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CO_2 reduction potentials through the market expansion and lifetime extension of used cars

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Abstract

This study develops an automobile life-cycle analysis framework considering lifetimes of new and used passenger cars. Using the analysis framework based on the Weibull survival distributions of new and used cars, I addressed the question of how the market expansion and lifetime extension of used cars affect life-cycle CO_2 emissions through the entire economy. The results show the following.Under the benchmark lifetime function, a 10% increase in the market share of used cars under benchmark average new vehicle lifetime of 11.50 years yields 16.9 million tons of CO_2 reduction in the cumulated life-cycle CO_2 emissions during 1993–2014. I further found that a combined policy of vehicle lifetime extension and market expansion of "used" cars can contribute toward a low-carbon transition society. I conclude that modifying the demand policy with a focus on "used" cars with higher fuel efficiency, as well as setting a target car age of used cars, would be environmentally beneficial.

Keywords: Passenger cars, Used car, Weibull survival distribution, Car replacement, Life-cycle CO_2

1 Background

Global warming has been getting more serious and made many countries consider measures for reducing CO_2 emissions (IPCC 2015). For this reason, global warming is an urgent issue to address through effective CO_2 emission reduction policies. Considering global CO_2 emissions in 2013 by sector, the second largest volume comes from the transportation sector, which accounts for 23% of the global CO_2 emissions. Because of a continued large contribution by the transportation sector, Melaina and Webster (2011) performed an analysis on the light vehicle sector in the USA and proposed practical measures for achieving CO_2 reduction targets. In Japan, the transportation sector generated 17% of the total amount of CO_2 emissions in 2012 (Ministry of Land, Infrastructure, Transport and Tourism; MLIT 2013), which marks an 4% increase during 1990–2012, due to the increase in the transportation volume of passenger cars (Ministry of the Environment 2014).

The market expansion of new and used passenger cars also affects the environment, because expanding the market of new passenger cars with relatively high fuel efficiencies (km/l) contributes to reducing CO_2 emissions during the driving phase, whereas it increases CO_2 emissions in the car manufacturing phase (Kagawa et al. 2011). An important point is that expanding the market of used cars with relatively low fuel efficiencies conversely contributes to increasing CO_2 emissions in the driving phase, whereas zero emission is achieved the car manufacturing phase. Regarding the use of used products, Curran (2010) showed that extending product life spans through the reuse of furniture and appliances in the UK has an effect on reducing waste and raw materials. There are two relevant previous studies on life-cycle emissions in the driving phase that include the impact of the fuel efficiencies of motor vehicles and their annual travel distance: Ou et al. (2010) and Pauliuk et al. (2012).

In Japan, the number of used car registrations in 2014 was 3.28 million, whereas new car registrations in the same year were 4.70 million (JADA: Japan Automobile Dealers Association 2015). This shows that the used car market has a strong influence on the current Japanese car market (JADA 2015). The number of used car registrations increased at an annual growth rate of 3% during 1990–2014 (Japan Light Motor Vehicle and Motorcycle Association 2015), and the market share of used cars increased 1.2-fold during the same period (JADA 2015). According to MLIT (2014), the average price of a used car in Japan is approximately ¥1 million, which is almost the same as in the USA and UK. However, the sizes of the used car market in the USA and UK are ¥33 trillion and ¥7 trillion, respectively, whereas the size of the market in Japan is ¥2.2 trillion. The numbers of used cars sold annually in the USA and UK in 2014 were 40.5 million and 7.1 million, respectively (National Independent Automobile Dealers Association 2014; British Car Auctions 2013), whereas 2.15 million used cars were sold in Japan, again being lower. The main reason for such differences in the used car markets between Japan, the USA, and UK is that consumers in the West can obtain more trustworthy information about vehicles, such as their maintenance and repair histories. Japan plans to adopt a traceability system by 2020 (MLIT 2014). However, it is not clear how much influence the expansion of the market share of used cars has had on the life-cycle CO_2 emissions from the passenger car sector.

In 2009, the Japanese government introduced a vehicle replacement scheme for the replacement of older cars with lower fuel efficiencies by new cars with higher fuel efficiencies in an attempt to reduce CO_2 emissions from the transportation sector (Ministry of Economy, Trade and Industry, Japan 2016). With this background, Kagawa et al. (2013) proposed an environmental impact assessment method for assessing the effectiveness of scrappage schemes for reducing CO_2 emissions through the entire life cycle of passenger cars. Lenski et al. (2010) had previously estimated the environmental benefits of introducing the “cash-for-clunkers” policy in the USA in 2009. However, since the assessment frameworks at that time (Lenski et al. 2010; Kagawa et al. 2011, 2013) did not consider vehicle lifetimes and the market for “used cars,” they ignored the environmental impacts of re-registering older cars as used cars. Before I analyze CO_2 emissions in the automobile sector, I considered vehicle lifetimes in line with Kagawa et al. (2006), Müller (2006), Murakami et al. (2010), and Oguchi et al. (2010). The lifetime distributions also play an important role in material stock and flow analysis (Nakamura et al. 2014; Pauliuk et al. 2017). In this context, the lifetime distribution analysis has been applied in a wide range of durable goods or material such as personal computers (Babbitt et al. 2009), air conditioner (Rapson 2014), and buildings (Nomura and Momose 2008).

This study considers the vehicle lifetimes and markets of both new and used cars and develops an automobile life-cycle input–output framework that considers the lifetimes and market shares of used cars. I used the car sales data during 1993–2014 (JADA 2015), a 2005 environmental input–output table (National Institute for Environmental Studies 2010), and the vehicle lifetime density function estimated by Kagawa et al. (2011). By applying the data sets to a life-cycle assessment framework proposed in this study, I address the question of how market expansion and lifetime extension of used cars affect life-cycle CO_2 emissions through the entire economy. From the results, this study examines whether introducing a demand policy with a focus on used cars would increase environmental benefits.

The remainder of this paper is organized as follows: Sect. 2 explains the methodology, Sect. 3 describes the data, Sect. 4 presents the results and discussion, and finally Sect. 5 gives conclusions, including further policy implications.

2 Methods

2.1 Lifetime function for new and used cars

As a case study, I focused on cars newly registered during 1993–2014, both those that remained with their original owners (new cars) and those that were re-registered after being de-registered (used cars). Firstly, this study models the scrappage rate of new passenger cars as a probability density function (namely a Weibull density function). The cumulative scrappage rate in terms of total original cars of a vintage for new cars that are registered in year 0 and de-registered in year t follows the Weibull distribution function described by Eq. (1) (e.g., Kagawa et al. 2011; McCool 2012; Oguchi and Fuse 2014).

$$F(t) = 1 - \exp\left\{-\left(\frac{t}{\eta}\right)^{m}\right\} \quad (t \geq 0)\,, \tag{1}$$

$$\mu = \eta\Gamma(1 + 1/m). \tag{2}$$

Here, m represents a shape parameter and η represents a scale parameter. μ in Eq. (2) represents average vehicle lifetime derived from the Weibull distribution function, and Γ in Eq. (2) is the gamma function. The cumulative survival rate at year t for new cars purchased at year 0 is also easily obtainable as $\phi_n(t) = 1 - F(t)$. It should be noted that we have $\phi_n(0) = 1$; in other words, all new cars purchased in year 0 survive in year 0.

Although we can estimate the number of cars “de-registered” after year 0 by using Eq. (1), we still cannot estimate the number of used cars re-registered after the car de-registrations. It is important to note that using Eq. (1), the cumulative survival rate of the used cars that were newly registered at year 0 and survive at year t after re-registration at year τ, $\phi_u(t, \tau)$, can be modeled and estimated through the following discretization.

$$\varphi_u(t,\tau) = \frac{\int_t^{\infty} f(s)\,\mathrm{d}s}{\int_\tau^{\infty} f(s)\,\mathrm{d}s} \approx \frac{1 - F(t)}{1 - F(\tau)} \quad (\tau < t), \tag{3}$$

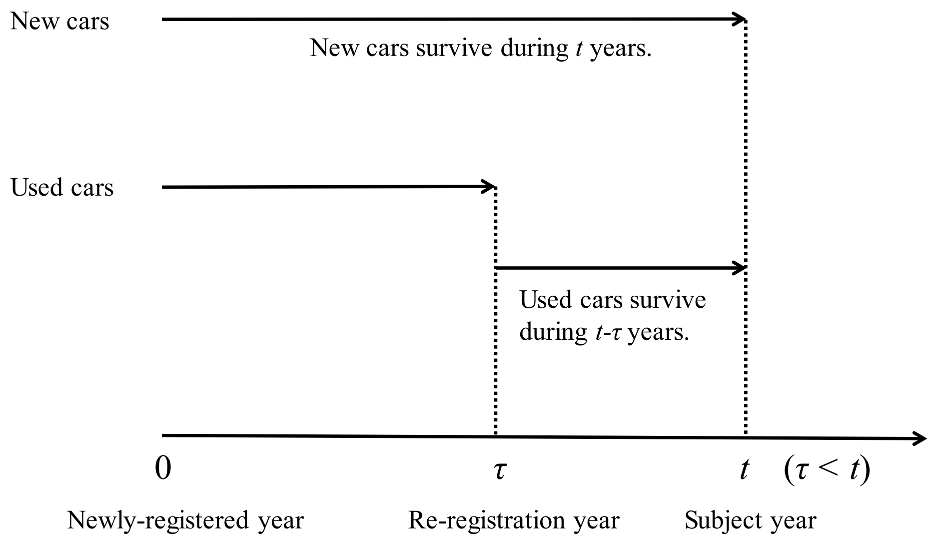

Fig. 1 Concept of the time variables in this study

where $f(s)$ denotes the Weibull probability density function of years for new cars purchased at year 0. Note that used cars survive during $t - \tau$ years whereas new cars survive during t years. The concept of the time variables in this study is described in Fig. 1.

The stock of passenger cars at year t, $S(t)$, can be estimated using Eq. (4).

$$S(t) = S_{\mathrm{n}}(t) + S_{\mathrm{u}}(t). \tag{4}$$

Here, $S_{\mathrm{n}}(t)$ and $S_{\mathrm{u}}(t)$ represent the stock of new passenger cars at year t and the stock of used cars at year t, respectively. Using the survival rates of new and used cars, the stock of new passenger cars and the stock of used cars also can be formulated, respectively, as follows:

$$S_{\mathrm{n}}(t) = B_{\mathrm{n}}(t) + \sum_{i=1}^{t-1} \varphi_{\mathrm{n}}(t-1)B_{\mathrm{n}}(i), \tag{5}$$

$$S_{\mathrm{u}}(t) = B_{\mathrm{u}}(t) + \sum_{i=1}^{t-2} \sum_{\tau=i+1}^{t-1} \varphi_{\mathrm{u}}(t-i, \tau-i)B_{\mathrm{u}}(\tau) \quad (i < \tau < t), \tag{6}$$

where $B_{\mathrm{n}}(t)$ and $B_{\mathrm{u}}(t)$ represent the numbers of new and used cars purchased at year t, respectively, $\phi_{\mathrm{n}}(t - i)$ is the survival rate for new cars in year t that are newly registered in year i, and $\phi_{\mathrm{u}}(t - i, \tau - i)$ is the survival rate for used cars that are newly registered in year i and survive at year t after re-registration at year τ. Nishijima (2016) applied this same stock dynamics model to estimate the number of new residential air conditioners sold.

Substituting Eqs. (5) and (6) into the right-hand side of Eq. (4) yields the following stock dynamic equation for new and used passenger cars.

$$\begin{aligned} S(t) &= S_{\mathrm{n}}(t) + S_{\mathrm{u}}(t) \\ &= B_{\mathrm{n}}(t) + B_{\mathrm{u}}(t) + \sum_{i=1}^{t-1} \varphi_{\mathrm{n}}(t-i) B_{\mathrm{n}}(i) \\ &\quad + \sum_{i=1}^{t-2} \sum_{\tau=i+1}^{t-1} \varphi_{\mathrm{u}}(t-i, \tau-i) B_{\mathrm{u}}(\tau). \end{aligned} \tag{7}$$

Here I explain how to solve the stock dynamic equation by assuming that passenger cars are newly registered at year 1 (i.e., $i = 1$ in Eqs. 5, 6). In addition, I assume that all new passenger cars are following the same lifetime distribution, irrespective of their vintage. Noting that no used cars at initial year 1 exist and hence $B_{\mathrm{u}}(1) = 0$, we have the following dynamic system of equations. It should be noted that when $t = 3$, $\tau = 2$, and $i = 1$, we have $\phi_{\mathrm{u}}(t - i, \tau - i) = \phi_{\mathrm{u}}(3 - 1, 2 - 1) = \phi_{\mathrm{u}}(2, 1)$. Here, $\phi_{\mathrm{u}}(2, 1)$ is the survival rate for used cars that are newly registered at year 1 and survive at year 3 after re-registration at year 2.

$$\begin{cases} S(1) = B_{\mathrm{n}}(1) + B_{\mathrm{u}}(1) = B_{\mathrm{n}}(1) \\ S(2) = B_{\mathrm{n}}(2) + B_{\mathrm{u}}(2) + \varphi_{\mathrm{n}}(1) B_{\mathrm{n}}(1) \\ S(3) = B_{\mathrm{n}}(3) + B_{\mathrm{u}}(3) + \varphi_{\mathrm{n}}(1) B_{\mathrm{n}}(2) + \varphi_{\mathrm{u}}(2,1) B_{\mathrm{u}}(2) + \varphi_{\mathrm{n}}(2) B_{\mathrm{n}}(1) \\ \vdots \end{cases}. \tag{8}$$

In this study, the stock of passenger cars in each year, $S(t)$, is taken to be steady state. Then, when the stock of passenger cars at steady state is given as S', the number of new passenger cars sold and used passenger cars re-registered can be estimated sequentially as follows:

$$\begin{cases} B_{\mathrm{n}}(1) = S'(1) \\ B_{\mathrm{n}}(2) + B_{\mathrm{u}}(2) = S'(2) - \varphi_{\mathrm{n}}(1) B_{\mathrm{n}}(1) \\ B_{\mathrm{n}}(3) + B_{\mathrm{u}}(3) = S'(3) - \varphi_{\mathrm{n}}(1) B_{\mathrm{n}}(2) - \varphi_{\mathrm{u}}(2,1) B_{\mathrm{u}}(2) - \varphi_{\mathrm{n}}(2) B_{\mathrm{n}}(1) \\ \vdots \end{cases}. \tag{9}$$

In Eq. (9), the total of new and used cars sold at year 2 can be estimated by $S' - \phi_{\mathrm{n}}(1)B_{\mathrm{n}}(1)$ (see the second equation in Eq. 9); however, the total of new and used cars sold at year 3 cannot be determined endogenously, because the second and third terms on the right-hand side of the third equation in Eq. (9) are unknown. Therefore, I here define and introduce a parameter for the "revival" rate of used cars (which is the ratio of used cars to the total number of sold cars) as θ; then, the number of new and used cars at each year can be calculated as shown in Eq. (10).

$$\begin{cases} B_{\mathrm{n}}(1) = S'(1) \\ B(2) = B_{\mathrm{n}}(2) + B_{\mathrm{u}}(2) = S'(2) - \varphi_{\mathrm{n}}(1) B_{\mathrm{n}}(1) = (1-\theta) B(2) + \theta B(2) \\ B(3) = B_{\mathrm{n}}(3) + B_{\mathrm{u}}(3) = S'(3) - \varphi_{\mathrm{n}}(1)(1-\theta) B(2) - \varphi_{\mathrm{u}}(2,1) \theta B(2) - \varphi_{\mathrm{n}}(2) B_{\mathrm{n}}(1) \\ \vdots \end{cases}, \tag{10}$$

where $B_{\mathrm{n}}(2) = (1 - \theta)B(2)$ and $B_{\mathrm{u}}(2) = \theta B(2)$ represent the number of cars newly registered at year 2 and the number of used cars re-registered at year 2, respectively. Thus, we can estimate the number of new cars and used cars sold over time as $B_{\mathrm{n}}(t)$ ($t = 1, 2, \ldots$) and $B_{\mathrm{u}}(t)$ ($t = 1, 2, \ldots$), respectively.

The number of the used cars that are newly registered in year i and surviving at year t after re-registration at year τ can also be obtained as Eq. (11).

$$H_{\mathrm{u}}(i,t-i)=\sum_{\tau=i+1}^{t-1}\varphi_{\mathrm{u}}(t-i,\tau-i)B_{\mathrm{u}}(\tau)\quad(i<\tau<t). \tag{11}$$

As a result, the number of the re-registered used cars of all vintages surviving at year t is

$$G_{\mathrm{u}}(t)=\sum_{i=1}^{t-2}\sum_{\tau=i+1}^{t-1}\varphi_{\mathrm{u}}(t-i,\tau-i)B_{\mathrm{u}}(\tau)=\sum_{i=1}^{t-2}H_{\mathrm{u}}(i,t-i). \tag{12}$$

Similarly, the number of new cars of all vintages surviving at year t is calculated as

$$G_{\mathrm{n}}(t)=\sum_{i=1}^{t-1}\varphi_{\mathrm{n}}(t-i)B_{\mathrm{n}}(i)=\sum_{i=1}^{t-1}H_{\mathrm{n}}(i,t-i). \tag{13}$$

By using Eq. (11), the numbers of the used cars and new cars of all vintages that are disposed of at year t are formulated, respectively, as

$$D_{\mathrm{u}}(t)=\sum_{i=1}^{t-2}\sum_{\tau=i+1}^{t-1}(1-\varphi_{\mathrm{u}}(t-i,\tau-i))B_{\mathrm{u}}(\tau), \tag{14}$$

$$D_{\mathrm{n}}(t)=\sum_{i=1}^{t-1}(1-\varphi_{\mathrm{n}}(t-i))B_{\mathrm{n}}(i). \tag{15}$$

From Eqs. (14) and (15), the total number of cars disposed of at year t is computed as $D(t)=D_{\mathrm{n}}(t)+D_{\mathrm{u}}(t)$.

2.2 Life-cycle CO_2 emissions of new and used cars

Defining the average fuel efficiency of an s vintage passenger car and its annual driving distance as $e(s)$ (km/l) and $d(s)$ (km), respectively, the gasoline consumption (liters) required to drive the passenger car for 1 year can be found by dividing the annual driving distance by the average fuel efficiency.

$$g(s)=\frac{d(s)}{e(s)}. \tag{16}$$

The direct CO_2 emissions of a passenger car associated with car driving are calculated by multiplying the gasoline consumption (liters) in Eq. (16) by the direct CO_2 emission intensity (i.e., direct CO_2 generated per unit of gasoline combustion on the road), r_{g} (t CO_2/l) as follows:

$$f_{\mathrm{g}}^{\mathrm{direct}}(s)=g(s)r_{\mathrm{g}}=\frac{d(s)}{e(s)}r_{\mathrm{g}}. \tag{17}$$

The indirect CO_2 emissions of a passenger car associated with car driving are also estimated by multiplying the gasoline consumption (liters) in Eq. (16) by indirect CO_2 emission intensity (i.e., indirect CO_2 generated per unit of gasoline production), r_c ($t\ CO_2/l$), as follows:

$$f_g^{\text{indirect}}(s) = g(s)r_c = \frac{d(s)}{e(s)}r_c. \tag{18}$$

Summing Eqs. (17) and (18) yields the direct and indirect emissions (i.e., life-cycle emissions) in the driving phase, formulated as follows:

$$f_g(s) = f_g^{\text{direct}}(s) + f_g^{\text{indirect}}(s). \tag{19}$$

The life-cycle CO_2 emissions of new and used cars registered at year t can finally be formulated as follows:

$$\begin{aligned} q(t) = &f_m B_n(t) + f_w D(t) + f_g(t) B_n(t) \\ &+ \sum_{s=1}^{t-1} f_g(s) H_n(s, t-s) + \sum_{s=1}^{t-2} f_g(s) H_u(s, t-s), \end{aligned} \tag{20}$$

where f_m represents the life-cycle CO_2 emission intensity for producing a new passenger car, f_w the life-cycle CO_2 emission intensity for scrapping an end-of-life passenger car, and $f_g(s)$ ($s = 0, 1, \ldots, T$) the life-cycle CO_2 emission intensity for driving an s vintage passenger. Accordingly, the first term on the right-hand side of Eq. (20) denotes the life-cycle CO_2 emissions in the pre-consumer phase, the second term the life-cycle CO_2 emissions in the scrapping phase of end-of-life passenger cars, the third term the life-cycle CO_2 emissions in the driving phase of passenger cars newly registered at year t, the fourth term the life-cycle CO_2 emissions in the driving phase of new cars registered during year 1 to year $t-1$, and the last term the life-cycle CO_2 emissions in the driving phase of used cars that newly registered and re-registered during year 1 to year $t-1$. It should be noted that the emissions in the driving phase of used cars (i.e., last term in Eq. 20) are affected by the emission intensity at driving phase of vintage cars that survived at year $t, f_g(s)$. The emission intensity at driving phase of vintage cars is assumed to be same with the emission intensity at newly registered year. In this study, life-cycle CO_2 emissions indirectly caused by selling used cars such as CO_2 emissions associated with transport, repair, and maintenance for used cars were neglected. The detailed life-cycle analysis of use cars is future study.

3 Data

In this study, I focused on passenger cars newly registered during 1993–2014. The dynamic analysis framework developed in the previous section was applied to the passenger cars newly registered in Japan during 1993–2014. The parameter settings and data sources for this case study are listed in Table 1. As in Kagawa et al. (2011), I focus herein on an ordinary passenger car with an internal combustion engine larger than 661 cc that was newly registered during 1993–2014. The two parameters, m and η, of the Weibull density function for ordinary passenger cars are set as 12.86 and 3.07,

Table 1 Parameter settings used in this analysis

Equation	Variable and parameter settings				Data source
Equation (1)	$m = 12.86$				Kagawa et al. (2011)
Equation (1)	$\eta = 3.07$				Kagawa et al. (2011)
Equation (16)	Vintage (s)	d (s)	e (s)	f_g (s)	
	1993	9989 (km)	12.3 (km/l)	2.387 (t CO_2-eq./car)	Ministry of Land, Infrastructure, Transport and Tourism, Japan (Japan 2015)
	1994	9890 (km)	12.3 (km/l)	2.363 (t CO_2-eq./car)	
	1995	9948 (km)	12.2 (km/l)	2.397 (t CO_2-eq./car)	
	1996	9916 (km)	12.3 (km/l)	2.370 (t CO_2-eq./car)	
	1997	9902 (km)	12.1 (km/l)	2.406 (t CO_2-eq./car)	
	1998	9835 (km)	12.4 (km/l)	2.331 (t CO_2-eq./car)	
	1999	10,037 (km)	12.9 (km/l)	2.287 (t CO_2-eq./car)	
	2000	9956 (km)	13.2 (km/l)	2.217 (t CO_2-eq./car)	
	2001	10,176 (km)	13.5 (km/l)	2.216 (t CO_2-eq./car)	
	2002	10,057 (km)	14.0 (km/l)	2.111 (t CO_2-eq./car)	
	2003	9915 (km)	14.6 (km/l)	1.996 (t CO_2-eq./car)	
	2004	9675 (km)	14.7 (km/l)	1.934 (t CO_2-eq./car)	
	2005	9411 (km)	15.0 (km/l)	1.844 (t CO_2-eq./car)	
	2006	9240 (km)	15.1 (km/l)	1.798 (t CO_2-eq./car)	
	2007	9253 (km)	15.5 (km/l)	1.755 (t CO_2-eq./car)	
	2008	9026 (km)	15.7 (km/l)	1.690 (t CO_2-eq./car)	
	2009	9127 (km)	16.5 (km/l)	1.626 (t CO_2-eq./car)	
	2010	8191 (km)	17.8 (km/l)	1.352 (t CO_2-eq./car)	
	2011	8403 (km)	18.3 (km/l)	1.349 (t CO_2-eq./car)	
	2012	8805 (km)	19.5 (km/l)	1.327 (t CO_2-eq./car)	
	2013	8953 (km)	21.1 (km/l)	1.247 (t CO_2-eq./car)	
	2014	9240 (km)	21.1 (km/l)	1.287 (t CO_2-eq./car)	
Equation (17)	$r_g = 0.00231$ (t CO_2-eq./l)				National Institute for Environmental Studies, Japan (2010)
Equation (18)	$r_c = 0.00063$ (t CO_2-eq./l)				National Institute for Environmental Studies, Japan (2010)
Equation (20)	$f_m = 6.426$ (t CO_2-eq./car)				National Institute for Environmental Studies, Japan (2010)
Equation (20)	$f_w = 0.057$ (t CO_2-eq./car)				National Institute for Environmental Studies, Japan (2010)

respectively (Table 1). I calculated the revival rate (which is the ratio of used cars to the total number of sold cars) from the JADA (2015) which describes the number of used car registrations and the number of new passenger cars sold in 2014. As a result, I took 0.4 for a benchmark value of the revival rate.

4 Results and discussion

4.1 Survival distributions of new and used cars

I now present the results of applying the method proposed in the previous section and discuss the role of passenger vehicle lifetime change and market expansion of used cars in CO_2 emission reduction policies. Using the two parameters, I can specify the lifetime distributions for cars newly registered during 1993–2014 and for used cars re-registered during the same period. In addition, as in Kagawa et al. (2011), I assumed that the lifetime functions for cars newly registered during 1993–2014 were all the same. Using the specified lifetime functions of new cars, I firstly estimated the survival rate of the used cars that are newly purchased at year 0 and survive at year t after re-registration at year τ, $\phi_u(t, \tau)$, using Eq. (3). The results are plotted in Fig. 2. We see that, for example, the cumulative survival rate of the used cars that are newly purchased in year 0 (i.e., year 1993 in this study) and survive 3 years after re-registration at year 3 (i.e., year 1998) can be estimated as 0.83 and this survival rate of used cars after 3 years is lower than that of new cars after 3 years (Fig. 2). Thus, as a used car ages, its survival rate will rapidly decrease over time.

4.2 Passenger car stock associated with vehicle lifetime changes

In this study, the stock of cars (number of vehicles owned) in each year is taken to be steady state during 1993–2014 even if the average lifetime of passenger cars changes, as shown in Eq. (9). Figure 3 shows the numbers of vehicles owned (one million vehicles) in 2014 for older cars newly registered and used cars re-registered during 1993–2014, as well as new cars newly registered in 2014, for a ±5-year change from the baseline lifetime (11.5 years) that represents the average lifetime of passenger cars. In Fig. 3, the numbers of vehicles owned of cars registered and used cars re-registered in the period of analysis from 1993 to 2014, covering 22 years, are shown in terms of four subperiods: 1993–1999, 2000–2006, 2007–2013, and 2014.

As Fig. 3 shows, holding the total number of vehicles owned (stock) fixed, changes in the average lifetime affect the proportions of new cars, older cars, and used cars. When the lifetime of passenger cars is reduced by 5 years, many older cars of relatively recent model years remain, and few cars that were manufactured and sold during 1993–2006 remain. This indicates that shortening the lifetime of passenger cars shortens the time that car owners own their cars, which they replace within a short period. This encourages the disposal of cars of relatively early model years, with many people purchasing new cars more recently.

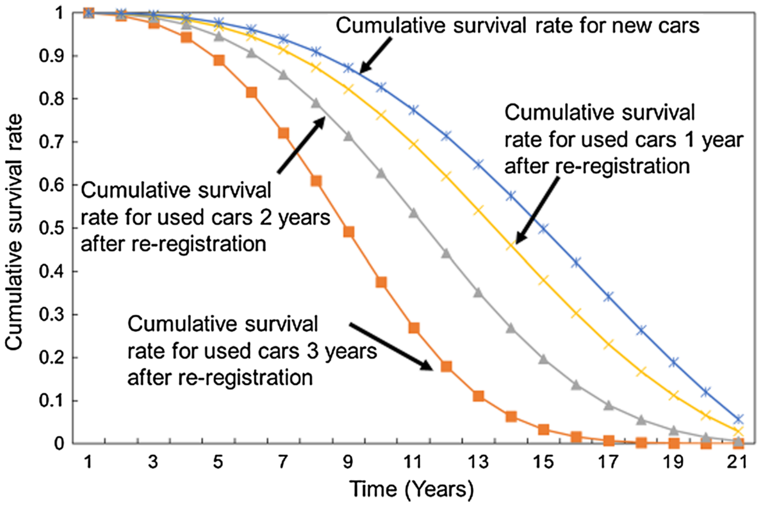

Fig. 2 Cumulative survival rate for new and used cars registered during 1993–2014

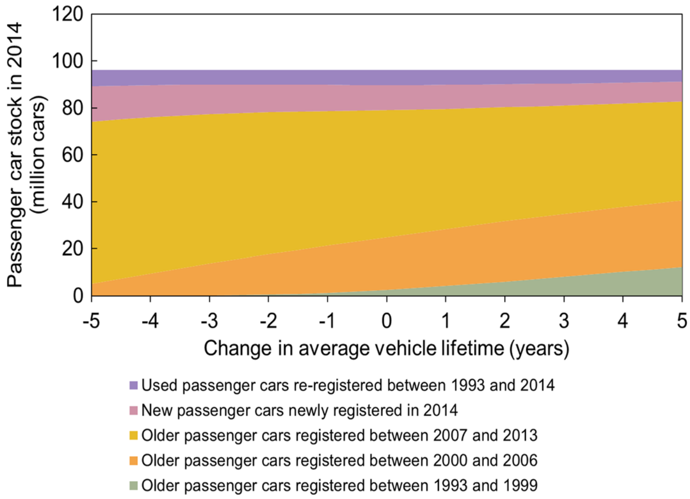

Fig. 3 Passenger car stock in 2014 under the lifetime change scenarios (benchmark: $\theta = 0.4$, $\Delta\mu = 0$)

Meanwhile, we can see that when the lifetime of passenger cars is extended, many older cars of relatively early model years remain (Fig. 3). When the lifetime is extended by 5 years, older cars manufactured and sold during 1993–2006 account for more than one-third of the total number of vehicles owned. Extending the lifetime reduces the demand for new cars and older cars of relatively recent model years.

Figure 3 shows that extending or shortening the lifetime of cars has almost no effect on the number of used cars owned that were re-registered during 1993–2013 and exist in 2014. This is because new cars account for a high proportion of the total number of vehicles owned, in addition to the short lifetime of used cars compared with new cars. For the baseline (change in average lifetime: 0 years), few used cars that were re-registered during 1993–2006 remain by 2014, accounting for less than 1% of the total number of vehicles owned.

4.3 Scenario analysis

Next, I explain the scenario analysis used to estimate the environmental impact that would occur if the market of used cars were to expand or decline over the 22 years covering 1993–2014. Figure 4 shows the effects of changes in the revival rate of used passenger cars re-registered between 1993 and 2014 on cumulative life-cycle CO_2 emissions during the study period. The vertical axis in Fig. 4 shows how the amount of cumulative CO_2 emissions associated with new and used cars registered during 1993–2014 (baseline emissions: 3131 million tons CO_2-eq. under a benchmark revival rate of 0.4 and benchmark average new vehicle lifetime of 11.50 years) is influenced by a change in the revival rate of used cars. Figure 4 shows that the CO_2 emissions associated with motor vehicle production substantially decrease due to an increase in the revival rate of used cars (i.e., market expansion of used cars), even though CO_2 emissions associated with gasoline combustion increase. The main reason for this is that a market expansion of used cars contributes to reducing the number of new motor vehicles sold; therefore, it has the

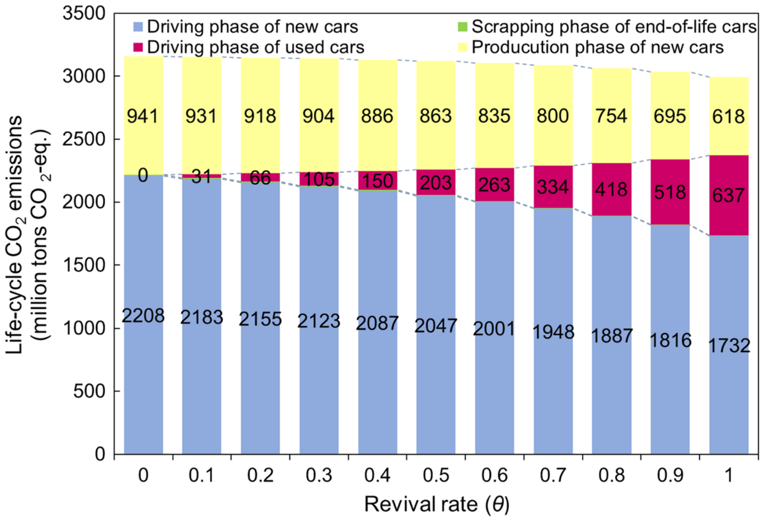

Fig. 4 Cumulative life-cycle CO_2 emissions of new and used cars registered during 1993–2013 under revival scenarios (benchmark: $\theta = 0.4$, $\Delta\mu = 0$)

effect of reducing the number of motor vehicles produced and the amount of CO_2 emissions associated with motor vehicle production.

On the other hand, market expansion of used cars increases the number of old and less fuel-efficient used vehicles still in service and consequently increases the CO_2 emissions from the vehicle fleet on the road. A crucial observation here is that total induced CO_2 emissions, i.e., the combined emissions from motor vehicle production, gasoline refining and combustion, and other services (see Fig. 4), decrease significantly due to a market expansion of used cars. Specifically, a 10% increase in the revival rate of used cars contributes to reducing CO_2 by approximately 0.54%. This finding implies that this market expansion policy would clearly contribute to a reduction in carbon emissions. We find that market expansion of used cars (i.e., a car reuse policy) can play a crucial role in mitigating climate change through a reduction in life-cycle greenhouse gas emissions attributable to the transport sector.

Furthermore, Fig. 5 shows the cumulative CO_2 emissions under combined scenarios of both changing the passenger vehicle lifetime and changing the revival rate of used cars. It is important to note that the baseline cumulative emissions are 3131 Mt CO_2. The important finding is that if the automobile lifetime increases by 1 year from 11.50 to 12.50 years and the revival rate of used cars is set to the baseline value of 0.4, cumulative life-cycle CO_2 emissions can be reduced by 0.6% from the baseline emissions. Note that the environmental benefit of 0.6% is actually considered to be significant, because the CO_2 emissions associated with manufacturing new vehicles are considerably reduced by the lifetime extension.

When a vehicle lifetime reduction policy, such as the vehicle replacement scheme of Japan, is introduced (see the report by the Japan Automobile Manufacturers Association; JAMA (2009) for the Japanese scheme) and the market share for vehicles targeted in the replacement scheme is expanded, significant attention should be paid to the additional materials and parts that are required for producing the target vehicles (e.g., hybrid

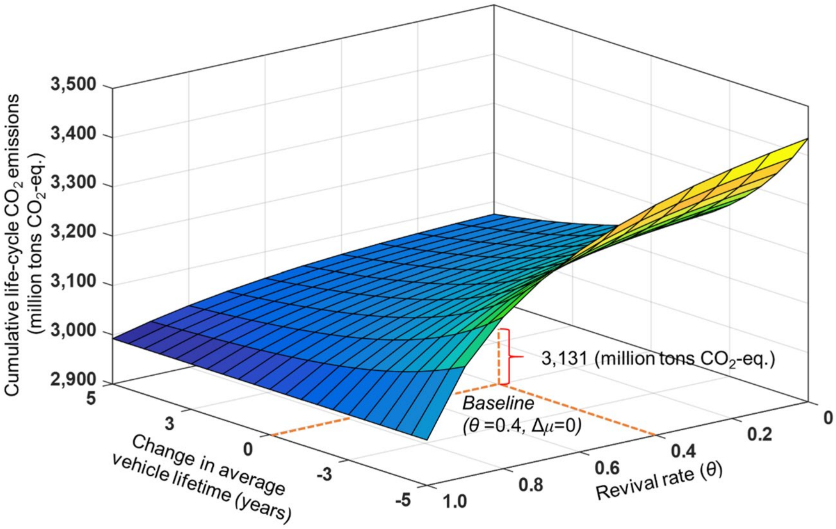

Fig. 5 Cumulative life-cycle CO$_2$ emissions of new and used cars registered during 1993–2013 under combined scenarios of average vehicle lifetime and revival rate

vehicles with greater fuel efficiency) and how their additional inputs will affect the environment through their productions.

Extending the lifetime of passenger vehicles and expanding the market share of used cars can bring about considerable environmental benefits (i.e., reduction in CO$_2$ emissions) as viewed in terms of the entire economy (Fig. 5). In contrast to the vehicle lifetime reduction policy, I rather propose a more effective combined policy of vehicle lifetime extension and market expansion of used cars to combat climate change. Specifically, governments can offer incentives to owners of older “greener” vehicles that have better fuel economies to retain and use these vehicles longer. This measure can maximize the environmental benefit as compared to previously introduced vehicle replacement schemes that focus on “new” vehicles. Finally, I conclude that the previous vehicle replacement schemes introduced by many developed countries such as Japan and the USA were not following an environmentally wise policy in the sense that the CO$_2$ reduction potential through the policy was very marginal.

In the Paris Agreement, adopted at COP21, held in Paris from November 30 to December 11, 2015, Japan set a target to reduce its territorial greenhouse gas emissions by 26% from 2013 levels by 2030 (Ministry of the Environment 2016). For the transportation sector, the target in the drafted agreement is to reduce emissions to 163 million tons by 2030, equal to 72% of the 225 million tons emitted in 2013 (JAMA 2016). Given that approximately 80% of emissions in the Japanese transportation sector are vehicle emissions in both the passenger and freight sectors, the key to achieving the reduction target lies in the choice of how to reduce vehicle emissions (Ministry of the Environment 2014).

In the interest of further reducing transportation sector emissions, the Japanese government has set forth as their technical and demand policies to improve fuel efficiency in new vehicles and increase the percentage of next-generation vehicles (through new vehicle sales), respectively (MLIT 2015). The present study has made clear that, together with these policies, further popularizing "used" vehicles in Japanese society could greatly contribute to achieving the reduction targets. Looking to revitalize the used vehicle market, MLIT is working to build a traceability system by 2020, which will compile a database of accident records, service records, fuel efficiency, number of owners, and other pertinent details for used vehicles (MLIT 2015). I propose that, using this traceability system to account for used vehicle safety and environmental performance, the government introduce a subsidy system to promote the purchase of used vehicles and further popularize used vehicles. The proposed demand policy should greatly contribute to building a low-carbon society.

5 Conclusion and policy implications

In this study, I proposed a comprehensive method for estimating how changes in passenger vehicle lifetimes of new and used cars and the car markets of new and used cars affect life-cycle CO_2 emissions. While demand-side policies such as vehicle replacement schemes are important for reducing CO_2 through the energy efficiency improvement, the emission reductions can be easily lost by the increase in the emissions in the production phase for new passenger cars. Without this perspective, a policy designed to reduce GHG emissions may result in increased emissions and further exacerbate global climate change. The results of this study suggest that the introduction of a subsidy policy for used vehicles and traceability systems could invigorate the used car market, to significantly contribute to reducing CO_2 emissions from transportation. In conclusion, using data from Japan, I have shown the critical importance of the fact that a combined policy of vehicle lifetime extension and market expansion of "used" cars can contribute toward a low-carbon transition society.

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