutral rather than loss-averse. However, Schweitzer and Cachon (2000) showed that if a manager has a preference for minimizing ex post inventory error, then she will exhibit the pull-to-center bias. In fact, using newsvendor model to capture the loss aversion effect is still in its early stages and need a further study (Wang and Webster, 2009). Therefore, in this article we incorporate the loss aversion and newsvendor model to study the influence of loss aversion on the optimal EV production quantity.

THE MODEL

Following are the notations and assumptions for our model analysis:

c manufacturer's production cost per unit of the electric vehicle;

X random demand of the electric vehicle;

x realized demand of the electric vehicle;

$F(x)$ cumulative distribution function (CDF) of X ;

$f(x)$ probability density function (PDF) of X ;

Q manufacture's production quantity of the electric vehicle;

p retail price per unit of the electric vehicle;

s salvage value per unit of the electric vehicle;

τ collection rate ($\tau \in [0,1]$),defined as a fraction of the Q units of the product that will be collected from consumers for recycling;

Δ margin per unit of the reused battery;

$C_L(\tau, Q)$ total collection cost when τQ units of the batteries are collected;

A variable collection cost in $C_L(\tau, Q)$ ($A > 0$);

B a scaling parameter that measures the costliness of collecting in $C_L(\tau, Q)$ ($B > 0$);

y per unit subsidy that company received from the government for realized demand;

λ the loss aversion coefficient ($\lambda \geq 1$) .

Assumption 1. $0 \leq s < c$.

Assumption 2. $F(x)$ is differentiable, invertible, and strictly increasing over $[0,1)$ and its generalized failure rate $g(x)$, defined as $g(x) = xf(x) / [1-F(x)]$, is increasing.

Assumption 3. $A < \Delta < A + (c-s)/\tau$.

Assumption 4. The collection rate τ is exogenous.

Assumption 5. $C_L(\tau, Q) = A\tau Q + B\tau^2$.

The profit function $\pi(Q, D = x)$ of electric vehicles production can be written as follows:

$$\pi(Q, D=x) = \begin{cases} (p+y)x + s(Q-x) - cQ + \Delta\tau Q - A\tau Q - B\tau^2, & if\ D \le Q \\ (p+y)Q - cQ + \Delta\tau Q - A\tau Q - B\tau^2, & if\ D > Q \end{cases} \tag{1}$$

From the profit function (1), the integrated firm's expected profit is comprised of her forward channel's expected profit for manufacturing and selling the new electric vehicles and her reverse channel's profit for collecting and reusing the used batteries.

The profit function Eq. (1) is an approximation of the real situation. From the profit function (1), the breakeven quantity q_{RY} for the production can be calculated when the profit is zero, as shown in the following equation:

$$q_{RY} = \frac{cQ - sQ - \Delta\tau Q + A\tau Q + B\tau^2}{p + y - s} \tag{2}$$

Based on Eq. (2), we have Corollary 1 to describe the influence of subsidies and battery recycling on the breakeven production quantity.

Corollary 1. The breakeven quantity $q_{RY}(Q)$ increases with subsidy y. If $\Delta Q > AQ + 2B\tau$ ($\Delta Q < AQ + 2B\tau$), then the breakeven quantity $q_{RY}(Q)$ decreases (increases) with respect to collection rate τ.

Eq. (2) reveals that when the order quantity is less than the breakeven quantity $q_{RY}(Q)$, the profit will be negative. According to loss aversion theory (see e.g., Kahneman and Tversky, 1979; Tversky and Kahneman, 1991), the EV manager in this case will be more sensitive to the losses than the equivalent gains with a certain reference point. A widely used piecewise-linear form of the loss aversion utility function can reflect the characteristics, as shown in the following form:

$$U(\pi) = \begin{cases} \pi - \pi_0, & \pi \ge \pi_0 \\ \lambda(\pi - \pi_0), & \pi < \pi_0 \end{cases} \tag{3}$$

where π_0 is the reference point.

Based on the above analysis and using the breakeven point $\pi_0(q_{RY}) = 0$ as the reference point, the model to maximize the expected utility of a loss-averse manager for selling EVs considering both subsidies and battery recycling can be written in the following manner:

$$
\begin{aligned}
Max\ EU_{\lambda YR} = & (\lambda - 1)\int_0^{q_{RY}} \left[(p+y)x + s(Q-x) - cQ + \Delta\tau Q - A\tau Q - B\tau^2 \right] f(x)\,dx \\
& + \int_0^{Q} \left((p+y)x + s(Q-x) - cQ + \Delta\tau Q - A\tau Q - B\tau^2 \right) f(x)\,dx \\
& + \int_Q^{\infty} \left((p+y)Q - cQ + \Delta\tau Q - A\tau Q - B\tau^2 \right) f(x)\,dx
\end{aligned} \tag{4}
$$

Eq. (4) is the objective function to maximize the expected utility for an EV manufacturer considering government subsidies, battery recycling and the loss aversion effect. As shown in Eq. (4), we use the breakeven point as the reference point in the model. If $\lambda = 1$ in the above model (4), there is no reference dependence and the model (4) reduces to the standard subsidized newsvendor model considering recycling.

Theorem 1. The expected utility function (4) is concave with respect to quantity Q.Then, there exists a unique and finite optimal production quantity $Q^*_{\lambda YR}$ that maximizes the integrated firm's expected profit in the above model, and $Q^*_{\lambda YR}$ satisfies the following fist-order condition:

$$
F\left(Q^*_{\lambda YR}\right) = \frac{(p + y - c + \Delta\tau - A\tau) + (\lambda - 1)(s - c + \Delta\tau - A\tau)F\left(q_{RY}\left(Q^*_{\lambda YR}\right)\right)}{p + y - s} \tag{5}
$$

Eq. (5) characterizes the integrated electric vehicle manufacturer's optimal production quantity of the original product in her forward channel considering loss aversion, subsidy and battery recycling. Some other factors also influence the optimal production quantity. The following Theorems 2 and 3 address the issue and provide further analysis on the expected utility.

Theorem 2.

(a) The optimal production quantity $Q^*_{\lambda YR}$ increases with respect to subsidy y, i.e. $\frac{\partial Q^*}{\partial y} > 0$.

(b) The optimal production quantity $Q^*_{\lambda YR}$ decreases with the degree of loss aversion, i.e. $\frac{\partial Q^*}{\partial \lambda} < 0$.

(c) If $\Delta Q - AQ - 2B\tau > 0$, the optimal production quantity $Q^*_{\lambda YR}$ increases with respect to collecting rate τ, i.e. $\frac{\partial Q^*}{\partial \tau} \geq 0$.

Theorem 3. $Q^*_{\lambda YR} \leq Q^*_{YR}$, $Q^*_{\lambda YR} \geq Q^*_{\lambda Y}$, $Q^*_{\lambda YR} \geq Q^*_{\lambda R}$.

It is noted that the theorem 3 shows that the optimal production quantity of a loss-averse decision maker with subsidies and battery recycling is less than that of a risk neutral decision maker with the same subsidies and battery recycling (i.e. $Q^*_{\lambda YR} \leq Q^*_{YR}$). The optimal production quantity of a loss-averse decision maker with subsidies and battery recycling is more than that of a risk neutral decision maker with the same subsidies (i.e. $Q^*_{\lambda YR} \geq Q^*_{\lambda Y}$). The optimal production quantity of a loss-averse decision maker with subsidies and battery recycling is more than that of a risk neutral decision maker with battery recycling (i.e. $Q^*_{\lambda YR} \geq Q^*_{\lambda R}$).

NUMERICAL EXPERIMENTS

To illustrate properties of the proposed model, we perform three groups of numerical experiments to reveal the influences of loss aversion coefficients, subsidies, and battery collecting rates on electric vehicle expected utility. As shown in both Figures 1 and 3, both the subsidy and battery collecting rates have positive impacts on the expected utility, whereas either the collecting rates or subsidies can enhance the influence of either subsidies or the collecting rates on the expected utility. Figure 2 shows that the loss aversion has a negative impact on the expected utility and that either subsidies or collecting rates can help offset the influence of loss aversion on the expected utility.

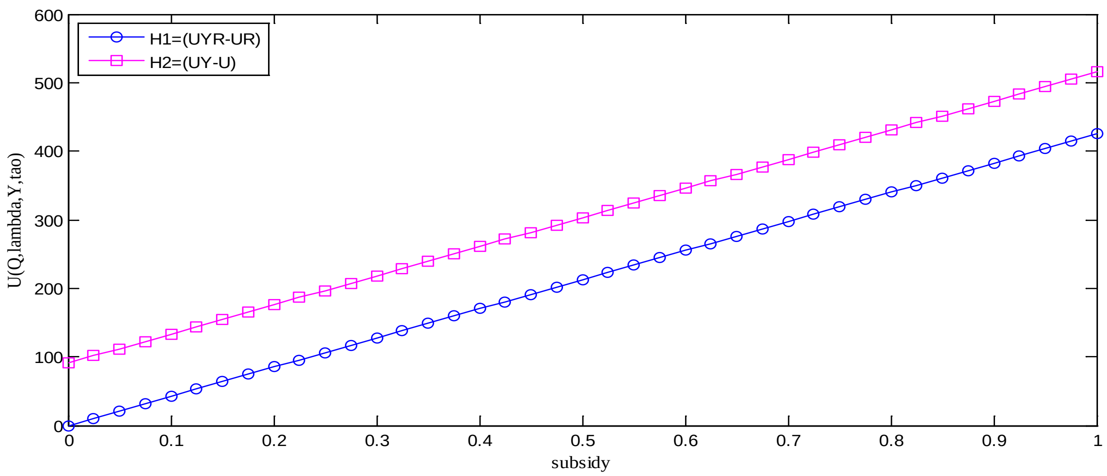

Figure 1– Expected utility differences under different subsidies

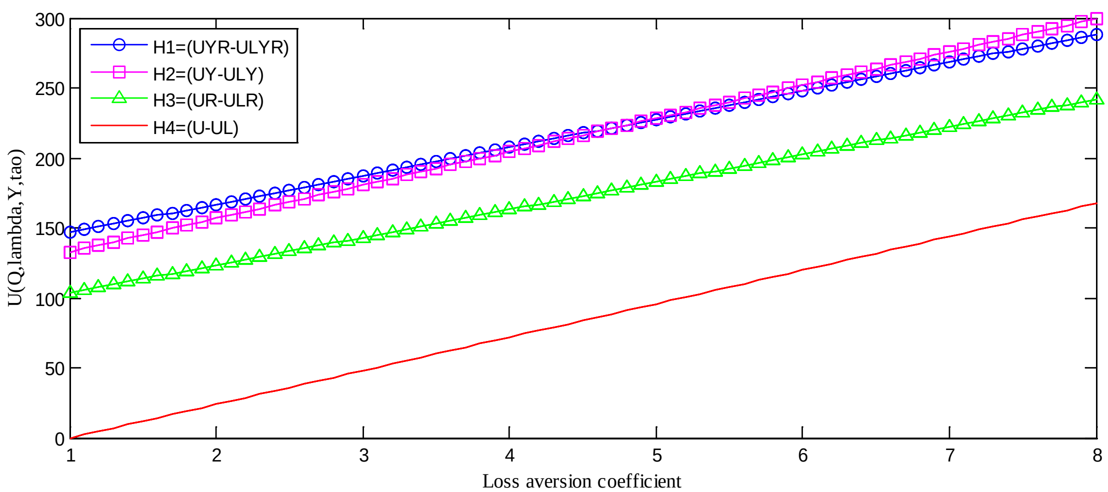

Figure 2– Expected utility differences under different loss aversion coefficients

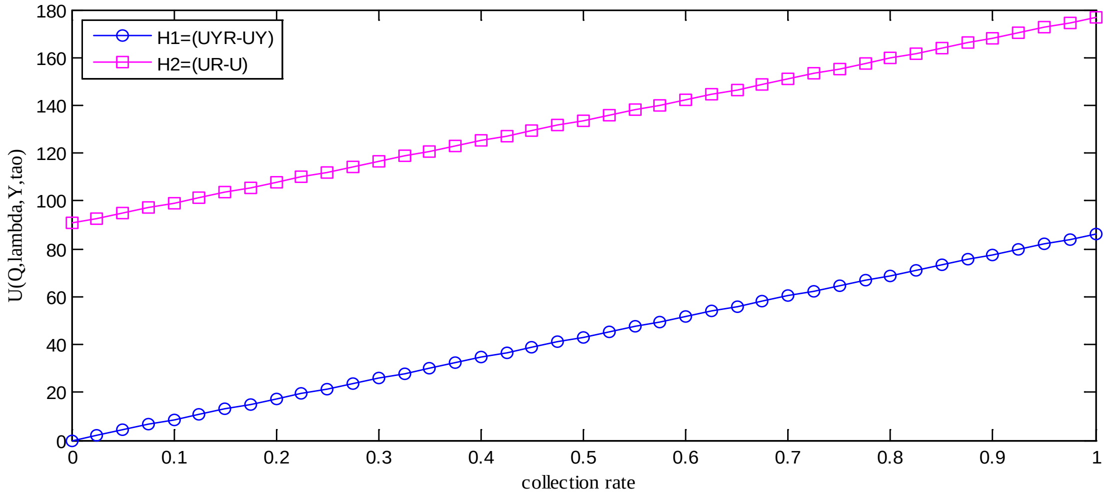

Figure 3–Expected utility differences under different collection rates

CONCLUSION

This paper extends previous loss-averse newsvendor model by incorporating both government subsidies and battery recycling to investigate how the optimal electric vehicle production strategy is influenced by loss aversion, subsidies, and battery recycling. We derived the analytical solutions for our model given the relevant constraints and performed different numerical experiments to evaluate the properties of the proposed model. The results demonstrate that loss aversion characteristics, subsidies, and battery recycling are important factors in determining the optimal production quantity and the expected utility of manufacturers. Particularly, the main findings are as follows. First, the optimal production quantity of a loss-averse decision maker is less than that of a risk neutral decision maker with the same subsidies and battery recycling. Second, the optimal production quantity of a loss-averse decision maker with subsidies and battery recycling is more than that of a risk neutral decision maker with subsidies. Finally, the optimal production quantity of a loss-averse decision maker with subsidies and battery recycling is more than that of a risk neutral decision maker with battery recycling.

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