Energy and CO₂ Benefit Assessment of Reused Vehicle Parts through a Material Flow Approach

Fernando Enzo Kenta Sato 1) Takaaki Furubayashi 2) Toshihiko Nakata 2)

1) Tohoku University, Graduate School of Engineering, Dept. of Management Science & Technology
6-6-11-815 Aramaki Aza Aoba, Aoba-ku, Sendai-shi, Miyagi 980-8579, Japan (E-mail: sato.fernando.enzo.kenta.q3@de.tohoku.ac.jp)
2) Tohoku University, Graduate School of Engineering
6-6-11-815 Aramaki Aza Aoba, Aoba-ku, Sendai-shi, Miyagi 980-8579, Japan

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ABSTRACT: The aim of this study is to quantitatively evaluate the benefits of reused vehicle parts through a material flow approach. The energy consumed by new components for vehicle repairing can be saved. Moreover, an appropriate use of materials obtained from end-of-life vehicles (ELVs) contributes to waste reduction. Each reused part has different material compositions, weights, and demand; thus, the total benefit is evaluated using inventory analysis by introducing the definition of embodied energy and CO₂ emissions. The Japanese ELV market was taken as a case study, and the results show that energy and CO₂ saved by reusing parts are approximately 35.3 GJ and 1,887 kg-CO₂ per vehicle, and 111 PJ and 6 MM ton-CO₂ for the market in Japan. Finally, possible measures to boost the current benefits are discussed.

KEY WORDS: environment, energy, resources, end-of-life vehicle, vehicle part reusing, material composition, energy use, CO₂ emission [D2]

1. Introduction

In the Paris agreement reached in 2015, 192 countries have signed the commitment to reduce 80% of the current CO₂ emission with a deadline of 2050. This commitment is an extremely challenging target, but demonstrates a strong and global necessity to change current measures regarding environmental preservation.

The energy consumed and CO₂ emitted in the transportation area accounts for approximately 30% of the total consumption and emission of a country. The automotive industry has been developing new technologies to improve vehicle efficiency and reduce dependency on fossil fuels. Over the past few decades, a considerable number of studies on energy consumption and CO₂ emission have been conducted with respect to vehicle life cycle and most of them have focused on the production and use phase of a vehicle. However, very few attempts have been made to evaluate the end-of-life phase and the effect of reused vehicle parts.

Reusing parts of vehicles implies that “When a user needs a particular part in order to repair his vehicle, that necessity will be covered by acquiring a second-hand part instead of a brand new one.” Accordingly, the production of a new part is not necessary, thus saving the energy consumed and CO₂ emitted in that process. Moreover, the reuse of materials contributes to waste reduction as part of environmental improvement and pollution prevention.

The aim of this study is to demonstrate the importance of reusing vehicle parts and numerically evaluate their current benefits from energy consumption and CO₂ emission viewpoints. For this purpose, the Japanese end-of-life vehicle (ELV) market was taken as a case study.

2. Background: ELVs and part reuse in Japan.

Japan is the third most important vehicle market worldwide. During 2009 to 2013, an average of 5,027,200 vehicles was annually sold (2). In addition, 3,474,000 vehicles were discarded in the same period, and it is estimated that the material generated in the ELV phase represents approximately 4,000,000 tons of annual waste. This is 6% of the 70,000,000 tons/year of waste generated throughout Japan.

The processing of the ELVs first involves collecting the parts in a dismantling company. Here, the fluids, batteries, tires, and airbags are initially removed as a preventive measure. Subsequently, based on the vehicle model and considering the auto parts market demand, certain components are extracted to be reused as second-hand parts. In the same stage, the remaining parts are extracted to be recycled as alternative raw material.

In the second step, vehicles are pressed so that they can be stacked and are then shipped to a shredder company where the metallic materials are separated for recycling. Finally, the automobile shredder residue (ASR) is obtained as remainders.

The reusable parts obtained from a dismantling company is analyzed in this study. These parts represent 20% to 30% of the
weight of each discarded vehicle, according to the reports from the Ministry of Economy, Trade and Industry (2,3) and The Japan Machinery Federation (4). It is worth mentioning that in monetary terms, 43% of the total reusable part sales correspond to overseas markets and the rest to the domestic one.

3. Analysis method and data collection

Figure 1 shows the conceptual graph of the proposed study, wherein the materials obtained from the ELVs benefit previous life cycle phases through the 3R activity (recycle, reuse, and reduce). This study is focused on the analysis of reused vehicle parts from a standpoint of energy and CO2 emissions. For this purpose, the concept of energy saving is defined as the “Energy that was conserved owing to the reuse of the parts,” and the CO2 saving as “The CO2 that is not emitted from the reuse of parts.”

To determine the aforementioned factors, the structure of Honda Accord 2011 is taken as the generic vehicle of study. Furthermore, the obtained results are reflected in the general values of the Japanese market.

On the other hand, Das et al. (5) and Nishimura et al. (6,7) defined the embodied energy and embodied carbon for different materials used in the automotive industry. The values were used to calculate the energy consumption and CO2 emission associated with vehicle parts and component production process.

![Fig. 1 Conceptual graph of the current study](image)

3.1. Selection of parts and verification of representativeness

An automobile is made up of more than 30,000 parts and components. They can be broadly divided into exterior parts, interior parts, engine, underbody, and electrical parts. In our study, they are termed as “parts” in order to avoid confusion.

First, based on the reused parts listed in the reports pertaining to vehicle recycling published by the Ministry of Economy, Trade and Industry (2) and The Japan Machinery Federation (4), 42 parts that are representative have been selected.

Second, the representativeness of the selected parts was verified from a standpoint of sales and weights. With regard to the first point, information obtained from the NGP Japan Automobile Recycling Business Cooperative Association (8) is analyzed. The mentioned cooperative is the most important association in Japan, housing 141 dismantling and trading companies of second-hand passenger-vehicle parts. Their market share is close to 30% (9) and their sales were 6,148,690 unit parts between September 2014 and August 2016. It should be noted that their sales include both the demand inside the local market and exports. From this viewpoint, the selected 42 parts represent 51.4% of the sales within 322 items that are commercialized.

In the case of weight representativeness, the weights of the parts of Honda Accord were considered the basis, as given in the study by Singh (10). Accordingly, the sum of the weights of the 42 selected parts represents almost 75% of the weight of the studied car (without taking into account the body structure, which is recycled as alternative raw material (8), and air bags and fluids, which cannot be reused as parts).

Therefore, it can be concluded that the selected 42 parts are representative.

3.2. Decomposition of parts and definition of “various parts”

Table 1 lists the estimated weights and material compositions of the 42 analyzed parts, based on the studies conducted by Singh (10), Burnham et al. (11), Burnham (12), Mallick (13), Mijailovic (14), Hadley et al. (15), and Presti (16).

As mentioned previously, the selected 42 parts represent 75% of the total weight of the recyclable parts obtained from a vehicle. The material compositions of the remaining 280 parts have been approximated as a generic item termed “various parts,” calculated as the composition of the studied vehicle minus the compositions of the 42 analyzed parts and excluding the no reusable parts (body structure, air bags, and fluids).

Figure 2 shows the total material structure of the generic vehicle used in this study (10), (11), (15), (16).

![Fig. 2 Materials used in terms of weight percentage of the studied vehicle](image)

3.3. Sales analysis of parts

The sales of the 42 parts between September 2014 and August 2016 are indicated in the far right column in Table 1. The values were obtained from the NGP Japan Automobile Recycling Business Cooperative Association (8). As mentioned earlier, the values obtained from this association are representative and can be taken as a general sample.

To better understand the destination of the vehicle parts, the vehicle and its components are analyzed as material flows, wherein not all the scrapped vehicles are reused as second hand parts, but are also recycled as alternative raw material and ASR.
Initially, to reflect the sales of each part as a percentage weight of the flow, the percentage weights of part (i) with respect to the flow of the total reused parts [%] are defined using (1).

\[
Weight\_pctP_i = \frac{Weight_P_i \times Sales_P_i}{\sum_{j} Weight_P_j \times Sales_P_j}
\]  

(1)

Table 1 Material composition, weight, and sales of the analyzed vehicle parts

| Part                | Weight (kg) | Material Composition | Sales (units) | Source |
|---------------------|-------------|----------------------|---------------|--------|
| **Exterior Parts**  |             |                      |               |        |
| Front bumper ASSY   | 13.86       | Steel: 57.43%        | 142,646       | c)     |
| Rear Bumper ASSY    | 12.34       | Iron: 63.21%         | 119,059       | c)     |
| Right Fender        | 4.03        | Plastic: 100.00%     | 116,786       | c)     |
| Left fender         | 4.03        | Foam: 100.00%        | 121,557       | c)     |
| Front right door ASSY | 28.18     | Rubber: 9.55%        | 70,588        | c)     |
| Front Left door ASSY | 28.18      | Glass: 9.55%         | 84,269        | c)     |
| Rear right door ASSY | 23.73      | Alum: 13.06%         | 56,094        | c)     |
| Rear Left door ASSY | 23.73       | Copper: 13.06%       | 104,220       | c)     |
| Windshield          | 13.94       | Misc: 100.00%        | 5,471         | b)     |
| Right door mirror   | 1.32        | Steel: 65.00%        | 99,152        | a)     |
| Left door mirror    | 1.32        | Iron: 65.00%         | 114,313       | a)     |
| Right headlight ASSY | 3.43       | Plastic: 8.00%       | 159,516       | a)     |
| Left headlight ASSY | 3.43        | Foam: 8.00%          | 158,654       | a)     |
| Bonnet hood         | 17.90       | Steel: 84.92%        | 108,469       | c)     |
| Trunk lid           | 12.37       | Iron: 80.44%         | 11,136        | c)     |
| Rear right taillight| 1.27        | Plastic: 85.00%      | 133,780       | a)     |
| Rear Left tail light| 1.27        | Foam: 85.00%         | 125,928       | a)     |
| Rear window glass   | 7.44        | Steel: 100.00%       | 8,342         | b)     |
| **Interior Parts**  |             |                      |               |        |
| Front seat (driver) | 22.87       | Steel: 69.96%        | 7,614         | c)     |
| Front seat (assistant) | 22.87   | Iron: 9.01%          | 1,787         | c)     |
| Rear seat           | 21.03       | Plastic: 12.02%      | 1,850         | c)     |
| **Engine Parts**    |             |                      |               |        |
| Engine ASSY         | 169.90      | Steel: 46.13%        | 135,853       | c)     |
| Muffler ASSY        | 14.29       | Iron: 99.99%         | 831           | b)     |
| Fuel tank           | 12.00       | Plastic: 100.00%     | 11,133        | a) c)  |
| Starter motor / cell motor | 1.50 | Steel: 36.10%       | 143,790       | b) a)  |
| Alternator / dynamo | 1.50        | Iron: 36.10%         | 177,027       | b) a)  |
| Radiator            | 4.42        | Steel: 85.00%        | 65,265        | a)     |
| **Underbody Parts** |             |                      |               |        |
| Transmission        | 96.70       | Steel: 30.00%        | 58,820        | b)     |
| Steering rack & pinion | 8.24    | Iron: 30.00%         | 58,394        | b)     |
| Right front drive shaft | 7.60  | Plastic: 100.00%     | 64,079        | b)     |
| Left front drive shaft | 7.60    | Foam: 100.00%        | 79,251        | b)     |
| Right front strut ASSY | 7.40    | Steel: 100.00%       | 47,709        | b)     |
| Left front strut ASSY | 7.40       | Iron: 100.00%        | 54,637        | b)     |
| Tire                | 43.44       | Steel: 15.00%        | 226,505       | a) d)  |
| Wheel               | 46.96       | Iron: 47.00%         | 70,369        | b) e)  |
| Right rear strut ASSY | 5.10      | Plastic: 100.00%     | 7,673         | b)     |
| Left rear strut ASSY | 5.10        | Foam: 100.00%        | 8,208         | b)     |
| Right front knuckle ASSY | 21.45 | Steel: 69.70%       | 17,150        | a) c)  |
| Left Front Knuckle ASSY | 21.45 | Iron: 69.70%        | 20,385        | a) c)  |
| **Electrical Parts**|             |                      |               |        |
| Cooler compressor   | 5.74        | Steel: 10.00%        | 108,303       | a)     |
| Cooler condenser    | 4.20        | Iron: 10.00%         | 38,580        | a)     |
| Battery             | 12.40       | Plastic: 6.10%       | 15,889        | b)     |
| **Various Parts**   | 0.97        | Steel: 0.95%         | 2,988,408      |       |

a) Authors estimation
b) Data from Burnham, a (11), (12)
c) Data from Singh, Harry (10)
d) Data from Presti (16)
e) Data from Hadley (15)
In (1), \( \text{Weight}_P \) [kg per vehicle] represents the weight of a unit part (i), and \( \text{Sales}_P \) [units] represents the corresponding sales in the studied period.

Second, the obtained flow is separated based on the material compositions of each part. The percentage weight of material (m) of part (i) with respect to the flow of the total reused parts [%] can be calculated using (2).

\[
\text{Weight}_{P_{i,m}} = \text{Material}_{i,m} \times \text{Weight}_{P_i} \tag{2}
\]

where \( \text{Material}_{i,m} \) [%] represents the weight percentage of material (m) of a part (i).

To convert the obtained relative weights into concrete weights of a vehicle, we multiply them by the weight of the studied vehicle (Honda Accord 2011, weight 1481 kg) and by the weight percentage of the vehicle reused as second hand parts, which is conservatively selected as 20\%. Hence, the weight of material (m) of a part (i) as reused parts [kg per vehicle] can be expressed as follows.

\[
\text{Weight}_{P_{i,m}} = \text{Vehicle Weight} \times 20\% \times \text{Weight}_{P_{i,m}} \tag{3}
\]

Fig. 3 shows the estimated material flow of an ELV based on the generic vehicle.

3.4. Calculation method of energy saving per vehicle

Das et al. (5) defined the embodied energy of materials comprising parts as “The energy contained in a fabricated material part, reflecting the energy required to process the material from raw material to finished product.” To put it plainly, for example, in case of a stamped part of a white body, the mentioned value includes the total energy consumed in producing 1 kg of the part, including the energy spent in the ore mining, smelting, steel rolling, and final press processes.

Although the same material is used for certain parts, the consumed energy can vary significantly depending on the production process. Hence, Das et al. (5) summarized the average energy consumed to produce each type of material in the automotive industry, as listed in Table 2.

Continuing with the same concept, \( \text{ESP}^{\text{Idel}} \) in (4) estimates the energy used for the production of one unit of a determined part (i). Moreover, this value represents the ideal or maximum energy saved per vehicle via reusing of part (i) [kJ per vehicle].

\[
\text{ESP}_{P_i}^{\text{Idel}} = \sum_m \text{EE}_m \times \text{Weight}_{P_i} \times \text{Material}_{i,m} \tag{4}
\]

Here, \( \text{EE}_m \) [kJ/kg] represents the embodied energy of a material (m) in the automotive industry.

Table 2 Embodied energy for vehicle production

| Material    | Embodied energy (kJ/kg) |
|-------------|-------------------------|
| Steel       | 63,965                  |
| Iron        | 63,965                  |
| Plastic     | 108,651                 |
| Foam        | 108,392                 |
| Glass       | 55,126                  |
| Rubber      | 153,749                 |
| Aluminium   | 341,924                 |
| Copper      | 126,768                 |
| Miscellaneous | 72,272            |
| Fluids      | 46,985                  |

Fig. 3 Material flow of an end-of-life vehicle
Moreover, the current exploitation level of the analyzed reused part (i) is expressed as the actual energy saved per vehicle via reusing of part (i) [kJ per vehicle] through Eq. (5).

\[ E_{SP}^{Real} = \sum_m E_{E_m} \ast WeightP_{l,m} \]  (5)

It should be made clear that the difference between \( E_{SP}^{det} \) and \( E_{SP}^{Real} \) represents the energy saving potential obtained by improving the current reusing level of each part (i).

3.5. Calculation method of CO₂ saving per vehicle

In previous studies, Nishimura et al. \(^6\) \((7)\) proposed embodied carbon values for different production sectors. The studies include embodied values for the Japanese passenger car industry, which are used in our study as a basis for determining the CO₂ saving potential. Table 3 lists the average values of CO₂ emitted per type of material in the automotive production, calculated on the basis of the aforementioned studies.

Continuing with the proposed energy saving calculation method, the amount of CO₂ saved by reusing a unit part (i) or the ideal CO₂ saved per vehicle by reusing a part (i) [kg CO₂ per vehicle] can be determined as follows.

\[ CO_{2}SP_{i}^{ideal} = \sum_m ECO_{2,m} \ast WeightP_{i} \ast Material.pct_{i,m} \]  (6)

where \( ECO_{2,m} \) represents the embodied CO₂ of a material (m) for the automotive industry [kg-CO₂/kg].

The current exploitation level of an analyzed part (i) or the actual CO₂ saved per vehicle by reusing a part (i) [kg CO₂ per vehicle] can be obtained using (7).

\[ CO_{2}SP_{i}^{Real} = \sum_m ECO_{2,m} \ast WeightP_{l,m} \]  (7)

Table 3 Embodied CO₂ for vehicle production

| Material       | Embodied CO₂ (kg-CO₂/kg) |
|----------------|--------------------------|
| Steel          | 5.51                     |
| Iron           | 7.71                     |
| Plastic        | 8.07                     |
| Foam           | 8.07                     |
| Glass          | 1.47                     |
| Rubber         | 13.58                    |
| Aluminum       | 5.51                     |
| Copper         | 6.24                     |
| Miscellaneous  | 7.38                     |
| Fluids         | 8.44                     |

It should be made clear that, similar to the difference between \( E_{SP}^{det} \) and \( E_{SP}^{Real} \), the difference between \( CO_{2}SP_{i}^{ideal} \) and \( CO_{2}SP_{i}^{Real} \) represents the CO₂ saving potential obtained by improving the reusing level of each part.

3.6. Calculation method of energy and CO₂ saving potential for the Japanese market

The results obtained above (from a standpoint of material, energy, and CO₂) are only for a unit vehicle and the calculations were based on a generic Honda Accord weighing 1,481 kg. To calculate the general values for the Japanese market, two representative aspects of vehicles are defined. First, the average weight of a Japanese vehicle \( Ave \) weight [kg]; and second, the number of cars scrapped annually in the same market, i.e., \( Ave \) Scrapped [units of vehicles]. The values of the same during the years 2009 to 2013 were obtained from the reports published by the Ministry of Economy Trade and Industry \(^1\) \(^{1}\) and the Ministry of Environment \(^1\) \(^{1}\).

The weight of material (m) of a reused part (i) for the entire Japanese market [kg/year] can be calculated as follows.

\[ WeightP_{l,m,JPN} = Ave \) Scrapped \ast Ave \) weight \ast \left( \frac{WeightP_{l,m}}{Vehicle Weight} \right) \]  (8)

The energy saved by reusing part (i) for the entire Japanese market [kJ/year] can be obtained by multiplying the above equation with each embodied energy value, listed in Table 2.

\[ E_{SP_{i}}^{Real,JPN} = \sum_m E_{E_m} \ast WeightP_{l,m,JPN} \]  (9)

Similarly, the CO₂ saved by reusing part (i) for the entire Japanese market [kg CO₂/year] is obtained as follows.

\[ CO_{2}SP_{i}^{Real,JPN} = \sum_m ECO_{2,m} \ast WeightP_{l,m,JPN} \]  (10)

The total saving potential for the Japanese market can be obtained as a summation of the individual values corresponding to each part (i).

4. Results and discussion

The results obtained using the proposed analysis method are presented in this section. First, the results pertaining to the energy saving and CO₂ saving potential per vehicle are indicated. Second, the estimated values for the entire Japanese market are calculated.

In the last subsection, the results are discussed, wherein possible strategies to improve them are proposed in addition to highlighting the benefits obtained from the reused parts.

4.1. Results of energy saving per vehicle

Fig. 4(a) shows the values of \( E_{SP}^{det} \) and \( E_{SP}^{Real} \) calculated for each analyzed part. As mentioned earlier, the difference between the values represents the remaining energy potential of each type of parts obtained by increasing their reusing levels.

Fig. 4(b) shows the energy flow of the ELVs in terms of the embodied energy, wherein the current energy saved by reusing the parts is estimated as 35,294 MJ per vehicle.

4.2. Results of CO₂ saving per vehicle

Similar to Fig. 4, Fig. 5(a) shows the values of \( CO_{2}SP_{i}^{det} \) and \( CO_{2}SP_{i}^{Real} \) calculated for each analyzed part. As mentioned earlier, the difference between the values represents the remaining CO₂ saving potential corresponding to each part obtained by increasing their reusing level.

It should be made clear that, similar to the difference between \( E_{SP}^{det} \) and \( E_{SP}^{Real} \), the difference between \( CO_{2}SP_{i}^{ideal} \) and \( CO_{2}SP_{i}^{Real} \) represents the CO₂ saving potential obtained by improving the reusing level of each part.

Table 3 Embodied CO₂ for vehicle production
Fig. 5(b) shows the CO₂ flow of the ELVs expressed in terms of the embodied CO₂, wherein the CO₂ saving potential obtained by reusing the parts is approximately 1,887 kg·CO₂ per vehicle.

4.3. Results of energy saving and CO₂ saving for the Japanese market

Fig. 6 shows the estimated energy and CO₂ saving potential obtained by reusing the vehicle parts. Here, the total saving values are estimated for the entire Japanese market and the total impacts are separated by each material composition.

4.4. Discussions

Previous studies indicated in the Handbook of automobile technology (18) shows that the energy consumed in the entire life cycle of a Volkswagen Golf A4 (1,059 kg) is approximately 325
GJ, which comprises 239.4 GJ and 85.6 GJ consumed in its use and production phase, respectively. On the other hand, the CO₂ emitted in its life cycle is 21,289 kg, wherein 4,402 kg corresponds to the emission in the production phase. Both the analyses do not take into account the ELV phase, which is unsatisfactory (Fig. 7).

The values 35.3 GJ and 1,887 kg pertaining to the energy and CO₂ saved by reusing of parts are not only compatible with the results mentioned above, but also demonstrate the significant effect of the reused parts on the entire life cycle.

Fig. 4 shows that reusing of vehicle parts made by aluminum maximizes the energy saving potential. On the other hand, within the reused parts, the engines are the major contributors from a standpoint of energy. However, because they are possibly near the sales saturation level, it should be noted that the parts with major energy saving potential are the transmissions, tires, wheels, and knuckles. In the case of CO₂ saving, the importance of material type became less, and this can be explained by a more similar level embodied CO₂ between them. On the other hand, in addition to energy saving, the engines are the major contributors, and the
parts with major CO₂ saving potential include the transmissions, tires, wheels, and knuckles.

These findings suggest several courses of action in order to boost the benefits from the reuse of vehicle parts. As a first observation, it can be proposed to concentrate on the use of high-embodied energy and CO₂ for vehicle parts with most demand in the aftermarket. This measure will be effective considering that the total material composition of the vehicle cannot be changed. Another possibility is improving the ease of disarming of the parts made by the aforementioned type of materials. Additionally, a third option could be increasing the demand of parts with high energy and CO₂ saving potential through unification of parts design in different vehicle models.

4.5. Further targets

Finally, a number of potential improvements of our calculation method need to be considered. First, the 322 analyzed parts have been taken as separated parts; nevertheless, few sub-assembly parts, particularly engine parts, have been commercialized and included in the mentioned quantity. Second, depending on the study, the reused parts are separated as rebuild parts, which are subjected to additional productive process. Adjustments in both topics will be part of future works. In this instance, considering that the aim of this study is to obtain representative values and because of the low energy and CO₂ emission they represent, their effect on the obtained results are considered insignificant.

5. Conclusions

This paper has highlighted the importance and benefits of reusing vehicle parts. The energy and CO₂ saved by reusing the parts have been calculated as 35.3 GJ and 1.887 kg-CO₂ per vehicle, respectively, and 111 PJ and 6 MM ton-CO₂ of saving considering the entire Japanese market.

Currently, the reused engines are the major contributors in both aspects. However, our research suggests that in order to maximize the benefits of the reused parts, efforts should be made to boost the ones with low demand but with high-embodied energy and CO₂.

On the other hand, considering the material composition, aluminum parts are the major contributors because of the high energy required in its productions process; their reuse has promising energy and CO₂ saving potential.

This study is the first step toward enhancing our understanding about the benefits of ELVs. Several courses of action were suggested in the vehicle design phase in order to create an energy and CO₂ efficient and closed vehicle life cycle. Moreover, waste minimization and the reutilization of the generated material are emphasized.

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