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Life cycle greenhouse gas analysis for automotive applications – A case study for taxis in Singapore

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Abstract

Within a life cycle analysis, we assess Greenhouse Gas (GHG) emissions and their environmental impact with respect to global warming for four different powertrain technologies. These are vehicles using petrol, diesel and Compressed Natural Gas (CNG) as well as Battery Electric Vehicles (BEVs). First, characteristics are derived for using the vehicles as taxis in Singapore. Then the upstream emissions of fuel and electricity supply are assessed in a Well-To-Tank (WTT) analysis and combined with the Tank-To-Wheel (TTW) emissions from fuel combustion in the engine. Electricity is found to cause least emissions per driven kilometre followed by CNG and diesel, whereas petrol ranks worst. The GHG emissions caused by the production of the respective vehicles are also analysed showing that BEVs cause highest emissions mainly due to the necessary battery production. However, after a total life-time mileage of 1.1 million km, the BEV taxi shows lowest emissions followed by the CNG vehicle. A brief sensitivity analysis proves that this result is quite stable and it shows that the vehicle consumption, the emission factor of the electricity generation in Singapore and the cycle stability of the battery have the greatest influence on the overall results.

Keywords: Life cycle, battery electric vehicle, electromobility, greenhouse gas emissions, environmental impact

1. Introduction

Like all fields of human life, mobility is also developing in line with current global megatrends. One of these major trends is urbanization which causes the majority of the world population to live in urban areas today [1]. As a result, the traffic load can lead to major logistic problems and limit both private and commercial transport in urban areas. Another key development today is the penetration of Information and Communication Technology (ICT) in almost every technology related sector: in the case of mobility, multiple ideas already exist which try to improve the efficiency of the transport sector for example by increasing vehicle occupancy. Furthermore, environmental concerns are expected to grow which will probably lead to stricter laws and regulations on vehicle emissions in most countries.

For all these reasons, TUM CREATE – a research cooperation between Nanyang Technological University (NTU) in Singapore and Technische Universität München (TUM) in Germany which is funded by the National Research Foundation (NRF) of Singapore – aims to develop an innovative and feasible vehicle concept that fulfils the requirements of future mobility in metropolitan cities like Singapore. One of the results is called EVA – Electric Vehicle Asia – which is a purpose-built taxi that can cover a significant share of efficient public transport in Asian megacities while at the same time providing a possibility for environmental friendly mobility.

However, the use of electric vehicles has some significant drawbacks: firstly, the limited range usually prohibits a high utilization of the vehicle. Thus, a suitable fast-charging technology is developed and will

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be tested on the EVA prototype. Further, the environmental impact of an electric vehicle strongly depends on the electricity mix used. Especially for Singapore, where about 80% of the electricity is generated by natural gas power plants, the question arises whether it is more environmentally friendly to use Compressed Natural Gas (CNG) as fuel for an Internal Combustion Engine (ICE). To answer this question, a Well-To-Wheel (WTW) analysis is performed for petrol, diesel, CNG and electricity and integrated in a Life Cycle Assessment (LCA) of vehicles using the energy carriers mentioned.

2. Methods

This section provides the methodology for the analysis described: it explains how LCAs are generally performed and what sources and values are used within this particular assessment.

2.1. Characteristics of life cycle assessment

Life cycle assessment is one of the most widely used methods for assessing and comparing the environmental impact of technological systems. System boundaries are introduced which include all relevant life phases of the product i.e. raw material supply, manufacturing, use and end-of-life treatment. All material flows crossing these system boundaries are assessed according to their environmental effect.

During the so-called *classification,* flows of substances which are different but have the same environmental consequences are grouped together, and during the subsequent *characterisation* step these material flows are weighted according to their severity. For example, CO_2 and CH_4 both are greenhouse gases and have an effect on global warming with different potency. CO_2 is chosen to be the reference substance for this *impact category* and 1 kg of emitted CH_4 is accounted with 25 kg CO_2-equivalents [2].

Generally, there are various impacts that can be assessed with this technique (e.g. human toxicity, depletion of fossil fuels or metals [3]) and advantages and disadvantages in these can be evaluated. In this analysis, however, only one impact category will be assessed, namely the *global warming potential* to which various greenhouses gases (GHGs) contribute. For this, the entire fuel supply chain is included within the system boundaries of the analysis just as the production of a vehicle with its individual powertrain technology.

2.2. Characteristics of vehicles used as a taxi

Especially in large cities, problems such as pollution and congestion are often caused by the local urban traffic. For this reason, policy-makers frequently try to decrease the share of vehicles in private use and to increase the share of public transport instead. In this context, taxis are quite an important element: in 2011, about 9 million passenger-km per day were covered by taxis in Singapore which represent about 19 % of the total public transport [4]. Annually, taxis drive a distance of about 135,000 km which is more than seven times the mileage of an average car. The life-time of a taxi can be assumed to be around 8 years as the certificate of entitlement – which every vehicle user in Singapore needs to purchase – is valid for this period of time. This results in an overall life-time mileage of about 1.1 million km which is several times higher than the mileage of a private vehicle.

Depending on the number of use days and depending on whether the taxi is used in one or in two shifts, the average distance driven per day can be estimated to be within 350-550 km. Since this mileage is quite high compared to the range of most electric vehicles, EVA is equipped with a high-power direct current (DC) charging technology. This enables a power of about 160 kW reducing the charging time to about 15 minutes. By this, electric vehicles, which would otherwise not be qualified for this purpose due to their limited range, can be used as taxis.

2.3. Powertrain technologies and greenhouse gas emissions from vehicle and battery production

Four powertrain technologies are compared to each other and their environmental advantages and disadvantages are analysed. These are: ICEs using petrol, diesel and CNG as well as electric motors with externally charged battery. In order to compare these powertrain technologies, generic vehicle characteristics are derived from data found in the literature, i.e. car manufacturer data and research reports [5]-[12]. For reasons of data availability, the properties of the electric vehicle concept EVA are used for the category of battery electric vehicles (BEVs).

The range of the key properties of the assessed vehicles can be found in Table 1.

Table 1. Characteristics of the assessed vehicles and powertrains

Characteristics	Petrol vehicle	Diesel vehicle	CNG vehicle	BEV
Vehicle weight incl. battery	1,100-1,500 kg	1,100-1,500 kg	1,200-1,600 kg	1,500 kg
Maximum power	70-90 kW	70-100 kW	70-110 kW	80 kW
Assumed tank or battery capacity	42 l	30 l	30 kg	50/35* kWh
Fuel or electricity consumption per 100 km **	6.2 l	4.8 l	4.4 kg	13.1 kWh
Additional consumption for A/C per 100 km	1.2 l	0.9 l	0.8 kg	2.6 kWh
Total fuel or electricity consumption per 100 km	7.4 l	5.7 l	5.2 kg	15.7 kWh
Time for tank or battery refill	~ 5 min	~ 5 min	~ 5 min	~ 15 min

* In order to prolong the life-time of the battery, only 70 % of its capacity is used.

** According to 100 km in the NEDC without air condition.

Obviously, the vehicles considered cannot provide exactly the same properties. Therefore, mean values are calculated from a sound base of vehicles similar to the class of small multi utility vehicles in order to ensure reliability of the generic values.

As the taxi should be suitable for Singapore, the energy consumption caused by air conditioning (A/C) – which is not considered in the New European Driving Cycle (NEDC) – is essential. It is assumed that the A/C compressor in the BEV has a Coefficient of Performance (COP) of 2.1. This value is 1.05 times higher for conventional vehicles as the transformation of electrical into mechanical energy is not necessary. The thermal load which has to be removed from the vehicle cabin is estimated to be 1700 W. The efficiencies of the ICEs in the NEDC are taken from a literature source [13]. As the compressor is directly driven by the engine and no power flow through the gearbox occurs, these values are further increased by the efficiency of the transmission (assumed to be 95 %).

Unlike the fuel consumption of a vehicle – which needs to be measured according to international standards – data regarding the environmental impact of production and end of life of a vehicle are not published for most vehicles. However, some car manufacturers publish reports on the life cycle performance of their cars on a voluntary basis [7]-[10]. Research institutions also often conduct assessments for which they use generic data of typical vehicles in order to model future vehicle concepts [6], [14]. These sources are used to estimate the environmental impact of the production of a BEV excluding the vehicle battery. It must be mentioned that EVA is a very light vehicle since a great share of its body is made of Carbon Fibre Reinforced Plastic (CFRP). This material, however, causes high GHG emissions during production, which means the figures taken from the literature sources have to be increased accordingly [15]. In accordance with the literature sources mentioned, the end-of-life phase of the assessed vehicles is considered negligible in this study. The results can be found in Table 2.

Table 2. GHG emissions from vehicle production

GHG Emissions	Petrol vehicle	Diesel vehicle	CNG vehicle	BEV
Emissions from vehicle production w/o battery	5,860 kg CO_2-eq.	6,130 kg CO_2-eq.	6,840 kg CO_2-eq.	8,310 kg CO_2-eq.
Emissions from battery production	15 kg CO_2-eq./kWh	15 kg CO_2-eq./kWh	15 kg CO_2-eq./kWh	150 kg CO_2-eq./kWh
Battery capacity	~ 0.8 kWh	~ 0.8 kWh	~ 0.8 kWh	50 kWh
Total emissions from production	5,870 kg CO_2-eq.	6,140 kg CO_2-eq.	6,850 kg CO_2-eq.	15,810 kg CO_2-eq.

A crucial part for the environmental impact of an electric vehicle is the vehicle battery. The installed capacity and the battery technology used determine the GHG emissions related to the production of this key component. The data given for the production of a lithium-ion (Li-ion) traction battery in the literature varies significantly throughout the individual sources [6], [14], [16], [17]. Within this study, an emission factor of 150 kg CO_2-eq. per kWh of installed Li-ion battery capacity is chosen. As lead-acid batteries are recyclable very well, the impact of the automotive SLI (starting, lighting, ignition) batteries in conventional vehicles is very small. It is reported to be about a tenth of the value that is considered for Li-ion batteries (Table 2) [18].

All batteries suffer from irreversible electro-chemical processes which occur during each charge and discharge, limiting the life-time of the battery. Battery cells which are used in BEVs are optimized to have high cycle stability. Thus, many battery manufacturers announce that about 2,000 full charge-recharge cycles are possible and if only a part of the battery capacity is used, the number of possible cycles increases significantly [19]. However, fast-charging is expected to decrease the number of possible cycles considerably but literature sources estimate that a suitable charging technology applied to certain battery technologies might still allow several thousand cycles [20].

As the assumed average mileage per working day varies between 350 km and 550 km (section 2.2) and the maximum range per charging cycle is slightly more than 200 km, the battery has to be charged at least twice or even three times a day. For a conservative estimate and considering that the battery capacity cannot always be used optimally, we assume an average of 3.5 charges per working day. It has to be mentioned that only 70 % of the battery capacity are used and not all cycles are expected to be done with fast-charging: between two shifts or especially if the taxi is used only for one shift per day, there is sufficient time for slow-charging which places significantly less strain on the battery. Even though the effect of fast-charging on the life-time of the battery is not predictable, we assume that significant improvements will occur within the next years. Hence, a number of 3,000 possible charging cycles for the calculations is estimated in this study. This results in a life-time of about 860 working days and thus a mileage of about 390,000 km. After this distance, we assume that the performance of the battery pack has reached the lower level of acceptance and it will become necessary to replace it by a new battery pack. A possible subsequent use in a stationary application is not considered in this study.

2.4. Fuel consumption and tank-to-wheel emissions

The so-called tank-to-wheel emissions (TTW) are released from the exhaust pipe of conventional vehicles due to the fuel combustion in the ICE. In case of BEVs, no TTW emissions occur at all of course. The emission factors of petrol, diesel and CNG differ significantly because of the different physical and chemical characteristics of these fuels. The respective emission factors are chosen from the literature and are shown in Table 3 [5].

Table 3. Fuels and their GHG emissions

Final energy	WTT emissions	TTW emissions	Consumption / 100 km		WTW emissions/100 km
Petrol	0.46 kg CO_2-eq./l	2.36 kg CO_2-eq./l	7.4 l	(66.2 kWh)	20.9 kg CO_2-eq.
Diesel	0.57 kg CO_2-eq./l	2.63 kg CO_2-eq./l	5.7 l	(56.8 kWh)	18.2 kg CO_2-eq.
CNG	0.39 kg CO_2-eq./kg	2.54 kg CO_2-eq./kg	5.2 kg	(65.1 kWh)	15.2 kg CO_2-eq.
Electricity	0.57 kg CO_2-eq./kWh	0.00 kg CO_2-eq./kWh	18.5 kWh		10.6 kg CO_2-eq.

The electricity consumption of the BEV is adjusted assuming a relatively low charging efficiency of 85 % due to high losses from fast-charging. This results in an electricity demand of 18.5 kWh/100 km from the grid.

2.5. Upstream emissions: well-to-tank emissions

Well-to-tank emissions (WTT) occur when primary energy is converted into final energy i.e. the processing of a fossil primary energy carrier into the fuel type which is used in an ICE. Each powertrain assessed requires a different type of fuel whose production causes different upstream emissions (Table 3). Upstream GHG emissions of conventional fuels in Singapore are found to be similar to European emissions: crude oil is mainly imported from OPEC countries and directly refined in Singapore. Gas supply is secured by pipelines from Malaysia and Indonesia which means that transport distances are quite short [21]. Due to the similar situation, it is possible to use data on upstream emissions within the European context for modelling the situation in Singapore [5]. The GHG emissions from electricity supply in Singapore are derived from data on upstream CO_2 and CH_4 emissions [22] using the common equivalent factors [2].

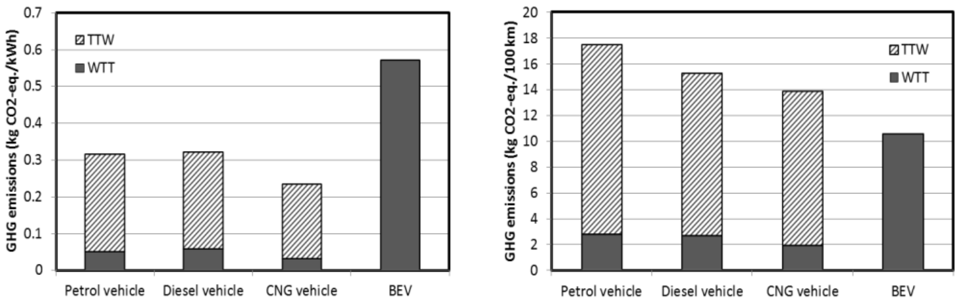
3. Results and Discussion

In this chapter, the results of assessing different powertrain technologies for taxis in Singapore will be presented and discussed.

3.1. Overall emissions: well-to-wheel

The upstream GHG emissions (WTT) per energy content are significantly higher for electricity than for fossil vehicle fuels (Fig. 1 (a)). This is caused by the higher upstream efficiencies of petrol, diesel and CNG production compared to the lower efficiency of electricity generation and distribution. However, electricity production in Singapore has changed from an oil-dominated generation to a gas-dominated one within the last decade, leading to considerable improvements regarding its GHG emissions [21], [23].

The total GHG emissions per final energy (WTW) are calculated based on the specific direct emissions in the vehicle (TTW) and the already mentioned upstream (WTT) emissions. As can be seen in Fig.1 (a), total emissions from petrol and diesel are on the same level at around 0.3 kg CO_2-eq./kWh whereas CNG emissions are lower. The GHG emissions per energy are highest for electricity in Singapore and obviously comprise only upstream emissions.



(a) (b)

Fig. 1. GHG emissions per kWh final energy (a) and GHG emissions per driven 100 km (b).

In order to achieve a holistic assessment of the powertrain technologies investigated, the specific fuel consumptions also have to be considered (Fig. 1 (b)). Despite the high upstream emissions, BEV taxis in Singapore achieve the lowest GHG emissions per driven distance compared to petrol, diesel and CNG cars. The reason for this is a relatively low final energy demand of the vehicle due to the high efficiency of the electric motor compared to conventional engines.

3.2. Emissions from vehicle and battery production

The GHG emissions from vehicle production can be found in Table 2. It can be seen that a petrol vehicle causes lowest emissions during manufacture whereas a diesel vehicle emits a slightly higher amount. A car using CNG is very similar to a petrol car: the same engine (with small adjustments) can be used; the fundamental differences are the additional natural gas tank and the additional ducting which lead to an increased amount of emissions. The high emissions caused during the production of an electric vehicle strongly depend on the size of the battery or – as in the case of EVA – the use of special lightweight materials.

3.3. Total life cycle emissions

Fig. 2 shows the accumulated GHG emissions over a certain life-time mileage for taxis with different powertrains in Singapore.

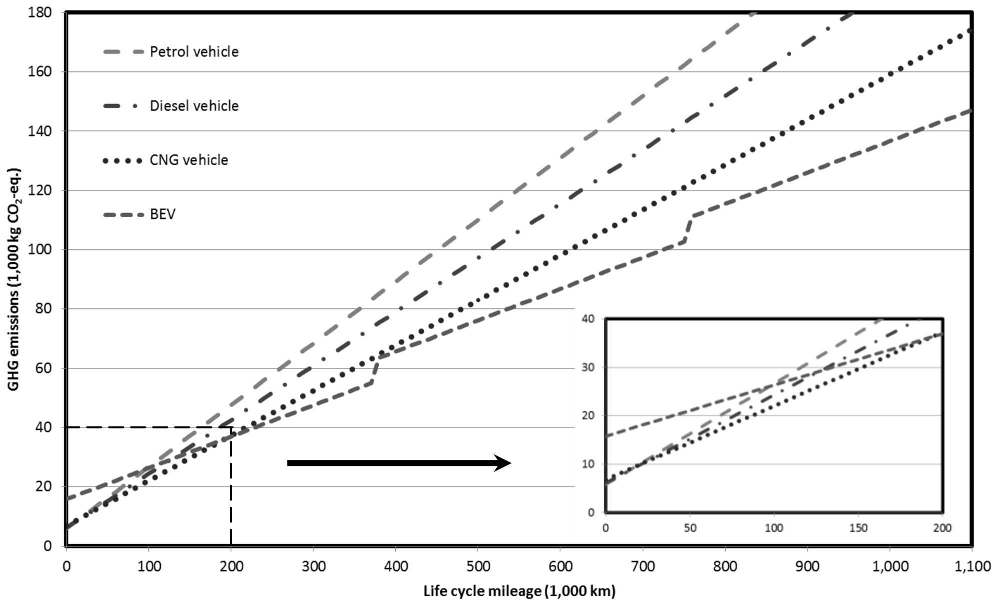


Fig. 2. GHG emissions during the life cycle of a taxi in Singapore.

The starting points of vehicles with ICEs are very close to each other, since the amount of emitted GHGs during their production is quite similar. The slope of the lines depends on the emissions during driving. Hence, the line representing the petrol vehicle is the steepest, followed by diesel and CNG. As the production of an electric vehicle leads to highest emissions, the y-intercept of its line is highest. However, as its slope is flatter than that of all other lines – due to the lowest emissions during driving – the BEV line becomes the lowest for greater mileages (over ~200,000 km). The steps in its graph indicate the renewal of the battery pack which results in additional emissions during the use phase. After the total life-time mileage of 1.1 million km, the BEV shows the lowest amount of GHG emissions (147,210 kg CO2-eq.). This is 15.6 % less compared to the amount of GHGs emitted by a CNG vehicle, 28.7 % less compared to a diesel car and 37.4 % below the emissions of a petrol vehicle.

These values are the outcome of the baseline (BL) analysis to which the results of the input parameter variation will be compared to in the next section.

3.4. Reliability of the results

Since this study assesses a yet non-existent BEV and long-term knowledge e.g. on the battery ageing in particular is currently not available, some assumptions and simplifications are used within this assessment. Further, much of the used data is derived from various literature sources providing different values. All the data used is checked for consistency and plausibility and average values from various sources are calculated in order to minimize potential deviations and errors. Additionally, a sensitivity analysis is performed to determine the influence of certain input parameters.

In Table 4 the influence of the input parameters used for the BEV is assessed. The table shows the relative change of the calculated GHG emissions after a parameter variation of +/- 20 %.

Table 4. Influence of input parameters of the BEV on its life cycle GHG emissions

	Input parameter variation: - 20 %	Input parameter variation: + 20 %
Varied input parameter for BEV	Variation to baseline calculation	Variation to baseline calculation
Upstream WTT emissions (BEV)	- 15.8 %	+ 15.8 %
Emissions battery production (BEV)	- 3.1 %	+ 3.1 %
Cycle stability of the battery (BEV)	+ 5.1 %	+/- 0.0 %
Energy consumption (BEV)	- 15.8 %	+ 15.8 %

Table 5 shows the consequences resulting from the same variation of the input parameters characterising the CNG vehicle. Only in one case – if the consumption of the CNG vehicle is decreased by 20 % – the total GHG emissions of the CNG vehicle are lower than the ones of the BEV. In all other calculations, BEVs emit the lowest amount of GHG emissions.

Table 5. Influence of input parameters of the CNG vehicle on its life cycle GHG emissions

	Parameter variation: - 20 %	Parameter variation: + 20 %
Varied input parameter of BEV	Variation to baseline calculation	Variation to baseline calculation
Upstream WTT emissions (CNG)	- 2.6 %	+ 2.6 %
Energy consumption (CNG)	- 19.2 %	+ 19.2 %

The consumption of both vehicle technologies and the upstream emissions of electricity show the highest influence among all parameters. Further, the cycle stability has a considerable influence if the number of battery replacements during the life-time of the BEV is altered. The emissions from the battery production and the upstream emissions of CNG are of minor importance.

It must be considered that the variation is set rather arbitrary to ± 20 % for all parameters. This does not necessarily represent the likely range of possible values or the expected future development. The upstream emissions of electricity are expected to decrease in the future as the share of renewable energies in the electricity mix will most probably rise. With future experience in battery technologies and manufacture, the production emissions and the cycle stability will certainly improve. A decrease of 20 % in the energy consumption of BEVs seems rather unlikely since efficiency is already quite high. The upstream emissions of CNG supply are assumed to rise in the future since fossil fuel deposits become scarcer and alternative production technologies like fracking have to be used, requiring more energy and causing more emissions. Nevertheless, it might be possible to achieve significant improvements in the consumption of CNG vehicles. This could be possible through a more efficient combustion process or the electrification of the powertrain.

4. Conclusion and Outlook

In this study, a holistic assessment of four different powertrain technologies was carried out. It was shown that BEVs used as taxis in Singapore lead to a decrease in GHG emissions. Admittedly, the outcome of the assessment strongly depends on hardly predictable parameters such as the effect of fast-charging on the life-time of the vehicle battery. Nevertheless, even if these influential parameters are chosen in favour of CNG vehicles, the GHG emissions of a BEV taxi are less for most of the possible calculations.

This analysis only covers four powertrains, with each using one particular type of fuel. Hybrid vehicles, however – which will increasingly penetrate the market in the future – might combine the advantages of two powertrains leading to a lower impact on global warming than the technologies assessed in this study. Also, a possible use of old vehicle batteries in stationary applications could not be considered. The consideration of these aspects might extend the insights given by this study.

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