Dynamic modelling of material flow and CO_2 emissions induced by introducing next-generation vehicles

Takahiro Kume[1,]*, Hiroki Hatayama[2], Ichiro Daigo[1], Yasunari Matsuno[1] and Yoshihiro Adachi[1]

[1]The University of Tokyo, Tokyo, Japan

[2] National Institute of Advanced Industrial Science and Technology, Tsukuba, Japan

*kume@mfa.t.u-tokyo.ac.jp

Abstract Recently, “next-generation vehicles” such as hybrid electric vehicles (HEVs) and electric vehicles (EVs) have attracted attention because they reduce CO_2 emissions in the use phase. Many researchers have been evaluating the energy consumption and CO_2 emissions for next-generation vehicles based on both a product life cycle assessment and long-term global analysis. However, there has been little discussion about the change of material flow, although some types of next-generation vehicles have considerably different material composition. This study presents the global steel, aluminum and copper flow for vehicles from 2005 to 2050 by using MFA (material flow analysis) and evaluates their recyclability in which the introduction of HEVs and EVs was considered. Then, the change of CO_2 emissions in the production and usage of the vehicles was also estimated.

1 Introduction

Recently, there is growing concern about global warming. The automobile industry, one of the responsible sectors for greenhouse gas emissions, has been developing “next-generation vehicles” such as hybrid electric vehicles (HEVs) and electric vehicles (EVs). These vehicles are expected to emit less CO_2 during the use phase than conventional vehicles with internal combustion engines (ICEVs). In recent years, several governments have announced HEV and EV sales targets, and the International Energy Agency (IEA) published a global scenario named “BLUE Map scenario” that achieves “a 30% cutting of CO_2 emissions in 2050 compared to 2005 levels” for the transport sector. (The overall target of the scenario is “a 50% reduction in global energy-related CO_2 emissions by 2050 compared to 2005 levels”) [1]. This scenario considers not only the penetration of next-generation vehicles but also regional differences in energy efficiency. Thus, the introduction of next-generation vehicles has often been evaluated from the point of energy consumption and CO_2 emissions. However, the changes in material flow have not been discussed thoroughly although the material composition of next-generation vehicles is different from ICEVs.

This study presents the change in global steel, aluminum and copper flow by the penetration of next-generation vehicles. The recyclability of aluminum and the change of CO_2 emissions were also investigated. The results were compared between two scenarios explained in section 2.

2 Methodology

To evaluate the contribution of vehicle innovations on the material flows and CO_2 emissions, two scenarios were considered as follow. In Scenario I, next-generation vehicles will not be introduced. All vehicles used in the future are conventional internal combustion engine vehicles (ICEVs). In Scenario II, HEVs and EVs will be introduced on the basis of the “BLUE Map scenario” which was proposed by the International Energy Agency (IEA). Along with these scenarios, the global steel, aluminum and copper flows for vehicles from 2005 to 2050 were estimated by using dynamic MFA (material flow analysis). Using these results, the change of the global CO_2 emissions in the production and usage of the vehicles was also investigated. Finally, the reduction potential of primary aluminum consumption was calculated in global scale using multimaterial pinch analysis.

2.1 Material flow analysis

Material stock, demand and discard related to the vehicles were analyzed by the number of vehicles owned, registered and discarded, and the average material use intensity for a vehicle. This study covered 50 countries that were divided 10 regions, which accounted for more than 90 % of the global number of vehicles owned in 2005.

To estimate the number of vehicles owned, this study employed the same approach developed by Dargay et al [2]. Most of the previous studies that analyzed future material use have been forecasting the material demand (consumption), for example, using the intensity of use hypothesis [3]. Nevertheless, it is a considerable attempt to regard material stock as the driver of the material cycle since demand arises when people sense a deficiency in supply in society. In this study, the authors assumed that the per capita stock of vehicles follows the logistic curve as a country develops:

$$s_t = s_{sat} \exp\left(\alpha \exp\left(\beta \times GDP_t\right)\right) \tag{1}$$

where s_t is the per capita stock in year t, s_{sat} is the saturation value of per capita stock, α and β are parameters, and GDP_t is the per capita GDP in year t. The parameters α, β and s_{sat} were determined with nonlinear regression on the data plot of the historical relationship between GDP_t and s_t. With Eq. (1), the number of vehicles owned from 2005 to 2050 was estimated using GDP and population prospects [4, 5]. Then, the number of vehicles registered and discarded was derived from the change in the number of vehicles owned using Population Balance Model and the statistics of the number of vehicles registered from 1979 to 2004.

2.2 CO_2 emissions evaluation

This study evaluated the global reduction potential of CO_2 emissions by introduction of next-generation vehicles. To estimate the amount of CO_2 emissions from vehicles, material production, assembly and use stage of the vehicles were considered. The amount of CO_2 emissions from material production stage was calculated using life cycle inventory data and the material production obtained by MFA in this study. CO_2 emissions in assembly stage took only energy consumption into account. Regarding CO_2 emissions in use stage, we considered not only regional differences of CO_2 intensity of electricity generation but also its improvement toward the future presented in BLUE Map scenario.

2.3 Multimaterial pinch analysis

Aluminum is usually used as an alloy by adding a few elements. The Japanese Industrial Standard (JIS) defines 40 or more alloy types, and these alloys are usually categorized into two types by the concentration of alloying elements: wrought alloys (less than ca. 5%) and cast alloys (ca. 15%). Although several kinds of alloys are used in a product, they are usually recovered from end-of-life products without separation. Moreover, some of the alloying elements cannot be removed from scrap and remain in the recycled aluminum. Therefore, in the current aluminum recycling, most wrought alloy scrap is not available for wrought alloy production, but is used for cast alloy production. However, appropriate separation and blending of scrap can contribute to further scrap use. This leads to a reduction in primary aluminum consumption, which needs huge energy in refinement. The minimum primary aluminum consumption would be achieved when Eq. (2) is satisfied.

Objective function = min $s_{primaryaluminum}$ is subject to:

$$\sum_i s_i = \sum_j d_j$$

$$u_{kj} \geq \frac{\sum_i \left(e_{ki} \cdot s_i \cdot r_{ij}\right)}{\sum_i \left(s_i \cdot r_{ij}\right)} \tag{2}$$

where s_i is the supply of scrap (and primary aluminum) i, d_j is the demand of alloy j, e_{ki} is the concentration of element k in scrap i, r_{ij} is the proportion of the scrap i recycled into alloy j, and u_{kj} is an acceptable concentration of element k in alloy j. The multimaterial pinch analysis solves Eq. (2), and provides the minimum primary aluminum requirement and the optimized recycling flows. For the multimaterial pinch analysis, both the amount and chemical composition of scrap were calculated for every end use (details are given in the paper [6]). Regarding alloying elements, Si, Fe, Cu and Mn were taken into account.

3 Results

The results of dynamic MFA were shown in Table 1 and 2. In Scenario II, steel demand and discard are 11.1 Mt less than those in Scenario I. However, the aluminum demand and discard are 3.4 Mt and 1.4 Mt larger than those in Scenario I, and the copper demand and discard are 10.8 Mt and 6.12 Mt larger than those in Scenario I, respectively. Especially, the global copper flow changed significantly by introducing next-generation vehicles. In Scenario II, the copper stock and demand for vehicles were about four times larger than those in Scenario I. These results show that the introduction of next-generation vehicles have a significant effect on the material flows, especially copper.

The amount of CO_2 emissions was estimated in Scenario I and Scenario II (Fig. 1). Total CO_2 emissions in Scenario I and Scenario II are 12 Gt and 6.9 Gt in 2050, respectively. These figures show that use stage accounts for the majority in the both scenarios. In 2050, CO_2 emissions from the material production stage are estimated at 705 Mt in Scenario I. In Scenario II, CO_2 emissions are 103 Mt (15%) larger than those in Scenario I. It showed that the introduction of next-generation vehicles could reduce CO_2 by 45% compared with Scenario I.

From the MFA and multimaterial pinch analysis, the minimum requirement of primary aluminum in 2050 was estimated as shown in Table. 3. In Scenario I, the global aluminum demand and discard are 58 Mt and 59 Mt, respectively. Of the discard, 49 Mt is available for secondary aluminum, whereas 9.5 Mt of scrap cannot be recycled due to the high concentration of alloying elements, which is denoted as unrecyclable scrap in Table 3. Most of the unrecyclable scrap is generated from vehicles because of the cast alloys used for the engine block. In Scenario II, 11 Mt of scrap cannot be recycled, which is larger than that in Scenario I. In Scenario II, the year 2050 is in transition from ICEVs to HEVs and EVs. The introduction of EVs is rapidly growing, while most of the end-of-life vehicles are still ICEVs and HEVs. As the share of EVs increases, the demand of cast alloy decreases. In contrast, vehicle scrap still contains cast alloys at a high concentration because most of the end-of-life vehicles are still ICEVs and HEVs. So the gap between supply and demand in aluminum grade yields more unrecyclable scrap in 2050.

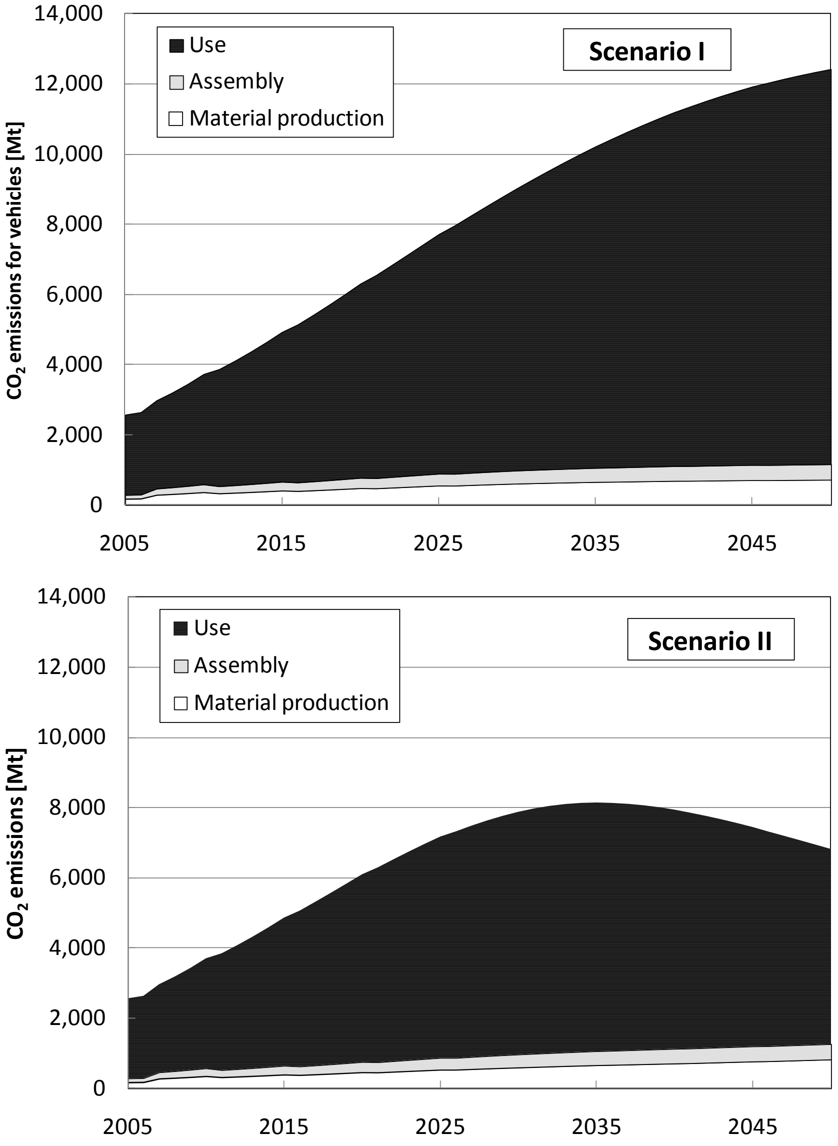

Fig.1: CO$_2$ emissions for vehicle in Scenario I and II.

Tab.1: The results of dynamic MFA in Scenario I in 2050.

Material	Stock [Mt]	Demand [Mt]	Discard [Mt]
Steel	3,510	228	202
Aluminum	558	36.0	32.1
Copper	55.0	3.54	3.17

Tab.2: The results of dynamic MFA in Scenario II in 2050.

Material	Stock [Mt]	Demand [Mt]	Discard [Mt]
Steel	3,300	217	191
Aluminum	594	39.4	33.4
Copper	191	14.3	9.25

Tab.3: Recyclability of aluminum in 2005, 2020, 2030, 2040 and 2050.

	Primary aluminum requirement [kt]		Unrecyclable aluminum scrap *1 [kt]	
	Scenario I	Scenario II	Scenario I	Scenario II
2005	11,400	11,400	0	0
2020	24,200	24,000	0	0
2030	11,900	13,300	3,520	4,520
2040	9,310	11,300	7,790	8,980
2050	8,530	11,250	9,560	11,200

*1 The scrap cannot be recycled due to the high concentration of alloying elements.

4 Conclusion

The introduction of next-generation vehicles was evaluated from the viewpoint of material cycle and CO_2 emissions. This study showed the introduction of next-generation vehicles leads to the change of the global steel, aluminum and copper flow. Especially, the minimum requirement of primary aluminum in Scenario II in 2050 was 2.7 Mt, which is larger than that in Scenario I. The vehicle innovation would have an effect on the aluminum recycling system in the future. The global CO_2 emissions from the vehicles were also estimated. The result showed that the introduction of next-generation vehicles leads to the reduction of CO_2 emissions for vehicles, whereas the increase in the ratio of the material production stage. Such studies should be applied to other technologies and industries to establish sound global material cycles in the future studies.

5 References

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