ICIC Express Letters
Volume **10**, Number **5**, May **2016**
ICIC International ©2016 ISSN 1881-803X
pp. 1143–1150

CONSIDERING RECYCLING CHANNELS OF AUTOMOTIVE LIFE CYCLE IMPACT ASSESSMENT STUDY

Nannan Du, Li Cui and Qinghua Zhu
School of Business
Dalian University of Technology
No. 2, Dagong Road, Liaodongwan District, Panjin 124221, P. R. China
Dnn0701@sina.com; { cuili; zhuqh }@dlut.edu.cn

Received October 2015; accepted January 2016

Abstract. *With environmental problem becoming more prominent and resources scarce pressure increasing gradually, all countries in the world take the problem of waste disposal as the issues which will affect the sustainable development of a nation. The automobile industry is one of the main industries of energy consumption. In order to save resources and reduce environmental pollution, the paper uses the method of life cycle assessment to discuss automobile's energy consumption and environmental impact in four stages of raw materials production, vehicle manufacturing, using and scrap recycling in our country. The recycling stage is divided into formal recycling and informal recycling and emphatically analyzes the formal recycling's impact on the environment. The results show that use stage is the largest energy consumption and environmental impact phase and recycling phase has the minimum energy consumption and environmental impact. The paper provides the basis for improving the entire automotive life cycle environmental performance and strengthens the regular recycling scrapped automobiles management.*
Keywords: Life cycle assessment, Recycling channels, Automotive

1. **Introduction.** As an environmental management instrument, the product life cycle assessment (LCA) can not only carry out the quantitative analysis and evaluation of the current environmental conflicts effectively, but also analyze and evaluate the product and its energy consumption and environmental impact, which is involved with the whole process from "the cradle to the grave" [1]. The relevant research about vehicles' life cycle assessment almost covered all kinds of vehicles' whole life cycle evaluation, the comparative study of all kinds of vehicles and the life cycle study of different kinds of vehicles' technology and fuels. While, as for the stage assessment of vehicles' life cycle, most of the existing literature focused on the raw material production, vehicle manufacturing and using stage, there were few papers about scrap recycling stage. In addition, they did not consider the different impacts of automobile energy consumption and environmental emissions brought by the formal to informal recovery ratio.

This paper carries out the whole life cycle assessment aiming at the vehicles from raw material production, vehicle manufacturing, using and scrap recycling four stages, and focuses on the assessment of the impact the formal recovery has on environment with ten thousand vehicles as targets. The purpose is to provide reference and basis for the implementation of extended producer responsibility system, improving the whole automobile life cycle environmental performance and strengthening the management of the scraped cars' formal recovery through the study.

2. **LCA of Automotive Products.** LCA is an analysis towards the direct and indirect impact a product or process has on environment during the whole life cycle. This paper selects 10,000 vehicles as targets, with the weight of 1,200 kilograms and powered by No. 93 gasoline. The product system boundary refers to the interface between the product system

and environmental or other products system [2]. In this paper, we divide the life cycle of automotive products into raw material production, automobile manufacturing, using and scrap recycling four stages.

3. Life Cycle Inventory Analysis of Automobile. The inventory analysis of LCA is the process of establishing the inventory towards the input and output data of the object of research in the system. The inventory analysis mainly includes the collecting and calculating of the relevant data so as to carry out the quantitative study on the relevant input and output of the target system.

3.1. Raw material production stage of automobile. Because of the complicated material structure of automobile, it is difficult to get the relevant data of all materials. The total input of energy is composed of two parts, namely the raw material energy and the fuel of technology. In the raw material production stage, this paper mainly considers metal and nonmetal, in which the metal term includes steel, iron, copper, aluminum and the nonmetal term includes plastic, rubber, glass, etc. Table 1 shows the proportion of vehicle's materials. As for the energy consumption, the paper mainly considers coal, oil, natural gas, electric power, water, etc. Among them, the data of energy consumption and gas emission of steel, iron, aluminum and copper comes from Reference [2]; the data of plastic, rubber and glass is calculated from a lightweight car of 1,105 kilograms in Reference [3], as shown in Table 2 and Table 3.

Table 1. The proportion of car's materials (average) [4]

Materials	Steel	Iron	Copper	Aluminum	Glass	Rubber	Plastic	Others
Proportion	60%	10%	2%	4%	3%	2%	15%	4%

Table 2. List of ten thousand cars' consumption of raw material and energy

Name	Usage (kg)	Total energy consumption (MJ)
Steel	7200000	847626810
Iron	1200000	156324950
Copper	240000	38387220
Aluminum	480000	711090340
Glass	360000	11520000
Rubber	240000	36000000
Plastic	1800000	122400000

Table 3. The production process of environmental emissions inventory of ten thousand cars of raw materials

Environmental impact type	Name	Steel	Iron	Copper	Aluminum	Glass	Rubber	Plastic
Gas Emission (kg)	VOC	33832.8	2684.4	109.2	1411.68	44.64	279.84	11057.4
	CO	244152	1270.8	453.36	2134.08	169.2	1596.72	4789.8
	NO_X	67816.8	2611.2	1612.32	13071.84	1155.6	2946.24	12524.4
	PM10	45489.6	2462.4	659.52	14075.04	452.52	1181.28	8137.8
	PM2.5	19900.8	1090.8	283.92	6543.36	259.92	438	3861
	CO_2	49111.2	1450.8	880.8	9329.28	703.44	1554.72	7111.8
	CH_4	133804.8	5448	23246.24	29595.84	2534.76	10450.8	17334
	N_2O	460.8	16.8	13.68	130.56	5.04	58.56	46.8
	SO_2	178884	6274.8	35859.6	34243.68	2078.64	8034.72	12477.6

3.2. **The whole car production stage.** The car body mainly includes body system, engine system, transmission system, traction motor, generator, controller, etc. The automotive fluids mainly include oil, brake fluid, transmission fluid, powertrain cooling liquid, windshield wiper fluid and additives. The assembly process mainly includes paint production and coating, lamp assembly, heat treatment, material handling, welding, air compression, etc. This paper does not consider the energy consumption and gas emission of the material transportation stage temporarily because of the complexity of automobile manufacturing technology and the limit of the data sources. The data of automobile production stage refers to the data of energy consumption and environmental emission of traditional automobiles which is included in Reference [5], and estimates basing on part of the data of an automobile of 1,090 kilograms which is referred to in Reference [6], as shown in Table 4.

Table 4. Ten thousand cars' production energy consumption and environmental emissions inventory

List Type	Classification	Impact Value
Energy Consumption (MJ)	Coal	68500000
	Crude Oil	404800000
	Natural Gas	776000
Air Pollution Emission (kg)	CO_2	218600000
	CH_4	7020000
	NO_X	367000
	SO_2	1270000
	Dust	57700
	CO	534000
	VOC	646000
	N_2O	2300
Solid Waste Emissions (kg)	Waste Residue	9220000
	Gangue	2779000
	Fly Ash	1511000
Water Pollutant Discharge (kg)	Wastewater	315100000
	Suspended Matter	6100
	Oil, Grease	6500
	COD	6400

3.3. **Using stage of automobile.** The energy consumption and environmental emission of automobiles' using stage mainly include the energy consumption and gas emission during the gasoline production stage and the tail gas emission and vehicle maintenance during the using stage.

(1) Gasoline production. In this paper it is the No. 93 gasoline, and the gasoline production mainly includes the following processes, namely the crude oil exploitation, transportation, gasoline manufacturing and processing the gasoline transportation, with gas station's gasoline product as the terminal. The integrated fuel consumption of fuel vehicles is 7.2 liter per 100 kilometers [5]. Because the vehicles selected in this paper will scrape after 600,000 kilometers driving and the total amount of gasoline needed is 43,200 liter, so the total weight of it is 31,320 kilograms with the density of 0.725 kg/L. In terms of the related data of the petroleum enterprises, the water consumption volume of the exploiting and producing 1 ton gasoline is 1,250 kilograms [3]. So the consumption of water resources for the production of gasoline is 39150 kg. Table 5 shows ten thousand cars' gasoline production energy consumption and environmental emissions inventory.

TABLE 5. Ten thousand cars' gasoline production energy consumption and environmental emissions inventory

List Type	Classification	Impact Value
Energy Consumption	Coal (MJ)	211441320
	Water (kg)	391500000
Air Pollution Emission (kg)	CO_2	3486072600000
	CH_4	10811664000
	N_2O	259956000
	CO	2076516000
	HCHO	31320000
	NO_X	111875040000
	NMHC	266220000
	SO_2	25904772000
	Dust	19246140000
Pollution of Waters (kg)	Suspended Matter	25700
	Oil, Grease	5099000
	COD	449400
	BOD_5	195400
Solid Waste Emissions (kg)	Fly Ash	7633000
	Gangue	11617000
	Waste Residue	295442000

(2) Using. The using stage of vehicles mainly includes the tail gas emission, the spare parts the maintenance of cars needs throughout the life cycle and the water consumed by automobile cleaning. The total weight of the gasoline consumed during the driving stage of the life cycle is 28,275 kilograms [3], the energy density of No. 93 gasoline is $4.5*10^7$J/kg, so the total energy consumption volume of the gasoline parts is 1,272,375MJ. There will be a spare parts replacement during the maintenance of the using stage, and the raw materials of these spare parts mainly include steel, iron, rubber, engine oil, etc. According to the statistic data of certain enterprise, the consumption volume of these raw materials during the maintenance are 830kg, 210kg, 350kg and 130kg respectively and the energy consumption volume of the raw material during the life cycle is 77,004.9MJ. The energy consumption and the environmental emission are shown in Table 6.

3.4. **The stage of scrap recycling.** The recovery and reuse of the scrapped vehicles includes recovery, dismantling, using disposal (reuse, remanufacturing, recycling), disposal and other relevant activities [7]. In 2013, Sina.com reported that, the scrapped vehicles recycling ratio of our country is only 20 percent per year, and the actual annual scrapped cars recycling volume of the enterprises that carry out the formal recovery and dismantlement is only 0.5-1 percent of the car ownership, which is much lower than the developed countries' level of 5-7 percent. According to the enterprise investigation and study, the scrapped cars reusing ratio of enterprises is up to 90 percent now. Each recovering a scrap car can save 1 ton fuel oil, 2.4 tons scrap iron and 45 kilograms nonferrous metal [8].

This paper selects two thousand cars, according to the proportion of 20% calculated the rate of formal recycling. The enterprise carrying out the formal recovery and dismantlement have got a more advanced dismantlement device. The efficiency of dismantlement is high and the environmental pollution is small. The scrap cars' formal recovery can be divided into recovering and using directly, recovering and using after remanufacturing, waste landfilling three conditions. Though the scale of informal recovery market is huge and the impact on environment is serious, the data of informal recovery is difficult to get. So, this paper will not consider the energy consumption and the environmental impact of

Table 6. Ten thousand cars' use stage of energy consumption and environmental emission inventory

List Type	Classification	Impact Value
Energy Consumption (MJ)	Gasoline consumption	12723750000
	Maintenance	770049000
Air Pollution Emission (kg)	CO_2	5974145000
	CH_4	94200
	CO	7332100
	NO_X	1307100
	HCHO	126200
	NMHC	4350600
	SO_2	78300
	Dust	339400
	N_2O	107400
Pollution of Waters (kg)	Wastewater	315100000
	Suspended Matter	6100
	Oil, Grease	6500
	Others	6400
Solid Waste Emissions (kg)	Waste Residue	2767000

Table 7. Two thousand scrap cars' recycling and dismantling of energy consumption and environmental impact list

List Type	Classification	Impact Value
Energy Consumption (MJ)	Coal	−36169765.2
Air Pollution Emission (kg)	CO_2	−4920000
	NO_X	3342
	CO	−21740
	HF	5.764
	Cr	0.0606
	CH_4	−0.0194
Water Discharge (kg)	Ba	−183.58
	Oil	−130.78
Solid Waste Emissions (kg)	Waste Residue	292400

it. The data of this part is worked out referring to a vehicle of 1,211 kilograms which is mentioned in Reference [9], as shown in Table 7.

4. **The Life Cycle Impact Assessment of Automobiles.** The life cycle impact assessment (LCIA) is to assess the life cycle's environmental impact of the object of research according to the data of inventory analysis stage. The stage will transform data to concrete type of effect and parameters so as to distinguish the different effects the every stage of the target's life cycle has on environment, and the stage offers necessary information to the life cycle's interpretation of results.

4.1. **Feature processing of life cycle.** Feature processing is to distribute the relative contributions of every kind of environment load project to the selected types of effect, and to determine the potential amount of contribution of every kind of environment load project's ecological effect. Use the difference of contribution to the same type of ecological effect made by different contaminants' under the condition that they have the same weight, and basing on one type of contaminants. Then use one of these contaminants to be the benchmark, assuming that its effect is 1, and compare other types of contaminants of the same amount with it. In this way, we can determine the relative effect potential of all types of contaminants. Every potential factor data comes from Reference [3]. In this paper, the global warming is represented by the equivalent of CO_2, the characteristic factors of CH_4, N_2O, CO and NO_x are 25, 298, 2, 320 respectively. The eutrophication of water body is represented by the equivalent of NO_3 and the characteristic factor COD, the eutrophication of water body are 5.94, 11.83 respectively. The acidification is represented by the equivalent of SO_2 and the characteristic factors of NO_x and HCL are 0.7 and 0.88 relatively. The photochemical smog is represented by the equivalent of C_2H_4 and the characteristic factors of CO, NO_x and CH_4 are 0.03, 0.028 and 0.006 relatively.

4.2. **Standardization and weighted processing.** The purpose of standardization is to eliminate the difference on quantity and order of magnitude of all kinds of effect types' single term result, and meanwhile, avoid it to affect the nature of the original result. Although the result after standardization has the comparability, the degree of importance of all types of environmental impact is different for a country or an area's sustainable development. So we need to give weights to different environmental impacts, and then, add up every terms. In this way, we can get the total environmental impact of automobiles [10]. The normalized factors and the weights in this paper come from Reference [11], and the result of giving weights to the normalized factors and the coefficient are shown in Tables 8-10.

Table 8. Environmental impact type standardization factor and weight coefficient

Effect Types	Normalized Factors	Weight Coefficient
Global Warming	8700kg CO_2-eq	0.83
The Eutrophication of Water Body	62kg NO_3-eq	0.73
Acidification	36kg SO_2-eq	0.73
Photochemical Smog	0.65kg C_2H_4-eq	0.51

Table 9. Life cycle energy consumption of automobiles (MJ)

Stages	Consumption
Raw Materials Production	1923349320
Vehicle Manufacturing	474076000
Using	13705240320
Scrap Recycling	−36169765.2

Table 10. Life cycle environmental impact of automobiles

Stages	Effect
Raw Materials Production	21477.289
Vehicle Manufacturing	185178.319
Using	24036415705.39
Scrap Recycling	−296.864

4.3. **Interpretation of results.** According to the data after standardization and the disposal of giving weights, the using stage has the most energy consumption and the most serious environmental impact during the whole life cycle of automobile. The reason is that, as a resource of high energy consumption, gasoline consumes a lot of resources during the process of production and using stage and has a serious impact on environment. During the recovery stage, most of the scrap cars were disposed via informal ways, because the

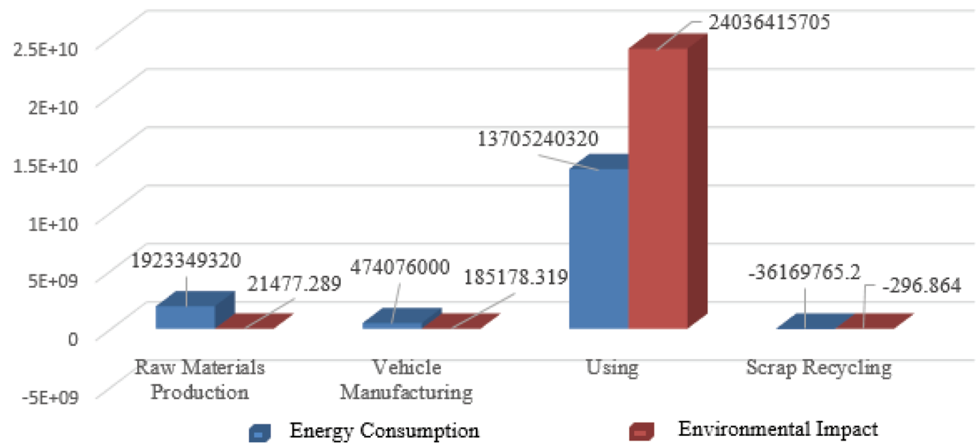

Figure 1. Life cycle assessment of automobiles

recovery ratio at present is low, which only reaches 20 percent. While, as for the enterprises that carry out the formal recovery, the utilization rate of scrap cars has reached 90 percent. The energy consumption of the scrap cars recovered formally is minus, and these cars have little environmental impact. The energy consumption and environmental emission of every stage are showed in chart 1.

5. **Conclusion.** This paper evaluates the whole life cycle, analyzes the different energy consumption and environmental impacts of raw materials production, vehicle manufacturing, using, scrap recycling four stages by using LCA. The order of the proportion of energy consumption from big to small is using stage, raw materials production stage, vehicle manufacturing stage and the scrap recycling stage. The using stage is the stage that has the most serious overall effect on environment. The disposal stage of scrapping has the smallest overall effect. With the efficiency of formal recovery becoming higher, the environmental impact will be smaller. Reducing the energy consumption of using stage and increasing the amount of cars recovered formally are the key to improve the whole environmental performance and promote the sustainable development of the industry.

In terms of the system of extended producer responsibility, relating the stakeholders that have the most serious impact on environment during the life cycle, and achieving the improvement of the whole environmental performance is the key emphasis in next step of research work.

Acknowledgements. This research is supported by China National Funds for Distinguished Young Scientists (No: 71025002); The National Basic Research Program of China (No: 2011CB013406); National Social Science Fund (No: 13&ZD147) and Scientific Research Project of Introduced talents (No: DUT14RC(3)076).

REFERENCES

[1] X. J. Zhen and B. Hu, Domestic literature review and the latest overseas research progress of life cycle assessment, *Science &Technology Progress and Policy*, vol.30, no.6, pp.155-160, 2013.
[2] Z. C. Liu, *Life Cycle Assessment Methodology of Original Manufacturing and Remanufacturing of an Engine*, Dalian University of Technology, Dalian, 2013.
[3] Y. L. Li, *Research on Key Link of Low Carbon Supply Chain about Light Vehicle Based on LCA*, Master Thesis, Beijing Jiao Tong University, Beijing, 2013.
[4] W. P. Schmidt, E. Dahlqvist, M. Finkbeiner et al., Life cycle assessment of lightweight and end-of-life scenarios for generic compact class passenger vehicles, *The International Journal of Life Cycle Assessment*, vol.9, no.6, pp.405-416, 2004.
[5] R. Yang, C. Feng, Y. W. Zhang, X. Q. Ma, J. Wu and Y. M. Chen, Life cycle assessment on hybrid electric vehicle, *Advances in New and Renewable Energy*, vol.2, no.2, pp.151-156, 2014.

[6] S. B. Wang, H. Dong, R. S. Wang, J. X. Yang and Q. H. Wu, Life cycle inventory of a China car, *Journal of Fudan University (Natural Science)*, vol.6, no.3, pp.328-334, 2006.
[7] H. F. Fang, *Research on the Key Problems in the Recovery of Automobile Products for Circular Economy*, Master Thesis, Hunan University, 2009.
[8] J. M. Liu, Retrieving and dismantling scrapped automobiles industry market analysis in China, *The Regeneration and Utilization of Non-ferrous Metal*, no.1, pp.8-10, 2004.
[9] K. M. Jeong, S. J. Hong, J. Y. Lee et al., Life cycle assessment on end-of-life vehicle treatment system in Korea, *Journal of Industrial and Engineering Chemistry*, vol.13, no.4, pp.624-630, 2007.
[10] X. N. Li, Z. G. Shi and G. F. Zhang, Automotive product life cycle assessment (LCA) study, *Technical Economy*, no.1, pp.1-4, 2007.
[11] C. Feng and X. Q. Ma, The energy consumption and environmental impacts of a color TV set in China, *Journal of Cleaner Production*, vol.17, no.1, pp.13-25, 2009.