Estimation of Vehicle Lifetime in the Used Car Market

by

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1. Introduction

Global warming has increasingly become a crucial problem and each country is required to take some measures for the climate mitigation. Focusing on the total CO_2 emissions in Japan in 2016, the automobile sector accounted for 15.4% of the total emission (Ministry of Land, Infrastructure, Transport and Tourism, 2017). Furthermore, the number of in-use cars in Japan has increased since 2012. In other words, the demands for automobiles have increased in recent years (Automobile Inspection and Registration Information Association, 2019). Hence, it is important to take measures in the automobile sector that make up a large proportion of the total amount of CO_2 emission in Japan and has a high possibility of market expansion.

The average *economic* lifetime of automobile (the number of years from a new car purchase to a car replacement) is 7 years according to the Motorcycle Market Trends in Japan in fiscal year 2017, but the coverage of the survey is only gasoline cars and not covered next-generation cars such as hybrid cars and electric cars (Japan Automobile Manufacturers Association, 2018). The number of gasoline car sales will have significantly decrease, while the demands of next-generation cars will have increase greatly by 2060 (IEA, 2017). For instance, Germany, France, and U.K. decided on a new policy to prohibit the sale of gasoline cars and diesel cars by 2030, 2040, and 2040, respectively. (Mitsui Global Strategic Studies Institute, 2018) In spite of these situations, there are only few studies about the life-cycle environmental impacts based on the economic vehicle lifetime of next-generation vehicles.

In Japan, the number of registration of used cars in 2017 was about 2.5 million, whereas the number of new car sales in 2017 were 4.4 million. Furthermore, the sales of used cars have yearly increased since 2015. This shows that used cars have gained in popularity in recent years and the importance of analyzing replacement cycle of next-generation cars that is expected to be distributed increasingly to the used car market.

In previous studies, it is revealed that vehicle lifetime extensions have a crucial role in the climate mitigation (Kagawa et al., 2011, 2008; Nishijima, 2017). Although the previous studies focused on a vehicle life-cycle from a new purchase to a disposal and used the *physical* vehicle lifetime (e.g., Weibull distribution), they did not consider *economic* vehicle lifetime with a focus of vehicle replacement cycle. Physical lifetime distributions have been applied in studies on material stock and flow analysis (e.g., Chen and Graedel, 2012; Nakamura et al., 2014; Pauliuk et al., 2017).

On the other hand, *economic* lifetime of vehicles determines the replacement behavior of consumers—that is, when consumers decide to replace their current vehicle by purchasing a new vehicle. To show the consumer replacement behavior for durable goods (e.g., for automobiles or household air conditioners) (Chevalier, 2005; Rapson, 2014; Rust, 1987) performed analyses that considers future expected cost, respectively. These kinds of analysis framework has a crucial role in the policymaking in relation to the product demand policy (Nakamoto and Kagawa, 2018), for example, estimated the impact of Japan's car inspection policy on lifecycle CO_2 emissions derived from cars and conclude that car owner's tend to avoid paying the high car inspection cost. However, they did not consider the vehicle replacement behavior of used car owners.

To address these issues, this study used the detailed micro data on vehicle replacements provided by the Car User Report 2017 (PROTO Corporation, 2017) and statistically estimated the *economic* vehicle lifetime with a focus of a vehicle life-cycle from a new or used car purchase to a car replacement. And then we estimated that the effect on the life-cycle analysis of next-generation vehicles and distribution in the used car market.

2. Methodology

In this study, we assume that the probability that car owners who possess new vehicles or used vehicle replace their car follows the Normal distribution or the Weibull distribution. Here we will describe each distribution. The probability that the cars purchased in year 0 replaced by year x is formulated as the Normal and the Weibull distribution function, respectively. The former is given by the following probability density function (PDF) and cumulative distribution function (CDF).

$$f(x)=\frac{1}{\sqrt{2\pi\sigma}}\exp\left\{-\frac{(x-\mu)^2}{2\sigma^2}\right\}\ (x\geq 0) \tag{1}$$

$$F(x)=\int_0^x f(y)dy=\int_0^x \frac{1}{\sqrt{2\pi\sigma}}\exp\left\{-\frac{(y-\mu)^2}{2\sigma^2}\right\}dy \quad (x\geq 0) \tag{2}$$

The PDF and CDF functions are given by

$$f(x)=\frac{\alpha}{\beta}\left(\frac{x}{\beta}\right)^{\alpha-1}\exp\left\{-\left(\frac{x}{\beta}\right)^{\alpha}\right\} \quad (x\geq 0) \tag{3}$$

$$F(x)=1-\exp\left\{-\left(\frac{y}{\beta}\right)^{\alpha}\right\} \quad (x\geq 0) \tag{4}$$

$$\lambda=\beta\boldsymbol{\Gamma}(1+1/\alpha) \tag{5}$$

respectively, where μ is the average of the normal distribution, σ^2 is the variance of the normal distribution, α is the shape parameter of the Weibull distribution, β is the scale parameter of the Weibull distribution, and $\boldsymbol{\Gamma}$ is the gamma function. (1) and (3) enable us to analyze replacement behavior of new car owners or used car owners. λ is the average of the Weibull distribution. The possibility that the cars purchased in year 0 is possessed until year x (i.e., cumulative survival probability) is given by $\varphi(x)=1-F(x)$. Here $\varphi(0)=1$ shows that the cars purchased in year 0 is all possessed at the same year.

We identify the probability of vehicle replacement by using replacement data. Specifically, we estimate the parameters of the Normal distribution and the Weibull distribution by a maximum likelihood method. Each of the log-likelihood function of this study can be formulated as follows.

$$L^N(\mu,\sigma)=\sum_{i=1}^{n}\left\{u\{X_i\le\gamma\}\log f(X_i;\mu,\sigma)+u\{X_i>\gamma\}\log\varphi(\gamma;\mu,\sigma)\right\} \quad (6)$$

$$L^w(\alpha,\beta)=\sum_{i=1}^{n}\left\{u\{X_i\le\gamma\}\log f(X_i;\alpha,\beta)+u\{X_i>\gamma\}\log\varphi(\gamma;\alpha,\beta)\right\} \quad (7)$$

Here, u represents the number of people who replaced their vehicle in the reference year, f represents the Weibull probability density function, X_i represents vehicle age at a point of replacement $(i=0.5,1.5,...,9.5)$, and $\gamma=10.5$. In this study, we assume that replacement is conducted at the middle of the reference year, i.e., consider the vehicles replaced in less than 1 year as being replaced in 0.5 year.

3. Data

This study used the vehicle database of Car User Report 2017 provided by the PROTO CORPORATION. The Car User Report 2017 focused on a wide variety of vehicle types of conventional gasoline vehicle, diesel vehicle, hybrid vehicle, plug-in hybrid vehicle, electric vehicle, and fuel cell vehicle and presented the information on how long car owners held their new cars after new car registrations. The report also describes how long car owners held their used cars after car re-registrations. We focused 932 drivers who owned new cars and released them to the second-hand market and 3221 drivers who owned used cars and similarly released them to the second-hand market. The service life for individual conventional gasoline vehicles was used to estimate the average economic lifetime of new and used vehicles, respectively. The other types of the vehicles were excluded in the lifetime analysis due to the small sample size.

4. Results

In this study, we focused on conventional gasoline vehicles purchased in Japan and estimated the probability that car owners replace older vehicles with newer vehicles over time. Table 1 shows the parameters of the probability density functions of Weibull distribution and Normal distribution estimated through the maximum likelihood method presented in previous section. From Table 1, we can analyze how long new and used cars could survive after an initial car registration.

The estimated two parameters (i.e., scale parameter and shape parameter) of the Weibull distribution for new vehicles were 11.6 and 1.9, respectively, whereas those parameters for secondhand cars were 5.48 and 2.06, respectively (Table 1). Similarly, the estimated two parameters (i.e., mean and standard deviation) of the Normal distribution for new vehicles were 9.57 and 4.4, respectively, whereas those parameters for used cars were 4.86 and 2.47, respectively (Table 1). Importantly, two different kinds of the probability distributions make a difference in economic lifetime of vehicles.

The economic lifetime for the new cars was estimated at 9.57 years under the Normal distribution, whereas the Weibull distribution provides a different value of the economic lifetime for the new cars, 10.29 years (Table 1). A crucial problem is which probability distribution is statistically supported. It is well-known that we can compare the relative quality of different statistical models using the Akaike's information criterion (i.e., AIC value) defined as $AIC = 2K - 2\tilde{L}$ where K is the number of parameters included in the statistical model and $\tilde{L}$ is the maximum log-likelihood estimated from the data. We assert that the model with relatively-smaller AIC value has a better quality.

From the results for new cars, the AIC value of the Normal distribution (-3703.42) is smaller than that of the Weibull distribution (-3657.54), therefore the Normal distribution is supported statistically. Consequently, the average economic lifetime of the new cars can be 9.57 years under the statistically-supported Normal distribution. Similarly, the Normal distribution for used cars is also supported statistically. The average economic lifetime of the used cars can be 4.86 years. In other words, car owners who purchased new cars, decided to sell their vintage cars to the second-hand market after 9.57 years on average. Car owners who purchased used cars, decided to sell their vintage cars more quickly than car owners who purchased new cars.

Figure 1 depicts the replacement probability functions of the Normal and Weibull distributions for new cars. It should be noted that the estimated parameters in Table 1 were used to obtain Figure 1. The replacement probability function for the new cars has the highest value of 9% at 10 years (see normal density function in Figure 1). Furthermore, looking at the cumulative survival rate easily obtained by the replacement distribution function (Figure 2), we found that only 43% of the new cars survives after 10 years from their initial car registrations, whereas 57% of them flows to the second-hand market. Only 2.4% of the used cars survives after 10 years from their car re-registrations, whereas 97.6% of them flows to the second-hand market again. Figure 3 also depicts the replacement probability functions of the Normal and Weibull distributions for used cars. The replacement probability function for the used cars shows the highest value of 16% at 5 years (see normal density function in Figure 3). Thus, the replacement cycle for the used cars is much faster than that of the new cars (Figure 2).

5. Conclusion

This study estimated the replacement probability density functions of new and used cars using the survey database for car owners and calculated the average 'economic' lifetime of the new and used cars, respectively. The major findings are twofold.

The statistical test using the AIC supports normal distribution of the replacement probability for both new and used cars than Weibull distribution widely used in the physical product lifetime analysis. This finding asserts that researchers should employ the normal distribution in order to model the economic life in service of vehicles

We also found that the average economic lifetime of the used cars can be 4.86 years. In other words, car owners who purchased new cars, decided to sell their vintage cars to the second-hand market after 4.86 years on average. Car owners who purchased new cars, decided to sell their vintage cars to the second-hand market after 9.57 years on average. Thus, car owners who purchased used cars, decided to sell their vintage cars more quickly at double the speed of replacement cycle than car owners who purchased new cars.

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Table 1. Estimated parameters of the replacement probability functions for new and used cars

	New car		Used car	
Distribution	Normal	Weibull	Normal	Weibull
Scale paremeter		11.60		5.48
Shape paremeter		1.90		2.06
Mean	9.57	10.29	4.86	4.86
S.D.	4.49	5.64	2.47	2.48
Log likelihood	-1853.71	-1830.77	-8463.60	-8061.17
	Number of obs.=932		Number of obs.=3221	

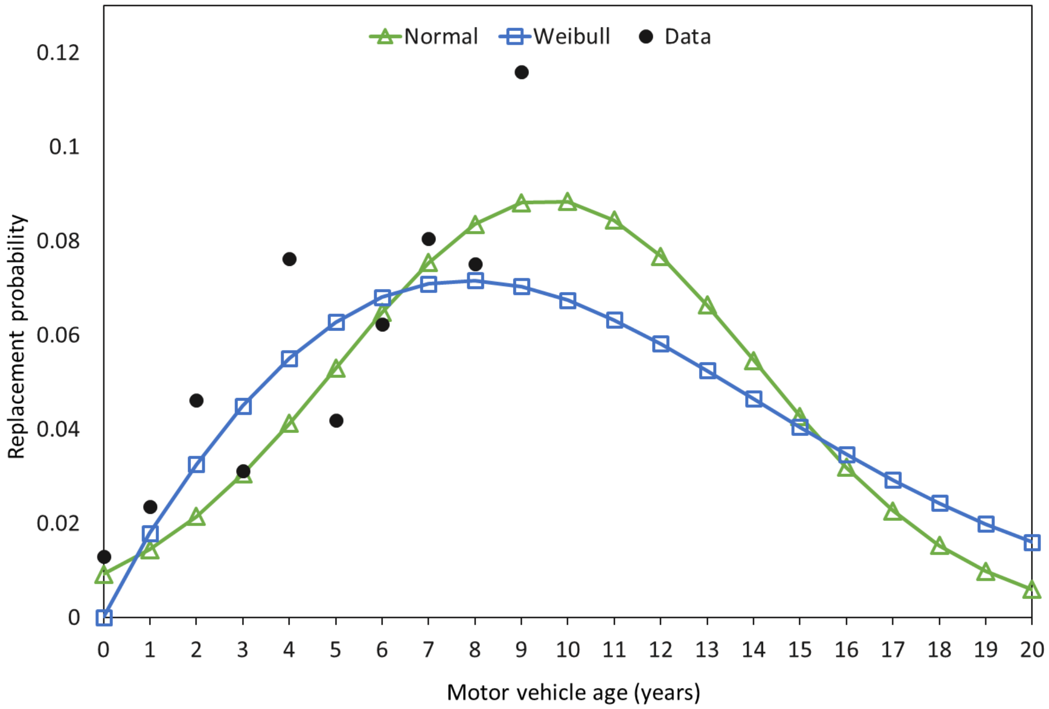

Figure 1. Replacement probability density functions for new cars

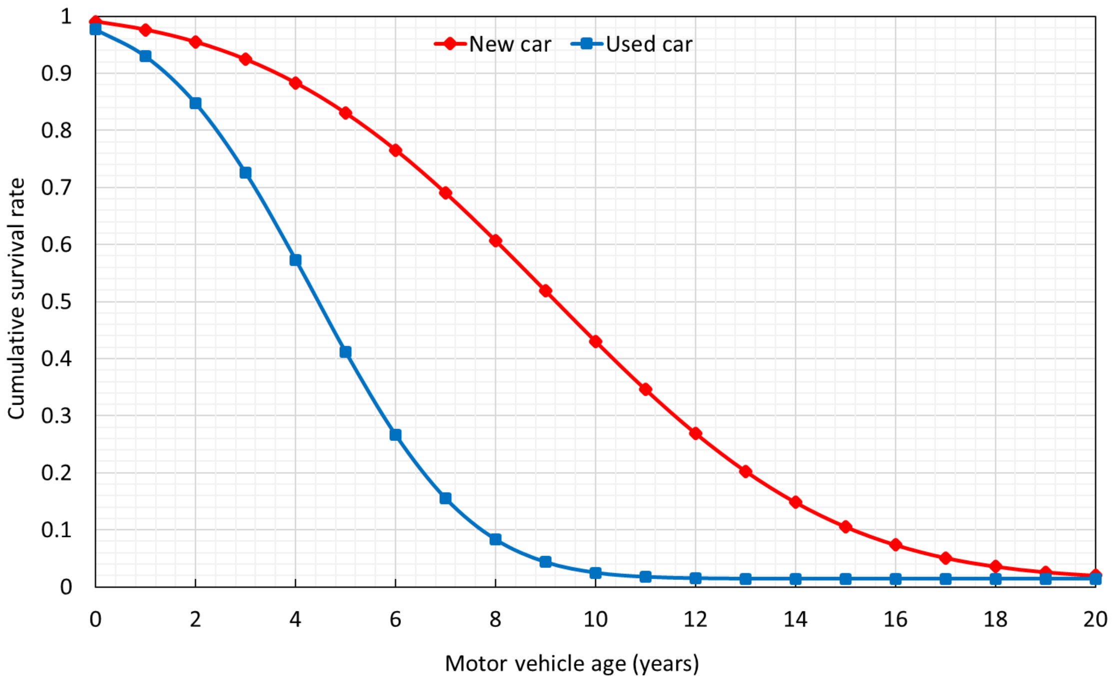

Figure 2. Cumulative distribution functions (i.e., normal distribution functions) for new and used cars

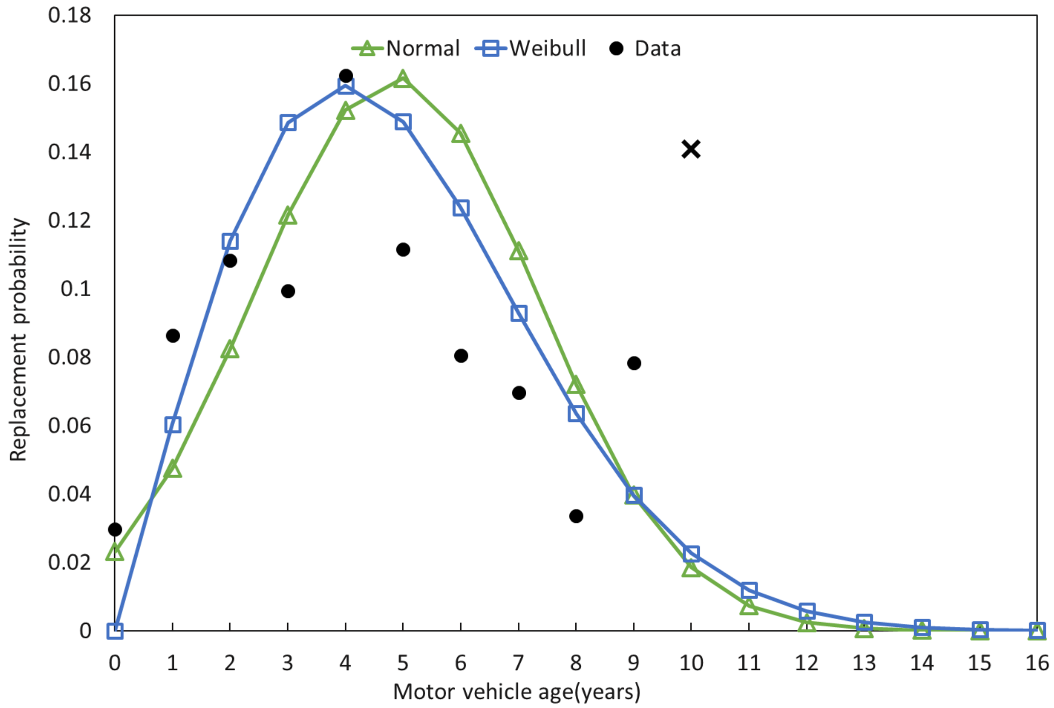

Figure 3. Replacement probability density functions for used cars