Carbon Footprint Analysis of Electric Taxis in Istanbul

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Abstract

The global climate change and fossil fuel dependency are two major important challenge for achieving sustainable transportation. Alternative vehicle technologies, especially electric vehicles, have great potential to reduce the environmental impacts from transportation and to diversify energy sources in transportation. In this study, carbon footprint of vehicles fueled by gasoline, diesel, liquefied natural gas (LPG), and electricity are analyzed and compared for possible candidates of taxi operations in a metropole city, Istanbul, Turkey. Environmentally extended multi-regional input-output analysis is conducted to evaluate the upstream (supply chain) emissions due to vehicle operations. According to the results, conventional vehicles which are powered by gasoline have the highest greenhouse gas emissions, while electric vehicles have the least. Upstream (supply chain) emissions of EVs is found to be highest compared to other options. The GHG emissions of EV and LPG vehicle are 130 and 123 gCO_2-eqv./km, respectively. LPG is the most common fuel source for taxis in Turkey, especially in Istanbul. Considering that the marginal difference in these two vehicle types is very low, the carbon emission reduction potential of the EV is lower than expected. This is mainly because of the high fossil fuel dependence in the electricity generation mix in Turkey. To utilize the carbon emission reduction potential of EV in Turkey, the use of renewable energy sources for electricity production should be increased.

Keywords

Carbon footprint, Green electric taxis, Life Cycle Assessment, Sustainable Transportation, Hybrid multi-regional input output analysis

1. Introduction

Nowadays, it is generally recognized that sustainable development is a major concern all over the world. Meeting today's needs in a way that it would not ruin the future generation's ability of achieving their needs is a widely accepted definition of sustainability (Brundtland Commission, 1987). Environmental sustainable development requires reducing greenhouse gas emissions (GHG), air pollution, and energy demand (Kucukvar et al., 2014c; Nuri Cihat Onat et al., 2014a; Tatari et al., 2015a). Sustainable transportation also known as Green Transportation is one of the major ingredients of sustainable development and as a result an important factor of environmental development (Ercan et al., 2016a). Transportation sector is responsible for 25% of world's GHG emissions. There is an increasing trend in transportation related GHG emissions in comparison to other sectors (Nuri Cihat Onat et al., 2016b, 2016c). The significant concerns such as global climate change, dependence to fossil fuels, and air pollutions in metropole cities are leading challenges towards achieving a sustainable transportation (Ercan et al., 2016b). Local and international governments are following sustainable transportation strategies such as replacing conventional vehicles which use fossil fuels by those which are using electricity like hybrid electric vehicles (HEV) or plug-in hybrid electric vehicles (PHEV). There is a growing movement toward these alternative vehicles because of their great potential in decreasing the negative effects of transportation sector. However, there are some difficulties in these "green vehicles" widespread implementation like customer's reluctance of buying these vehicles or lack of infrastructure

(Melaina and Bremson, 2008). There are many different national agencies and international organizations which introduce and support green vehicle technologies to increase these vehicles' adoption among people and also promote their market share (IPCC, 2007). Many studies analyze the environmental consequences of these transportation systems. Large number of these researches have employed life-cycle approaches to assess the environmental impacts of conventional and electric vehicles such as greenhouse gas emissions and energy consumption (Hawkins et al., 2013; Noori et al., 2016; Onat et al., 2017; Onat, 2015a; Shepherd, 2014). On the other hand, there are some studies which have evaluated the social and economic effects of electric vehicles (Onat et al., 2014a), safety (Alirezaei et al., 2017; Tatari et al., 2015b) and operating cost (Onat, 2015b).

Unlike individual BEV/PHEV owners, a taxicab business operates tens of taxis in an organized way and has up to ten times more travel distance per vehicle, which makes taxi businesses a better potential candidate for electric vehicle adoption. Furthermore, as taxis travel relatively smaller distances per trip in urban environments, below highway speed, their daily operations fit well for existing characteristics of BEV/PHEV (shorter range, lower maintenance and operation cost compared to traditional vehicles). There are over 800 Nissan electric taxis (Leaf) in European cities as of 2016. While the electric taxi market in Europe is growing quickly, the number of electric taxis is still very low compared to average number of taxicabs in a metropole city (e.g. #taxi in London is ≈24,000). Taxi Electric in Amsterdam is the first taxi service switched a 100% electric taxi fleet in 2011. Currently, electric taxis are driven in cities of Stockholm, Prague, Barcelona, Rome, Amsterdam, London, Dublin, Madrid, Budapest and some metropoles of USA, Canada, and China. There are approximately 18,000 taxis in Istanbul and only one electric taxi on roads. There is a strong need for a comprehensive research about feasibility and efficient/sustainable operation options (e.g. energy and carbon footprints, battery charging patterns, optimal charging locations, cost/benefit analysis, driving conditions and patterns) for large-scale transition to BEV/PHEV taxis. In this research, a comprehensive multi-regional input-output (MRIO) life cycle assessment model is developed to analyze carbon footprint of possible alternative vehicle options for taxis in Istanbul. Results of this study, can be helpful for city level policy making. The proposed LCA method is also a novel approach in terms of its capability to track environmental impacts through global supply chains of transportation operations.

1.1 Life Cycle Assessment (LCA):

Life Cycle Assessment (LCA) is a widely-used method to track environmental impacts of products, processes, and goods (N.C. Onat et al., 2014). LCA quantifies the environmental impacts of products and services from their raw material acquisition phase up to the end-of-life phase (Rebitzer, 2004). In the literature, three different approaches of LCA; process-based LCA (P-LCA), input-output based LCA (IO-LCA), and hybrid LCA have been used in many studies (Finnveden et al., 2009; Guinée et al., 2001; Mohamed Abdul Ghani et al., 2017; Park et al., 2016). P-LCA divides the overall manufacturing process into different processes and assesses the direct environmental impacts of a product or service for a specific process (Norgate et al., 2007; N.C. Onat et al., 2016; Tatari et al., 2012). P-LCA can capture a limited part of supply chain components and only analyze the environmental impacts of certain process like manufacturing, transportation, use and end-of-life. Defining the boundary of the analysis is an important issue in P-LCA and can lead underestimation of the environmental impacts due to cut-off criteria (Egilmez et al., 2013; Gumus et al., 2016a, 2016b; Kucukvar and Tatari, 2013; Suh et al., 2004). Deciding on what should be included in analysis and what should be excluded might ignore some important environmental impacts and consequently underestimate the results (Onat et al., 2014c). To overcome these issues, Input Output LCA (IO-LCA) method was introduced in 2000s. IO-LCA method quantifies the overall environmental impacts of product or service (Egilmez et al., 2016; Kucukvar et al., 2014a; Tatari and Kucukvar, 2012). All transactions and emissions of different industrial sectors are included in this model, so the boundary of assessment is very inclusive. Besides, circularity effects are within the analysis since the transactions of a sector with itself is included in model. IO-LCA model is able to identify the direct, indirect and total supply chain environmental emissions. IO-LCA calculates the environmental impacts between different industrial sectors. IO-LCA indicates how increased demand of a sector's output can affect the output of emissions to the environment. Matthews et al., (2008) used the IO-LCA and indicated that on average 14% of the total supply chain carbon emissions are produced by the industry itself, and the rest stem from supply chains. On the other hand, all processes cannot be defined using IO-LCA due to aggregated structure of sectors within an economy. In such cases, P-LCA and IO-LCA is combined to overcome such difficulties. In this regard, Hybrid LCA, the combination of P-LCA and IO-LCA, is a powerful approach to evaluate sustainability effects of specific process as well as effects on supply chain scale. The methodologic contribution of this study is the use of a hybrid MRIO based LCA model to analyze carbon footprint of alternative-fuel taxi options.

2. Methodology:

Direct and indirect (related to supply chain) carbon emissions of alternative vehicle options for taxi operations is calculated a novel hybrid MIRO based LCA model. The functional unit of the LCA analysis per kilometer travel. In other words, GHG emissions is calculated per kilometer travel of a vehicle. Five different vehicle types, gasoline, diesel, liquefied natural gas, plug-in hybrid electric, and battery electric vehicles, are analyzed and compared. Because the operation phase is the most carbon-intensive phase (Michalek et al., 2011; Nuri Cihat Onat et al., 2016a; Onat et al., 2015), the life cycle phases of automobile manufacturing and end-of-life is excluded. In operation phase, there are two important sub-phase: Well-to-tank (WTT) and Tank-to-well (WTT). First one encompasses the supply chain of fuels from raw material extraction to vehicles to be used. WTT represent the direct emissions (tailpipe emissions) during vehicle operation. The tailpipe emissions using process level data, while WTT impacts are calculated using MRIO modeling, which refers to hybridization of the MRIO model.

2.1 Multi-Regional Input-Output Analysis:

MRIO modelling approach is used to evaluate the environmental effects associated with the consumption such as carbon footprints, connection between energy and water, food or land consumption. The values in input-output tables show the sale and purchase relationship between different industrial sectors in a country. It provides the flows of production and consumption of sectors within a national economy. MRIO models is an improved version of single region IO-models, hence they are capable of capturing global monetary transactions among different countries and regions. The MRIO model used widely to analyze the environmental impacts of economic activities at global scale. The MRIO model enables the tracing of a product or service produced by a sector and its consumption by other sectors in different regions. And so we can simply determine the total consumption of a product by summing up its individual consumptions by economic sectors of different regions. The MRIO model tracks the regional and global impacts of trades between different sectors of different countries (Egilmez et al., 2013; Kucukvar et al., 2014b; Noori et al., 2015, 2013; Tatari et al., 2012). MRIO framework includes all imports and exports per country and economic sector. All imports and exports between regions and industrial sectors are combined and make a financial accounting framework. Then this inter-industry transaction is added to primary inputs between sectors and final demand (Wiedmann, 2011). Many studies analyzed the environmental footprint of consumption, production trade, and nations by using MRIO databases (Kucukvar and Samadi, 2015; N. Onat et al., 2017). For instance, Kucukvar et al., (2016) investigated energy-climate-manufacturing nexus using MRIO modeling encompassing regional and global supply chains of manufacturing industries. In another study, Kucukvar et al., (2015) developed a global, scope-based carbon footprint modeling for effective carbon reduction policies in manufacturing sectors using MRIO analysis. Zhao et al., (2016) analyzed carbon and energy footprints of electric delivery trucks using a hybrid MRIO life cycle assessment.

There are multiple multi-regional input-output data bases (Dietzenbacher et al., 2013; Lenzen et al., 2013; Tukker et al., 2013; Wood et al., 2014). In this study we used EXIOBASE database for the MRIO model that we applied to evaluate the GHG emissions of WTT (upstream) phase. The direct and indirect financial flows between different sectors of different countries are EXIOBASE (Wood et al., 2014) and then Leontief inverse is applied (Leontief, 1970) to find the consumption of inputs required in operation phase, impacts contributed to WTT stage.

In Eq. 1, , the A^{RS}_{ij} shows the direct requirement matrix. In this matrix, rows accounts for national and global required inputs to produce one unit of output. $a^{RS}_{ij\,s}$ as an element of this matrix indicates the input from sector i of country R which is traded for output of industry j of in country S. And the total economic output can be calculated by global Leontief model, as given in formula:

$$x^r = [(I - A^{RS}_{ij})^{-1}]f_i^r \qquad \text{Eq. (1)}$$

We obtain total requirement matrix, $(I-A^{RS}_{ij})^{-1}$, which is also known as the Leontief inverse (Leontief, 1970). Then multiply it by f_i^r which shows the economic output of sector i in country R and zero elsewhere and calculate the total output vector, X^r. In this formula, I is the unite matrix. By multiplying this total output vector by factor impacts, E_{dir}, we calculated the total environmental impacts corresponding to per million Euro of output produced by sectors of operation phase:

$$r= E_{dir}x=E_{dir}[(I- A^{RS}_{ij})^{-1}]\ f_i^r \qquad \text{Eq. (2)}$$

In this study, we considered different types of vehicles which can be used as taxi in Istanbul. We considered conventional internal combustion engine vehicles (CV) which uses gasoline or diesel or an alternative fuel such as Liquefied Petroleum Gas (LPG) to run. Besides conventional vehicles, alternative ones including battery electric vehicle (BEV) and plug-in hybrid electric vehicle (PHEV) are in our analysis. Internal combustion engines are replaced by electric motors in BEV and uses electric batteries which produce electricity. PHEV uses rechargeable batteries that can be recharged by external sources of electric power. The detailed information of car models we analyzed in this study are in Table 1.

Table 1. Vehicles properties

	Gasoline	Diesel	LPG	PHEV	EV
Brand	Renault Clio	Renault Clio	Renault Clio	Toyota Prius	Renault Zoe
Model[1]	Icon 1.2 EDC 120 bg	Icon 1.5 dCi EDC 90 bg	Icon 1.2 EDC 120 bg	-	-
Battery Capacity[2]				8.8 kwh	22 kwh
Cylinder Volum[3]	1197 cm^3	1461 cm^3	1197 cm^3		
Range[4]				40 km electric battery Total range= 640 km	100-150 km
Fuel Consumption /100 km[5]	5.3 lt	3.6 lt	6.36 lt	15.5 kwh electricty 4.35 lt gasoline	13.6 kwh
Sale Price[6]	71.800 TL	82.150 TL	71.800 TL	101.725 TL	66.500 TL
Motor Vehicle Taxe(twice a year)[7]	646 TL	1035 TL	646 TL	0 TL	0 TL
Battery cost /month[8]	0 TL	0 TL	0 TL	0 TL	442 TL
Salvage Value	23.933 TL	27.383 TL	23.933 TL	33.908 TL	22.166 TL

Here, environmental impacts in WTT stage are calculated by using the multipliers per £M output of operation sector. Table 2 shows the different sectors included in operation phase. Then, we used production price (£) for producing one gallon of petroleum or one kWh electricity to calculate fuel cost per kilometer of each vehicle. And the environmental impacts related to WTT stage of operation phase is gained by multiplying the monetary value of consumption per kilometer and the associated sector multiplier given in Table 2. Also, the fuel economy (FE) of the vehicles are in table 1. The FE values of the vehicles are similar to their currently available models in the market. FE of CV which use gasoline, diesel, and LPG are 5.3, 3.6, and 6.36 liter per kilometer respectively. The FE for EV is 13.6 kWh/km and EF for PHEV is considered as 4.35 liter/km in gasoline mode and 15.5 kWh/km in electric mode.

[1] https://www.cdn.renault.com/content/dam/Renault/TR/global-brochures/Clio-201610.pdf
[2] http://www.toyota.com/priusprime/, https://www.cdn.renault.com/content/dam/Renault/TR/global- brochures/ZOE.pdf

[3] https://www.cdn.renault.com/content/dam/Renault/TR/global-brochures/Clio-201610.pdf
[4] http://www.toyota.com/priusprime/ , https://www.cdn.renault.com/content/dam/Renault/TR/global-brochures/ZOE.pdf
[5] https://www.cdn.renault.com/content/dam/Renault/TR/global-brochures/Clio-201610.pdf http://www.toyota.com/priusprime/ , https://www.cdn.renault.com/content/dam/Renault/TR/global-brochures/ZOE.pdf
[6] http://www.yenivasita.com/araba/renault/clio , http://www.toyota.com/priusprime/, https://www.arabam.com/sifir-km/renault-zoe
[7] http://www.resmigazete.gov.tr/main.aspx?home=http://www.resmigazete.gov.tr/eskiler/2016/12/20161227.htm&main=http://www.resmigazete.gov.tr/eskiler/2016/12/20161227.htm
[8] https://www.renault.co.uk/renault-finance/battery-hire.html

Table 2. GHG emissions corresponding to per million Euro of output of associated sectors

Life Cycle Phase		Industry Code	Industry Type	GHG emissions (kg-CO_2-eqv.) per million Euro
Vehicle operation	***Electric power generation, transmission, and distribution***	i40.11.a	Production of electricity by coal	1,4381,645.28
		i40.11.b	Production of electricity by gas	5,491,543.535
		i40.11.c	Production of electricity by nuclear	0
		i40.11.d	Production of electricity by hydro	172,555.5347
		i40.11.e	Production of electricity by wind	173,847.5988
		i40.12	Transmission of electricity	4,731,406.277
		i40.13	Distribution and trade of electricity	4,742,705.313
	Petroleum refineries	i23.2	Petroleum Refinery	1,567,280.001
	Automotive repair and maintenance, except car washes	i50.a	Sale, maintenance, repair of motor vehicles, motor vehicles parts, motorcycles, motor cycles parts and accessories	503,127.0895

To calculate TTW impacts, we use the direct energy consumption, GHG emissions, and FE of each vehicle. PHEV needs a different calculation because they have both gasoline and electricity mode. The portion that PHEV use electricity to run is determined by utility factor (UF). Using the capacity of electric battery of Toyota Prius (PHEV), 40 km capacity, and daily 350 km driven distance by this vehicle as a taxi in Turkey, UF is of electricity equals to 40/350. It shows that 0.11 portion of daily traveling is run by electric mode and the rest are run by using gasoline. Then, we can calculate the total environmental impacts for PHEV as follows:

$$(\text{Impacts per kilometer}) = UF\times \{FE_{Elct.} \times (\text{WTT impacts}_{\text{Power generation}}) + (\text{TTW impacts})\} + (1-UF) \times \{1/ FE_{\text{gasoline}}\times (\text{WTT impacts}_{\text{gasoline production}}) + (\text{TTW impacts})\} \quad \text{Eq. (3)}$$

The first part of Eq. 3 represents the impacts related to electricity mode consumption and the second part indicates the environmental impacts associated with the gasoline mode. the UF for three types of CV (Gasoline, diesel, and LPG) is equal to 0 while it is 1 for EV. Maintenance and repair (M&R) of the vehicles is another factor to consider in operation phase. The M&R cost for EV and PHEV are less than conventional vehicles because of less maintenance required for electric motors and having fewer components (Delucchi and Lipman, 2001; Faria et al., 2012). The M&R costs of each vehicle is multiplied by the environmental impact multiplier of the operation sector.

3. Results and discussion

The quantified environmental impacts attributed to operation phase of each vehicle type is shown in Figure.1. Total amount of GHG produced per kilometer is the summation of GHG emission for generating electric power, transmitting, distributing, petroleum refineries, and repair and maintenance, except car washes of operation phase. Figure 1a. shows the percentage contribution of each phase (WTT and TTW) and M&R. According to the results, contribution of upstream impacts (WTT) dominates the total GHG emissions for gasoline, diesel, LPG, and PHEV. On the other hand, because the EV doesn't have any tailpipe emissions, all of the emissions associated with EV occurs in the fuel supply chain (electricity generation).

Fig. 1b. shows the GHG emissions per kilometer travel in each phase for each vehicle type. According to the analysis results, the gasoline vehicle has the highest amount of emissions per km, while rest of the alternatives has considerable lower emissions. Diesel type vehicle has the least GHG emission associated with WTT stage and EV accounts for the highest GHG produced in upstream part of vehicle operation. LPG type has the least GHG amount produced in TTW stage while gasoline type produces the most GHG in this stage. EV emits less GHG contributed to maintenance stage, however diesel type has the highest GHG in this stage in comparison to other types of vehicles. But, overall, CV which uses gasoline has the highest GHG emissions for petroleum refinement activity in operation, followed by PHEV as the second highest, and EV has the lowest emission among considered vehicle types.

As can be seen from Fig. 1b, the GHG emissions of EV and LPG vehicle are 130 and 123 gCO_2-eqv./km, respectively. LPG is the most common fuel source for taxis in Turkey, especially in Istanbul. Considering that the marginal difference in these two vehicle types is very low, the carbon emission reduction potential of the EV is lower than expected. This is mainly because of the high fossil fuel dependence in the electricity generation mix in Turkey. High shares of coal and natural gas in the electricity generation mix limit the potential benefits of EVs in terms of carbon emissions.

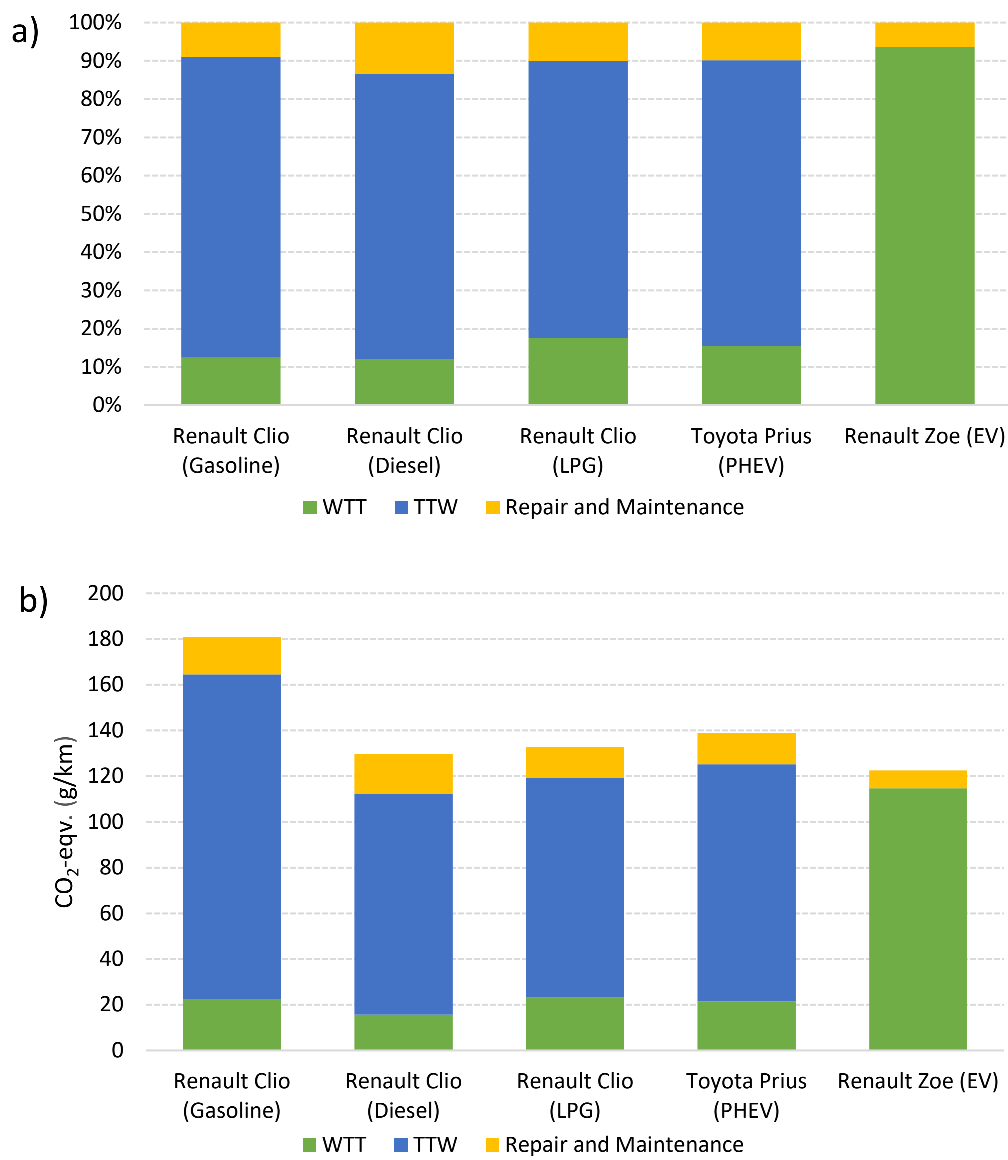

Figure 1. GHG emissions (g-CO_2-eqv. per km)

According to Climate Action Network during the U.N. Climate Summit (Burck, 2009) Turkey's performance toward rising GHG emissions was not sufficient though many policies were acted in 2009. After 2012, Turkey has promoted in its performance of dealing with GHG emissions because of integrating more renewable energy plants with electricity system. Transportation in Turkey is one of the sectors that has a high potential to reduce growing GHG emissions. Turkey's growing population and consequently increasing demand for vehicles force government and organizations to act serious policies toward transportation sector. Within this sector, taxis attract more attention because of their increasing number as well as more traveling distance in comparison to other vehicles in a daily life. As it is obvious from the results, Turkish government should promote the adoption of EV among taxi drivers to have more reduction in GHG emissions, while increasing the use of renewable energy sources for electricity production. By using more EV as taxi, large proportion of fuel consumption can be removed. Besides having cleaner air and lower GHG emissions, Turkey can benefit from many consequences such as less fuel dependency to other countries.

4. Conclusions

Recently, increasing level of awareness regarding the effects that GHG have on ecological balance as well as raising fuel prices have been attracted the attention of governments and automobile manufacturers toward vehicles which use alternative energy sources like electricity. This study focused on the environmental aspects of macro-level sustainability for five different types of vehicles which can be used as taxi in Turkey. In this study, Hybrid MRIO model, has been used to evaluate the environmental impacts of operation phase. We concentrated on operation phase since it is the most influential stage in terms of environmental effects in comparison to other life cycle stages. Amount of GHG produced in operation phase, as an indicator of environmental impacts has been analyzed and quantified by a Hybrid MRIO model. GHG emission in vehicles' operation includes electric power generation, transmission, distribution, petroleum refineries, and repair and maintenance, except car washes. Our results showed that conventional vehicles which are powered by gasoline emit the highest GHG while electric vehicles accounts for the least amount. In terms of GHG emissions, EV is a great competitor to conventional ones. This assessment aims to guide Turkish government to act policies to attract consumers' attention, especially taxi owners to electric vehicles in Turkey. Besides the fact that EV are superior in terms of environmental cleanness, Turkey can help them to be cost effective. One of these policies might be changing the motor vehicle tax policy. The reduction in amount of motor vehicle tax for EV can be a one of motivations to adopt EV among taxi drivers.

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