COMPARISON OF ENVIRONMENTAL PERFORMANCES OF PASSENGER VEHICLES IN KAMPALA/UGANDA

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Master's Thesis

Department of Environmental Engineering

Programme in Environmental Science

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ABSTRACT

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Kampala is rapidly growing and widening and in a few years to come authorities have to choose on the specific modes of passenger transport that are required to serve the city dwellers. To make decisions on such a critical issue various studies and researches have to be carried out. This thesis can be among the studies that can set a groundwork for a procedure that can be used to efficiently select the best passenger transportation modes for the city in relation to environmental sustainability. Using the Life Cycle Assessment (LCA) method, the energy inputs and emissions from the 14-seater minibuses (Kamunye), 29-seater minibuses (Coaster), BodaBoda motorcycles and the three-wheeler TukTuk motorcycles while transporting passengers were quantified. Inventory results were normalized to environmental effects per kilometer covered while transporting a passenger using a specific motor vehicle. Simapro 8.5.0 software was used to analyze the inventory data and results were evaluated in terms of impact categories such as acidification potential, global warming potential, fossil fuel based abiotic depletion potential among others. The findings of this thesis are very important to the Kampala city administration and other authorities of cities in other developing countries while deciding on the most sustainable passenger transportation system from an environmental point of view.

Keywords: Kampala city, Life cycle assessment, Public transportation.

ÖZET

KAMPALA/UGANDA'DA YOLCU TAŞIYAN ARAÇLARIN ÇEVRESEL PERFORMANSLARININ KARŞILAŞTIRILMASI

Muhammad KALIFA

Çevre Mühendisliği Anabilim Dalı

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İkinci Danışman: Dr. Öğr. Üyesi Alp ÖZDEMİR

Hızla büyüyen ve genişleyen bir şehir olan Kampala'da yöneticilerin, birkaç yıl içinde kentiçi yolcu taşımacılığı için önemli kararlar vermesi gerekmektedir. O nedenle bu konuda karar vermek için çeşitli çalışmaların ve araştırmaların yapılmasına ihtiyaç vardır. Bu tez çalışması, çevresel sürdürülebilirlik ile ilgili olarak kent için optimum yolcu taşımacılığı modlarını seçmede kullanılacak bir prosedürün geliştirilmesini amaçlamaktadır. Bu amaç doğrultusunda tezde, Yaşam Döngüsü Değerlendirmesi (LCA) yöntemi kullanılarak, 14 kişilik minibüslerden (Kamunye), 29 kişilik minibüslerden (Coaster), "BodaBoda" motosikletlerinden ve üç tekerlekli "TukTuk" motosikletlerinde yolcular taşınırken çıkan gaz emisyonları ve bu araçların enerji girdileri ölçülmüştür. Envanter sonuçları, belirli bir motorlu araç kullanarak bir yolcu taşınırken katedilen kilometre başına çevresel etkilere göre normalleştirilmiştir. Envanter verilerini analiz etmek için lisanslı Simapro 8.5.0 yazılımı kullanılmış ve sonuçlar, diğer çevresel etki kategorileri arasında asidifikasyon potansiyeli, küresel ısınma potansiyeli, abiyotik kaynakların (fosil yakıtlar) tükenme potansiyeli gibi etki kategorileri açısından değerlendirilmiştir. Bu çalışmanın bulgularının, çevresel açıdan en sürdürülebilir yolcu taşımacılığı sistemine karar verirken Kampala kent yönetimi ve diğer gelişmekte olan ülkelerdeki şehirlerin yöneticilerine de katkıda bulunacağı düşünülmektedir.

Anahtar Sözcükler: Kampala şehri, Yaşam döngüsü değerlendirme, Kent içi yolcu taşımacılığı.

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Muhammad KALIFA

10/08/2020

STATEMENT OF COMPLIANCE WITH ETHICAL PRINCIPLES AND RULES

I hereby truthfully declare that this thesis is an original work prepared by me; that I have behaved in accordance with the scientific ethical principles and rules throughout the stages of preparation, data collection, analysis and presentation of my work; that I have cited the sources of all the data and information that could be obtained within the scope of this study, and included these sources in the references section; and that this study has been scanned for plagiarism with “scientific plagiarism detection program” used by Eskişehir Technical University, and that “it does not have any plagiarism” whatsoever. I also declare that, if a case contrary to my declaration is detected in my work at any time, I hereby express my consent to all the ethical and legal consequences that are involved.

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GLOSSARY OF SYMBOLS AND ABBREVIATIONS

A.C	:	Air Conditioner
ACC	:	American Chemistry Council
ADB	:	Asian Development Bank
ADP	:	Abiotic Depletion Potential
ADP_{ff}	:	Fossil Fuel based Abiotic Depletion Potential
AP	:	Acidification Potential
API	:	American Petroleum Institute
APA	:	American Psychological Association
BEV	:	Battery Electric Vehicle
BOD	:	Biochemical Oxygen Demand
BRT	:	Bus Rapid Transport
BSI	:	British Standards Institution
CFC	:	Chlorofluorocarbon
CFP	:	The database for the Carbon Footprint of Products Japan
CML	:	Leiden University Institute of Environmental Sciences
COD	:	Chemical Oxygen Demand
COMCEC	:	Standing Committee for Economic and Commercial Cooperation of the Organization of the Islamic Cooperation
CPCB	:	Central Pollution Control Board-Ministry of Environment, Forest and Climate Change of India
DB	:	Dichlorobenzene
EBIR	:	Equal Benefit Incremental Reactivity
EEA	:	European Environment Agency
EIA	:	United States Energy Information Administration
EIME	:	Environmental Improvement Made Easy
ELCD	:	European reference Life Cycle Database
EoL	:	End of Life
EP	:	Eutrophication Potential
EPA	:	United States Environmental Protection Agency
ESMAP	:	Energy Sector Management Assistance Program

EU	:	European Union
EV	:	Electric Vehicles
FAETP	:	Freshwater Aquatic Eco-Toxicity Potential
FEV	:	Fuel Cell Electric Vehicle
GHG	:	Greenhouse Gas
GWP	:	Global Warming Potential
HC	:	Hydrocarbon
HCFC	:	Hydro-chlorofluorocarbon
HEV	:	Hybrid Electric Vehicles
HTP	:	Human Toxicity Potential
IBO	:	Austrian Institute for Healthy and Ecological Building GmbH
ICE	:	Internal Combustion Engine
ICE	:	Inventory of Carbon and Energy
ICEVe	:	Conventional Internal Combustion Engine Vehicle powered by aqueous ethanol
ICEVf	:	Conventional Internal Combustion Engine Vehicle powered by gasoline and aqueous ethanol
ICEVg	:	Conventional Internal Combustion Engine Vehicle powered by gasoline
ICTI	:	Integrated City Transportation Infrastructure Program
IEA	:	International Energy Agency
INTALInC	:	International Network for Transport and Accessibility in Low Income Communities
IPCC	:	Intergovernmental Panel on Climate Change
IPT	:	Intermediate Public Transport
ISO	:	International organization for Standardization
JICA	:	Japan International Cooperation Agency
KCCA	:	Kampala Capital City Authority
LCA	:	Life Cycle Assessment
LCI	:	Life Cycle Inventory
LCIA	:	Life Cycle Impact Assessment
LCV	:	Light Commercial Vehicle
LPG	:	Liquid Petroleum Gas

MAETP	:	Marine Aquatic Eco-Toxicity Potential
MDC	:	More Developed Countries
MOIR	:	Maximum Ozone Incremental Reactivity
MoWT	:	Republic of Uganda Ministry of Works and Transport
MSETP	:	Marine Sedimental Ecotoxicity Potential
NGO	:	Non-Government organization
NMT	:	Non-Motorized Transport
NMVOC	:	Non-methane Volatile Organic Compound
ODP	:	Ozone Depletion Potential
OECD	:	organization for Economic Co-operation and Development
PBT	:	Public Bus Transport
PHEV	:	Plug-in Hybrid Electric Vehicle
PKM	:	Passenger Kilometer
PKT	:	Passenger Kilometer Travelled
PM	:	Particulate Matter
POP	:	Photochemical Oxidation Potential
PwC	:	Price Waterhouse Coopers
REGIS	:	Regional Geographic Information System
SUV	:	Sport Utility Vehicle
TETP	:	Terrestrial Ecotoxicity Potential
TfL	:	Transport for London
TRACI	:	Tool for the Reduction and Assessment of Chemical and other Environmental Impacts
TWC	:	Three Way Catalytic Converter
UAE	:	United Arab Emirates
UN	:	United Nations
UN-Habitat	:	United Nations Human Settlements Programme
UNRA	:	Uganda National Roads Authority
US LCI	:	US Life Cycle Inventory Database
US	:	United States of America
VOC	:	Volatile Organic Compound
WTW	:	Well to Wheels

1. INTRODUCTION

There are estimations that not later than the year 2050 68% of the population of the world will live in towns (Yang, Lei, & Li, 2019). In most European countries the people living in the cities are above 70% of the total country populations and estimations state that by 2030 a 10% increase is expected that is 80% of the population will be city dwellers. In cities with high population densities the demand for energy, mobility, raw materials, accommodation and leisure parks often exceeds the supply (Holden & Norland, 2005). Transportation is among the services which form the backbone of economies and when goods move from one place to another urban centers grow into cities, people's ways of living improve and different regions become interlinked (Paladugula, et al., 2018). The general trend regarding the increase of rural and urban population in the world cities in the period between 1950-2050 is given in Figure 1.1. Similarly, the trend in population growth is presented in Figure 1.2 for Uganda.

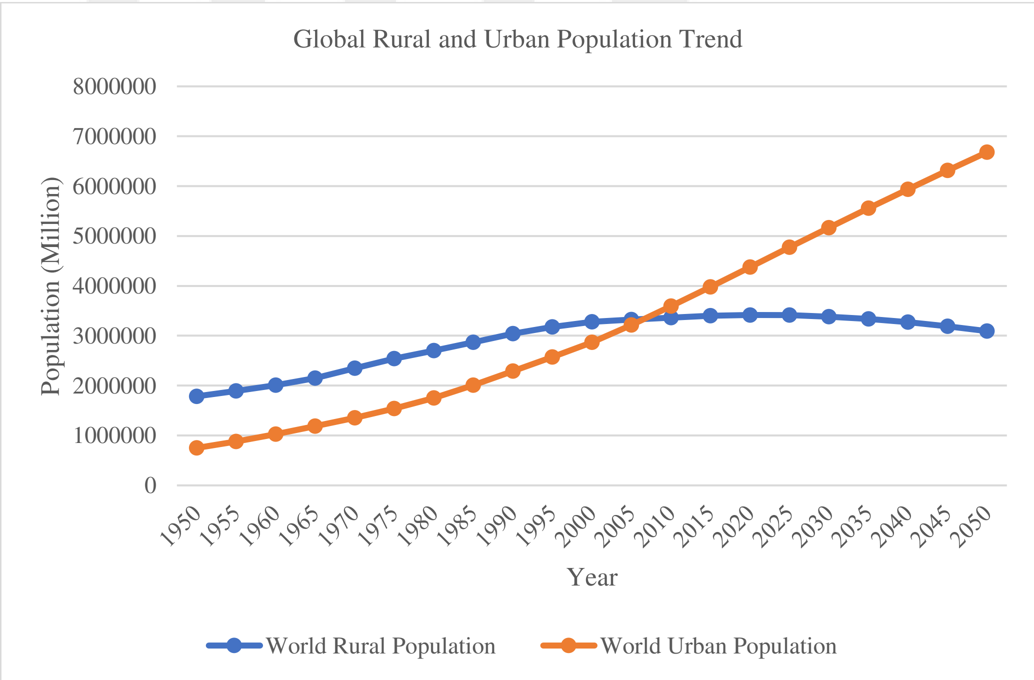

Figure 1.1. *World urban and rural population, 1950-2050 (United Nations, Department of Economic and Social Affairs, Population Division, 2018)*

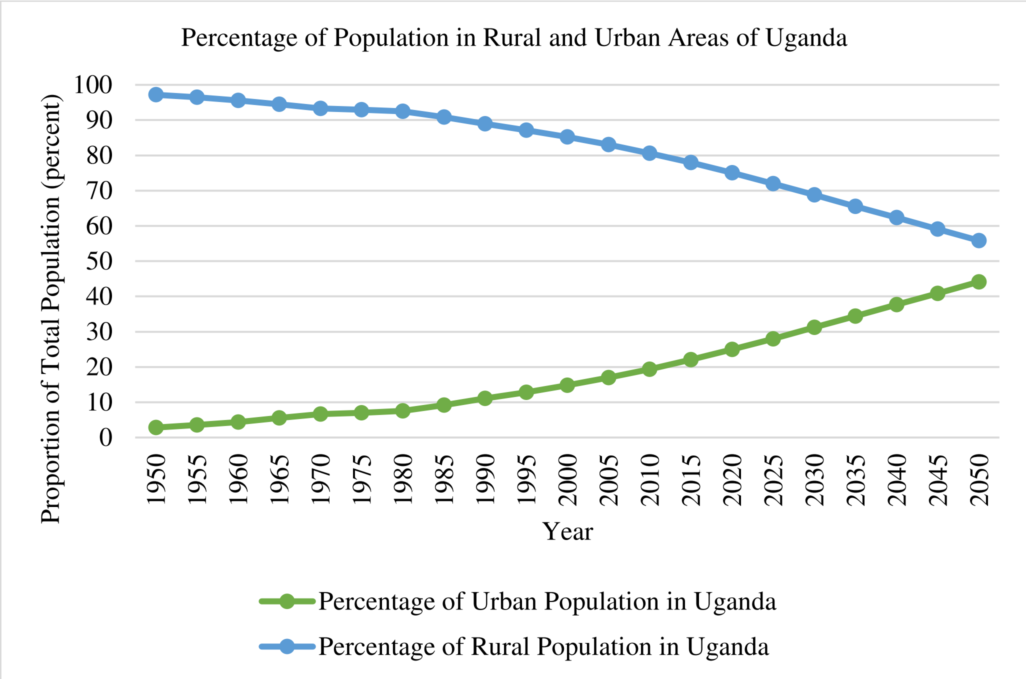

Figure 1.2. *Status of the population living in Ugandan urban areas, 1950-2050 (United Nations, Department of Economic and Social Affairs, Population Division, 2018)*

It has been observed that the urban population has grown together with per capita incomes, trips per capita, and demand for public transport services in most parts of the world. To deal with this situation especially the high demand for transport services, governments try to provide public transport systems particularly in cities of developed countries.

This is not the case in some developing and most poor countries where governments have no resources to support public transport. In such countries informal service providers transport passengers from one place to another (United Nations Human Settlements Programme (UN-Habitat), 2013).

It is noteworthy to mention that internal combustion diesel and petrol engines support the passenger transportation sector today. However, in some cities especially in developed countries the railway system provides transportation services to a large number of people (Kalghatgi, 2019). The transport industry has many benefits but it also has its costs. In relation to its costs, statistics have it that in 2016 this sector contributed to the highest nitrogen oxide emissions and about 27% of the European Union's (EU) total greenhouse gas (GHG) emissions. It is important to note that with the development of the world economy and population growth in the future, more people will live in cities, which also means that energy consumption and environmental emissions from urban transport will increase.

In this thesis, it is aimed to compare the different transportation options related to urban passenger transportation in the city of Kampala/Uganda using the LCA method. In the second chapter after the introduction, the passenger transportation vehicles within the cities of different countries are examined.

Passenger transport vehicles in developed countries such as Scotland; developing countries like Malaysia and third world countries such as Zambia are explored. Factors that influence the amount of emissions produced by motor vehicles to the environment were also mentioned in this section.

This thesis study was mainly based on the environmental performance of internal combustion engine vehicles with different passenger capacities, weights or dimensions, lifespans and the type of fuel (diesel or gasoline) used in passenger transportation. The environmental impacts of such vehicles are directly related to the consumption of the two main vehicle fuel types gasoline and diesel. These fuels were discussed in detail in the second chapter in order to understand the role they play while passenger transport vehicles are producing emissions such as nitrogen oxides, Sulphur dioxide, carbon monoxide etc.

In the third section, the public transportation system in Kampala city, the capital of Uganda, was discussed. Land use policy, one of the most important factors affecting public transport efficiency in Kampala, was examined. As a result of poor planning and the land use policies in Kampala city, urban passenger transport vehicles which were adopted were examined.

In the fourth chapter, LCA method was discussed. The various stages of LCA were explained and various software that can be used for LCA analysis were also mentioned in this section. In the fifth chapter, a literature review about the implementation of LCA method in determining the environmental performance of passenger transport was given. In this chapter, different studies about passenger transportation carried out by different researchers were discussed and the results obtained from such studies were examined.

In the sixth section, the implementation of LCA method to evaluate the environmental performance of passenger transportation in Kampala city was exhibited. The application of licensed Simapro 8.5.0 software in LCA analysis method was explained in this chapter. In the seventh chapter, the findings and discussions regarding the environmental performance of passenger transport using the selected vehicles were scrutinized. In the last section, the conclusion of the LCA study, and suggestions about the study were given.

2. URBAN PASSENGER TRANSPORT AND ENVIRONMENTAL EFFECTS

Road transport particularly a car-based system has been promoted in most cities of the developed countries of North America and Oceania. European cities on the other hand spend their money on the advancement of systems of public mass transport and non-motorized transport. In general, subway and surface rail services, tram, buses, taxis and bicycles are the main means of transport in the more developed countries (MDC) of the World (Transport for London (TfL), 2019).

In London for instance much as majority of the people use personal cars a significant portion of the population depends on London subway and Docklands light rail to travel. New York city's situation is quite the opposite to that of London, more than half of New York's population rely on the services of the subway system and the minority drive their personal vehicles to access their work stations (United States Census Bureau, 2018). In addition, some cities such as Berlin, Helsinki and Finland have more than one main transportation system (Statistics Finland, 2020). Data on vehicles used in most developed cities is shown in Table 2.1.

Table 2.1. *Energy consumption factors and rates for transport modes (Pérez-Martínez & Sorba, 2010)*

Modes	Passengers	Average speed (km/h)	Usage (%)	Energy consumption (kWh/passenger km)
Regional train	724	59	37	0.13
Intercity train	190	71	36	0.09
Intercity express train	189	89	70	0.08
Fast train	350	160	66	0.07
Middle class car	5	100	58-35	0.33-0.49
Conventional bus	50	45	80-55	0.11-0.13
Aircraft	266	700	80-55	1.22-2.03
Train	190	100	36-31	0.23-0.28

In developed countries, there are projects aimed at reducing private vehicle ownership and moving from fossil fuels as an energy source in the transportation sector to more renewable energy sources. Shared mobility has been introduced in form of car sharing, ride sharing and vehicle hauling. For instance, the city council in Paris launched the electric car sharing service known as Autolib. Vehicle hauling service Uber has also been adopted in different major cities of the developed world. In addition, the use of electric vehicles such as the Nissan Leaf released in 2010 has been adopted. Autonomous vehicles have also been invented to join the vehicle fleet in the developed world. Such innovations and projects are expected to reduce pollutant emissions, consumption of energy and traffic jam related to the public transport sector (Sprei, 2018).

On the other hand, cities in developing countries have a mixture of public transport modes. Some of the modes are similar to those used in the cities of more developed countries, while other modes are similar to those found in the least developed countries. In the cities of developing countries, personal cars, three and two-wheeled motorcycles, city buses, minibuses, metros, trams and bus rapid transit systems provide transportation services to the citizens.

Travels by motorcycles dominate the transport sector in Jakarta city in Indonesia a developing country albeit a well-established bus rapid transit system exists (COMCEC, 2015). In Rio de Janeiro city of Brazil another developing country, public buses are more dominant in the transport sector compared to metro and tram (Moovit, 2020). Gaborone city in Botswana a developing country in sub-Saharan Africa has an advanced passenger rail and city bus system. In developing countries, for example China, electric bicycles and mopeds have been adopted. In some cities vehicles used to provide mass transport are being converted from consuming conventional gasoline and diesel to natural gas and other forms of renewable energy (Sperling & Claussen, 2004).

In most cities of under-developed countries private vehicles in form of minibuses, vans, motorcycles and autorickshaws transport passengers from place to place without scheduled routes (United Nations Human Settlements Programme (UN-Habitat), 2013). While motorcycles and mopeds are dominant in Kathmandu Nepal, motorized TukTuk is the best form of transportation in Dhaka, Bangladesh. On the other hand, the 14-16 passenger capacity minibus is the main mode of transportation for urban transportation in Lusaka-Zambia, Harare-Zimbabwe, Bissau-Guinea Bissau and other African cities (Mbara, 2015). It should be noted that most of the vehicles used in transportation in the cities of underdeveloped countries are second-hand imported from Asian countries like Japan and China. Some vehicles used in under-developed countries are converted from transporting goods to transporting passengers (Kumar, Foster, & Barret, 2008).

2.1. Factors Influencing vehicle Emissions

Emissions from vehicles can be categorized in three ways namely lifetime emissions, volatile emissions as well as exhaust gas emissions. Exhaust emissions such as nitrogen oxides (NO_x), Carbon monoxide (CO), Carbon dioxide (CO_2) and hydrocarbons are generally produced as the engine burns the fuel (Nouri & Morency, 2015). The quantity and ingredients of vehicle exhaust emissions depends on the following factors.

Fuel type: Different fuel have different components which react when the fuel is burnt. The burning process results into emissions which are usually in form of greenhouse gases. Nouri & Morency (2015) state that compared to gasoline engines, diesel engines are thermodynamically more productive. It is also stated that a conventional vehicle powered by gasoline in North America can emit 43% extra CO_2 compared to the same vehicle powered by diesel as the source of energy.

Vehicle type: Features of a vehicle in form of but not limited to mass, technology, shape, engine size can determine how much fuel it consumes for a given distance and how much emissions it can produce while covering that distance. Variations in the vehicle features can sometimes be reflected in the changes in the amount of emissions generated. For instance a 2013 model of Ford Fusion with 1.6 L engine size can consume 8.0 L/100 km in a city environment while a vehicle of the same make and model but with a 2.5 L engine size can consume 9.2 L/100 km in a city road environment. This shows that if the vehicle engine size is considered, small vehicle engine sizes can result into high fuel efficiency and low exhaust emissions.

Accumulated mileage: The shorter the average life of the vehicle, the lower the consumption of diesel, gasoline and exhaust gases. In addition, the older the vehicle gets the more its emission control systems deteriorate. Because of this, older vehicles end up producing more pollutants into the atmosphere than the newer vehicles.

Temperature: Temperature is an environmental factor that influences the generation of emissions from vehicles. During cold weather, the vehicle engine's temperature may be low which may result in low engine efficiency. Low engine efficiency is one of the reasons for the generation of exhaust emissions.

Air conditioning: During hot temperatures air conditioners are used to cool the interior of the vehicles. In so doing the vehicle not only consumes more fuel but also its fuel efficiency drops, this results in the generation of higher amounts of pollutants.

Road pavement status: The nature, state and feel of road's surface can determine the vehicle's fuel efficiency. When the road surface is too rough, the friction between the tires and the road force the vehicle to demand for greater power and more fuel. In relation to this factor, under 48km/h, vehicles consume lesser fuel per unit distance on concrete roads than on asphalt roads (Sumitsawan, Ardekani, & Romanoschi, 2009).

Traffic jam: When vehicles on the roads are congested during peak hours of the day, their speeds reduce below the optimum speed which increases their emission rate per kilometer in regions with high traffic jam volatile organic compounds (VOC) and CO_2 are 250% more than in regions with flowing traffic (Kumar & Tripathy, 2014).

2.2. Road Transport, Fuel Consumption and Emissions

Today, most buses, vans, cars and motorcycles run on petrol and diesel as the source of energy. 30% to 70% of the unrefined petroleum put into oil refineries is turned into diesel and gasoline fuels. Diesel and gasoline make up roughly 95% of the energy used for road-based transport in the countries of the OECD and a significant part of energy based taxes (Harding, 2014).

In 1971 19% of total energy consumption in OECD was related to the transport sector and in 2009 this percentage rose to 28%. Within the transport sector, 89% of the transport energy in 2010 was consumed by road-based vehicles in OECD.

It is important to note that fuel-based emission rates are less sensitive to engine size as well as engine load and have less variability than time-dependent emission rates. Therefore, it is preferable to develop fuel-based emission inventories rather than operating time-based inventories (Frey, Rasdorf, & Lewis, 2010).

2.3. Automotive Fuels and Their Effects on Emissions

Fuels such as petroleum, coal as well as natural gas are the major energy sources in many countries at present, however in so doing the planet earth is exacting a heavy toll. In the transport sector gasoline and diesel are the widely used forms of fossil fuels and during their consumption they result into the generation of different pollutants.

2.3.1. Gasoline

Today, most automotive engines run on gasoline. Aromatics, olefins, normal paraffins, iso-paraffins and in a lower degree cycloparaffins are part of the nearly 400 non-identical hydrocarbons varieties found in gasoline. The most important factors affecting the performance of gasoline are volatility, sulfur content, additives and octane value.

Volatility is a gauge of how effortlessly steam is generated by a fuel. The high volatility of gasoline makes it vaporize with ease. The vaporized fuel mix with air to burn. It should be noted that only fuel in form vapor supports burning (Hollembeak, 2005).

Crude oil contains sulfur and so does gasoline. On combination with oxygen, sulfur burns to create sulfur dioxide. Sulfur can reduce the efficiency of the catalytic converter which enables the pollutants to exit the exhaust pipe unfiltered. A decrease in the amount of sulfur within the fuel results in low benzene, HC, NO_x and CO emissions especially in vehicles equipped with a catalytic converter (Pundir, 2007).

To raise the gasoline fuel's octane level tetraethyl and other compounds of lead have been added for a long time. However, due to technological advancement in the automotive industry some devices for example the catalytic converter cannot work efficiently when a fuel contains lead. This has led to the absence of leaded fuel on the market nowadays. The gauge of how effortlessly fuel vapor can ignite is known as the octane rating. It should be noted that fuels with a high-octane rating are difficult to ignite and burn slower than their counterparts with lower octane ratings.

A spark starts a 0.003-second-long burning task in a gasoline powered engine. The perfect fuel burning process (quite rare) yields CO_2, water vapor and heat. The CO_2 is formed when carbon atoms contained in the fuel combine with oxygen. The combination of Hydrogen atoms contained in the fuel and atmospheric oxygen results in the formation of H_2O. Gasoline engines produce high amounts of CO, VOCs as well as NO_x and moderate amounts of particulate matter (Chevron Corporation, 2007). It is worth noting that incomplete fuel burning is the root cause of HC emissions which are major pollutants that contribute to the formation of ground level ozone.

When the fuel burns efficiently and completely CO_2 is formed. When the oxygen is inadequate, the oxygen-fuel vapor mixture stops burning prematurely which results in the formation of carbon monoxide. When the temperature in the engine fuel combustion chamber goes beyond 1371^0C, the combination of nitrogen with oxygen forms N_2O and other oxides. However, when the temperature is reduced the amount of nitrogen oxide emissions also falls (Hollembeak, 2005).

CO_2 is an important emission as it can be used to estimate the efficiency of engine combustion chamber. Higher values of CO_2 are preferred to low amounts because it is a sign of complete and efficient fuel combustion process.

2.3.2. Diesel

For a long time, heavy vehicles have relied on diesel as the source of energy and of recent light vehicles also run on diesel. This is due to a number of reasons among which include its ability to enable engines efficiently consume it and gain a high torque at low speeds. In addition, on a per liter basis, diesel fuel contains approximately 10% more energy than gasoline fuel. While diesel contains 35.9 megajoules (MJ) per liter, gasoline contains 32.6 MJ per liter.

Just like gasoline, characteristics such as viscosity, sulfur content, volatility, cetane ratio and density influence the performance of a diesel engine and the engine emissions generation rate. Because diesel possesses a high thermal energy content, engines that run on high density (low API gravity) diesel are more powerful as compared to their counterparts which run on low density diesel (Pundir, 2007).

In addition to power changes due to fuel density, differences in the viscosity of diesel may influence the amount of engine power output. Fuel is expected to run smoothly from the diesel fuel system and be sprayed by injectors. The manner in which the spray of fuel occurs in the engine combustion chamber is to a large extent influenced by the fuel's viscosity.

The volatility of diesel is lower than that of gasoline yet it is volatility and quality that determines the quantity of residues of carbon formed by diesel. The higher the volatility the lower the amount of residues of carbon formed.

Cetane rate is the gauge that shows the quality of diesel fuel in relation to ignition or burning. Diesel fuels with a higher cetane number ignite faster than their counterparts with low cetane numbers. Diesel also contains sulfur although its sulfur content is higher than that of gasoline. The sulfur-oxygen combination forms oxides of sulfur such as sulfur trioxide (SO_3) and sulfur dioxide (SO_2).

The temperature and pressure rise in the diesel engine during compression is ideal for the injection of fuel, atomization, evaporation and burning of fuel in the chamber (Bennett, 2014). Perfect and complete combustion of diesel results in the formation of carbon dioxide, water vapor and nitrogen while incomplete combustion causes the formation of SO_2, NO_x, PM and CO (Chevron Corporation, 2007).

Fuel combustion chambers are usually very hot places reaching 1600°C which provide ideal conditions for the formation of NO_x. More and more NO_x can be generated as temperatures rise higher and higher beyond CO_2.

Diesel usually combusts in a heterogeneous manner which gives rise to the formation of PM emissions. After fuel injection into a very hot and highly pressurized combustion chamber, areas which have high concentrations of fuel and low oxygen concentration may develop. Such areas rarely support efficient and complete fuel burning resulting in the formation and concentration of particles which afterwards are observed as exhaust smoke.

Uncombusted or partially combusted molecules of fuel which originate from more than one source are generally called hydrocarbon emissions. Due to the ability of diesel engines to operate at low fuel-air ratios, their hydrocarbon emissions rates are relatively low. It should also be noted that combustion chambers which are rich in fuel but poor in oxygen are ideal for the formation of carbon monoxide emissions. Therefore, high levels of oxygen in the combustion chamber reduce the amount of CO emissions.

3. PUBLIC TRANSPORT IN KAMPALA-UGANDA

Challenges related to transport in developing countries are quite different from the transportation hardships in the developed countries of the World and this variation is more or less related to land use policies adopted in these countries. The efficiency of city's transport system can be determined by various factors however land use is among the most significant factors. Greater social, environmental and monetary benefits can be enjoyed if there is a strong coordination between land use and transport (Cervero, 2013).

Uganda like any other country experiences urbanization and this process can be best observed in Kampala city. Rural-urban migration, economic growth, industrial growth and population growth are among the main causes of urbanization in Kampala city.

Urban expansion is a synonym for urbanization. It involves the extension of the populations from towns to rural areas, relocation from high density to areas with low density in the outer parts of the city and increased utilization of personal cars as transport means (Kushwaha & Deep, 2020). Urban expansion is the manner in which urban centers develop focusing on the fashion of how population density is allocated to urban space and how the space in urban areas is divided (OECD, 2018). Therefore, the blossoming of the city of Kampala is characterized by 3.7% faster annual urban expansion than other urban areas in Uganda.

Distant workplaces, the blooming of low population density in the fashion of recurring detached homes and reliance on cars describes urban sprawl in Kampala city as seen in Image 3.1 (Nnaggenda-Musana & Vestbro, 2013). Standing alone bungalows in Image 3.2 and development forms characterized by low population density are also part of urban development in Kampala's formal and informal residential areas.

Image 3.1. *Single-storey houses in informal settlements in the city of Kampala (Moore, 2009)*

Image 3.2. *Single-storey houses in formal settlement areas in the city of Kampala (Simisa, 2009)*

Population density is one of the main factors that determine the success of public transport system. Public transport services are believed to be very efficient in areas with high population densities due to the fact that such areas possess high rates of trip per capita and thus enhance the viability and feasibility of transport services (Guerra & Cervero, 2012). In addition, people living in areas of high population density face few challenges related to the distance from their homes to bus stops which enables them to reduce travel times to their destinations (Balcombe, et al., 2004).

Population density, inefficient land use policy and urban sprawl are believed to be among the major hinderances to the success of public transport services in Kampala city. This has cleared the way for the private individuals to provide public transport services within the city.

3.1. The KCCA Strategic Plan's Implementation Failure as a Catalyst for Chaos

The strategic plan 2014-2019 spelled out KCCA (Kampala Capital City Authority) efforts to focus its planning and development within a long-term framework. The Plan focused on building a vibrant, attractive and sustainable city. It listed the themes and strategic objectives to be pursued and the programs/projects to be implemented over the period.

Strategic objectives, programs and projects to guide the city development agenda for the five years were identified. For each program area a number of projects were put forward. They were to be implemented to realize the set strategic objectives. Programs included planned and green urban environment, economic growth theme, integrated city transportation infrastructure, social development, health and education, urban governance and operational excellence.

The program which was directly in line with public transport was the Integrated City Transportation Infrastructure Program (ICTI). The focus of this program was to pave over 1000 kms of roads, install streetlights on over 1000 kms of road, rehabilitate drainage channels, introduce vehicle terminals including the old and new taxi parks as well as to introduce and fully integrate modern transport modes.

The projects under the Integrated City Transportation Infrastructure (ICTI) program were improvement, expansion and upgrading of Kampala's road network; designing and reconstruction of traffic junctions; introduction of flyovers; introduction of alternative mass public transport systems; developing of transport management policies and systems; revamping and expansion of street lighting network as well as the city parking management project.

With an expectation of reduced time in traffic congestion and a well-integrated transport network in Kampala city, a budget worth USD 1,204,500 was allocated to the implementation of this program for the period 2014-2019. Different projects shared various portions of this budget as shown in Figure 3.1.

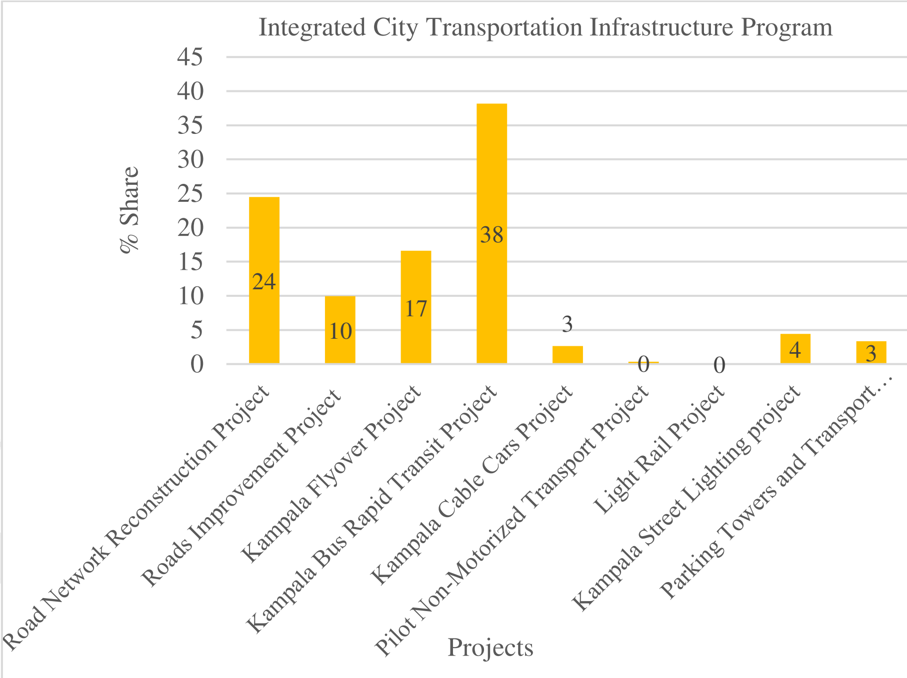

Figure 3.1. *Budget allocation for the different projects*

Among the projects under the integrated city transportation infrastructure program, the Kampala bus rapid transit project was allocated USD 460,000 which is approximately 38% of the budget. Other mass public transport systems such as the light rail project, the cable car project and the non-motorized transport were also considered in this plan.

The City Bus services: Through partnering with investors from the private sector, KCCA had plans to reintroduce the city buses with affordable charges. City buses were expected to be very suitable to the current roads available in the city and efficient alternatives to the dominant 14-seater Kamunye minibuses in Kampala. According to this strategic plan, the city buses service was expected to be rolled out before the end of calendar year 2014 and was to initially serve the central business area on a daily basis and eventually be rolled out to the rest of the City.

Kampala Bus Rapid Transport (BRT) network: KCCA in conjunction with Ministry of Works and Transport and Uganda National Roads Authority (UNRA), was to undertake the construction of a BRT pilot phase of 25 kms from Kireka to Bwaise with a spur to Zana on Entebbe Road. Construction was expected to be operational by 2019 considering the available funds.

Pilot Non-Motorized Transport (NMT): Because walking is the most basic urban transport mode for all short-to-medium length travel, and bicycling play an essential role in urban transport in most poor countries, KCCA in the financial year 2014/15 was to introduce non-motorised transport in some sections of Kampala city. As of now sections of Namirembe road and Luwuum Street are complete non-motorized roads within the city.

The Kampala Cable Cars system: Pre-feasibility study was done on a Cable Car System as an innovative and attractive approach to public transport. Detailed feasibility and design for a pilot phase from parts of Kawempe to New Taxi Park and Makindye was expected.

Light rails (metro train) services: In the five years KCCA was to encourage the resumption of the commuter rail services on the current railway line and further sanction a feasibility study that would guide the introduction of light rail transit under a public-private partnership arrangement to ease movement to and within the city. The study was to form the basis for engaging the private sector, it was also to guide on the type of risks to be borne by KCCA and the private investor. Introduction of the light rails was expected to compliment the other forms of transport and further augment public transport systems in Kampala and its suburbs.

The proposed development and strategies highlighted in this plan were to be achieved mainly through government financing, local revenue mobilization, help from development partners and public-private partnerships. It should also be noted that most of the objectives of this plan have not yet been achieved which has acted as a catalyst for the informal public transport system in Kampala-Uganda.

3.2. Urban Passenger Transportation Vehicles in Kampala City

More than 1.5 million people live and work in the city. Employees in the city of Kampala cover a distance of 30 km every day to take home the bread (INTALInC, 2019). Road transport is the main form of transportation in Uganda, which carries more than 90% of passengers and cargo.

The total number of motor vehicles is about 1.4 to 2 million vehicles, including motorcycles, and about 50% of all these vehicles are in the Greater Kampala Metropolitan Area. The Kampala metropolitan area shown in Figure 3.2 consists of the city of Kampala and its neighboring city centers, which include Entebbe, Mukono, Wakiso, Kira and Nansana.

Figure 3.2. *Map showing the Greater Kampala Metropolitan Region (JICA, 2010)*

The Kampala region whose population growth rate is about 4.5 is roughly 970 kilometers squared, its longest east-west distance is around 430 km, the utmost north-south breadth is in the region of 55 km (George, 2014). Public transportation trips in 2003 (excluding BodaBodas) were around 460000 or 800000 daily during the busy period (afternoon). In 2009, these figures had risen to about one million (MoWT, 2009).

Uganda imports about 70000 motor vehicles and about 100000 motorcycles annually. Of these, brand new vehicles (about 10%) are purchased by the government, embassies and NGOs. Those between the ages of 1-4 are about 20%, those between the ages of 5-8 are about 30% and those over the age of 8 are around 40%.

Most of the vehicles used are imported from Japan, Singapore, South Africa, China, the United Arab Emirates (UAE) and the United States (US). Currently, the most popular form of transportation in Kampala is 14 passenger Kamunye minibus with 46%, followed by BodaBoda with 32% and cars, buses and trucks with only 2%. Today walking is the most important form of transportation for most non-business trips, which is rated at 46% in the greater Kampala metropolitan area. This is mostly due to low incomes, expensive fares and limited access of Kamunye to some communities (KCCA, 2014).

The fuel consumed by the modes of transportation in Uganda is diesel and gasoline. Information on fuel types is shown in Table 3.1.

Table 3.1. *Vehicles used in cities across Uganda (McCall, Stone, & Tait, 2017)*

Vehicle type	Diesel	Gasoline
BodaBoda (motorcycle)	0%	100%
Minibus (Kamunye)	77%	23%
Company/private minibus/bus/truck	77%	23%

3.2.1. Kamunye minibus

The most common public transportation vehicle in Kampala is the 14-person minibus shown in Image 3.3. In 2002, there were about 4000 Kamunyes in Kampala, which accounted for 70% of road use. In a transportation census made in 2013, it was estimated that there were 16000 Kamunyes in the city (Haas, 2017).

Image 3.3. *14-seat Kamunye used in Kampala (Rachit. 14, 2017)*

Approximately 82.6% of the people in the city of Kampala used Kamunye while approximately 8.5% used BodaBoda (Otunola, 2018). In 2016, KCCA estimated that Kamunye type vehicles accounted for 21% of all vehicles and carried 82% of people in the city of Kampala (Evans, O'Brien, & Ng, 2018).

At an average of 12-hours Kamunye can perform 7 journeys every day (Kamuhanda & Schmidt, 2009). It is believed that large buses and minibuses in Africa can cover approximately 190 km a day for example, in Ethiopia-Addis Ababa, minibuses cover distances of 180 km per day compared to 138 km per day for big buses. According to studies which were conducted to develop a long-term integrated BRT system for the Kampala metropolitan area, approximately 854500 people rely on Public services of transport (McCall, Stone, & Tait, 2017).

Owing to stiff traffic jam, Kamunye is a major threat to the environment because it produces emissions of hydrocarbon that pose a danger to the environment. It is estimated that 14 passenger Kamunye, which operates every day in Kampala, the capital of Uganda, produces more than 96715 tons of carbon emissions annually (Matovu, Tickodri-Togboa, & Musasizi, 2015).

Toyota Hiace is a light commercial van manufactured by Japanese car maker Toyota and the technical specifications of this vehicle are shown in Table 3.2. The engine size used by Toyota Hiace ranged from 2 to 3 liters, gasoline for the first model and diesel for models released in recent years (Be Forward, 2020). Most models are rear-wheel drive, but part-time or full-time all-wheel drive versions are also manufactured. They possess a standard diesel injection fuel system.

Table 3.2. *Technical specifications for a Toyota Hiace minibus (Toyota, 2020)*

Vehicle	Toyota Hiace
Engine	4-cylinder 2.7-liter diesel engine
Fuel	Diesel
Model year	2004 model
Engine volume (cc)	2494
Vehicle curb weight (kg)	1820

Kamunye has two seats next to the driver. There are also four rows and three seats in each row. In the first three rows, the third seat is created with seats that can be folded. Kamunye has no specified fares and no timetable, it just sets out when it's full. Kamunye run on frequent courses with stops decided at the passenger's wish. All Kamunye with operating licenses are characterized by a white and blue band (van der Griend & Siemonsma, 2011). It should be noted that much as the Kamunye are old model, they are still being imported into Uganda, transport service providers are not yet able to buy the latest models of Kamunye.

3.2.2. BodaBoda

It is estimated that 40000 motorcycles were working on the avenues of Kampala in 2010. Bajaj Boxer was the most prevalent model of motorcycle preferred by riders of motorcycle taxis in Uganda in 2013 (Sin Yi, 2016).

The exhaust emission standards submissive and energy efficient 100 cc four stroke engine motorcycles are claimed to be more widespread in Uganda as a public transportation option in the world and day-to-day it is approximated that about 800000 BodaBoda tours are completed (Goodfellow, 2019).

BodaBoda motorcycles shown in Image 3.4 are two-wheeled, single-passenger motor vehicles which not only operate in the center of Kampala city but also run on the poor and inaccessible roads in most residential areas of the city (Öbom, 2019). Businesspeople in urgent need to reach their work stations, vulnerable people in high-priority need to reach health centers and school going children who cannot afford school buses rely more on the services of BodaBoda (INTALInC, 2019).

Image 3.4. *BodaBodas in Kampala city (Derrick, 2019)*

Although motorcycle CO_2 emissions are not greater than those released by cars, motorcycles produce high amounts of black carbon. Two-stroke motorcycle engines can discharge smaller particles than heavy diesel trucks (Matovu, Tickodri-Togboa, & Musasizi, 2015). In 2016, KCCA approximated that BodaBodas made up 42% of the vehicles and carried 9% of the people in Kampala. In addition, it was approximated that 64% of the trips made by BodaBodas go to and from the Kampala city center, 15% transport passengers between mostly Kampala, Wakiso and Mukono districts and 20% do not cross from district to district (Evans, O'Brien, & Ng, 2018).

An average of 23 people can be transported by one BodaBoda per day and almost half of these people are believed to use the same BodaBoda day-to-day. This number of daily passengers (23) is also stated by a private firm which deals in BodaBoda business known as Tugende.

According to the research conducted by the Japan International Cooperation Agency (JICA), motorcycle tours on the two major roads (Jinja road and Bombo road) in Kampala city in 2010 are presented in Figure 3.3. Shorter journeys suit BodaBodas while longer journeys suit Kamunye. Journeys which are short in nature are usually executed in the city center, and this is the main reason why there are more BodaBoda journeys within the center of the city than in the suburbs of Kampala city.

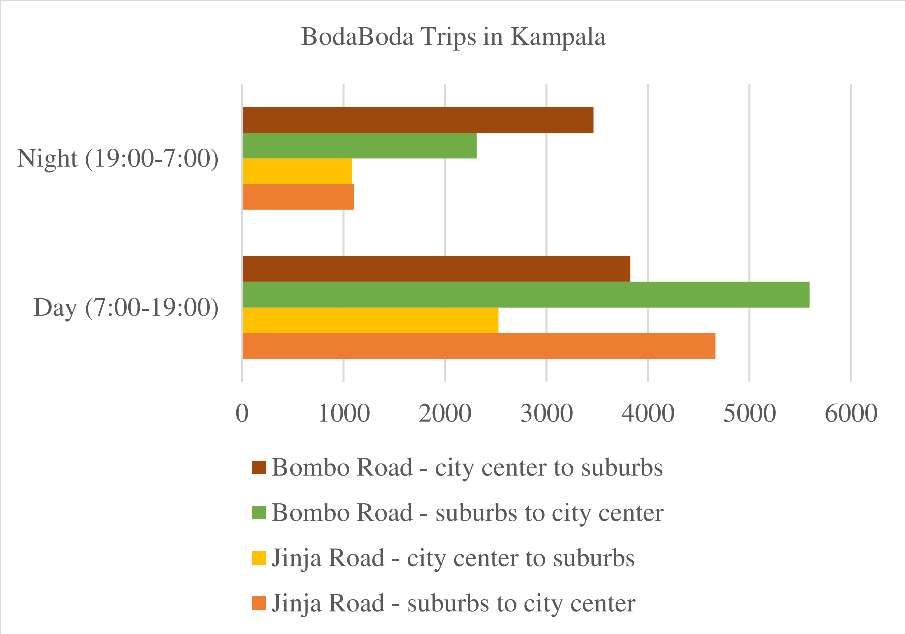

Figure 3.3. *Trips by motorcycles on the two main roads within Kampala city (JICA, 2010)*

BodaBoda performs excellently on congested roads in the city center and muddy roads in the poor residential neighborhoods. The unmatched features of BodaBoda include but not limited to effective brake system, high level of stability on the road and ease of handling even at high speeds. The general characteristics of the popular Bajaj motorcycle are shown in Table 3.3.

Table 3.3. *Technical specifications for a motorcycle (Iyer, 2012)*

Vehicle	**75-125 cc motorcycle**
Curb weight (kg)	108
Engine capacity (cc)	94-125
Maximum power (kw)	5.4-8.7
Fuel	Gasoline
Engine	Single cylinder, four stroke, natural air cooled

3.2.3. Coaster

In the1980s, the 29-passenger minibus was presented to the market as the third-generation model of Mitsubishi Rosa. This model is widely used in Santa Cruz de la sierra

(Bolivia), the city of Panama (Panama), Amman (Jordan) and is the only type of minibus used for public transport in the cities here (Wikipedia, 2020).

Features of the minibus used in Kampala are shown in Table 3.4. In Kampala, minibuses are called Coaster minibuses and do not serve on all routes in the city. The Coaster, shown in Image 3.5 serves a large number of passengers traveling daily from Kampala to Lungujja and from Kampala to Mukono. Coasters pick up and drop off commuters at the same stops utilised by the Kamunye and their fares per passenger are lower than those of BodaBoda, Kamunye and TukTuk. It should be noted that much as the Coasters are old model, they are still being imported into Uganda, transport service providers are not yet able to buy the latest models of Coaster.

Table 3.4. *Technical specifications for Coaster minibus (CardealPage, 2020)*

Vehicle	**Mitsubishi Rosa**
Engine volume (cc)	4560
Fuel	Diesel
Curb weight (kg)	3700
Engine	4.9-liter, 4 cylinders
Model year	1997 model

Image 3.5. *The Coaster used in Kampala city (Berry, 2009)*

3.2.4. TukTuk

Most of the three wheeled vehicles used in Kampala are designed to carry three passengers in addition to the driver and are named Tuk tuk. TukTuk, shown in Image 3.6, is utilized in urban centers over distances which are short in nature. They are rarely used to go for longer distance due to their slowness, instability on the road and high exposure to air pollution.

Image 3.6. *The type of TukTuk used in Kampala city (HendeMoto, 2019)*

TukTuk is believed to be material efficient during its manufacturing stage and highly fuel efficient during its operation stage. TukTuk is designed in a way that passengers and the driver are not affected by weather conditions like sunshine and rain as it is with motorcycles. TukTuk riders are also protected by the windshield and can easily handle this vehicle as it is equipped with handlebars similar to those of a motorcycle (Iyer, 2012). On average, a four stroke TukTuk is capable of consuming only one litre of fuel and it travels 30 to 31 km (Mallik & Arefin, 2018). Other features of TukTuk are shown in Table 3.5.

Table 3.5. *Technical specifications for Bajaj TukTuk (Iyer, 2012)*

Vehicle	**TukTuk**
Displacement (cc)	173.5
Maximum power kW @ rpm	6.0 kW @5000 rpm
Vehicle curb weight (kg)	388

It is reported that in 2000 in Srilanka, each TukTuk could cover an average distance of 24 kilometers per liter and its annual fuel consumption was 49000 tons of gasoline (Munasinghe, et al., 2003). It is approximated that more than 400 TukTuks provide transport services to people within Kampala city even if they operate without passenger transport licenses (Henry, 2019).

There are several areas where TukTuks operate and these include Nateete, Nakawuka, Kisenyi, Abayita ababiri and Kansanga. The TukTuk charges per passenger per kilometre are less than those of BodaBoda. However, due to its attractiveness as a business venture, it is expected to be found on many roads within the city of Kampala in the near future.

4. LIFE CYCLE ASSESSMENT (LCA) METHOD

LCA is a mechanism for gauging the impacts to the environment of a material, product or service from its creation through to scrapping. Each and every undertaking during the product's lifecycle gives rise to environmental impacts due to natural resource utilization and emissions generation (Greenspec, 2020).

LCA procedure is quantitative and encompasses impacts to the environment connected to the discharges in a specific system boundary, often but not limited to global warming potential as an impact category. LCA models and data are utilized by many firms and enterprises to decide on specific and critical undertakings (Caffrey & Chinn, 2015).

LCA respects a product's entire life, from feedstock unsheathing, through power and materials production to final scrapping as shown in Image 4.1. Such a detailed tool easily spots likely burdens to the environment between life cycle phases and eases the task of averting such burdens.

Image 4.1. *Life cycle stages of a service or product (Project HUB-360, 2018)*

A product or service's environmental aspects are the areas of concentration for the LCA tool. The product or service's economic and social aspects are usually handled by other approaches but not LCA however those approaches can be combined with LCA to achieve a robust estimate of the situation at hand (BSI, 2006).

LCA can help in many ways, such as spotting opportunities to upgrade the environmental aspects of services at various phases in the life cycle. Industrial, governmental as well as organizational decisions can also rely on findings of the LCA methodology in undertakings such as product or process designing and tactical planning. LCA is a vital tool in marketing the services and products of an entity as it enables firms formulate environmental product declarations for their commodities.

The principles of an LCA obey the International Standards Organization (ISO) 14040-environmental management, life cycle assessment, principles and framework (ISO, 2006a) and the ISO 14044-environmental management, life cycle assessment, requirements and guidelines (ISO, 2006b).

If an LCA is to be conducted, the mentioned standards have to be complied with observing the following stages.

• Goal and Scope Definition

• Inventory Analysis

• Impact Assessment

• Interpretation

4.1. Goal and Scope Definition

The goal and scope definition establish the initial and the most key part of the LCA. The purposes, restrictions and constraints of the study are outlined at this stage. The achievements of the LCA are to a large extent determined by the width, depth and details of the study scope therefore it has to be defined with utmost clarity. In the scope, the product system under study and its functions are described. The system boundary, functional unit, chosen impact categories, allocation strategy, method of impact assessment and interpretations are also defined in the scope. The scope also clarifies on the nature of the final report’s type and format, quality and quantity of data required, considered presumptions as well as study restrictions (Jolliet, et al., 2003).

4.1.1. Functional unit

A product or service can have more than one functions. Therefore, if an LCA is to be conducted, the scope of the study specifies the function that is to be put under scrutiny. The functional unit states the quantity of function of the product or service to be scrutinized. Provision of the reference to which the inputs and outputs concerning a system are related is the major usefulness of a functional unit. With a reference, various components of the system under study can be easily compared. The comparability of LCA outcomes is very vital when assessing dissimilar systems. To guarantee that comparisons are executed on a common basis, the establishment of the reference flow is very vital. It should be noted that a reference flow refers to the quantity of a material required to execute a specific function (BSI, 2006).

4.1.2. System boundary

In LCA elements of systems are put in a nutshell to form a model. The unit processes that are to be considered for scrutiny are outlined under the system boundary. Figure 4.1 shows the process flow chart (Tabatabaie & Murthy, 2016). Depending on the study's purpose and scope, the elements of the physical system under study can be selected, the target audience can be defined, presumptions can be listed and study constraints can also be outlined. The system boundary is usually composed of life cycle stages, unit processes and flows. Lifecycle stages may be in form of production, consumption, maintenance as well as disposal. Unit processes may include mineral extraction, energy production, reuse, recycle and energy recovery. Flows may include water, power, chemicals, wastes, emissions etc. (Watson & Wiedemann, 2019).

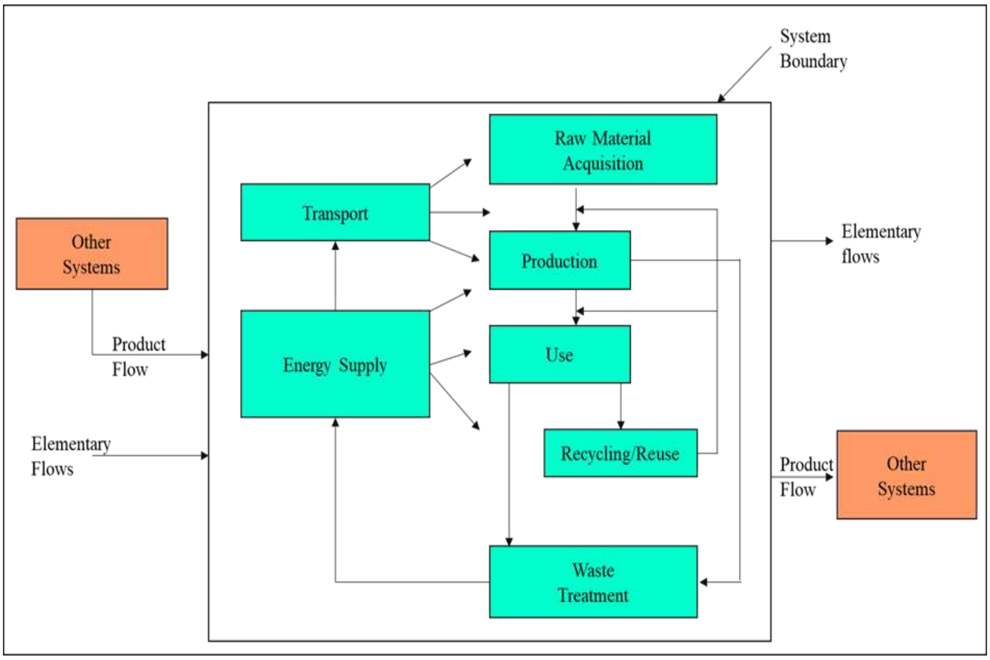

Figure 4.1. *Process flow chart (Bossagh & Hassanzadeh, 2012)*

There are four main options for defining the system limits used and they include:

Cradle to Grave: It includes the material and energy production chain and all processes from feedstock extraction, manufacturing, conveyance and consumption to the scrapping process of the product.

Cradle to Gate: Includes all processes from feedstock unsheathing to manufacturing stage. Impacts to the environment as a result of a product's manufacturing process are the main concern in this option.

Grave to Gate: Processes from the utilization of a product and scrapping of a product are the major concern in this approach. Proceedings after the product leaves the production site are usually discussed and scrutinized in this approach from an environmental viewpoint.

Gate to Gate: This approach mainly focusses on the undertakings within the assembly plant or production site from an environmental point of view.

4.2. Inventory Analysis

Life Cycle Inventory analysis is the second phase of the LCA, which includes assembling and giving values to the inputs and outputs related to a process/system. Inventory analysis contains; data gathering, data computation approaches, data accessibility and quality. Emission estimates are allocated to operations within the boundaries of the system under investigation. Inventory analysis includes data gathering, data computation and tabulation of LCI values.

4.2.1. Data collecting

The data gathering phase consumes a lot of time in addition to being very vigorous. For each unit process, qualitative and quantitative data in form of but not limited to energy inputs, feedstock inputs, auxiliary inputs, rubbish, exhaust gases, wastewater and heavy metals to the soil. The description of the origin of this data is very important at this stage (Yoshida, Clavreul, Scheutz, & Christensen, 2014).

4.2.2. Data calculation

Data calculation involves validation of the gathered data, data affiliation with unit processes and data affiliation with the functional unit's reference flow. The energy resources used in the calculation of energy flows, the efficiency of the conversion and distribution of the energy, and the inputs and outputs related to the production and use of this energy are taken into account. All calculation approaches are registered and the presumptions considered are listed and expounded. The same computation steps are implemented harmoniously throughout the investigation. When determining the basic flows affiliated with manufacturing, the verified production mix is utilized whenever possible to reflect the various types of resources consumed (Verbeeck & Hens, 2010).

4.2.3. Associating data with unit process and functional unit

For each unit process, a befitting flow in relation to which quantitative data for the inputs and outputs of the unit process are computed. The computation outcomes in all the system input and output data is in one way or another related to the functional unit. LCI can be computed using tools such as SimaPro and GaBi.

4.2.4. LCA software and its importance

An LCA looks like an intimidating piece of work particularly with the enlarging system boundary as a result of a complex system under investigation. To solve that hinderance Gabi, Simapro, Umberto LCA+, openLCA, eBalance, Environmental Improvement Made Easy (EIME), Quantis Suite, Team 5 (PwC) and REGIS and other programs are utilized to simplify LCA.

These programs have various databases such as Ecoinvent, GaBi, IBO, CFP, ICE, Synergia as well as ELCD and have appropriate impact assessment methods for life cycle impact assessment analysis. Databases are made up of data about instruments, inventories for emissions from standard operations observed in government, industrial and research institutions and a collection of impact factors (Jolliet, et al., 2003).

Inventory databases can be from profit-oriented sources such as Ecoinvent (Weidema, et al., 2013) and public sources such as the US Life Cycle Inventory Database (US LCI). Inventories for special processes are accessible from various entities namely Glass for Europe (Usbeck, Pflieger, & Sun, 2011) and the American Chemistry Council (ACC). Impact databases are also accessible from profit-oriented and non-profit-oriented sources such as the Tool for the Reduction and Assessment of Chemical and other environmental Impacts (TRACI) and IMPACT 2002+.

4.3. Life Cycle Impact Assessment (LCIA)

The quantity and magnitude of likely impacts of LCI results to the environment are evaluated at this LCA step. Here the inventory data is affiliated to specific impact categories and category indicators. Characterization factors simplify this step as they ease the allocation of various outputs to specific impact categories. LCIA is a broad step and for it to be executed an impact assessment method has to be selected, LCI data has to be classified and data characterization has to be implemented. To obtain robust outcomes LCIA results can also be normalized, grouped and weighted although it is optional (Jolliet, et al., 2003).

4.3.1. Impact assessment methods

There are different methods that can be used to perform a life cycle impact assessment. TRACI or Leiden University Institute of Environmental Sciences (CML) are among the popular methods used to classify and characterize environmental impacts of products and services. The LCIA methods can either be problem-oriented (midpoint) or damage-oriented (endpoint). The relationships of these approaches are shown in Figure 4.2.

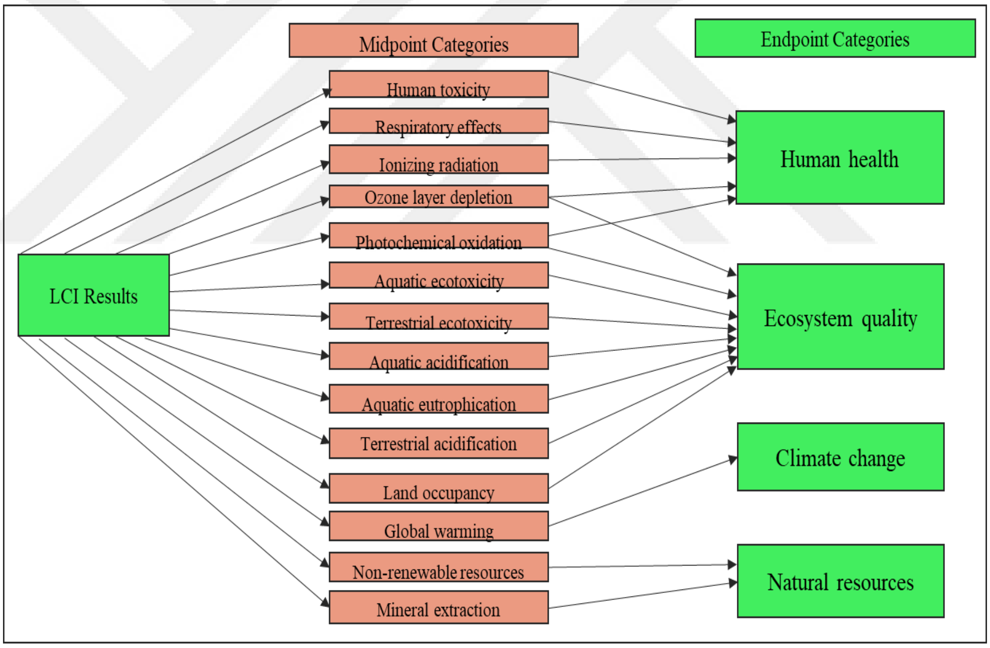

Figure 4.2. *Relationship between endpoint and midpoint LCIA approaches (Foley, Rozendal, Hertle, Lant, & Rabaey, 2010)*

In the problem-oriented approach (midpoint) flows such as emissions are put under a specific environmental impact category that they contribute to. In relation to elements such as methane, carbon monoxide which represent other elements in specific impact categories, specific flows are evaluated. Due to the fact that it is a complex process midpoint CML and TRACI methods are utilized to execute the characterization task. The difference between the endpoint and midpoint LCIA approaches is shown in Table 4.1 and the comparison of CML and TRACI methods are shown in Table 4.2.

Table 4.1. *Difference between endpoint and midpoint LCIA approaches (Sala, Pant, Hauschild, & Pennington, 2012)*

Category	Midpoint	Endpoint
Global Warming	CO_2- eq.	Temperature rise
Acidification	SO_2- eq.	Acid rain
Eutrophication	N- eq	Ecosystem loss
Ozone Layer	CFC-11- eq.	Human health
Ecosystem	Triethylene glycol eq.	Ecosystem loss
Human Health	Human health eq.	Human health

Table 4.2. *Comparison of TRACI and CML midpoint methods (Rathore & Mondal, 2018)*

CML	Unit	TRACI	Unit
GWP	kg CO_2- eq.	Global Warming Air	kg CO_2- eq.
ODP	kg R11- eq.	Ozone Depletion Air	kg CFC 11- eq.
AP	SO_2- eq.	Acidification Air	mol H + eq.
EP	kg Phosphate-eq.	Eutrophication Air	kg N- eq.
POP	kg Ethene-eq.	Eutrophication Water	kg N- eq.
HTP	kg DB-eq.	Smog Air	kg NO_x- eq.
TETP	kg DB-eq.	Human Health Cancer Air	kg Benzene- eq.
FAETP	kg DB-eq.	Human Health Cancer Water	kg Benzene- eq.
MAETP	kg DB-eq.	Ecotoxicity Air	kg 2,4- Dichlorophenoxyace
ADP	kg Sb- eq.	Ecotoxicity Water	kg 2,4- Dichlorophenoxyace
		Human Health Criteria Air-Point Source	kg $PM_{2,5}$- eq.
		Human Health Non-Cancer Air	kg Toluene- eq.
		Human Health Non-Cancer Water	kg Toluene- eq.

The CML method was invented by Leiden University Institute of Environmental Sciences and focuses on a number of environmental impact categories expressed in terms of emissions to the environment. The CML method includes classification, characterization and normalization. Impact categories for global warming potential and ozone layer depletion potential are based on IPCC factors.

Damage-oriented methods (endpoint) also begin by classifying a system's flow into various impact categories, but impact categories are also divided into endpoint categories such as damage to human health, ecosystem quality or damage to resources. The use of such approaches tries to give emissions a real economic or environmental result. Ecoindicator 99 is an example of a damage-based method. The endpoints used are easier to interpret and transmit to other stakeholders (Mahmud, Huda, Farjana, & Lang, 2019).

4.3.1.1. Mandatory elements of LCIA

LCIA stage has mandatory elements during the analysis namely selection of impact categories, classification and characterization.

Selection of impact categories: More than one impact category is usually selected as the focus of an LCA study. The preference of impact categories often relies on: the study's purpose, the environmental impacts of the service under investigation, and the choice of method of impact assessment.

Classification: The outcomes of the LCI phase include more than one discharge. LCI results are assigned to one or more impact categories after the respective impact categories are selected. If substances contribute to more than one impact category, they are classified as contributors to the respective categories.

Characterization: Characterization spots and gives values to the environmental impact of the product system under investigation. After assigning the LCI outcomes to impact categories, characterization factors should be applied to the respective amounts. Characterization factors are included in the effect category methods such as CML or TRACI. The procedures for characterization are shown in Figure 4.3. LCI results are converted to reference units using characterization factors. For example, the reference substance and reference unit for the category of "global warming potential" is defined as kg CO_2 equivalent. All discharges that promote global warming are transformed to kg CO_2 equivalent in line with the relevant characterization factor. It is worth noting that each emission has its own characterization factor.

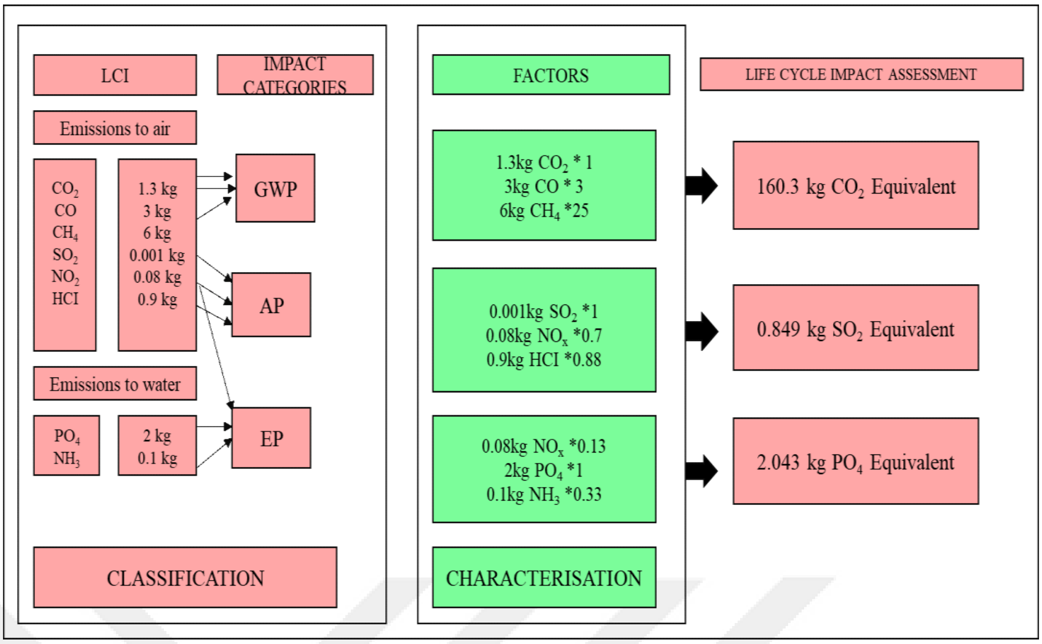

Figure 4.3. *Procedure for classification and characterization in LCA (Su, Li, Zhu, & Lin, 2017)*

CML as an impact assessment method and its impact categories

CML method was created by the University of Leiden in the Netherlands in 2001 and it is made up of thousands of flows. This method is divided into baseline shown in Table 4.3 and non-baseline shown in Table 4.4, the baseline being the most common impact categories used in LCA.

Table 4.3. *Impact categories included in the method CML baseline (EnvironDec, 2018)*

Impact category group	Name of the impact category in the method
Acidification	Acidification potential-average Europe
Climate change	Climate change-GWP100
Depletion of abiotic resources	Depletion of abiotic resources-elements, ultimate reserves
	Depletion of abiotic resources-fossil fuels
Ecotoxicity	Freshwater aquatic ecotoxicity-FAETP inf, Marine aquatic ecotoxicity-MAETP inf, Terrestrial ecotoxicity-TETP inf
Eutrophication	Eutrophication-generic
Human toxicity	Human toxicity-HTP inf
Ozone layer depletion	Ozone layer depletion-ODP steady state
Photochemical oxidation	Photochemical oxidation-high NO_x

Table 4.4. *Impact categories included in the method CML-non baseline (adm-global, 2020)*

Impact category group	Name of the impact category in the method
Acidification	Acidification potential-generic
Climate change	Climate change-GWP100 (incl. NMVOC average), Climate change-GWP20, Climate change-GWP500, Climate change-lower limit of net GWP100, Climate change-upper limit of net GWP100
Depletion of abiotic resources	Depletion of abiotic resources-elements, economic reserve, Depletion of abiotic resources-elements, reserve base
Ecotoxicity	Freshwater aquatic ecotoxicity-FAETP inf. (extended), FAETP100, FAETP20, FAETP500, Freshwater sedimental ecotoxicity-FSETP inf, FSETP100, FSETP20, FSETP500 Marine aquatic ecotoxicity-MAETP inf. (extended), MAETP100, MAETP20, MAETP500 Marine sedimental ecotoxicity-MSETP inf, MSETP100, MSETP20, MSETP500 Terrestrial ecotoxicity-TETP inf. (extended), TETP100, TETP20, TETP500
Eutrophication	Eutrophication-average Europe
Human toxicity	Human toxicity-HTP inf. (extended), Human toxicity-HTP20, Human toxicity-HTP100, Human toxicity-HTP500
Ionizing Radiation	Radiation
Photochemical oxidation	Photochemical oxidation-high NO_x
Land use	Land use-land competition
Odor	Odor
Ozone layer depletion	Ozone layer depletion-ODP steady state (incl. NMVOC average), ODP10, ODP15, ODP20, ODP25, ODP30, ODP 40, ODP 5
Photochemical oxidation	Photochemical oxidation-EBIR (low NO_x), Photochemical oxidation-high NO_x (incl. NMVOC average), Photochemical oxidation-high NO_x (incl. NO_x, NMVOC average), Photochemical oxidation-low NO_x, Photochemical oxidation-MOIR (high NO_x)

Global warming: Global warming is the effect of rising hotness in the lower atmosphere. Incoming radiations raise the temperatures of the phase of the atmosphere near the earth's surface. The mentioned radiation is absorbed by CO_2, methane, nitrogen dioxide, CFCs among others. The absorption of heat by the mentioned gases is among the major causes of the rise in temperatures above the normal level due to the greenhouse effect. When the earth's temperatures exceed the threshold, polar ice caps are affected which results in sea level rises (Stranddorf, Hoffmann, & Schmidt, 2005).

Ozone layer depletion: The ozone layer in the upper levels of the atmosphere is getting thin day by day and this to a larger extent is attributed to pollutants such as hydrochlorofluorocarbons (HCFCs), chlorofluorocarbons (CFCs) and halons. When this layer gets thinner and thinner the rays from the sun reach the earth's surface without any interruption. Once these rays interact with human bodies the skin, eyes and immune system can be affected severely. It is not only humans that are affected by these rays, plants, insects and aquatic organisms also feel their impacts (UNEP, 1999).

Photochemical oxidant formation: Once oxides of nitrogen and hydrocarbons react with sunlight this environmental impact occurs. Human activities have a significant contribution on the concentration of nitrogen oxides and hydrocarbons in the atmosphere. As a result of the aforementioned reaction peroxyacetyl nitrate, ozone, aldehydes, alcohols, acids among others can be formed together with their detrimental impacts to humans, plants and other living organisms (Altenstedt & Pleijel, 1998).

Acidification: Due to several factors acids may accumulate in the atmosphere and once they get back onto the earth's surface and mix with water and soil acidification occurs. Oxides of nitrogen, sulfur and ammonia play a significant role in the acidification process (Koch, 1999).

Eutrophication: When water bodies experience high concentrations of nutrients, plants such as algae flourish and as a result the oxygen available for other living organisms within the water body reduces. This in turn affects the aquatic ecosystems as some organisms may become extinct. Nutrients such as phosphorous and nitrogen from agricultural activities, wastewater treatment plants among other sources are to a larger extent responsible for eutrophication in most aquatic environments (La Rosa, 2016).

Toxicity: Once living organisms get exposed to toxic chemicals they may be damaged detrimentally. This damage may be categorized into human toxicity, terrestrial ecotoxicity, freshwater aquatic ecotoxicity, marine aquatic ecotoxicity. Toxicity is usually estimated with respect to dichlorobenzene equivalents (McKone & Hertwich, 2001).

Abiotic resources depletion: Renewable and non-renewable resources constitute the feedstock basis of societies and the economy. For humans to survive on earth for generations, they need to depend on resources that exist in their surroundings. Resources such as coal and petroleum provide energy for human economic activities while resources like minerals, metals and plants provide feedstocks for mankind to process various products needed for day to day wellbeing. However, while resources especially the non-renewables are being utilized their reserves reduce. In addition to this, the utilization of resources results in the generation of wastes and emissions that are usually harmful to the environment (Springer, 2018).

4.3.1.2. Optional elements of LCIA

LCIA stage has optional elements such as normalization, grouping and weighting.

Normalization: Normalization is the computation of the size of the category indicator results in proportion to a distinct reference information. The usefulness of normalization is to better understand the relative size for each indicator result of the product system under investigation. Normalization transforms an indicator outcome by dividing it by a distinct reference value. Reference values may be in form of aggregate inputs and outputs that can be global, national or regional, for a particular locality. To ease the normalization procedure, CML baseline and non-baseline can be utilized due to the fact that it contains normalization factors which include: EU25, EU25+3, 2000, The Netherlands, 1997, West Europe, 1995, World, 1990, World, 1995 and World, 2000 (Hischier, et al., 2010).

For example, the normalization procedure can be applied as follows to find the carbon footprint of milk. Assuming that one (1) liter of milk has an effect of approximately 1 kg CO_2, and assuming that global greenhouse gas emissions in 2010 are approximately 7 tons of CO_2 per capita. One (1) liter consumed by one person has an impact of approximately 1/7000 = 0.00014 person-year effect per liter of milk. Thus, if a person consumes 50 liters of milk per year, the milk consumption of that person will be equivalent to the effect of 0.007 people per year or an average person's average climate change of 0.7% per year (PRé Sustainability, 2014).

Grouping: Grouping is the process of forming one or more clusters composed of different impact categories. Grouping may be executed through either sorting impact categories in a specific hierarchy or sorting them on a nominal basis.

Weighting: Weighting is the procedure of transforming indicator outcomes of dissimilar impact categories utilizing numerical variables based on value choices.

4.3.1.3. Sensitivity analysis and other LCIA data quality analysis methods

Techniques such as but not limited to uncertainty analysis, gravity analysis and sensitivity analysis can be applied to assess the results of outcomes from LCIA. Uncertainties in data and assumptions can be better monitored through applying the uncertainty analysis. To find out the data that results into the largest contribution to the indicator result a gravity analysis is utilized (BSI, 2006).

Sensitivity analysis a tool which was applied in this thesis is very vital when it comes to finding out the rigor of study outcomes and their responsiveness to data, assumptions and models. The salient variables of the LCA model can be identified using this tool and in so doing the quality of data can be improved in case it is insufficient to strengthen the decisions made from the findings of the study (Wei, et al., 2015). In situations where researchers need to ascertain the interconnection amidst quality of input data and the quality of the model output, the sensitivity analysis tool is used (Sakai & Yokoyama, 2002).

4.4. Interpretation

Interpretation is a stage of LCA where the findings from inventory analysis and impact assessment are handled together. The interpretation stage generally yields results that are consistent with the purpose and scope defined. The findings of this interpretation can be in the form of a conclusion and recommendation consistent with the purpose and scope of the study to decision makers. Life cycle interpretation also aims to come up with a smoothly comprehensible absolute and harmonious presentation of the outcomes of an LCA, in accordance with the purpose and scope definition of the study (Pennington, et al., 2004).

5. LITERATURE ON URBAN PASSENGER TRANSPORT RELATED LCA

Petrauskienė, Skvarnavičiūtė, & Dvarionienė (2020) using SimaPro 8.5 software carried out a comparative life cycle assessment of electric and conventional vehicles in Lithuania. The goal of the LCA was to evaluate and compare the environmental impacts associated with the production, use and disposal of electric and conventional vehicles. For comparing the environmental emissions of different vehicles, a functional unit of 1 km drive distance was determined. The scope of this analysis included the fuel cycle as well to wheel (WTW) and the vehicle life cycle that follows a cradle to grave approach. The WTW stages cover energy resource extraction, energy carrier production and distribution as well as energy conversion in the vehicle. The equipment life cycle or cradle to grave analysis covers materials production, equipment manufacturing, maintenance, end of life of vehicle and road infrastructure. The Recipe method at the midpoint and endpoint levels was used to perform the impact assessment based on Recipe 2008. In terms of environmental impact categories at the midpoint, climate change, human toxicity, ionizing radiation, metal depletion and fossil depletion were determined according to the categories where the burden was the greatest in the analysis. LCA database Ecoinvent 3 was used as a source of background life cycle inventory data. The results at midpoint level revealed that in terms of climate change electric vehicles of 2015 electricity mix generate more GHG emissions than those of conventional vehicles fueled with petrol and diesel. At the endpoint level conventional petrol vehicles had the highest environmental damage in all impact categories.

Shinde, Dikshit, & Singh (2019) carried out a life cycle environmental performance of public road transport modes in metropolitan regions in India. The environmental performance of public bus transport (PBT) and intermediate public transport (IPT) modes, viz. taxi and auto-rickshaw, in Mumbai Metropolitan Region was assessed and compared at off-peak, average and peak levels of vehicle occupancy. The inventory data was obtained from literature and GaBi database. The study captured both vehicle operation (tail-pipe emissions) and non-operation components (vehicle manufacturing, maintenance and fuel production). GaBi 6.5 software together with CML 2001 method were used to assess the environmental impact in terms of global warming, acidification, eutrophication, photochemical ozone creation, abiotic depletion potential and primary energy demand. The functional unit of the study was defined as passenger kilometer travelled in 15 years and the study results showed that tail-pipe emissions dominated the life cycle environmental impact of PBT (75% of 17.2 g CO_2-eq/PKT), taxi (78% of 85 g CO_2- eq/PKT) and auto-rickshaw (78% of 78 g CO_2-eq/PKT).

Bastos, Marques, Batterman, & Freire (2019) using SimaPro software conducted a study titled “environmental impacts of commuting modes in Lisbon: A life-cycle assessment addressing particulate matter impacts on health.” In the study car, bus, train, subway, motorcycle and bicycle were compared for eight impact indicators. Vehicle manufacturing stage, vehicle operation stage (including fuel production), vehicle maintenance stage, vehicle end-of-life, infrastructure construction, infrastructure maintenance and infrastructure end-of-life stage were considered. Ecoinvent and institutional reports provided the data for the inventory purposes. The functional unit considered was the commuting of one individual for one year and results were presented in terms of both vehicle km and passenger km travelled. Cumulative Energy Demand method, IPCC method, EUTREND model, in ReCiPe and the Accumulated Exceedance model were used to calculate the inventory data to come up with the environmental impact categories. Impact categories considered included non-renewable energy, global warming, acidification, terrestrial eutrophication, freshwater eutrophication, marine eutrophication, particulate matter in take and health effects from human exposure to PM2.5. The results revealed that internal combustion personal vehicles had larger impacts than other modes in most categories, but electricity-powered modes (transit and personal vehicles) had generally higher freshwater eutrophication impacts.

de Souza, et al. (2018) using SimaPro 7.0.1 software compared the environmental performance of traditional vehicles with different fuel options, plug-in hybrid and electric vehicles for an environmentally sustainable transportation system in Brazil with life cycle assessment method. The functional unit for this study was driving 1 km under Brazilian average conditions. The scenarios included: conventional internal combustion engine vehicle (ICEVg) powered by gasoline, conventional internal combustion engine vehicle powered by aqueous ethanol (ICEVe), conventional internal combustion engine vehicle (ICEVf) powered by gasoline and aqueous ethanol (flexible-fuel vehicle), Plug of hybrid electric vehicle (PHEV), battery electric vehicle (BEV). The system boundaries included the production of energy (fuel production, electricity generation and powertrain production, vehicle usage stages and the recycling process of vehicles and batteries. Different fuel consumption and powertrain configurations for a vehicle were considered good for scenarios. In this study, CML 2 Baseline 2000 (v 2.03) impact assessment method was used to analyze the inventories from various research reports and characterise the impact categories such as ADP, fossil fuels based ADP (ADP_{ff}), GWP, HTP, POP, AP and EP. The results showed that the electric battery-powered vehicle had the lowest environmental impact in general, followed by vehicles using ethanol.

Cox & Mutel (2018) studied environmental and cost performance of current and future motorcycles. LCA method was used to compare the driving of different motorcycles for one kilometer averaged over the entire vehicle lifetime. The system boundary for this study was cradle to grave and included both the equipment life cycle as well as the well to wheel fuel chain. Four categories of engine sizes, three types of powertrains and various fuel supply chains were discussed. Traditional gasoline (Internal Combustion Engine Vehicle, ICEV), battery powered electric (BEV) and fuel cell electric (FEV) motorcycles with production years from 1990 to 2030 were discussed. Motorcycle energy consumption was modeled according to the World harmonized motorcycle test cycle and calibrated with data measured from existing motorcycles. The Ecoinvent 3.2. database was used to provide datasets on electricity production and gasoline consumption by motorcycles. An LCIA using the ReCiPe 2008 method from a hierarchy perspective was carried out. Impact categories included climate change, photochemical oxidant formation and particulate matter formation. Findings showed that smaller motorcycles had better environmental performance than larger motorcycles. City driving was found to have a lower environmental impact per km than highway driving. It was found out that existing and new generation BEV had similar environmental performance advantages.

Sopha, Setiowati, & Ma'mun (2017) carried out an environmental assessment of motorcycle using a life cycle perspective. A functional unit of one passenger per kilometer (pkm) was used to estimate the resource consumption and emissions through the entire life cycle of a motorcycle. In this study, vehicle manufacturing stage containing components production, plant construction as well as motorcycle assembly, motorcycle fuel production stage, vehicle operation stage containing vehicle operation as well as vehicle maintenance stage and vehicle end of life stage were considered. The foreground LCI was compiled through observation, interview, and secondary data, while the background LCI was based on Ecoinvent data v.2.0. CML 2000 impact assessment method was used to analyze the inventory data and characterize the impact categories.

Results showed that the environmental impacts of the chosen function unit constitute ADP of 0.515 g Sb-eq., GWP of 176 g CO_2 eq, HTP of 1.1 g 1.4-DCB-eq, and AP of 0.544 g SO_2-eq, respectively. Operation (usage stage) of the motorcycle was the most contributor to GWP and AP, while manufacturing stage was the most contributor to HTP.

Cuéllar, Buitrago-Tello, & Belalcazar-Ceron (2016) using OpenLCA software examined the life cycle emissions of a bus rapid transit (BRT) system and a comparison was made with other passenger transport modes in Bogota, Colombia. The functional unit chosen for this well to wheels LCA was grams of pollutant per km- number of passenger transported (g/pkm). The impact categories considered in this study were global warming and $PM_{2.5}$ as well as CO and NO_x emissions. Vehicles included; four-stroke motorcycle (less than 150 cc), four-stroke motorcycle (150-220 cc), three-way catalytic converter (Three way catalytic converter, TWC) filter E10 car (larger than 1400cc), E10 car without TWC (1400 less than cc), E10 with TWC (10% ethanol gas, E10) car (larger than 1400cc), E10 car with TWC (less than 1400cc), Electric car, E10 taxi, liquid petroleum gas (Liquid Petroleum Gas, LPG) taxi, B5 (5% biodiesel diesel fuel, B5) bus (16-19 passengers), LPG bus (16-19 passengers), B5 bus (19-32 passengers), B5 bus (35- 60 passengers), liquid petroleum gas bus (120 passengers). Life cycle assessment and lifelong approach were applied. Ecoinvent v2.2 database and all information available in the city were used to perform LCA analysis. Fossil fuels, biofuels, and electricity were recognized as energy sources. Diesel and natural gas buses, as well as fast transit buses such as electric passenger cars, motorcycles, gasoline vehicles, light duty vehicles such as taxis, and electric and diesel buses, were also considered as public transport vehicles. The results showed that public transport buses, including BRT, produced the lowest CO_2, CO and NO_x emissions. The lowest $PM_{2.5}$ emissions were observed by electric BRT and natural gas buses. It was stated that the highest $PM_{2.5}$ emission was caused by motorcycles and private cars, and the highest NO_x emission occurred in taxis.

Cooney, Hawkins, & Marriott (2013) carried out a life cycle assessment of diesel and electric public transport buses. In this LCA study the aim was to compare the environmental effects of conventional buses and electric buses. System boundary consisted of; diesel engine manufacturing, diesel fuel manufacturing, generic parts manufacturing, generic bus shell manufacturing, electricity production, li-ion battery manufacturing, electric drive components manufacturing, charging infrastructure manufacturing, diesel bus maintenance, traditional diesel bus operation, electric bus operation, electric bus maintenance and charging infrastructure maintenance. This study used IMPACT 2002 method to categorize environmental impacts of LCI results based on Ecoinvent v2.2 database, the Carnegie Mellon University Green Design Institute tool and U.S. LCI database. The functional unit for this study was 1 vehicle-kilometer over a 12-year lifetime. Impact categories considered in this study were global warming, ozone layer depletion, respiratory inorganics, carcinogens, non-carcinogens, respiratory organics, soil acidification, aquatic acidification, aquatic eutrophication, aquatic ecotoxicity and soil ecotoxicity. According to the results, the vehicle use phase, which includes diesel production or combustion for conventional buses and electricity production for electric buses, dominated the most impact categories.

Sundvor (2013) conducted a life cycle assessment for private and public transport. Two different types of vehicles were analyzed in the study: bus transit vehicles (intercity bus, diesel bus, compressed natural gas bus) and private vehicles (SUV, hatchback special vehicle and subcompact special vehicle). Vehicle production stage, vehicle operation and vehicle destruction stage were analyzed using Arda LCA software. The database used in this study was the Ecoinvent v2.2 and the Recipe framework was the method used to convert the emissions of hazardous substances into impact category indicators. Much as it is not a popular software, Arda software has been employed by several researchers at Norwegian University of Science and Technology to carry out various life cycle evaluation studies in different fields. Impact categories considered for this study included fossil depletion, human toxicity, marine eutrophication, metal depletion, particulate formation, photochemical oxidant formation and terrestrial acidification. According to the study results the intercity bus, which covers the same distance as the diesel bus emitted less GHG emissions. For passenger transportation purpose when the intercity bus was compared with the diesel and compressed natural gas buses in terms of emission pkm, it was found out that it (intercity bus) was the least efficient mode. In terms of kg GHG emissions per km of travel, all the three bus technologies were shown to be more environmentally beneficial than the hatchback, SUV and Subcompact vehicles.

To date, no studies have been conducted using the LCA methodology to determine the environmental performance of urban transportation in Kampala city, UGANDA.

6. MATERIALS AND METHOD

6.1. Goal and Scope

The aim for this thesis was to determine the environmental performance of passenger transport using four different combustion engine vehicles with different passenger capacities, weights or dimensions, lifespans and the type of fuel used (diesel or gasoline) from cradle to grave in Kampala city-Uganda.

6.2. Functional Unit

The functional unit of this study is to transport 1 passenger 1 km; It was selected as “passenger-km”. However, for the transportation of 1 passenger “passenger km”, each process that creates the system boundaries needs a functional unit. The Table 6.1 shows the functional units of all the processes required to accomplish the transportation of a passenger for one kilometer.

Table 6.1. *Functional units for the major processes within the scope of this study*

Process	Quantity	Unit	Explanations
Vehicle manufacturing	1	Product (P)	At this stage, the production of vehicles was considered.
Vehicle shipment	1	tkm	At this stage, transportation of vehicles from China to Uganda was considered.
Vehicle operation	1	km	At this stage, the production of fuel and the use of vehicles to transport passengers was considered.
Vehicle maintenance	1	Product (P)	At this stage, replacement of vehicle parts such as tires was considered.
Vehicle end of life	1	Product (P)	At this stage, recycling of some parts of the vehicles and disposal of some parts was considered.

6.3. System Boundaries

The system boundaries of this thesis work as shown in Figure 6.1 were the stages that include vehicle manufacturing, vehicle shipment, vehicle operation, vehicle maintenance and vehicle end of life.

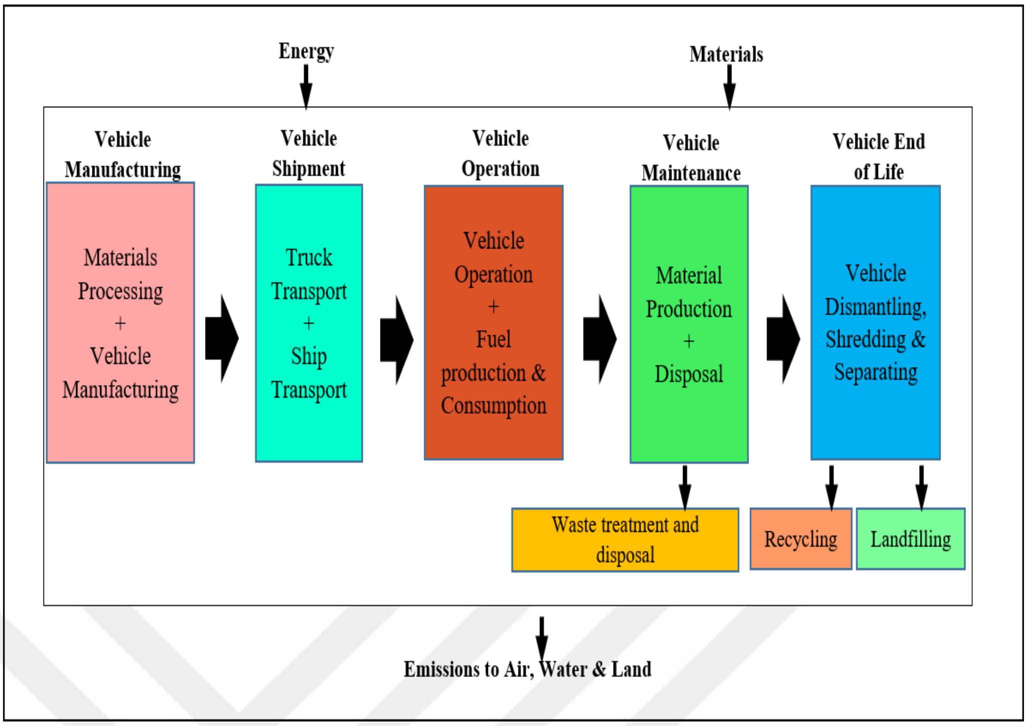

Figure 6.1. *System boundaries for the LCA study*

6.4. Life Cycle Inventory Analysis (LCI)

LCI data can be divided into foreground and background data. The foreground data represent processes such as the production phase, the use phase, the vehicle end of life stage and the fuel supply chains. Background data represents the rest of the economic system, that is, the required products and processes as input to the foreground system. LCI analysis was implemented respecting the ISO 14040 and 14044 standard which includes data gathering and procedures used to compute inputs (energy, fuels and materials flows) and outputs (energy flows, gas discharges, wastewater and solid wastes) and this data was obtained from sources such as those presented in Table 6.2.

Table 6.2. *Table showing sources from which data inventory was obtained*

Process	Inventory data source
Vehicle manufacturing	Ecoinvent database, literature and simple equations.
Vehicle shipment	Ecoinvent database, internet website and simple calculations.
Vehicle operation	Ecoinvent database, questionnaires, simple equations and literature.
Vehicle maintenance	Literature, Ecoinvent database and simple calculations.
Vehicle end of life	Literature, Ecoinvent database and simple calculations.

The vehicles discussed in this study differed in terms of passenger capacities, dimensions or weights, usage times (lifespans) and the type of fuel used (diesel or gasoline). LCA analysis was carried out to calculate the environmental impacts of transportation in the city, considering the different public transportation vehicles currently used in Kampala.

LCA database Ecoinvent v2.2 and v3.3 was used on several occassions as the source of the background life cycle inventory data.

Vehicles selected for evaluation in this study were.

1. 29 passenger diesel minibus weighing 3700 kg, known as Coaster
2. 14 passenger diesel minibus weighing 1280 kg, known as Kamunye
3. 3 passenger gasoline three wheels motorcycle with a weight of 388 kg, known as TukTuk.
4. Single (1) passenger gasoline two-wheeled motorcycle, weighing 108 kg, known as BodaBoda.

6.4.1. Vehicle manufacturing phase

As shown in Figure 6.1, the first stage of the system boundaries for the LCA study conducted in this thesis was vehicle manufacturing. It was assumed that the types of vehicles used in passenger transportation in Kampala were four (Kamunye, BodaBoda, TukTuk and Coaster) and all of them were produced in China. China was considered due to the fact that according to the information provided by Ecoinvent database, the description of the data for the scooter used to represent TukTuk and BodaBoda shows that motorcycles are produced anywhere in Asia and sold anywhere in Europe. Ecoinvent description shows that during motorcycle production transport is involved and it is in form of transporting already made motorcycles from Asia and sell them in Europe. This thesis specified the country of manufacturing as China since specific studies about the vehicles considered in this study did not specify any particular country. In addition, the destination of these vehicles was Uganda which is in Africa not Europe. Hence to achieve specificity in this thesis, the data concerning transportation during vehicle manufacturing was made in such a way that the country of manufacture is China, Europe is the source of raw materials and the final destination of vehicles is Uganda in Africa. In relation to that the bus used to represent Kamunye and Coaster was produced in Germany and transportations during manufacturing were within Germany. To achieve harmony in the thesis these buses were also assumed to be produced in China so that there is simplicity to the researcher. The transportations involved during the production of these buses were also modified to obey the assumption that raw materials are transported from Europe to China.

At this stage, the manufacturing of all materials (steel, aluminum, rubber, plastic) used for the production of vehicles and the electricity production used in China were taken into consideration. In general, there are two main assembly lines in the automotive assembly facility: body and chassis assembly lines. In the body assembly line, the assembly sequence begins with the receiving area of the coil (typically made of steel and aluminum). After passing the test, the bobbin is waited for blanking, the gaps are transferred to the stamping press lines to construct different vehicle panels. Panels such as wheelhouse, bonnet, doors, pillars, trunk, floor pan, and roof are fed to the body welding area (Omar, 2011). These panels are integrated to construct the car shell. The integration of such panels is done first by using tension welding to keep the parts in place and then by using permanent spot welding. The completed body is then lifted to the paint line. The paint booth area cleans automobile shells in immersion tanks and applies a layer of conversion coating followed by an electro-coating. The chassis gives support to the subassemblies and other constituents of a vehicle. The material used for the construction of the chassis is usually carbon steel. The chassis is made up of the steering system, brakes, engine, wheels and suspension system.

Motor vehicle assembly plants use energy for many different end uses throughout the facility and the main energy used is electricity, steam, gas and compressed air. The biggest energy consumers are paint shops. In addition, the majority of emissions to air generated during motor vehicle assembly are essentially volatile organic compounds emitted from dyeing and finishing processes. Wastewater is also produced and is mainly caused by spray booth wash water.

During the manufacturing phase, life cycle inventories for vehicle manufacture were obtained from both the Ecoinvent database and literature studies related to a particular vehicle. Vehicles consist of many systems that can be divided into sub-systems. Two major systems considered in vehicle models are the vehicle body and vehicle chassis components.

The data used for the LCI of vehicle manufacturing and maintenance was calculated and adapted from the Ecoinvent database; Chinese electric mixture shown in Figure 6.2 was adopted for the vehicle manufacturing phase.

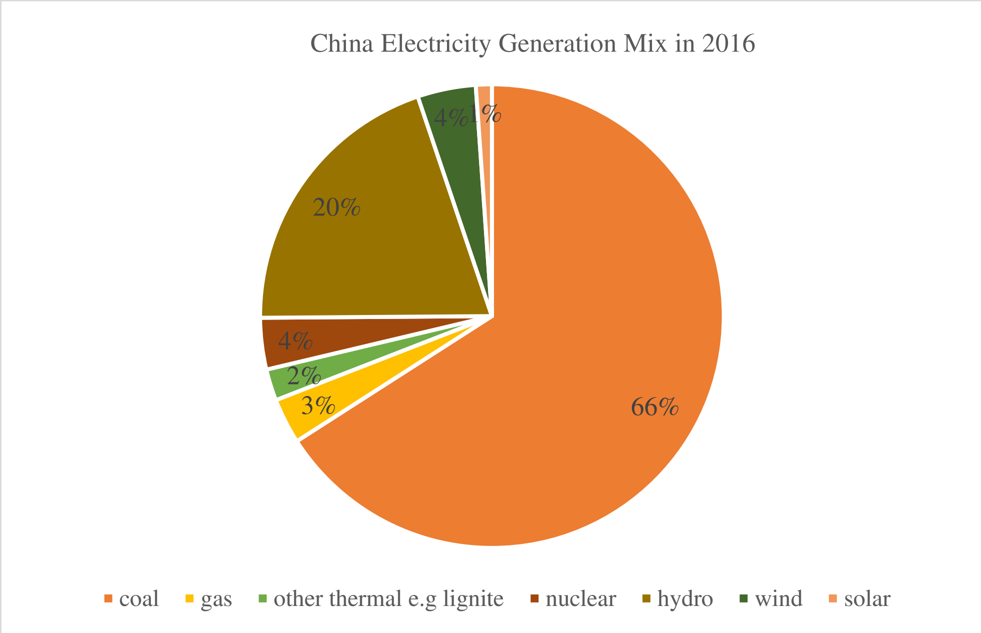

Figure 6.2. *Chart showing the electricity generation mix for China in 2016* (China Energy Portal, 2017)

All the vehicles under evaluation in this thesis could not be found in Ecoinvent database in their exact form, others were not even available in the database. For this reason, the already available vehicles in the database were modified to resemble the vehicles under scrutiny mainly on the basis of weight, fuel consumption, lifespan and fuel type. Table 6.3 shows the vehicles present in Ecoinvent database which facilitated this life cycle assessment process.

Table 6.3. *Vehicles that are modified to resemble means of transport under investigation*

Vehicle	Weight (kg)	Ecoinvent vehicle to be modified
Coaster	3700	11000 kg Volvo 8500 bus consuming 0.3498 kg of diesel per km.
Kamunye	1820	11000 kg Volvo 8500 bus consuming 0.3498 kg of diesel per km.
TukTuk	388	90 kg 50 cc scooter consuming 0.0252 kg of gasoline per km.
BodaBoda	108	90kg 50 cc scooter consuming 0.0252 kg of gasoline per km

In order to obtain the amount of requirements needed for the production of a specific vehicle (Coaster, Kamunye, TukTuk or BodaBoda) all the requirements for the production of the Ecoinvent vehicle shown in Table 6.3 were expressed in terms of the required vehicle according to equation (Eq.) 6.1 below.

$$Mat_{sv} = \frac{Mat_{eiv} \times Wt_{sv}}{Wt_{eiv}} \quad (6.1)$$

Here; Mat_{sv} is the amount of requirements needed for the production of a specific vehicle, Mat_{eiv} the amount of material (kg) used to produce the Ecoinvent vehicle to be modified, Wt_{sv} weight of a specific vehicle among those considered in this study, Wt_{eiv} the weight of the Ecoinvent vehicle to be modified.

6.4.1.1. Inventory data for the manufacturing (production) of a BodaBoda

LC inventory for BodaBoda production was based on production processes and materials for the production of a 90kg 50cc e-scooter found in the Ecoinvent 2.2 and 3.3 database available in the SimaPro 8.5.0. software. The materials used in the production process were assumed to be imported from Europe to China where the final production of the scooter took place. The scooter included an ICE engine running at a maximum speed 60-70km/h. In addition to the data obtained from the Ecoinvent database, some data on the main components of the motorcycle was based on the findings of the report prepared by Asian Development Bank-ADB (2009) on motorcycles.

It is important to mention that the weight of BodaBoda was assumed to be 108 kg. Due to the lack of specific information on the production of a BodaBoda, a 90 kg scooter production data available in the Ecoinvent database was accepted without changing the values. The values of plastic components were taken from ADB (2009).

It was assumed that the requirements needed to produce a 90 kg scooter were not very different from those needed to produce a 108 kg motorcycle. It was assumed that BodaBoda was produced in China and the electricity used as energy source was based on the Chinese electricity generation mix. The materials and amount of materials used to produce BodaBoda are shown in Appendix-1a.

6.4.1.2. Inventory data for the manufacturing (production) of a TukTuk

LC inventory for the production of 3 passenger TukTuk was based on production processes and materials for the production of a 50cc e-scooter available in the Ecoinvent 2.2 and 3.3 database. This scooter had a weight of 90 kg and had a maximum speed of 60-70 km/h. The scooter was assumed to be produced in China, but the materials used for production process were imported from Europe. The specific information on the main components of a TukTuk, was obtained from the findings of the studies carried out by Shinde, Dikshit, & Singh (2019) on the production of a TukTuk.

The amount of material required to manufacture a TukTuk was obtained as follows: Data from the Ecoinvent database for 90 kg e-scooters was expressed in terms of a 388 kg TukTuk except the amount of energy required. Thus, the amount of material required for a 388 kg production was obtained. This amount of material obtained was further expressed in terms of the percentages of materials forming a TukTuk provided Shinde, Dikshit, & Singh (2019).

The amount of energy required for a TukTuk production was obtained as follows; An average amount of energy was obtained by adding the amount of energy in kWh required to produce three different motorcycles. This average amount of energy was multiplied by the weight of TukTuk. According to ADB (2009), 3510 kWh (27.9 kWh/kg) was consumed to produce 126 kg of a 125cc motorcycle. According to ADB (2009), 1534 kWh (16.3 kWh/kg) was consumed to produce a 100-cc scooter weighing 94.0 kg. According to Patnayak, Bansal, & Mathur (2004), 3.4 kWh/kg was consumed to produce a motorcycle. Thus, the average amount of energy consumed to produce a motorcycle or a TukTuk in this thesis was 15.9 kWh/kg. It should therefore be noted that the energy used to produce TukTuk was not obtained through modifying Ecoinvent data but through averaging findings from various peer reviewed research articles.

In this thesis the average amount of energy required to produce a motorcycle was assumed to be equal to the average amount of energy required to produce a TukTuk. Some data on the production of a TukTuk was not based on studies by Shinde, Dikshit, & Singh (2019), ADB (2009) and Patnayak, Bansal, & Mathur (2004). Such data was obtained by expressing the data provided by the Ecoinvent database for a 90 kg 50cc scooter in terms of a 388 kg TukTuk. Thus, the equation (6.1) was used.

The transportation stage during the manufacturing phase included the shipment of materials to produce vehicle components. These materials were assumed to be imported from Europe to Asia. The total amount of material was 613.2 kg.

The 613.2 kg of raw material were transported by material trucks for 37.3 km, by cargo ship for 13,000 km and by rail for 373.4 km. The materials and amount of materials used to produce TukTuk were shown in Appendix-1b.

6.4.1.3. Inventory data for the manufacturing (production) of a Coaster

LCI inventory data for 29 passenger Coaster production was based on representative data for 11000 kg bus production of a German company with environmental management. This data was available in Ecoinvent 2.2 and 3.3.

Inventory included material, energy and water usage processes in vehicle manufacturing (final assembly, engine manufacture and metal parts manufacturing in the years 2000, 2002 and 2000 respectively). Rail and road transport of materials used in the production process was also taken into consideration in the study.

In order to obtain the amount of requirements for the production of a 3,700 kg Coaster, all the requirements for the production of an 11,000 kg bus provided by the Ecoinvent database were expressed in terms of a 3700 kg Coaster. Thus, the equation 6.1 was utilized. The materials used and the quantity of materials used to produce the coaster were shown in Appendix-1c.

6.4.1.4. Inventory data for the manufacturing (production) of a Kamunye

LC inventory data for the production of 14 passenger Kamunye was based on representative data for the production of trucks/buses (low entry Volvo 8500 bus vehicle 12 l engine) of a German company with environmental management. This data was available in Ecoinvent 2.2 and 3.3 database.

Inventory included material, energy and water usage processes in vehicle manufacturing (final assembly, engine manufacture and metal parts manufacturing in years 2000, 2002 and 2000 respectively). Rail and road transport of materials used in the production process was taken into consideration in the study.

In order to obtain the amount of requirements for the production of 1,820kg Kamunye, all the requirements for the production of an 11,000 kg Volvo bus provided by Ecoinvent were expressed in terms of an 1820 kg Kamunye. Equation 6.1 was also employed at this level to ease the calculations. The materials and amount of materials used to produce Kamunye were shown in Appendix-1d.

6.4.2. Vehicle shipment

The vehicle shipment from where they were produced included the import of the vehicles from China (place of production) to Uganda (place of use) as shown in Figure 6.3. The transportation phase of the vehicles starts from the factory in China. Vehicles are transported by a truck for 20 kilometers to Hongkong port in China. A cargo ship is then used to transport vehicles to the Mombasa port in Kenya, where trucks are again used to transport passenger vehicles from Mombasa port to Nakawa in Kampala-Uganda.

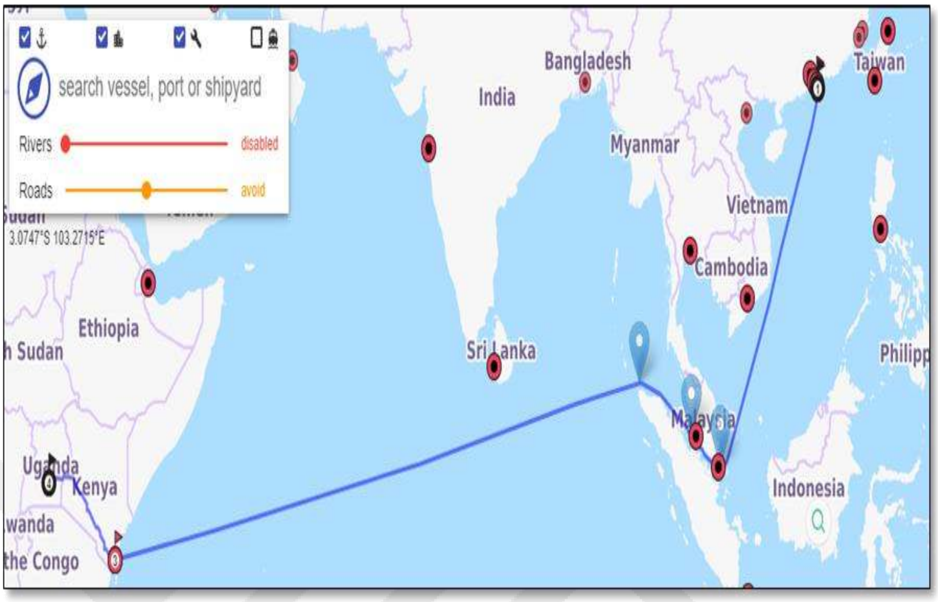

Image 6.1. *Route used to transport vehicles from China to Uganda* (Searoutes, 2020)

The truck used to transport vehicles from production facilities in China was based on the 12-ton diesel truck provided by the Ecoinvent 2.2 and 3.3 database. 20 km was considered as the distance this truck traveled from the vehicle manufacturing facility to the Hongkong port in China. In this study, only the operation phase of the truck was taken into consideration. The transportation of vehicles from the production facility (China) to the Hongkong port (China) was presented in Appendix-2a. The tonnage of the truck used in the vehicle shipment stage was not used in any calculation carried out in this thesis.

A transoceanic cargo ship used to transport vehicles from Hongkong port (China) to Mombasa port (Kenya) was based on a 40,000-ton cargo ship provided by Ecoinvent 2.2 and 3.3 database. 11334 km was considered as the distance between the two ports. In this study, only the operational phase of the cargo ship was considered. The ton per km for each vehicle considered in this study was shown in Appendix-2b. The tonnage of the transoceanic cargo ship was not involved in any calculations carried out in this thesis.

A 12-ton cargo truck was used to transport vehicles from Mombasa port to their final destination, Nakawa (Uganda). This truck was based on the 12-ton diesel truck provided by the Ecoinvent 2.2 and 3.3 database. 1125 km was considered the distance between Mombasa and Nakawa. In this study, only the operation phase of the truck was taken into consideration. The ton per kilometer for each vehicle selected for this study was shown in Appendix-2c. The tonnage of the truck considered in this thesis was not used in any calculations carried out in this thesis.

6.4.3. Vehicle operation stage

The vehicle operation phase contains data on vehicle tail pipe emissions and fuel production. During the operation phase, the effects of fuel production and emissions from vehicle operation were calculated. The methodology used in European Environment Agency (EMEP/EEA) air pollutant emission inventory guidebook 2016-Update July, 2018 was used to calculate the emissions of vehicles selected during the operation phase.

Vehicle operation

In some studies, this stage is called the tank to wheels stage. The term Tank-to-Wheel (TTW) refers to a stage which involves filling the vehicle with fuel and consuming that fuel while driving that vehicle. The operation stage of a vehicle considers the exhaust pipe emissions and fuel utilization. Air pollution from buses, motorcycles and cars mainly occurs as a result of discharges from tail pipe (Messagie, Boureima, Coosemans, Macharis, & Van Mierlo, 2014).

Crude oil extraction (oil and gas production)

To find crude oil, likely localities are subjected to detailed analysis, including sedimentary basin analysis and reservoir characterization. The oil found later is obtained by oil drilling. Crude oil is passed through hot furnaces and the resulting liquids and vapors are discharged into the distillation units. Inside the distillation units, liquids and vapors are divided into petroleum constituents known as fractions respecting their boiling points. Heavy fractions settle at the bottom while light fractions such as gasoline float at the top. After the distillation process, heavy, low-value distillation fractions can be converted to lighter, higher-value products such as gasoline. Both incoming crude oil and outgoing end products are temporarily stored in large tanks in a tank farm near the refinery. Trucks, trains and pipelines convey the final products from storage tanks to other places for utilization. The main environmental impacts of the oil refining process are high levels of energy consumption, atmospheric emissions such as CO_2, CO, NO_x, SO_x, as well as PM, water emissions and waste generation (Republic of Turkey Ministry of Environment and Urbanisation, 2013).

6.4.3.1. Vehicle operation (vehicle fuel combustion)

In order to find the tail pipe emissions from the vehicles selected for this study, collective passenger vehicle operators were interviewed to obtain data on the daily mileage and fuel consumption for their vehicles. Questionnaires were filled in for record management purposes and were shown in Appendix-3a. According to the European Environment Agency (EMEP/EEA) air pollutant emission inventory guidebook 2016-Update July, 2018, there are several methods to estimate exhaust emissions from the road transport system. The method applied for this study accepted the fuel as an indicator of activity with average fuel-specific emission factors.

Interviews and surveys were conducted to find out the fuel consumption of the vehicles selected for this study, and one-on-one interviews were carried out with the selected passenger car operators in the Kampala city. Data on the type of vehicle, the route of operation, the distance of the route, the number of trips per day, the type of fuel used in liters, and the amount of fuel consumed per trip were collected and shown in Appendix-3b. The data obtained from the survey was used to calculate the average amount of fuel in liters consumed per km traveled by a particular vehicle in the Kampala city. The average fuel consumption in liters per kilometer was expressed in terms of kilograms per kilometer basing on studies by Hsu (2011), Chen, Braisher, Crossley, Stone, & Richardson (2010), Giwa, Sulaiman, & Nwaokocha (2017) and Zhou & Cai (2014). The results of this conversion were presented in Appendix-3c. Some emission factors were obtained from the EMEP/EEA air pollutant emission inventory guidebook 2016-Update July 2018. Average emission factors of the Tier 1 method were used because detailed information on vehicle emissions in Uganda was insufficient. As shown in Table 6.4. Coaster and Kamunye were categorized as light commercial vehicles (LCV) while TukTuk and BodaBoda are accepted as L category vehicles (L).

Table 6.4. *Average emission factors based on Tier 1 method* (EEA, 2018)

Category	**Fuel**	**CO**	**NMVOC**	**NOx**	**PM**	**N_2O**	**NH_3**	**Unit**
Kamunye (LCV)	Diesel	7.40	1.54	14.91	1.52	0.06	0.04	g/kg fuel
Coaster (LCV)	Diesel	7.40	1.54	14.91	1.52	0.06	0.04	g/kg fuel
TukTuk (L)	Gasoline	497.70	131.40	6.64	2.20	0.06	0.05	g/kg fuel
Boda Boda (L)	Gasoline	497.70	131.40	6.64	2.20	0.06	0.05	g/kg fuel

The approximate consumption of fuels according to transportation category shown in Table 6.5 was calculated based on meeting with individuals providing transportation services in Kampala city.

Table 6.5. *Estimated vehicle fuel consumption (Appendix-3b interview results)*

Category	Fuel type	Consumption amount (kg/km)
Kamunye (LCV)	Diesel	0.14
Coaster (LCV)	Diesel	0.22
TukTuk (L)	Gasoline	0.049
Boda Boda (L)	Gasoline	0.035

Estimated pollutant emissions per vehicle per kilometer was calculated according to the EMEP/EEA air pollutant emission inventory guidebook 2016-Update July 2018 and were shown in Table 6.6. Here, it should be noted that the exhaust emissions of vehicles were calculated by multiplying fuel consumption and emission factor according to the vehicle type.

Table 6.6. *Estimated exhaust emissions from passenger vehicles used in Kampala*

Category	Fuel	CO	NMVOC	NO_x	PM	N_2O	NH_3	Unit
Kamunye	Diesel	1.03	0.21	2.07	0.21	7.78E-3	5.28E-3	g/km
Coaster	Diesel	1.63	0.34	3.28	0.33	12E-3	8.36E-3	g/km
TukTuk	Gasoline	24.39	6.44	0.33	0.11	2.89E-3	2.45E-3	g/km
Boda Boda	Gasoline	18.91	4.99	0.25	0.08	2.24E-3	1.90E-3	g/km

In order to reduce the uncertainties in estimated emission amounts from the selected public transportation vehicles, the following assumptions were taken into consideration; Road transportation systems for India are not much different from those for developing countries such as Uganda; Public transport in Kampala always runs at full passenger capacity (100%). Considering the above assumptions, the results of the study conducted by the Central Pollution Control Board-Ministry of Environment, Forest and Climate Change of India-CPCB (2015) were accepted and the data used was shown in Table 6.7 below.

Table 6.7. *Emission factors for road vehicles* (CPCB, 2015)

Category	Model	CO	HC	NO_x	PM	CO_2	Unit
Diesel (<3000cc) Kamunye	1996-2000	3.00	1.28	2.48	0.66	333.31	g/km
Diesel (>3000cc) Coaster	2000	3.66	1.35	2.12	0.48	401.25	g/km
4 Stroke gasoline BodaBoda (100-200cc)	After 2000	1.48	0.50	0.54	0.04	24.82	g/km
4 Stroke gasoline TukTuk (<200)	After 2005	2.29	0.77	0.53	0.02	73.80	g/km

The results of the study using the Tier 1 method (Table 6.6) and the CPCB (2015) of the Republic of India (Table 6.7) have been averaged and shown in Table 6.8. The results are used to analyze tail pipe emissions during the operation phase of vehicles.

Table 6.8. *Main pollutants from vehicles*

Vehicle types	CO	HC	NMVOC	NO_X	PM	CO_2	N_2O	NH_3	Unit
Diesel (<3000cc) Kamunye	2.01	1.27	0.21	2.28	0.43	333.31	0.008	0.005	g/km
Diesel (>3000cc) Coaster	2.64	1.36	0.35	2.70	0.41	401.24	0.012	0.008	g/km
Gasoline (100-200cc) BodaBoda	10.20	0.50	4.99	0.40	0.06	24.82	0.002	0.002	g/km
Gasoline (<200) TukTuk	13.34	0.77	6.44	0.43	0.06	73.80	0.003	0.002	g/km

Averages were taken whenever a pollutant was appearing in both Table 6.6 and Table 6.7. If the value of the pollutant appears once in a particular table (Table 6.6 or Table 6.7), it was considered the amount to be used for analysis without modification. The amounts for analysis were presented in Table 6.8.

Some emissions were not calculated using the methodology used to achieve results in Table 6.8. In such cases, emissions from the Ecoinvent database were expressed according to equation (6.2) below.

$$Pollutant_{sv} = \frac{Fuel_{sv} \times Pollutant_{eiv}}{Fuel_{eiv}} \qquad (6.2)$$

Here; $Pollutant_{sv}$ is the amount of pollutants per km produced by a specific vehicle, $Fuel_{sv}$ the amount of fuel per km consumed by a specific vehicle among those under study (Coaster, Kamunye, TukTuk or BodaBoda), $Pollutant_{eiv}$ the amount of pollutants per km produced by the modified Ecoinvent vehicle corresponding to a specific vehicle among those under study, $Fuel_{eiv}$ the amount of fuel per km consumed by the modified Ecoinvent vehicle corresponding to a specific vehicle out of those under study.

6.4.3.2. Emissions generated by BodaBoda during operation phase

The scooter provided by the Ecoinvent database consumed 0.0252 kg of gasoline per kilometer, and because of this consumption, it releases different amounts of pollutants which are presented in the database. On the other hand, a BodaBoda used in Kampala consumes 0.038 kg of gasoline per kilometer. To find out the amount of emissions produced by a BodaBoda, the emissions produced by the scooter provided by the Ecoinvent consuming 0.0252 kg of gasoline are expressed in terms of the amount of fuel consumed by BodaBoda in Uganda per kilometer. The amount of pollutants emitted by BodaBoda per km was obtained according to equation (6.2). Emissions produced by BodaBoda during the operation phase were shown in Appendix 4a.

6.4.3.3. Emissions generated by TukTuk during the operation phase

The scooter provided by the Ecoinvent database consumed 0.0252 kg of gasoline per kilometer and from this consumption released the amount of pollutants provided by the Ecoinvent database. TukTuk used in Kampala consumed 0.049 kg of gasoline per kilometer. To find out the amount of emissions produced by TukTuk, the amount of emissions produced by the scooter provided by Ecoinvent database, which consumes 0.0252 kg of gasoline was expressed in terms of a TukTuk, which consumes 0.049 kg of gasoline per kilometer. Equation 6.2 was also used here to ease the calculations. Emissions produced by TukTuk during the operation phase were shown in Appendix-4b.

6.4.3.4. Emissions generated by Kamunye during the vehicle operation phase

As for Kamunye, Volvo 8500 bus provided by the Ecoinvent database consumed 0.3498 kg of diesel per 1 kilometer and produced the amount of pollutants provided by the Ecoinvent database from this consumption. On the other hand, Kamunye used in Kampala consumed 0.139 kg of diesel fuel per kilometer.

To find out the amount of emissions produced by Kamunye, emissions generated by the bus provided by the Ecoinvent database, which consumes 0.3498 kg of diesel, were expressed in terms of a Kamunye which consumed 0.139 kg of diesel fuel per kilometer.

Equation 6.2 was utilized to execute this process. Emissions produced by Kamunye during the operation phase were shown in Appendix-4c.

6.4.3.5. Emissions generated by the Coaster during the operation phase

The Volvo 8500 bus, provided by the Ecoinvent database, consumed 0.3498 kg of diesel per kilometer, and from this consumption it produced the amount of pollutants provided by the Ecoinvent database. The Coaster used in Kampala consumed 0.22 kg of diesel fuel per kilometer.

To findout the amount of emissions produced by Coaster, emissions generated by the bus provided by the Ecoinvent database, which consumes 0.3498 kg of diesel, were expressed in terms of a Coaster which consumed 0.22 kg of diesel fuel per kilometer. Equation 6.2 was vital at this stage. Emissions produced by Coaster during the operation phase were shown in Appendix-4d.

6.4.3.6. Vehicle occupancy and functional unit (pkm)

The effect of each passenger per kilometer covered on the amount of pollutants produced by a vehicle during the operational phase was calculated and the results were presented in Table 6.9. In this thesis it was assumed that each passenger vehicle considered operated at full capacity (100% occupancy rate).

Table 6.9. *Vehicle occupancy and functional unit (pkm)*

Vehicle type	Occupancy rate	Passenger	km	Functional unit
BodaBoda	100%	1	1.00	1 passenger-km
Kamunye	100%	14	0.071429	1 passenger-km
Coaster	100%	29	0.034483	1 passenger-km
TukTuk	100%	3	0.333333	1 passenger-km

6.4.4. Fuel production

LCI for diesel and gasoline production used by selected vehicles was based on data provided by Ecoinvent 2.2 and 3.3 database. Diesel production was based on low sulfur/CHU in regional storage. Gasoline production was based on gasoline, two stroke blends and gasoline in regional storage, and low sulfur in regional storage. All stages of fuel production in the Ecoinvent database were taken into account for diesel and gasoline production.

6.4.5. Vehicle maintenance

In addition to the materials removed from the vehicle during the maintenance phase, the effects of the materials put on a particular vehicle during its lifetime were also examined. The maintenance phase usually includes lubricant oil consumption, tires, brake parts and flushing water throughout the life of the vehicles.

Maintenance or replacement of the vehicle body is quite uncommon unless the vehicle is scratched Mayyas, Qattawi, Mayyas, & Omar (2012). The main environmental impacts of maintenance undertakings are waste and expired vehicle constituents Keivanpour & Kadi (2015).

Three conditions are respected in maintenance operations; these include maintenance material production, waste and other maintenance processes. In most cases, new materials are used instead of the recycled materials. For example, new tires are made from a synthetic rubber derived from oil. According to Our Renewable Future (2020) a barrel of oil is utilized in the manufacturing of synthetic rubber used to make a tire.

Worn out parts such as tires produce waste that has a negative impact on the environment. While energy and natural resources are consumed to produce new components, worn components are disposed of as waste. In addition, component manufacturing activities generate discharges that are detrimental to the environment Viktoria, van Loon, Olsson, & Klintbom (2018).

This thesis assumed that the damaged part was only replaced with a new part, that is, second-hand parts were not considered for replacement. Uganda electricity generation mix was adopted during the maintenance phase. In Uganda, 100% of the electricity is generated from hydropower plants.

The vehicles selected in this thesis had different life spans. For this study, it was assumed that BodaBoda and TukTuk had a 5-year lifetime and Coaster and Kamunye had a 15-year lifetime. During this lifetime, various parts of the vehicle were removed and new parts were installed on to the vehicle. Maintenance LCI of rubber tires was based on the study carried out by Giannouli, de Haan, Keller, & Samaras (2007) as shown in Table 6.10.

Table 6.10. *Rubber utilization during the life of the vehicles*

Vehicle	Rubber (kg)	Tires	Tire lifetime (km)	Thesis tire lifetime (km)	Replacement (times)	Lifetime tires (tires)	Consumed Rubber (kg)	Lifetime Distance (km)
Coaster	8.2	6	60000	112949.3	5	30	246.0	564746.3
Kamunye	8.2	4	60000	120997.5	7	28	229.6	846982.5
BodaBoda	5.1	2	40000	178850	2	4	20.4	357700.0
TukTuk	4.0	3	40000	119227.3	2	6	24.0	238454.5

It should be noted that in Table 6.10 the weight of each tire for a specific vehicle, the number of tires found on a specific, the average lifetime of a tire according to Giannouli, de Haan, Keller, & Samaras (2007), the lifetime for each tire according to this thesis, average number of times tires are changed during vehicle lifetime, the total number of tires used during the entire vehicle lifetime, total amount of rubber consumed to produce the total number of tires and the total distance covered by the vehicle during its lifetime was given. This information was very important during the vehicle maintenance in relation to rubber consumption.

In the waste treatment stage of the maintenance phase, it was assumed that the amount of old material was equal to the amount of new material used to maintain the vehicle. In addition, the amount of sulfuric acid and lead used in the maintenance phase for a TukTuk was kept the same as that used in the maintenance of the scooter provided by the Ecoinvent database.

Ecoinvent database provided the amount of material besides rubber needed to maintain a specific vehicle amidst those being focused on in this thesis according to equation (6.3).

$$Maint_{sv} = \frac{Maint_{eiv} \times Wt_{sv}}{Wt_{eiv}} \quad (6.3)$$

Here; $Maint_{sv}$ is the amount of material besides rubber needed to maintain a specific vehicle, $Maint_{eiv}$ the amount of material (kg) used to maintain the Ecoinvent vehicle to be modified, Wt_{sv} the weight of a specific vehicle among those considered in this study, Wt_{eiv} the weight of the Ecoinvent vehicle to be modified.

Materials used for BodaBoda repair and maintenance

The Ecoinvent database provided the amount of material needed to maintain a 90 kg scooter. Utilizing equation 6.3 this data was expressed in terms of a 108 kg BodaBoda used in Kampala as shown in Appendix-5a.

Materials used for TukTuk repair and maintenance

The Ecoinvent database provided the amount of material needed to maintain a 90 kg scooter. With the help of equation 6.3 this data was expressed in terms of a 388 kg TukTuk used in Kampala as shown in Appendix-5b.

Materials used for Coaster repair and maintenance

The Ecoinvent database provided the amount of material required for the maintenance of the 11,000 kg ICE Volvo 8500 bus. Employing equation 6.3 this data was expressed in terms of a 3700 kg Coaster used in Kampala as shown in Appendix-5c.

Materials used for Kamunye repair and maintenance

The Ecoinvent database provided the amount of material needed to maintain the 11,000kg ICE Volvo 8500 bus. Through applying equation 6.3 this data was expressed in terms of 1820 kg Kamunye used in Kampala as shown in Appendix-5d.

6.4.6. Vehicle end of life stage

Once a bus, motorcycle or car has completed its useful life, it is detoxified. Fluids, batteries and other hazardous materials are removed (Vermeulen, Van Caneghem, Block, Baeyens, & Vandecasteele, 2011). It is hauled to the scrap yard without its dangerous constituents. In the scrap yard, workers dismantle the vehicle completely with the aid of hydraulic tools (Gradin, Luttropp, & Björklund, 2013). Material fractions are divided into metals, recyclable polymers, glass and non-recyclable constituents during disassembly.

Vehicle metallic and dismantled constituents that require shredding, such as rubber and plastic, are conveyed to a shredding mill where they are grinded into smaller pieces. These parts are mainly separated automatically with the aid of magnets and air currents (Berzi, Delogu, Giorgetti, & Pierini, 2013). Magnetic metals and heavy materials are recycled. The remaining constituents, which cannot be recycled, are hauled to landfills for final disposal.

Dismantling, shredding and separating processes consume electricity as input and produce steel, iron, aluminum, polymers and other materials as output. The advantages of recycling steel, aluminum and other recyclable materials are expounded by including the avoided burdens within the system boundary (Belboom, Lewis, Bareel, & Léonard, 2016). This stage consisted of life cycle inventory for handling vehicles in the scrap yard. It also included recycling materials from vehicles.

Data on manual dismantling and separation of vehicle components was based on the literature from past studies. The background system, such as transportation, fuels, recycling, electricity, storage and avoided burden processes, was modeled using data from the Ecoinvent database.

Finally, at the vehicle end of life stage, the benefits of recycling and the effects of dismantling, shredding and separation were also taken into account. The benefits of recycling were subtracted from the total value of the effects of other stages of the considered vehicle life cycle.

6.4.6.1. Material recovery rates

Material recovery rates were summarized in Appendix-6a, Appendix-6b, Appendix-6c and Appendix-6d. The figures were based on the results of the study on manual dismantling of vehicles conducted by Gradin, Luttropp, & Björklund (2013).

6.4.6.2. Energy consumption and transportation at the vehicle end of life stage

Uganda electricity generation mix was used to model the electricity consumed during the shredding and hand disassembling processes. These data were taken from the study by Gradin, Luttropp, & Björklund (2013) and shown in Appendix-7a, 7b, 7c, 7d and 8a, 8b, 8c, 8d.

In this study, avoided burden was taken into consideration. The values of the recyclable components of the vehicles were entered into SimaPro software for analysis. Non-recyclable components were considered waste for treatment. These non-recyclable materials were prepared for landfilling.

6.4.7. Relationship between inventory data and functional unit (pkm)

The functional unit used in this study was transporting a passenger for a distance of one kilometer using a particular vehicle. The functional unit for this study had two components. The two components were the consumption of the vehicle as a product and the provision of a service (passenger transport) using a vehicle.

6.4.7.1. Use of the vehicle as a product

Different vehicles have different lifetimes and carry different passengers. The equation (6.4) below was used to find the value of the use of the vehicle throughout its lifetime.

$$V.U = \mathrm{O.M} \qquad (6.4)$$

Here; $V.U$ is the vehicle usage throughout its lifetime, *O* the occupancy level, *M* the amount of mileage covered by the vehicle during its lifetime.

The results from the equation were expressed in terms of passengers per kilometer.

The result of the equation (6.4) was divided by 1 to find the impact of a passenger per kilometer covered throughout the life of the vehicles.

The results of the equation (6.5) below was presented in Table 6.11.

$$I = \frac{1}{\mathrm{O.M}} \qquad (6.5)$$

Here; *I* is the Impact of a passenger per kilometer covered throughout the life of the vehicles, *O* the occupancy level, *M* the amount of mileage covered by the vehicle during its lifetime.

Table 6.11. *Data on the consumption of a particular vehicle in terms of pkm*

Vehicle type	Occupancy rate (%)	Vehicle usage-vehicle (product)/pkm	Unit
BodaBoda (1)	100	0.0000027958	product
Kamunye (14)	100	0.0000000843	product
Coaster (29)	100	0.0000000611	product
TukTuk (3)	100	0.0000013979	product

The value obtained in Equation (6.5) was used to find the effect of carrying one passenger per kilometer using a particular vehicle. This value was used during the manufacturing phase, the shipment phase, the maintenance phase and the end of life phase of a particular vehicle.

6.4.7.2. Provision of a service using a vehicle (passenger transport)

It was assumed that the public transportation vehicles in Kampala travel when they are 100% or fully loaded. The equation (6.6) below was used to find the effect of a passenger carried over a kilometer in a fully loaded passenger vehicle.

$$I_{operation} = \frac{1}{N} \tag{6.6}$$

Here; $I_{operation}$ is the effect of a passenger carried over a kilometer in a fully loaded vehicle, N the number of passengers at vehicle full capacity (100% occupancy level).

In a fully loaded passenger vehicle, the effect of a passenger during a journey of 1 kilometer was obtained. This impact was expressed in terms of kilometers. The value in kilometers obtained from the equation (6.6) above was used only in the operation phase of the selected vehicles in this study.

7. RESULTS AND DISCUSSIONS

In this chapter, according to the results of the impact assessment of the passenger transportation (for passenger-km) using the public means available in Kampala, the depletion of abiotic resources on an elemental basis (ADP, kg Sb eq.), fossil fuel based abiotic resources depletion (ADP_{ff}, MJ), global warming potential (GWP, kg CO_2 eq.), acidification potential (AP, kg SO_2 eq.), eutrophication potential (EP, kg PO_4^{-3} eq.), human toxicity potential (HTP, kg 1,4-DB eq.), toxic effect on freshwater ecosystem (FAETP, kg 1,4-DB eq.), toxic effect on land ecosystem (TEP, kg 1,4-DB eq.), photochemical oxidation potential (POP, kg C_2H_4 eq.) and ozone layer depletion potential (ODP, kg CFC-11 eq.) in terms of pkm were investigated and scrutinized.

It is important to point out that at the vehicle end of life stage the vehicle is more or less regarded as a waste. If the end of life results are positive it signifies an environmental load or consumption of valuable resources. When these results are in negatives it shows that the environmental impacts of vehicle end of life phase are smaller than the benefits from this stage.

The negative values show an environmentally friendly management of waste through recycling, reuse and recovery. In this thesis most components of the vehicles considered were assumed to be recycled and this resulted into negative values for vehicle end of life stage. When components of the vehicles are reused, recycled or recovered, virgin materials are saved and this reduces the burden on the resource reserves and the environment.

7.1. Life Cycle Impact Assessment (LCIA)

The evaluation of the inventory results described in chapter 6.4 was made with Simapro 8.5.0 using CML-IA baseline V3.03/World 2000 impact assessment method.

7.1.1. Characterization results

The characterisation results for the LCIA of passenger transportation using the public means in Kampala were presented in Table 7.1. The characterization graph according to the impact categories was given in Figure 7.1. This graph presented the percentage environmental impact of passenger transportation using each vehicle to each impact category.

Table 7.1. *Comparative characterization results in terms of pkm at 100% occupancy level*

Impact category	Unit	Coaster	Kamunye	BodaBoda	TukTuk
ADP	kg Sb eq.	1.3E-08	1.0E-08	3.9E-08	3.7E-08
ADP_{ff}	MJ	4.3E-01	5.5E-01	2.2E+00	1.0E+00
GWP (GWP100a)	kg CO_2 eq.	2.0E-02	3.1E-02	6.9E-02	4.7E-02
ODP	kg CFC-11 eq.	4.9E-09	6.0E-09	2.1E-08	9.4E-09
HTP	kg 1,4-DB eq.	2.5E-03	2.5E-03	3.6E-01	1.5E-01
FAETP	kg 1,4-DB eq.	1.5E-04	1.9E-04	7.9E-04	3.8E-04
TEP	kg 1,4-DB eq.	2.5E-05	2.6E-05	9.3E-05	5.7E-05
POP	kg C_2H_4 eq.	6.8E-06	9.4E-06	6.1E-04	2.6E-04
AP	kg SO_2 eq.	9.0E-05	1.3E-04	5.0E-04	2.3E-04
EP	kg PO_4^{---} eq.	1.7E-05	2.8E-05	8.1E-05	3.3E-05

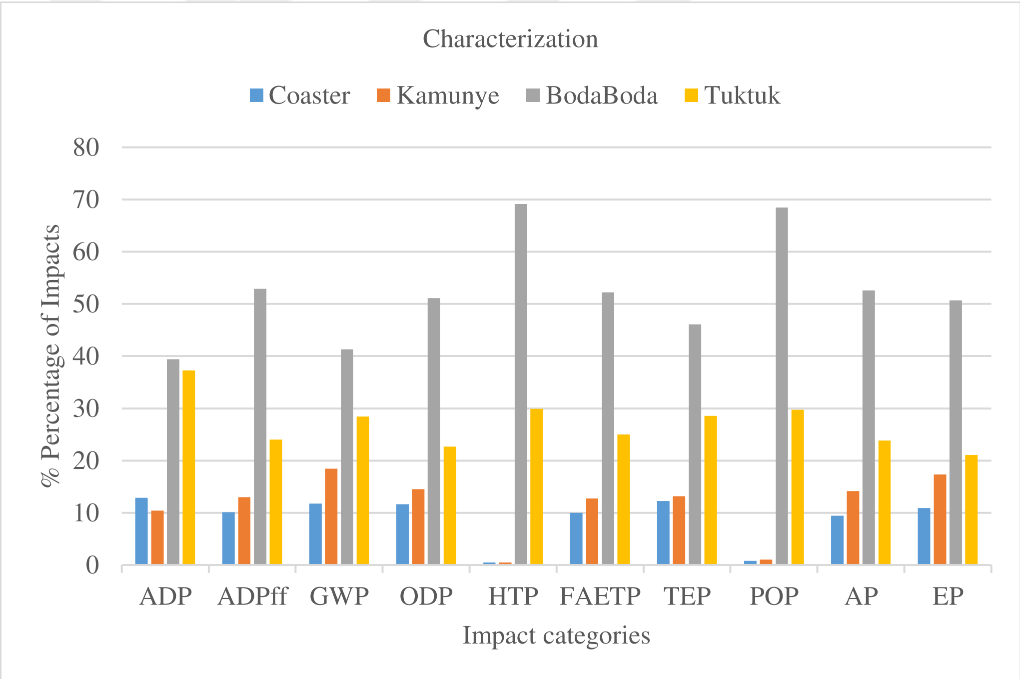

Figure 7.1. *Comparative characterization results in terms of pkm at 100% occupancy level*

7.1.2. Normalization results

After applying normalization on characterization results the impact category indicators all have the same unit which makes it easier to compare them. The normalization results were presented in Table 7.2 and Figure 7.2 (percentage).

Table 7.2. *Comparative normalization results in terms of pkm at 100% occupancy level*

Impact category	Coaster	Kamunye	BodaBoda	TukTuk
ADP	6.0E-17	4.9E-17	1.8E-16	1.7E-16
ADP_{ff}	1.1E-15	1.4E-15	5.9E-15	2.7E-15
GWP (GWP100a)	4.7E-16	7.4E-16	1.6E-15	1.1E-15
ODP	2.1E-17	2.7E-17	9.4E-17	4.2E-17
HTP	9.6E-16	9.7E-16	1.4E-13	6.0E-14
FAETP	6.4E-17	8.1E-17	3.3E-16	1.6E-16
TEP	2.3E-17	2.4E-17	8.5E-17	5.2E-17
POP	1.9E-16	2.5E-16	1.6E-14	7.2E-15
AP	3.8E-16	5.6E-16	2.1E-15	9.5E-16
EP	1.1E-16	1.7E-16	5.1E-16	2.1E-16
TOTAL	3.4E-15	4.3E-15	1.7E-13	7.2E-14

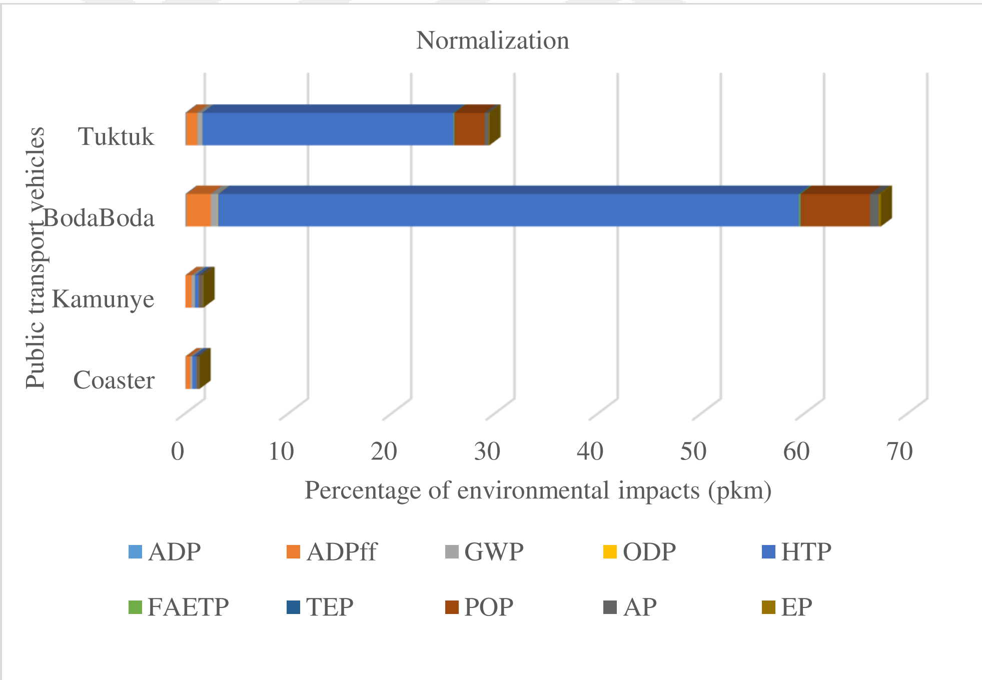

Figure 7.2. *Comparative normalization graph in terms of pkm*

According to the normalization results it was determined that a significant part of the environmental impacts arising from passenger transportation using the public means in Kampala city due to the human toxicity, photochemical oxidation, fossil fuel based abiotic depletion, acidification and global warming potential.

Figure 7.3 showed the effect of carrying "1 passenger per 1 kilometer" on the abiotic depletion potential by using selected public transportation vehicles. Abiotic depletion potential (ADP) is an indicator of potential negative effects on the availability of mineral resources. It is calculated in terms of kg Sb equivalent. There was an impact of more than 60% from the vehicle manufacturing stage on the depletion of abiotic mineral resources. On the other hand, the vehicle operation, maintenance, shipment and end of life stages's effect was approximately 40%. The cause of such a scenario was thought to be the consumption of lead, chromium and copper in the vehicle manufacturing and fuel production processes. When the components from end of life vehicles are recycled the following burdens can be avoided; -2.8.E-10 kg Sb eq./pkm for Coaster, -1.9.E-10 for Kamunye, -6.5.E-10 for TukTuk and -3.9.E-10 for BodaBoda.

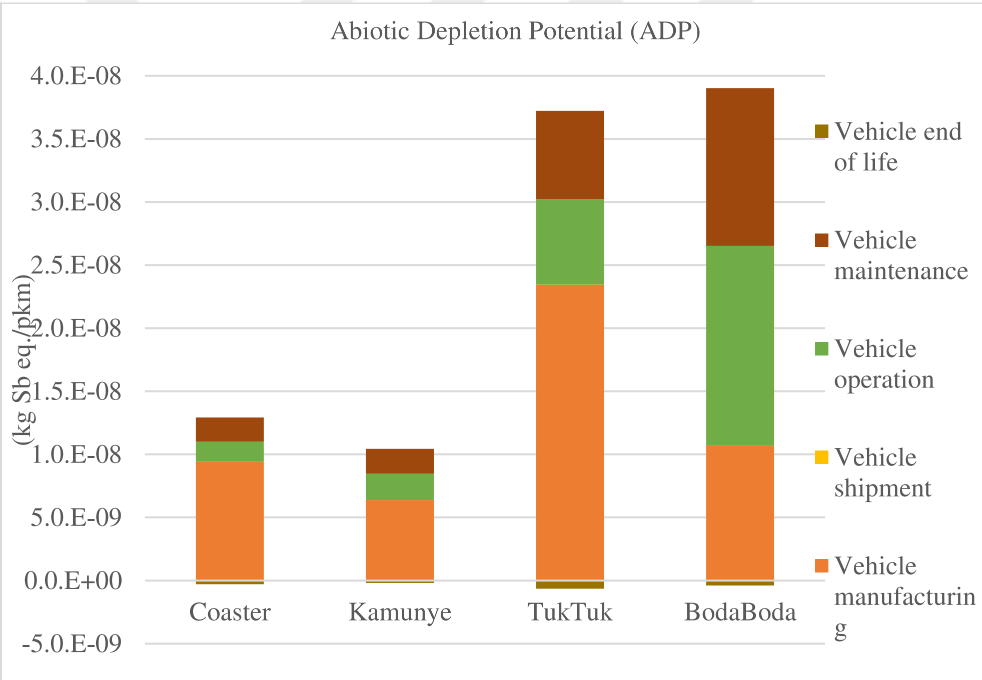

Figure 7.3. *Comparative abiotic depletion potential graph (pkm)*

Figure 7.4 showed the effect of carrying 1 passenger per 1 kilometer on abiotic depletion potential-fossil fuels (ADP_{ff}) using selected public transport. This category of environmental impact refers to the use of non-renewable fossil fuels. It is given in MJ. While the vehicle operation stage had a more than 90% effect on the depletion of fossil fuel based abiotic resources, there was an effect of less than 10% from vehicle manufacturing, shipment, maintenance and end of life stages. The consumption of crude oil, natural gas and coal during fuel production process was thought to be the cause of this situation. When the components from end of life vehicles are recycled, the following burdens can be avoided; -4.3.E-04 MJ/pkm for Coaster, -2.9.E-04 for Kamunye, -9.9.E-04 for TukTuk and -5.4.E-04 for BodaBoda.

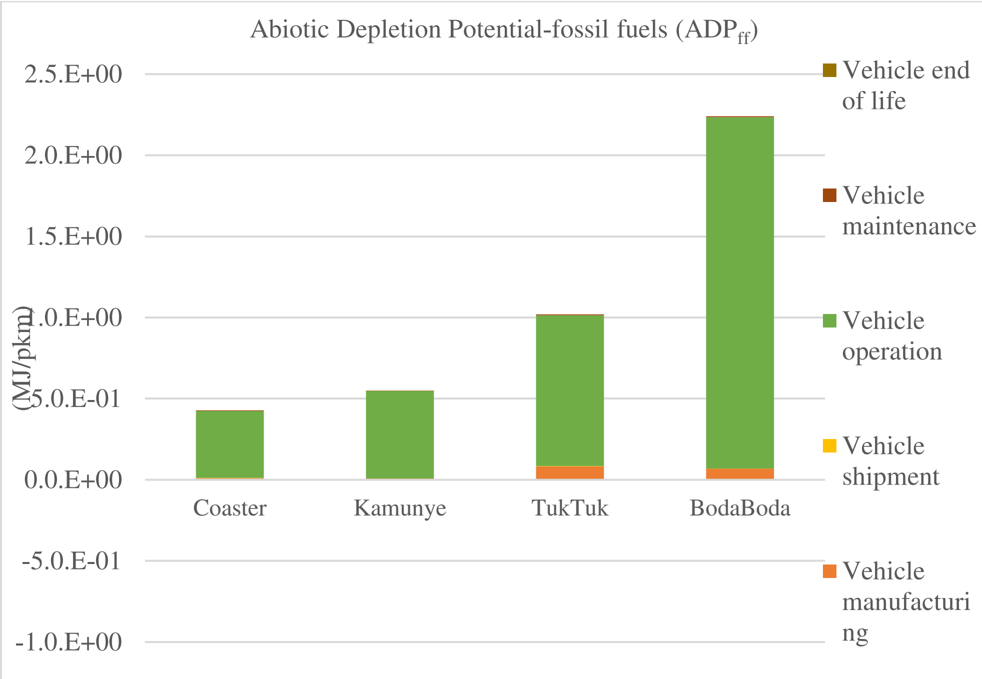

Figure 7.4. *Fossil fuel-based ADP for passenger transport (pkm)*

Figure 7.5 showed the effect of carrying 1 passenger per 1 kilometer on the global warming potential (GWP100a) using selected public transport. GWP100a is expressed in kg CO_2 equivalent. When urban passenger transport was scrutinized in terms of GWP, its impact was calculated as 0.02kg CO_2 eq./pkm, 0.031 kg CO_2 eq./pkm, 0.069 kg CO_2 eq./pkm and 0.047 kg CO_2 eq./pkm for Coaster, Kamunye, BodaBoda and TukTuk respectively. It was observed that the vehicle operation stage has a higher impact on global warming than vehicle manufacturing, shipment, maintenance and end of life stages. This observation is believed to have been brought about by carbon dioxide emissions whose largest percentage was as a result of vehicle fuel combustion processes. When the components from end of life vehicles are recycled, the following burdens can be avoided; -4.1.E-05 kg CO_2 eq./pkm for Coaster, -2.8.E-05 for Kamunye, -9.4.E-05 for TukTuk and -5.3.E-05 for BodaBoda.

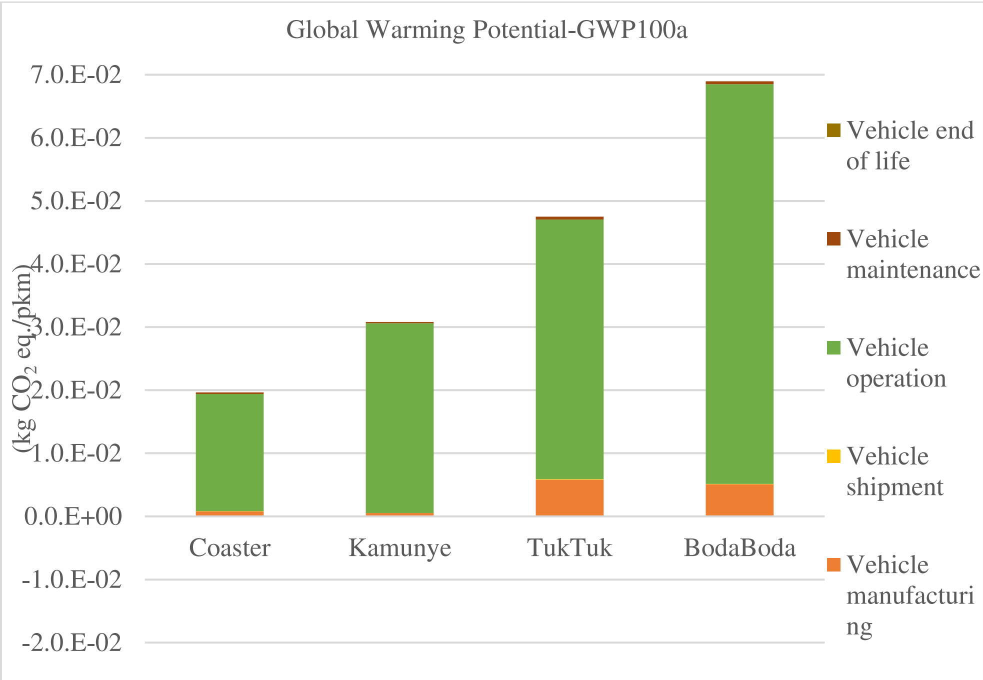

Figure 7.5. *Graph for comparison of global warming potential in terms of pkm*

Ozone layer depletion potential (ODP) is expressed in kg CFC-11 equivalent. Figure 7.6 showed the effect of carrying pkm on this impact category using selected public means in Kampala city. In the ODP, it was determined that the impact of the vehicle operation stage was higher than the impact of vehicle manufacturing, shipment, maintenance and end of life stages. It was estimated that the fuel production process made more than 90% contribution to ODP during the vehicle operation stage of the life cycle. Crude oil production and natural gas transport contribute approximately 99% to the formation of Bromotrifluoromethane and Bromochlorodifluoromethane, Tetrachloromethane and 1,2-Dichlorotetrafluoroethane or Halon 1301, Halon 1211, CFC-114 and CFC-10, respectively. When the components from end of life vehicles are recycled, the following burdens can be avoided; -3.1.E-12 kg CFC-11 eq./pkm for Coaster, -2.1.E-12 for Kamunye, -7.0.E-12 for TukTuk and -3.7.E-12 for BodaBoda.

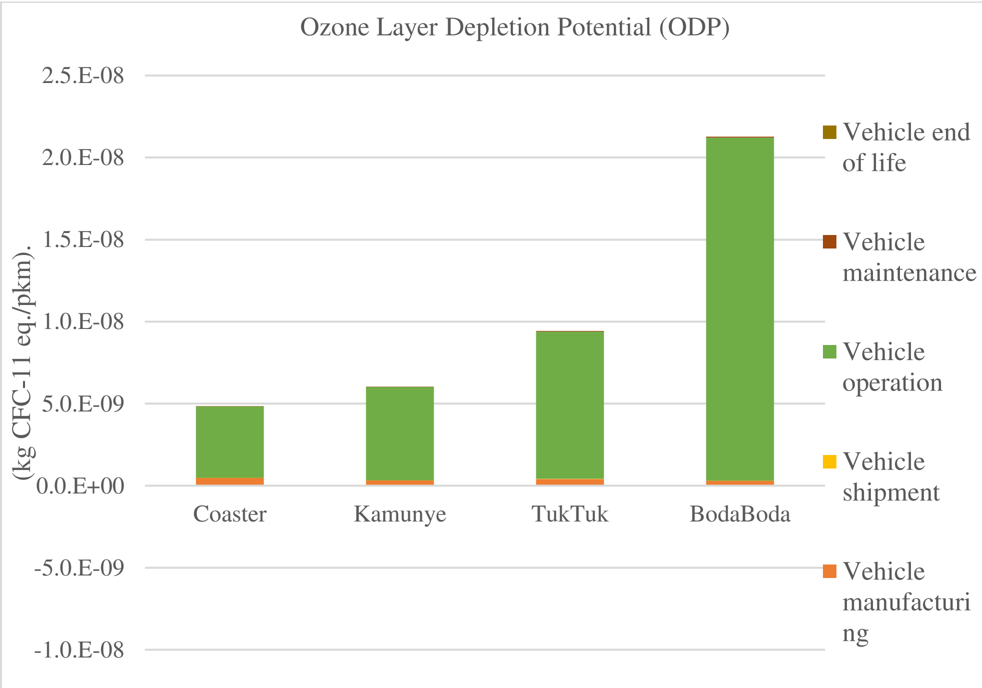

Figure 7.6. *Comparative ozone layer depletion potential (pkm)*

Figure 7.7 showed the effect of carrying 1 passenger per 1 kilometer on the potential for Human toxicity (HT) using selected transport means in Kampala. HTP is given in kg equivalent to 1.4 dichlorobenzene. Most of the HTP emissions were produced during the vehicle operation stage for BodaBoda, TukTuk and Kamunye. However, for Coaster, approximately 50% of total HTP emissions were produced during production and 49% of total HTP emissions were produced during operation. When the toxicity on humans was examined, it was seen that tail pipe emissions from fuel combustion as well as steel production processes contributed to the release benzene, barium and chromium. When the components from end of life vehicles are recycled, the following burdens can be avoided; -9.7.E-06 kg 1,4-DB eq./pkm for Coaster, -6.6.E-06 for Kamunye, -2.2.E-05 for TukTuk and -1.3.E-05 for BodaBoda.

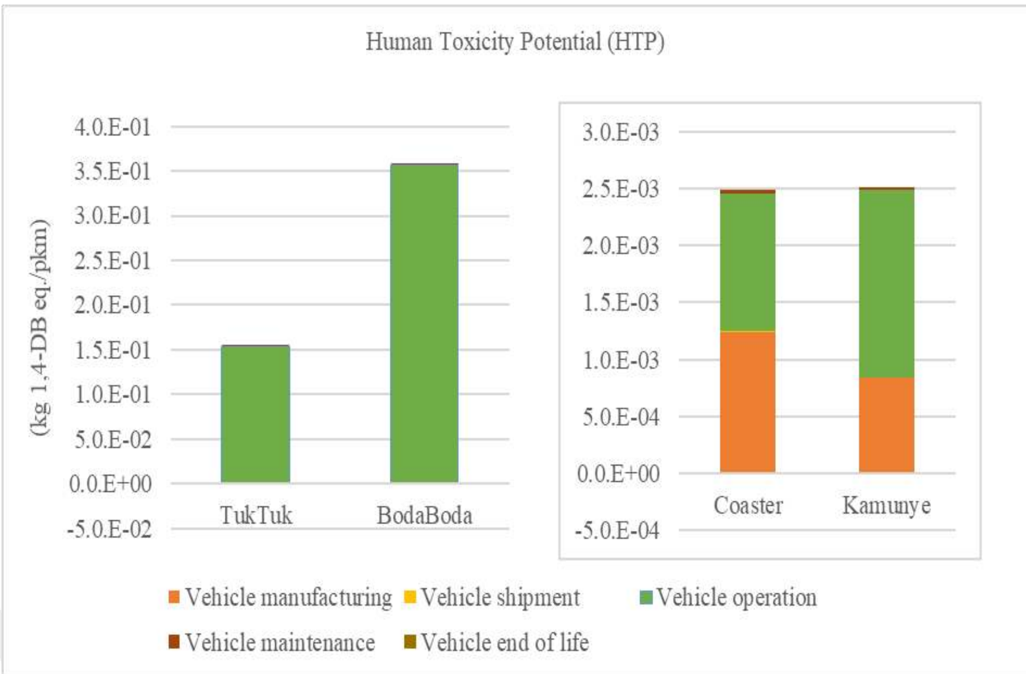

Figure 7.7. *Comparative human toxicity potential graph (pkm)*

Figure 7.8 showed the effect of carrying 1 passenger per 1 kilometer on freshwater aquatic ecotoxicity potential (FAETP) by using selected public transportation vehicles. FAETP is given in kg equivalent 1.4 dichloro benzene. This effect was calculated as 0.00015 kg 1.4 DB eq./pkm in Coaster, 0.00019 kg 1.4 DB eq./pkm in Kamunye, 0.00079 kg 1.4 DB eq./pkm in BodaBoda and 0.00038 kg 1.4 DB eq./pkm in TukTuk. The toxic effect on fresh water resources is caused by the barium, formaldehyde, zinc and copper emissions mainly generated by fuel production processes during vehicle operation stage. When the components from end of life vehicles are recycled, the following burdens can be avoided; -2.2.E-07 kg 1,4-DB eq./pkm for Coaster, -1.5.E-07 for Kamunye, -5.0.E-07 for TukTuk and -2.8.E-07 for BodaBoda.

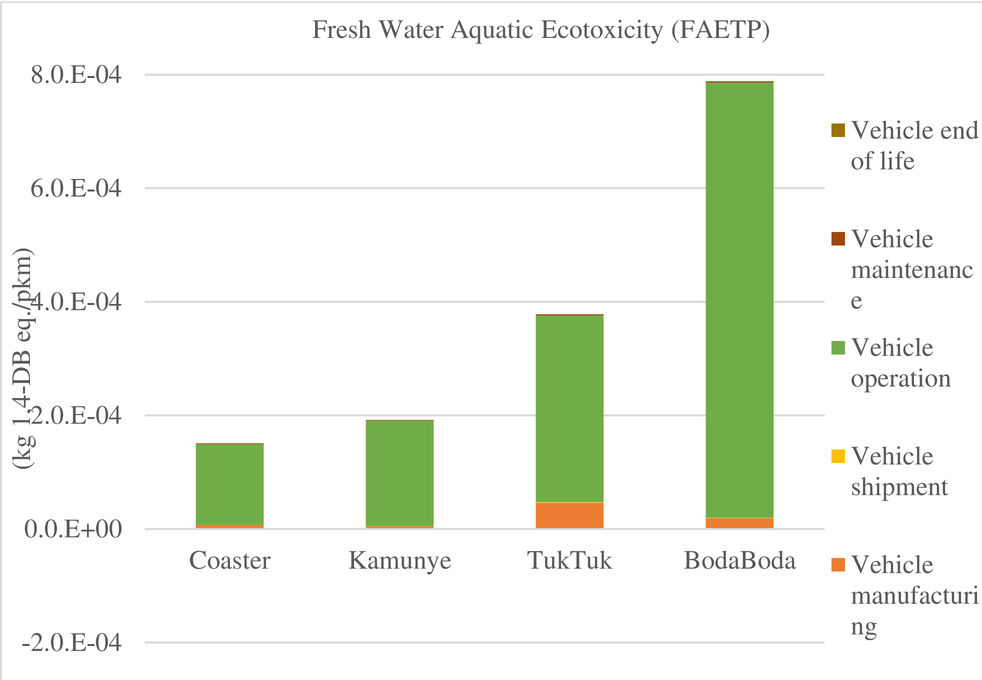

Figure 7.8. *FAETP among passenger vehicles (pkm)*

Figure 7.9 showed the effect of carrying 1 passenger per 1 kilometer on terrestrial ecotoxicity potential (TEP) by using selected public transportation vehicles. TEP is given in kg 1.4 dichlorobenzene equivalent. Chromium and mercury which are generated as a result of energy production, distribution and consumption processes during fuel production (vehicle operation) and steel, zinc and copper production (vehicle manufacturing) are believed to be the main causes of this environmental impact. When the components from end of life vehicles are recycled, the following burdens can be avoided; -7.2.E-08 kg 1,4-DB eq./pkm for Coaster, -4.9.E-08 for Kamunye, -1.7.E-07 for TukTuk and -9.7.E-08 for BodaBoda.

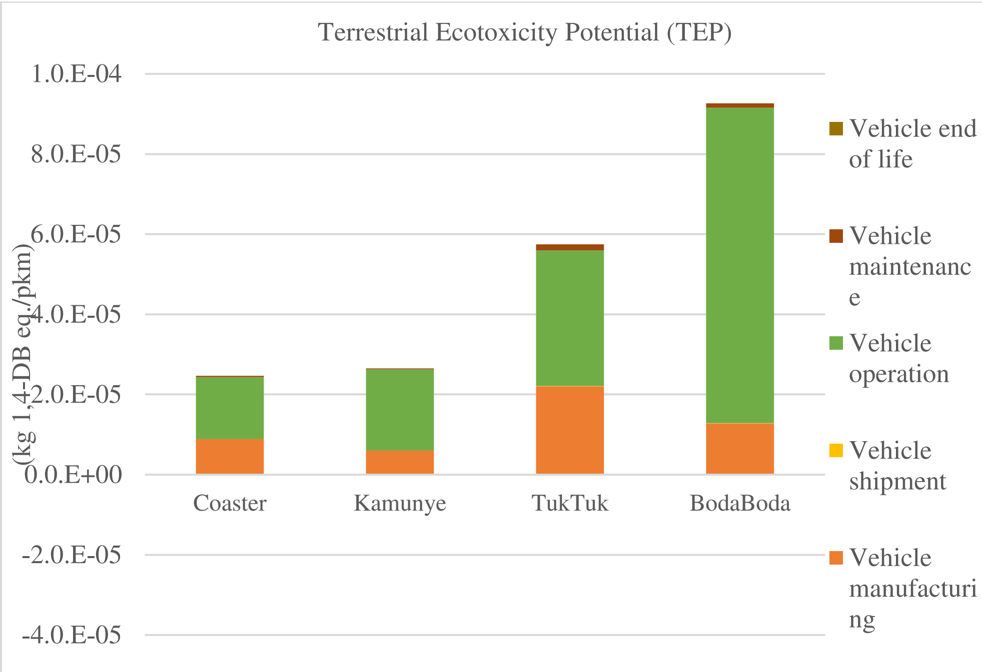

Figure 7.9. *TEP graph comparing passenger vehicles (pkm)*

Figure 7.10 showed the effect of carrying 1 passenger per 1 kilometer on the photochemical oxidation potential (POP) using selected public transportation vehicles. POP effect is calculated in kg C_2H_4 equivalent. The POP effect of Coaster, Kamunye, BodaBoda and TukTuk was 6.8E-06 C_2H_4 eq./pkm, 9.4E-06 C_2H_4 eq./pkm, 6.1E-04 C_2H_4 eq./pkm and 2.6E-04 C_2H_4 eq./pkm respectively. It is believed that carbon dioxide emissions generated as a result of vehicle fuel combustion processes during the vehicle operation stage caused this environmental impact. When the components from end of life vehicles are recycled, the following burdens can be avoided; -6.4.E-09 kg C_2H_4 eq./pkm for Coaster, -4.3.E-09 for Kamunye, -1.5.E-08 for TukTuk and -6.8.E-09 for BodaBoda.

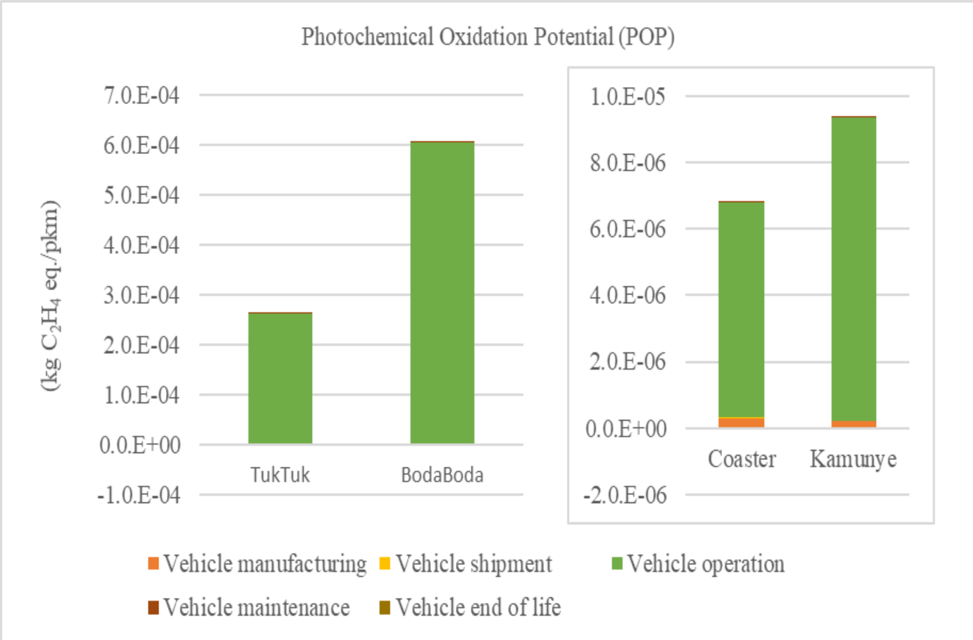

Figure 7.10. *Comparative graph for photochemical oxidation potential (pkm)*

Figure 7.11 showed the effect of carrying 1 passenger per 1 kilometer on the acidification potential (AP) using selected public transportation vehicles. AP is expressed in kg SO_2 equivalent. It was found out that in Coaster, Kamunye, BodaBoda and TukTuk the vehicle operating stage had a bigger impact on AP than vehicle manufacturing, shipment, maintenance and end of life stages. After critical analysis the results showed that fuel production and vehicle fuel combustion processes generated enough sulfur dioxide and nitrogen oxides to cause the acidification effect. When the components from end of life vehicles are recycled, the following burdens can be avoided; -1.2.E-07 kg SO_2 eq./pkm for Coaster, -8.4.E-08 for Kamunye, -2.9.E-07 for TukTuk and -1.6.E-07 for BodaBoda.

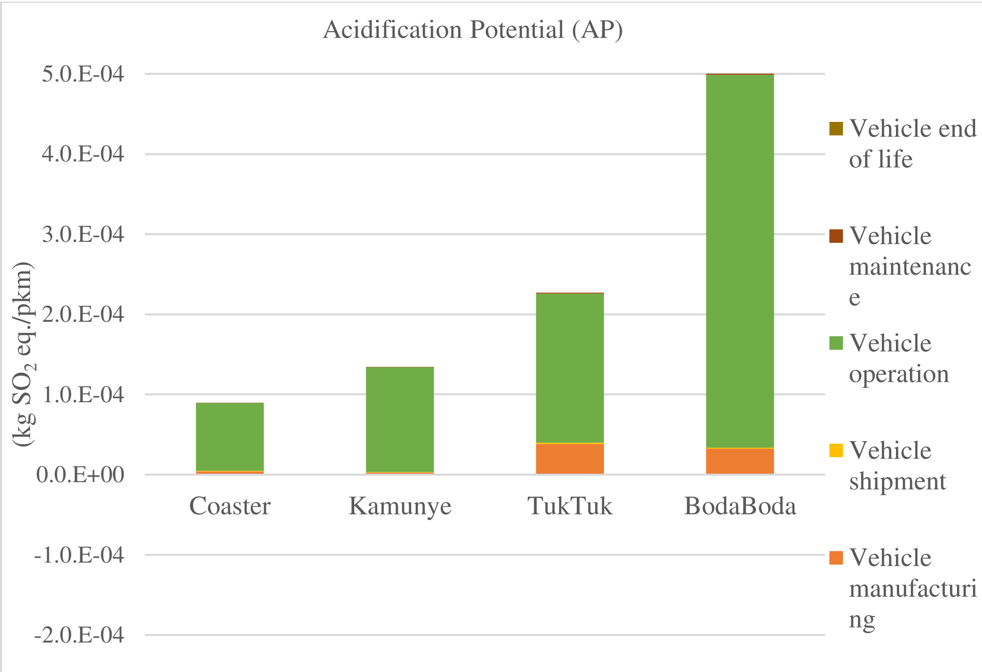

Figure 7.11. *Comparative acidification potential graph for passenger transportation*

Figure 7.12 showed the effect of carrying 1 passenger per 1 kilometer on the eutrophication potential (EP) by using selected public transportation vehicles. EP is expressed in kg PO_4 equivalent. After analyzing the urban passenger transport in as far as eutrophication potential is concerned, its effect was calculated as 3.30E-05 kg PO_4 eq./pkm for TukTuk, 8.10E-05 kg PO_4 eq./pkm for BodaBoda, 2.80E-05 kg PO_4 eq./pkm for Kamunye and 1.70E-05 kg PO_4 eq./pkm for Coaster. Nitrogen oxides, mostly from vehicle fuel combustion processes and phosphates from fuel production processes had a major impact on EP. When the components from end of life vehicles are recycled, the following burdens can be avoided; -2.7.E-08 kg PO_4 eq./pkm for Coaster, -1.8.E-08 for Kamunye, -6.2.E-08 for TukTuk and -3.5.E-08 for BodaBoda.

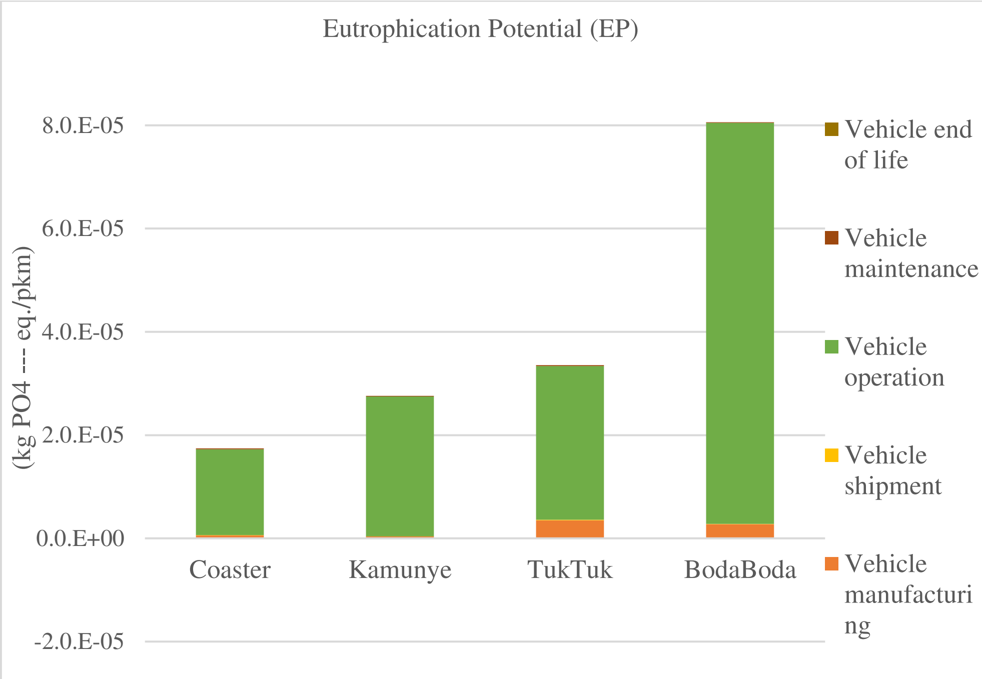

Figure 7.12. *Comparative eutrophication potential graph (pkm)*

7.2. Sensitivity Analysis

In this thesis a sensitivity analysis was performed to assess the impact of percentage vehicle occupancy on the cradle to the grave emissions of passenger transportation. The results of this analysis were shown in Figure 7.13. Sensitivity analysis was conducted to evaluate the effect of the number of the passengers on the environmental impacts in terms of percentages. Occupancy levels of 25%, 50%, 75%, 100%, 125%, 150%, 175% and 200% were considered. It is important to note that for instance at 200% occupancy level there are 2 passengers on the motorcycle, 6 passengers in TukTuk, 28 passengers in Kamunye and 58 passengers in Coaster. For Coaster and Kamunye some passengers can stand while others are sitting. This means that these occupancy levels are logical and possible. In Figure 7.13, Figure 7.14, Figure 7.15 and Figure 7.16 it was shown that the change in the percentage of passenger occupancy has an effect on the environmental impacts of passenger transportation. According to the sensitivity analysis environmental impacts of transporting a passenger have a very high sensitivity when the occupancy level was below 100%. Above 100% occupancy level the sensitivity is moderate. This trend was shown by all the vehicles considered in this thesis.

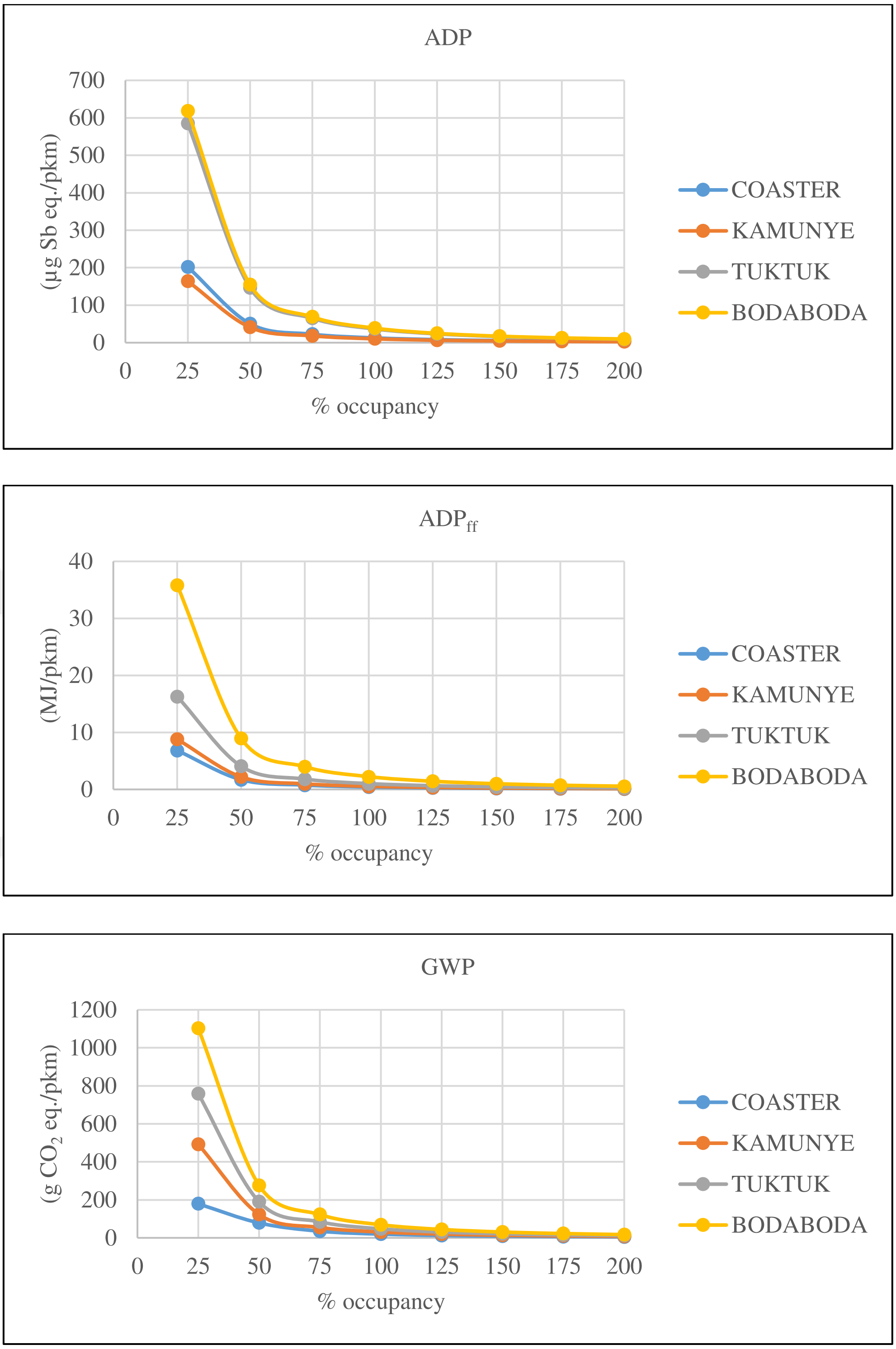

Figure 7.13. *Impact of vehicle occupancy on emissions of passenger transportation (ADP, ADP_{ff}, GWP)*

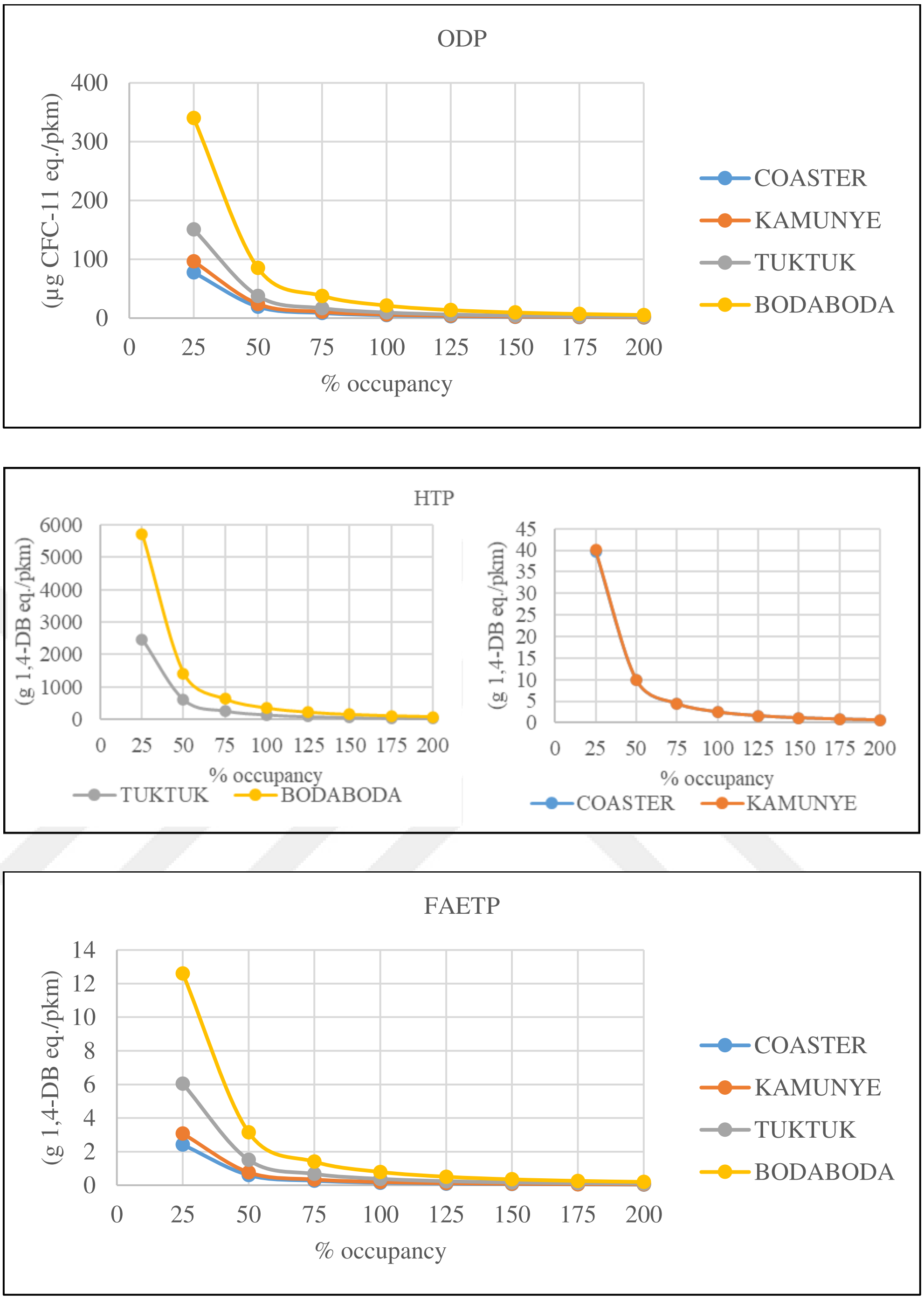

Figure 7.14. *Impact of vehicle occupancy on emissions of passenger transportation (ODP, HTP, FAETP)*

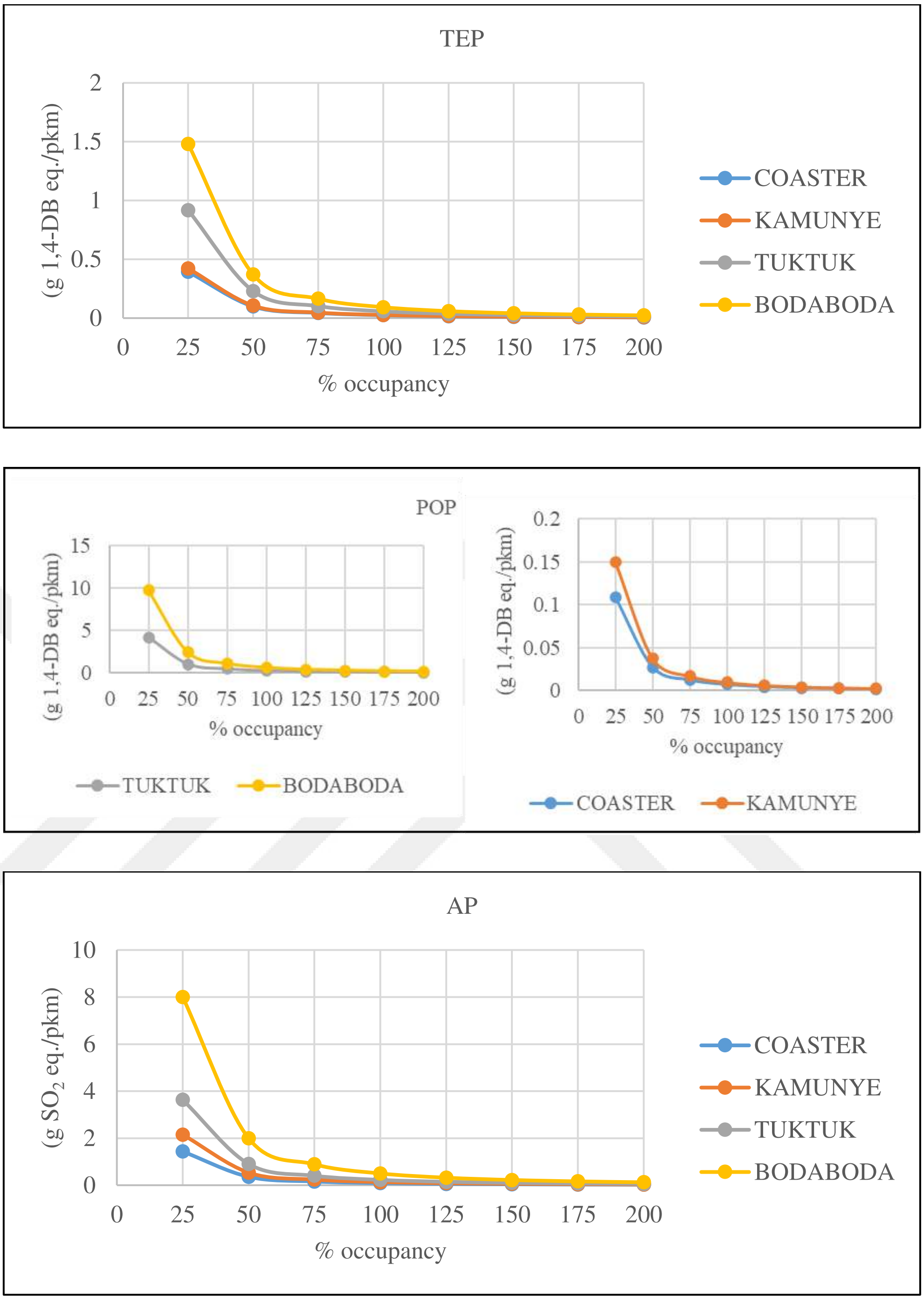

Figure 7.15. *Impact of vehicle occupancy on emissions of passenger transportation (TEP, POP, AP)*

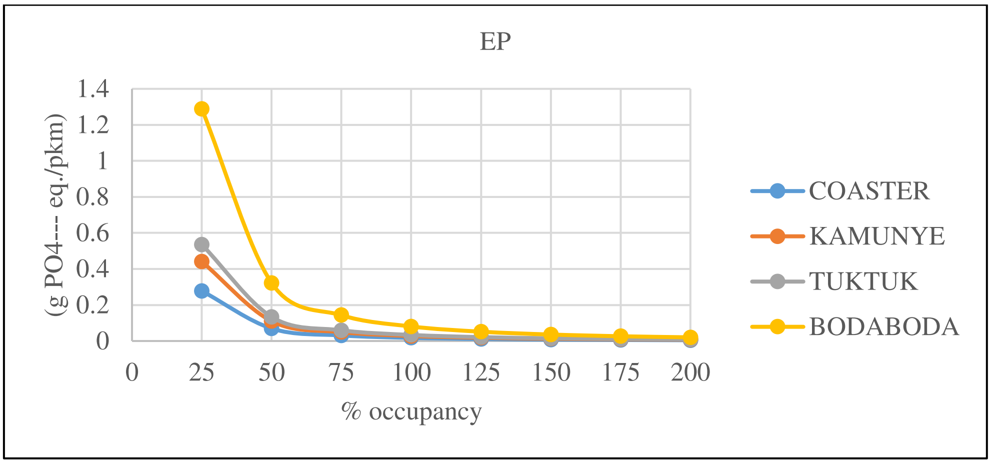

Figure 7.16. *Impact of vehicle occupancy on emissions of passenger transportation (EP)*

For impact categories ADP_{ff}, GWP, ADP and TEP any passenger occupancy above 50% in the Coaster results into lower emissions per pkm, while occupancy level below 50% causes more emissions per pkm than the BodaBoda at 100% occupancy.

8. CONCLUSION AND SUGGESTIONS

KCCA officials together with various development partners have for a long time struggled to establish an effective public transport system in Kampala city to reduce traffic congestion, air pollution and other problems. In this thesis study, the current public transportation system in Kampala was evaluated from an environmental perspective in order to fully understand the effects of each type of transportation used in the city and to compare the effects of these transportation types.

In this thesis besides the raw materials production processes that had a big impact on mineral based abiotic depletion potential, it was observed that fuel production processes and vehicle fuel combustion processes had a significant impact to the major impacts of passenger transport such as human toxicity, photochemical oxidation potential, fossil fuel based abiotic potential, acidification and global warming as well as abiotic depletion potential for vehicle.

According to the findings obtained from this thesis study, the environmental performance of the public transport system in Kampala city was as follows:

- 89.58% of environmental impacts for the Kamunye were from the operation stage, 9.6% from the manufacturing (production) stage, 0.8% from the maintenance stage, 0.15% from the shipment stage and -0.13% from the end of life stage.
- 97.95% of TukTuk's environmental impacts were realized during the operation phase, 1.65% from the production stage, 0.39% from the maintenance stage, 0.03% from the shipment stage and -0.03% from the disposal stage.
- For Coaster, 80.5% of environmental impacts resulted from operation stage, 18.1% from production stage, 1.3% from maintenance stage, 0.3% from shipment stage and -0.2% end of life stage.
- 99.3% of environmental impacts for BodaBoda resulted from the operation stage, 0.53% manufacturing stage, 0.14% maintenance stage, 0.0079% shipment stage and -0.0065% end of life stage.

Life cycle impact results per passenger kilometer traveled in this thesis and previous studies in the literature were compared in Table 8.1 and Table 8.2.

Table 7.3. *Interstudy comparisons of results for Coaster in this thesis and bus in other studies*

Impact Category	Unit (pkm)	Coaster (This thesis)	**Bus** (Shinde, Dikshit, & Singh, 2019)	**Bus** (Bastos, Marques, Batterman, & Freire, 2019)
ADP	µg Sb eq.	13	15.3	_
ADP_{ff}	MJ	0.4	0.3	0.9
GWP	g CO_2 eq.	20	17.1	59.3
ODP	kg CFC-11 eq.	5.E-09	_	_
HTP	g 1.4-DB eq.	2.5	_	_
FAETP	kg 1.4-DB eq.	2.E-04	_	_
TEP	kg 1.4-DB eq.	3.E-05	_	_
POP	mg C_2H_4 eq.	6.8	10.8	_
AP	mg SO_2 eq.	90	6.6	_
EP	mg PO_4^{---} eq.	17	11.7	3

Table 7.4. *Comparisons of results for BodaBoda and TukTuk in relation to motorcycle and autorickshaw*

Impact Category	Unit (pkm)	BodaBoda (Thesis)	**Motorcycle** (Sopha, Setiowati, & Ma'mun, 2017)	**Motorcycle** (Bastos, Marques, Batterman, & Freire, 2019)	TukTuk (Thesis)	**Autorickshaw** (Shinde, Dikshit, & Singh, 2019)
ADP	µg Sb eq.	39	515000	_	37	252
ADP_{ff}	MJ	2.2	_	2	1	1.6
GWP	g CO_2 eq.	69	176	137.9	47	78
ODP	kg CFC-11 eq.	2.E-08	_	_	9.E-09	_
HTP	g 1.4-DB eq.	360	1.1	_	150	_
FAETP	kg 1.4-DB eq.	8.E-04	_	_	4.E-04	_
TEP	kg 1.4-DB eq.	9.E-05	_	_	6.E-05	_
POP	mg C_2H_4 eq.	610	_	_	260	142
AP	mg SO_2 eq.	500	544	_	230	166
EP	mg PO_4^{---} eq.	81	_	8.5	33	196

A study of Shinde, Dikshit, & Singh (2019) shows the abiotic depletion potential of bus as 15.3 micrograms Sb-eq./pkm which is slightly higher than the 13 micrograms

Sb-eq/pkm obtained in this thesis for Coaster/bus. Shinde, Dikshit, & Singh (2019) and Bastos, Marques, Batterman, & Freire (2019) further states the fossil fuel based abiotic depletion potential of bus as 0.3 MJ/pkm and 0.9 MJ/pkm respectively. The results of this thesis in relation to fossil fuel based ADP of a bus (Coaster) 0.4 MJ/pkm is in the range of 0.3 to 0.9 MJ/pkm. The fossil fuel based ADP for motorcycle was 2.0 MJ/pkm as claimed by Bastos, Marques, Batterman, & Freire (2019), this value is very close to the 2.2 MJ/pkm stated by this thesis in relation to motorcycle (BodaBoda).

The GWP impact of bus asserted by this thesis 20 g CO_2-eq./pkm was very close to that reported by Shinde, Dikshit, & Singh (2019) 17.1 g CO_2-eq./pkm but quite lower than the 59.3 g CO_2-eq./pkm stated by Bastos, Marques, Batterman, & Freire (2019). However, the GWP impact of motorcycle revealed in this thesis was very low as compared to that foundout by Sopha, Setiowati, & Ma'mun (2017) 176 g CO_2-eq./pkm and Bastos, Marques, Batterman, & Freire (2019) 137.9 g CO_2-eq./pkm.

The values associated with the environmental performance of autorickshaw or TukTuk obtained in this thesis were only compared to those presented by Shinde, Dikshit, & Singh (2019). In this contrast ADP_{ff} results were agreeing to each other, scores of GWP and AP had a difference of less than 50% between each other while results of ADP, POP and EP were much far away from eachother. Other than being hard to access, the data used to analyse the environmental impacts of using a Kamunye and TukTuk for passenger transportation were very hard to model and this is believed to be the main cause of the wide differences between results obtained in the studies compared in this thesis.

All in all, the operation stage was identified as the most vital step in the vehicles lifetime in terms of environmental impact and if decision makers reduce the impacts of this stage, the impacts of passenger transport can be remarkably reduced. In addition, coasters showed significantly higher emissions per pkm when their occupancy level was below 50%, in such conditions low capacity vehicles at their 100% occupancy presented low emissions per pkm. To achieve a scenario with the lowest environmental impacts, Coasters and Kamunyes should therefore only operate when passenger load is assured to be over 50%, in situations when the number of passengers is below 50%, passengers in need of transport should be served by TukTuk and BodaBoda. In this desirable scenario it is believed that the best combination would be that of TukTuk and Coaster.

To sum up, in the KCCA 2014-19 strategic plan, KCCA aims to deliberately encourage the use of high-passenger public transport modes and to prevent the use of low-passenger vehicles including Kamunye and BodaBoda. This is an environmentally sound objective which is in line with the findings of this thesis and KCCA should find ways to implement this objective as it will result into an environmentally sound urban transport system for Kampala city. In addition, an LCA based on data obtained from the laboratory through measuring the material inputs and outputs during the entire life of vehicles can provide more specific results to improve the quality of the findings of this thesis.

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APPENDIX

Appendix-1a. *Data for BodaBoda manufacturing*

Materials	Ecoinvent database	ADB, 2009	Accepted data	Unit	Contribution (%)
Total Steel	91.8		91.8	kg	73
Steel, low-alloyed, at plant/RER U	6.6		6.6	kg	
Reinforcing steel, at plant/RER U	44.6		44.5	kg	
Sheet rolling, steel/RER U	27.1		27.1	kg	
Section bar rolling, steel/RER U	13.6		13.6	kg	
Total Copper	1.4		1.4	kg	1.1
Wire drawing, copper/RER U	0.7		0.7	kg	
Copper, at regional storage/RER U	0.7		0.7	kg	
Total Plastic	40.4	9.4	9.4	kg	8
Polyethylene, HDPE, granulate, at plant/RER U	15.3	3.6	3.6	kg	
Polypropylene, granulate, at plant/RER U	7.4	1.7	1.7	kg	
Polyvinylchloride, at regional storage/RER U	2.4	0.6	0.6	kg	
Injection moulding/RER U	15.3	3.6	3.7	kg	
Rubber					
Synthetic rubber, at plant/RER U	3.0		3.0	kg	2
Paint					
Alkyd paint, white, 60% in solvent, at plant/RER U	0.4		0.4	kg	0.3
Aluminium					
Aluminium, production mix, at plant/RER U	15		15	kg	12
Chromium					
Chromium, at regional storage/RER U	0.2		0.16	kg	0.1
Nickel					
Nickel, 99.5%, at plant/GLO U	0.3		0.3	kg	0.2
Platinum					
Platinum, at regional storage/RER U	1.1E-04		1.1E-04	kg	8.6E-05

Appendix-1a (continuation). *Data for BodaBoda manufacturing*

Materials	Ecoinvent database	ADB, 2009	Accepted data	Unit	Contribution (%)
Palladium					
Palladium, at regional storage/RER U	2.0E-05		2.0E-05	kg	1.6E-05
Zinc					
Zinc, primary, at regional storage/RER U	0.4		0.4	kg	0.3
Ethylene					
Ethylene, average, at plant/RER U	1.2		1.2	kg	1.0
Sulphuric acid					
Sulphuric acid, liquid, at plant/RER U	0.1		0.1	kg	0.0
Lead					
Lead, at regional storage/RER U	2.1		2.1	kg	1.7
TOTAL MATERIALS	156.1		125.2	kg	100
Total Energy	49.3	3510	3510	kWh	
Natural gas, burned in industrial furnace >100kW/RER U	30.2	2149.7	2149.7	kWh	61.2
Electricity, medium voltage, at grid/JP U	18	1280.9	1280.9	kWh	36.5
Light fuel oil, burned in industrial furnace 1MW, non-modulating/RER U	1.1	79.4	79.4	kWh	2.3
Water					
Tap water, at user/RER U	215.5		215.5	kg	
Transport					
Transport, lorry >16t, fleet average/RER U	5.8		5.8	tkm	
Transport, transoceanic freight ship/OCE U	1870.1		1870.1	tkm	
Transport, freight, rail/CH U	57.8		57.8	tkm	
Road vehicle plant/RER/I U	0		0	p	
Emissions to air					
NMVOC, non-methane volatile organic compounds, unspecified origin	0.3		0.3	kg	
Heat, waste	64.8		64.8	MJ	

Appendix-1a (continuation). *Data for BodaBoda manufacturing*

Materials	Ecoinvent database	ADB, 2009	Accepted data	Unit	Contribution (%)
Emissions to water					
COD, Chemical Oxygen Demand	0.013		0.013	kg	
BOD5, Biological Oxygen Demand	1.7E-03		1.7E-03	kg	
Phosphate	6.7E-05		6.7E-05	kg	

Appendix-1b. *Data for TukTuk manufacturing*

Materials	Equation 6.1 Results	(Shinde, Dikshit, & Singh, 2019)	Average energy (15.9 kWh*388 kg)	Accepted data	Contribution (%)
Steel (kg)	396	333		332.8	49.9
Steel, low-alloyed, at plant/RER U (kg)	29	24		24.0	
Reinforcing steel, at plant/RER U (kg)	192	161		161.5	
Sheet rolling, steel/RER U (kg)	117	98		98.0	
Section bar rolling, steel/RER U (kg)	59	49		49.2	
Copper (kg)	6	7		6.7	1
Wire drawing, copper/RER U (kg)	3	3		3.3	
Copper, at regional storage/RER U (kg)	3	3		3.3	
Plastic (kg)	174	131		131.4	19.7
Polyethylene, HDPE, granulate, at plant/RER U (kg)	66	50		49.8	
Polypropylene, granulate, at plant/RER U (kg)	32	24		23.9	
Polyvinylchloride, at regional storage/RER U (kg)	10	8		7.8	
Injection moulding/RER U (kg)	66	50		49.8	

Appendix-1b (continuation). *Data for TukTuk manufacturing*

Materials	Equation 6.1 Results	(Shinde, Dikshit, & Singh, 2019)	Average energy (15.9 kWh*388 kg)	Accepted data	Contribution (%)
Aluminium (kg)					10.5
Aluminium, production mix, at plant/RER U (kg)	65	70		70.0	
Alkyd paint (kg)					4.8
Alkyd paint, white, 60% in solvent, at plant/RER U (kg)	2	32		32.0	
Synthetic rubber (kg)					
Synthetic rubber, at plant/RER U (kg)	13			12.7	
Chromium (kg)					
Chromium, at regional storage/RER U (kg)	1			0.7	
Nickel (kg)					
Nickel, 99.5%, at plant/GLO U (kg)	4.0E-01			0.4	
Platinum (kg)					
Platinum, at regional storage/RER U (kg)	4.6E-04			0.0	
Palladium (kg)					
Palladium, at regional storage/RER U (kg)	8.7E-05			0.0	
Zinc (kg)					
Zinc, primary, at regional storage/RER U (kg)	2			1.7	
Ethylene (kg)					
Ethylene, average, at plant/RER U (kg)	5			5.3	
Sulphuric acid (kg)					
Sulphuric acid, liquid, at plant/RER U (kg)	2.3E-01			0.2	
Lead (kg)					
Lead, at regional storage/RER U (kg)	4			3.8	

Appendix-1b (continuation). *Data for TukTuk manufacturing*

Materials	**Equation 6.1 Results**	(Shinde, Dikshit, & Singh, 2019)	**Average energy (15.9 kWh*388 kg)**	**Accepted data**	**Contribution (%)**
Glass (kg)		16		15.5	4
Total Materials (kg)	667				
Tap water					
Tap water, at user/RER U (kg)	929			928.9	
Energy (kWh)	213		6153.2		
Natural gas, burned in industrial furnace >100kW/RER U (kWh)	130		3768.4	3768.4	
Electricity, medium voltage, at grid/JP U (kWh)	78		2245.5	2245.5	
Light fuel oil, burned in industrial furnace 1MW, non-modulating/RER U (kWh)	5		139.3	139.3	
Transport					
Transport, lorry >16t, fleet average/RER U (tkm)	25			22.9	
Transport, transoceanic freight ship/OCE U (tkm)	8062			7971.6	
Transport, freight, rail/CH U (tkm)	249			229.0	
Road vehicle plant/RER/I U (p)	0			0.0	
Emissions to air					
NMVOC, non-methane volatile organic compounds, unspecified origin (kg)	1.4			1.4	
Heat, waste (MJ)	279			279.4	
Emissions to water					
COD, Chemical Oxygen Demand (kg)	5.6E-02			5.6E-02	
BOD5, Biological Oxygen Demand (kg)	7.5E-03			7.5E-03	
Phosphate (kg)	2.9E-04			2.9E-04	

Appendix-1c. *Data for Coaster manufacturing*

Materials	Ecoinvent database (11000 kg)	According to equation 6.1	Unit	Contribution (%)
Water, well, in ground	69.5	23.4	m^3	
Total Steel	6322.8		kg	50.3
Reinforcing steel, at plant/RER U	4540	1527.1	kg	
Steel, low-alloyed, at plant/RER U	22.8	7.7	kg	
Sheet rolling, steel/RER U	568	191.1	kg	
Section bar rolling, steel/RER U	502	168.9	kg	
Chromium steel 18/8, at plant/RER U	690	232.1	kg	
Total Copper	218		kg	1.7
Copper, at regional storage/RER U	109	36.7	kg	
Wire drawing, copper/RER U	109	36.7	kg	
Aluminium	1670		kg	13.3
Aluminium, production mix, at plant/RER U	1670	561.7	kg	
Total Glass	980		kg	7.8
Flat glass, coated, at plant/RER U	490	164.8	kg	
Tempering, flat glass/RER U	490	164.8	kg	
Acids				
Acetic acid, 98% in H_2O, at plant/RER U	0.066	0.02	kg	
Nitric acid, 50% in H_2O, at plant/RER U	0.1	0.03	kg	
Hydrochloric acid, 30% in H2O, at plant/RER U	0.2	0.1	kg	
Sulphuric acid, liquid, at plant/RER U	34	11.4	kg	
Total Iron	1532			12.2
Pig iron, at plant/GLO U	502	168.9	kg	
Cast iron, at plant/RER U	1030	346.5	kg	
Plastic	553		kg	4.4
Polyethylene, HDPE, granulate, at plant/RER U	553	186.0	kg	

Appendix-1c (continuation). *Data for Coaster manufacturing*

Materials	Ecoinvent database (11000 kg)	According to equation 6.1	Unit	Contribution (%)
Paint	30		kg	0.2
Alkyd paint, white, 60% in solvent, at plant/RER U	30	10.1	kg	
Rubber	405		kg	3.2
Synthetic rubber, at plant/RER U	405	136.2	kg	
Brass				
Brass, at plant/CH U	3	1.0	kg	
Refrigerant				
Refrigerant R134a, at plant/RER U	2	0.7	kg	
Diesel				
Diesel, at regional storage/RER U	167	56.2	kg	
Oil				
Lubricating oil, at plant/RER U	80.1	26.9	kg	
Lead				
Lead, at regional storage/RER U	90	30.3	kg	
Rock wool				
Rock wool, packed, at plant/CH U	396	133.2	kg	
Propylene				
Propylene glycol, liquid, at plant/RER U	26	8.7	kg	
Bitumen				
Bitumen, at refinery/RER U	54	18.2	kg	
Sodium hydroxide				
Sodium hydroxide, 50% in H2O, production mix, at plant/RER U	0.381	0.1	kg	
Lime				
Lime, hydrated, packed, at plant/CH U	0.31	0.1	kg	
Total Materials		12563.9	kg	
Water				
Tap water, at user/RER U	16400	5516.4	kg	
Energy				
Natural gas, burned in industrial furnace >100kW/RER U	34000	11436.4	MJ	

Appendix-1c (continuation). *Data for Coaster manufacturing*

Materials	Ecoinvent database (11000 kg)	According to equation 6.1	Unit	Contribution (%)
Electricity, medium voltage, production UCTE, at grid/UCTE U	4740	1594.4	kWh	
Light fuel oil, burned in industrial furnace 1MW, non-modulating/RER U	906	304.7	MJ	
Diesel, burned in building machine/GLO U	20.1	6.8	MJ	
Transport				
Transport, lorry >16t, fleet average/RER U	1060	356.5	tkm	
Transport, freight, rail/RER U	2460	827.5	tkm	
Road vehicle plant/RER/I U	0	0	p	
Emissions to air				
Benzene	0.0131	0.004	kg	
Methane, fossil	0.0165	0.006	kg	
Carbon monoxide, fossil	1.0	0.3	kg	
Carbon dioxide, fossil	633	212.9	kg	
Dinitrogen monoxide	0.02	0.008	kg	
Ammonia	0.02	0.008	kg	
NMVOC, non-methane volatile organic compounds, unspecified origin	7.9	2.7	kg	
Nitrogen oxides	6	2.0	kg	
Sulfur dioxide	0.1	0.04	kg	
Toluene	5.5E-03	1.9E-03	kg	
Xylene	5.5E-03	1.9E-03	kg	
Particulates, > 10 um	1.1E-02	3.7E-03	kg	
Particulates, > 2.5 um, and < 10um	2.1E-02	7.1E-03	kg	
Particulates, < 2.5 um	0.3	0.1	kg	
Lead	1.9E-08	6.4E-09	kg	
Cadmium	1.7E-06	5.8E-07	kg	
Copper	2.9E-04	9.9E-05	kg	
Chromium	2.9E-04	9.9E-05	kg	
Nickel	1.2E-05	4.1E-06	kg	

Appendix-1c (continuation). *Data for Coaster manufacturing*

Materials	Ecoinvent database (11000 kg)	According to equation 6.1	Unit	Contribution (%)
Selenium	1.7E-06	5.8E-07	kg	
Zinc	1.7E-04	5.8E-05	kg	
Mercury	3.5E-09	1.2E-09	kg	
Heat, waste	17100	5751.8	MJ	
Emissions to water				
COD, Chemical Oxygen Demand	0.1	0.04	kg	
BOD5, Biological Oxygen Demand	0.1	0.04	kg	
TOC, Total Organic Carbon	0.06	0.02	kg	
DOC, Dissolved Organic Carbon	0.06	0.02	kg	
Waste to treatment				
Treatment, sewage, to wastewater treatment, class 1/CH U	15.9	5.4	m^3	
Treatment, lorry production effluent, to wastewater treatment, class 1/CH U	2.2	0.7	m^3	

Appendix-1d. *Data for Kamunye manufacturing*

Materials	Ecoinvent database (11000 kg)	According to equation 6.1 (1820 kg)	Unit
Water, well, in ground	69.5	11.5	m^3
Steel			
Reinforcing steel, at plant/RER U	4540	751.2	kg
Steel, low-alloyed, at plant/RER U	22.8	3.8	kg
Sheet rolling, steel/RER U	568	94	kg
Section bar rolling, steel/RER U	502	83.1	kg
Chromium steel 18/8, at plant/RER U	690	114.2	kg
Copper			
Copper, at regional storage/RER U	109	18	kg
Wire drawing, copper/RER U	109	18	kg
Aluminium			

Appendix-1d (continuation). *Data for Kamunye manufacturing*

Materials	Ecoinvent database (11000 kg)	According to equation 6.1 (1820 kg)	Unit
Aluminium, production mix, at plant/RER U	1670	276.3	kg
Glass			
Flat glass, coated, at plant/RER U	490	81.1	kg
Tempering, flat glass/RER U	490	81.1	kg
Acids			
Acetic acid, 98% in H_2O, at plant/RER U	6.6E-02	1.1E-02	kg
Nitric acid, 50% in H_2O, at plant/RER U	9.9E-02	1.6E-02	kg
Hydrochloric acid, 30% in H2O, at plant/RER U	1.9E-01	3.1E-02	kg
Sulphuric acid, liquid, at plant/RER U	34	5.6	kg
Iron			
Pig iron, at plant/GLO U	502	83.1	kg
Cast iron, at plant/RER U	1030	170.4	kg
Plastic			
Polyethylene, HDPE, granulate, at plant/RER U	553	91.5	kg
Paint			
Alkyd paint, white, 60% in solvent, at plant/RER U	30	5	kg
Rubber			
Synthetic rubber, at plant/RER U	405.0	67.0	kg
Brass			
Brass, at plant/CH U	3	0.5	kg
Refrigerant			
Refrigerant R134a, at plant/RER U	2	0.3	kg
Diesel			
Diesel, at regional storage/RER U	167	27.6	kg
Oil			
Lubricating oil, at plant/RER U	80.1	13.3	kg
Lead			

Appendix-1d (continuation). *Data for Kamunye manufacturing*

Materials	**Ecoinvent database (11000 kg)**	**According to equation 6.1 (1820 kg)**	**Unit**
Lead, at regional storage/RER U	90.0	14.9	kg
Rock wool			
Rock wool, packed, at plant/CH U	396.0	65.5	kg
Propylene			
Propylene glycol, liquid, at plant/RER U	26.0	4.3	kg
Bitumen			
Bitumen, at refinery/RER U	54.0	8.9	kg
Sodium hydroxide			
Sodium hydroxide, 50% in H2O, production mix, at plant/RER U	3.8E-01	6.3E-02	kg
Lime			
Lime, hydrated, packed, at plant/CH U	3.1E-01	5.1E-02	kg
Water			
Tap water, at user/RER U	16400	2713.5	kg
Energy			
Natural gas, burned in industrial furnace >100kW/RER U	34000	5625.5	MJ
Electricity, medium voltage, production UCTE, at grid/UCTE U	4740	784.3	kWh
Light fuel oil, burned in industrial furnace 1MW, non-modulating/RER U	906	149.9	MJ
Diesel, burned in building machine/GLO U	20.1	3.3	MJ
Transport			
Transport, lorry >16t, fleet average/RER U	1060	175.4	tkm
Transport, freight, rail/RER U	2460	407	tkm
Road vehicle plant/RER/I U	0.0	0.0	p
Emissions to air			
Benzene	1.3E-02	2.2E-03	kg
Methane, fossil	1.7E-02	2.7E-03	kg
Carbon monoxide, fossil	9.7E-01	1.6E-01	kg

Appendix-1d (continuation). *Data for Kamunye manufacturing*

Materials	Ecoinvent database (11000 kg)	According to equation 6.1 (1820 kg)	Unit
Carbon dioxide, fossil	633.0	104.7	kg
Dinitrogen monoxide	2.23E-02	3.7E-03	kg
Ammonia	2.23E-02	3.7E-03	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	7.9E+00	1.3E+00	kg
Nitrogen oxides	6.0E+00	9.9E-01	kg
Sulfur dioxide	1.2E-01	2.0E-02	kg
Toluene	5.5E-03	9.1E-04	kg
Xylene	5.5E-03	9.1E-04	kg
Particulates, > 10 um	1.1E-02	1.8E-03	kg
Particulates, > 2.5 um, and < 10um	2.1E-02	3.5E-03	kg
Particulates, < 2.5 um	2.5E-01	4.2E-02	kg
Lead	1.9E-08	3.1E-09	kg
Cadmium	1.7E-06	2.9E-07	kg
Copper	2.9E-04	4.9E-05	kg
Chromium	2.9E-04	4.9E-05	kg
Nickel	1.2E-05	2.0E-06	kg
Selenium	1.7E-06	2.9E-07	kg
Zinc	1.7E-04	2.9E-05	kg
Mercury	3.5E-09	5.7E-10	kg
Heat, waste	17100.0	2829.3	MJ
Emissions to water			
COD, Chemical Oxygen Demand	1.3E-01	2.1E-02	kg
BOD5, Biological Oxygen Demand	1.3E-01	2.1E-02	kg
TOC, Total Organic Carbon	5.5E-02	9.1E-03	kg
DOC, Dissolved Organic Carbon	5.5E-02	9.1E-03	kg
Waste to treatment			
Treatment, sewage, to wastewater treatment, class 1/CH U	15.9	2.6	m^3
Treatment, lorry production effluent, to wastewater treatment, class 1/CH U	2.2	3.6E-01	m^3

Appendix-2a. *Transportation of vehicles within China*

Vehicle	Vehicle weight (Tonne)	Distance (km)	Vehicle tkm
Coaster	3.7	20	74.00
Kamunye	1.82	20	36.40
BodaBoda	0.108	20	2.16
TukTuk	0.388	20	7.76

Appendix-2b. *Vehicle shipment from China to Mombasa*

Vehicle	Vehicle weight (Tonne)	Distance (km)	Vehicle tkm
Coaster	3.7	11334.2	41936.70
Kamunye	1.82	11334.2	20628.30
BodaBoda	0.108	11334.2	1224.10
TukTuk	0.388	11334.2	4397.69

Appendix-2c. *Vehicle transportation between Mombasa and Nakawa*

Vehicle	Vehicle weight (Tonne)	Distance (km)	Vehicle tkm
Coaster	3.7	1125	4162.50
Kamunye	1.82	1125	2047.50
BodaBoda	0.108	1125	121.50
TukTuk	0.388	1125	436.50

Appendix-3a. *Questionnaires Filled During Face to Face Interviews*

Diesel – 3400 per Ltr
Petrol – 3700 per Ltr

FUEL CONSUMPTION FOR BODA BODA MOTORCYCLE ON ROUTE TO OR FROM KAMPALA CITY CENTRE (1)

For bodas with no stage 16 trips (32 trips to & from) 30000shs per day

Route: Nakawa to Kampala

Type of fuel: Petrol

Either, Amount of fuelconsumedpertrip in liters: 0.203 Ltrs

Or, Amount of fuelconsumedpertrip in Uganda shillings: 750/=

Number of tripsperdayto Kampala citycentre 20 trips (To & From)
15000 per day for stage bodas

FUEL CONSUMPTION FOR BODA BODA MOTORCYCLE ON ROUTE TO OR FROM KAMPALA CITY CENTRE (2)

Route: Kibuye to Kampala (Jinja road)

Type of fuel: Petrol

Either, Amount of fuelconsumedpertrip in liters: 0.27 Ltrs

Or, Amount of fuelconsumedpertrip in Uganda shillings: 1000/=

Number of tripsperdayto Kampala citycentre 30 trips (To & From)
30000 per day

FUEL CONSUMPTION FOR BODA BODA MOTORCYCLE ON ROUTE TO OR FROM KAMPALA CITY CENTRE (3)

Route: Natete to Kampala

Type of fuel: petrol

Either, Amount of fuelconsumedpertrip in liters: 0.27 Ltrs

Or, Amount of fuelconsumedpertrip in Uganda shillings: 1000/=

Number of tripsperdayto Kampala citycentre 30 trips (To & From)
30000 per day

FUEL CONSUMPTION FOR BODA BODA MOTORCYCLE ON ROUTE TO OR FROM KAMPALA CITY CENTRE (4)

Route: Kibuye to Kampala (clock tower)

Type of fuel: petrol

Either, Amount of fuelconsumedpertrip in liters: 0.162 Ltrs

Or, Amount of fuelconsumedpertrip in Uganda shillings: 600/=

Number of tripsperdayto Kampala citycentre 40 trips
24000 per day

Routes can include; Nakawa- Kampala, Nateete- Kampala, Bwaise- Kampala, Bugolobi- Kampala, Kibuye- Kampala. Onerouteortwoareenough

Kabalagala to Kampala
Petrol
0.27 Ltrs (30000 per day)
1000/=
30 trips

FUEL CONSUMPTION FOR TUK TUK THREE WHEELED MOTORCYCLE ON ROUTE TO OR FROM KAMPALA CITY CENTRE (1)

Route: Kansanga to Kampala (Kisenyi)

Type of fuel: petrol

Either, Amount of fuelconsumedpertrip in liters: 0.43 Ltrs.

Or, Amount of fuelconsumedpertrip in Uganda shillings: 1562.5/=

Number of tripsperdayto Kampala citycentre: 15 trips

25000 per day

FUEL CONSUMPTION FOR TUK TUK THREE WHEELED MOTORCYCLE ON ROUTE TO OR FROM KAMPALA CITY CENTRE (2)

Route: Natete - to Kampala (Kisenyi)

Type of fuel: Petrol

Either, Amount of fuelconsumedpertrip in liters: 0.405 Ltrs.

Or, Amount of fuelconsumedpertrip in Uganda shillings: 1500/=

Number of tripsperdayto Kampala citycentre: 20 trips (20)

30000 per day

FUEL CONSUMPTION FOR TUK TUK THREE WHEELED MOTORCYCLE ON ROUTE TO OR FROM KAMPALA CITY CENTRE (3)

Route: Natete to Kasenge

Type of fuel: petrol

Either, Amount of fuelconsumedpertrip in liters: 0.54 Ltrs.

Or, Amount of fuelconsumedpertrip in Uganda shillings: 2000/=

Number of tripsperdayto Kampala citycentre: 20 trips

40000 per day

FUEL CONSUMPTION FOR TUK TUK THREE WHEELED MOTORCYCLE ON ROUTE TO OR FROM KAMPALA CITY CENTRE (4)

Route: Natete - to - Kampala.

Type of fuel: Petrol

Either, Amount of fuelconsumedpertrip in liters: 0.405 Ltrs.

Or, Amount of fuelconsumedpertrip in Uganda shillings: 1500/=

Number of tripsperdayto Kampala citycentre: 30 trips

45000 ~~30000~~ per day

Routes can include; Nateete- Kasenge, Kisenyi- Katwe, Owino market- Katwe.

Tworouteswillyieldthebestresultsfor me.

For Kasenge to Natete I asked 3 people but they were giving me same infor. and they do load passengers likes taxis not as bodabodas.

FUEL CONSUMPTION FOR MINIBUSES (KAMUNYE) ON ROUTE TO OR FROM KAMPALA CITY CENTRE (1)

Route: Ggaba Kampala

Type of fuel: Diesel

Either, Amount of fuelconsumedpertrip in liters: 3.53 Ltrs (1.76 ltrs per trip)

Or, Amount of fuelconsumedpertrip in Uganda shillings: 12000 (6000 For 1 trip)

Number of tripsperdayto Kampala citycentre 5 trips (10 trips To & From)

60000 Shs per day

FUEL CONSUMPTION FOR MINIBUSES (KAMUNYE) ON ROUTE TO OR FROM KAMPALA CITY CENTRE (2)

Route: Luzira Kampala

Type of fuel: Diesel

Either, Amount of fuelconsumedpertrip in liters: 4.41 (2.205 per trip)

Or, Amount of fuelconsumedpertrip in Uganda shillings: 15000 (7500 For 1 trip)

Number of tripsperdayto Kampala citycentre 4 trips (8 To & From)

60000 Shs per day

FUEL CONSUMPTION FOR MINIBUSES (KAMUNYE) ON ROUTE TO OR FROM KAMPALA CITY CENTRE(3)

Route: Bweyogerere TO Kampala

Type of fuel: Diesel

Either, Amount of fuelconsumedpertrip in liters: 3.68 Ltrs

Or, Amount of fuelconsumedpertrip in Uganda shillings: 12500/=

Number of tripsperdayto Kampala citycentre 6 trips (To & From)

75000 Shs per day

FUEL CONSUMPTION FOR MINIBUSES (KAMUNYE) ON ROUTE TO OR FROM KAMPALA CITY CENTRE(4)

Route: Entebbe to Kampala

Type of fuel: Diesel

Either, Amount of fuelconsumedpertrip in liters: 2.35 Ltrs

Or, Amount of fuelconsumedpertrip in Uganda shillings: 8000/=

Number of tripsperdayto Kampala citycentre 8 trips (to & From)

64000 Shs per day

Routes can include; Nakawa- Kampala, Nateete- Kampala, Bwaise- Kampala, Bugolobi- Kampala, Kibuye- Kampala....Onerouteortwoareenough

1 trip = To & Fro

Diesel

1 Ltr = 3400/3400

Petrol

1 Ltr = 3700

Natete-to-Kampala (49000 Shs per day)

Diesel

1.47 Litrs

5000/=

8 trips (to & From)

FUEL CONSUMPTION FOR COASTER (29 PASSENGER MINIBUS) ON ROUTE TO OR FROM KAMPALA CITY CENTRE (1)

Route: Busega to Kampala (Rosa bus)

Type of fuel: Diesel

Either, Amount of fuelconsumedpertrip in liters: 3.68 Ltrs.

Or, Amount of fuelconsumedpertrip in Uganda shillings: 12500/=

Number of tripsperdayto Kampala citycentre 6 trips (To & From)

75000 per day

FUEL CONSUMPTION FOR COASTER (29 PASSENGER MINIBUS) ON ROUTE TO OR FROM KAMPALA CITY CENTRE (2)

Route: Busega to Kampala (Isuzu bus)

Type of fuel: Diesel

Either, Amount of fuelconsumedpertrip in liters: 4.41 Ltrs

Or, Amount of fuelconsumedpertrip in Uganda shillings: 15000/=

Number of tripsperdayto Kampala citycentre 6 trips (To & From)

90000 per day

FUEL CONSUMPTION FOR COASTER (29 PASSENGER MINIBUS) ON ROUTE TO OR FROM KAMPALA CITY CENTRE (3)

Route: Mukono to Kampala

Type of fuel: Diesel

Either, Amount of fuelconsumedpertrip in liters: 5.88 Ltrs.

Or, Amount of fuelconsumedpertrip in Uganda shillings: 20000/=

Number of tripsperdayto Kampala citycentre 4 trips

80000 per day

FUEL CONSUMPTION FOR COASTER (29 PASSENGER MINIBUS) ON ROUTE TO OR FROM KAMPALA CITY CENTRE (4)

Route: Jinja to Kampala (Isuzu bus)

Type of fuel: Diesel

Either, Amount of fuelconsumedpertrip in liters: 29.41 Ltrs

Or, Amount of fuelconsumedpertrip in Uganda shillings: 100,000/=

Number of tripsperdayto Kampala citycentre 2 trips

200000 per day

Routes can include; Kampala – Lungujja (Busega). Since it is theonlyroute in Kampala whichusesonlycoasters, it will be theonlysource of information.

Mukono to Kampala (Rosa bus)

Diesel

5.88 Ltrs

20,000

4 trips

(80,000 per day.)

Appendix-3b. *Results from face to face interviews*

Route	Kilometer	Fuel	Liters per turn	Liter/ kilometer	Daily turns	Passenger capacity
14 passenger Kamunye						
Ggaba-Kampala	10.3	Diesel	1.8	0.2	10	14
Luzira- Kampala	9.7	Diesel	2.2	0.2	8	14
Bweyogere- Kampala	10.9	Diesel	1.8	0.2	6	14
Natete- Kampala	7.1	Diesel	0.7	0.1	8	14
1 passenger Boda Boda						
Nakawa- Kampala	6.4	Gasoline	0.2	0.03	20	1
Kibuye- Kampala	3.1	Gasoline	0.3	0.09	20	1
Natete- Kampala	7.1	Gasoline	0.3	0.04	20	1
Kibuye- Kampala	3.1	Gasoline	0.2	0.05	20	1
3 passenger TukTuk						
Kansanga- Kampala	5.4	Gasoline	0.4	0.08	16	3
Nateete- Kampala	7.1	Gasoline	0.4	0.06	20	3
Nateete- Kansanga	7.1	Gasoline	0.5	0.08	20	3
Nateete- Kampala	7.1	Gasoline	0.4	0.06	30	3
29 passenger Coaster						
Busega- Kampala	7.6	Diesel	1.8	0.2	6	29
Busega- Kampala	7.6	Diesel	2.2	0.3	6	29
Mukono- Kampala	22.4	Diesel	5.9	0.3	8	29

Appendix-3c. *Liter to kilogram conversion table*

Fuel	Units	Quantity	Reference
Diesel	kg/L	0.7 (~0.8)	(Hsu, 2011)
Diesel	kg/L	0.7 (~0.8)	(Giwa, Sulaiman, & Nwaokocha, 2017)
Gasoline	kg/L	0.7 (~0.7)	(Chen, Braisher, Crossley, Stone, & Richardson, 2010)
Gasoline	kg/L	0.7 (~0.7)	(Zhou & Cai, 2014)

Appendix-3d. *Liter to kilogram conversion table*

Vehicle	Fuel type	Average fuel consumption (liter/kilometer)	Average fuel consumption (kg/ kilometer)
14 passenger Kamunye	Diesel	0.2	0.2*0.7 =0.14
29 passenger Coaster	Diesel	0.3	0.3*0.7 =~0.22
1 passenger BodaBoda	Gasoline	0.05	0.05*0.7 =0.035
3 passenger TukTuk	Gasoline	0.07	0.07*0.7 =0.049

Appendix-4a. *Inventory data for BodaBoda operation*

Emissions to air	Ecoinvent database	BodaBoda Inventory	Unit
Carbon dioxide, fossil	7.9E-02	2.5E-02	kg
Sulfur dioxide	4.0E-07	6.1E-07	kg
Cadmium	4.6E-10	6.9E-10	kg
Copper	3.1E-07	4.6E-07	kg
Chromium	5.3E-09	8.0E-09	kg
Nickel	5.1E-09	7.6E-09	kg
Zinc	1.3E-07	1.9E-07	kg
Lead	1.5E-08	2.3E-08	kg
Selenium	3.8E-10	5.7E-10	kg
Mercury	7.6E-13	1.1E-12	kg
Chromium VI	3.8E-12	5.7E-12	kg
Carbon monoxide, fossil	9.7E-03	1.0E-02	kg
Nitrogen oxides	2.3E-04	4.0E-04	kg
Particulates, < 2.5 um	1.6E-05	6.0E-05	kg
Particulates, > 10 um	7.5E-06	1.1E-05	kg
Particulates, > 2.5 um, and < 10um	8.5E-06	1.3E-05	kg

Appendix-4a (continuation). *Inventory data for BodaBoda operation*

Emissions to air	**Ecoinvent database**	**BodaBoda Inventory**	**Unit**
NMVOC, non-methane volatile organic compounds, unspecified origin	2.4E-03	5.0E-03	kg
Methane, fossil	2.1E-04	3.2E-04	kg
Benzene	1.2E-04	1.8E-04	kg
Toluene	2.8E-04	4.2E-04	kg
Xylene	2.5E-04	3.7E-04	kg
Formaldehyde	3.7E-06	5.5E-06	kg
Acetaldehyde	1.7E-06	2.6E-06	kg
Ammonia	1.9E-06	1.9E-06	kg
Dinitrogen monoxide	9.3E-07	2.2E-06	kg
PAH, polycyclic aromatic hydrocarbons	3.8E-10	5.7E-10	kg
Heat, waste	5.7E-01	8.6E-01	MJ
Emissions to Water			
Zinc	1.7E-07	2.6E-07	kg
Copper	4.0E-09	6.1E-09	kg
Cadmium	6.0E-11	9.0E-11	kg
Chromium	2.9E-10	4.3E-10	kg
Nickel	7.8E-10	1.2E-09	kg
Lead	2.5E-09	3.7E-09	
Emissions to Soil			
Zinc	1.7E-07	2.6E-07	kg
Copper	4.0E-09	6.1E-09	kg
Cadmium	6.0E-11	9.0E-11	kg
Chromium	2.9E-10	4.3E-10	kg
Nickel	7.8E-10	1.2E-09	kg
Lead	2.5E-09	3.7E-09	kg

Appendix-4b. *Inventory data for TukTuk operation*

Emissions to air	Ecoinvent database	TukTuk Inventory	Unit
Carbon dioxide, fossil	7.9E-02	7.4E-02	kg
Sulfur dioxide	4.0E-07	7.8E-07	kg
Cadmium	4.6E-10	8.9E-10	kg
Copper	3.1E-07	6.0E-07	kg
Chromium	5.3E-09	1.0E-08	kg
Nickel	5.1E-09	9.8E-09	kg
Zinc	1.3E-07	2.5E-07	kg
Lead	1.5E-08	3.0E-08	kg
Selenium	3.8E-10	7.4E-10	kg
Mercury	7.6E-13	1.5E-12	kg
Chromium VI	3.8E-12	7.4E-12	kg
Carbon monoxide, fossil	9.7E-03	1.3E-02	kg
Nitrogen oxides	2.3E-04	4.3E-04	kg
Particulates, < 2.5 um	1.6E-05	6.2E-05	kg
Particulates, > 10 um	7.5E-06	1.5E-05	kg
Particulates, > 2.5 um, and < 10um	8.5E-06	1.6E-05	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	2.4E-03	6.4E-03	kg
Methane, fossil	2.1E-04	4.1E-04	kg
Benzene	1.2E-04	2.4E-04	kg
Toluene	2.8E-04	5.4E-04	kg
Xylene	2.5E-04	4.8E-04	kg
Formaldehyde	3.7E-06	7.1E-06	kg
Acetaldehyde	1.7E-06	3.3E-06	kg
Ammonia	1.9E-06	2.0E-06	kg
Dinitrogen monoxide	9.3E-07	3.0E-06	kg
PAH, polycyclic aromatic hydrocarbons	3.8E-10	7.3E-10	kg
Heat, waste	5.7E-01	1.1E+00	MJ

Appendix-4b (continuation). *Inventory data for TukTuk operation*

Emissions to air	**Ecoinvent database**	**TukTuk Inventory**	**Unit**
Emissions to Water			
Zinc	1.7E-07	3.3E-07	kg
Copper	4.0E-09	7.8E-09	kg
Cadmium	6.0E-11	1.2E-10	kg
Chromium	2.9E-10	5.6E-10	kg
Nickel	7.8E-10	1.5E-09	kg
Lead	2.5E-09	4.8E-09	kg
Emissions to Soil			
Zinc	1.7E-07	3.3E-07	kg
Copper	4.0E-09	7.8E-09	kg
Cadmium	6.0E-11	1.2E-10	kg
Chromium	2.9E-10	5.6E-10	kg
Nickel	7.8E-10	1.5E-09	kg
Lead	2.5E-09	4.8E-09	kg

Appendix-4c. *Inventory data for Kamunye operation*

Emissions to air	**Ecoinvent database**	**Kamunye Inventory**	**Unit**
Carbon dioxide, fossil	1.1E+00	3.3E-01	kg
Sulfur dioxide	3.5E-05	1.4E-05	kg
Cadmium	3.7E-09	1.5E-09	kg
Copper	9.9E-07	3.9E-07	kg
Chromium	2.3E-08	9.3E-09	kg
Nickel	3.0E-08	1.2E-08	kg
Zinc	7.5E-07	3.0E-07	kg
Lead	2.8E-08	1.1E-08	kg
Selenium	3.5E-09	1.4E-09	kg
Mercury	7.0E-12	2.8E-12	kg
Chromium VI	3.5E-11	1.4E-11	kg
Carbon monoxide, fossil	3.2E-03	2.0E-03	kg
Nitrogen oxides	1.3E-02	2.3E-03	kg

Appendix-4c (continuation). *Inventory data for Kamunye operation*

Emissions to air	Ecoinvent database	Kamunye Inventory	Unit
Particulates, < 2.5 um	4.4E-04	4.3E-04	kg
Particulates, > 10 um	5.7E-05	2.3E-05	kg
Particulates, > 2.5 um, and < 10um	6.2E-05	2.5E-05	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	7.5E-04	2.1E-04	kg
Methane, fossil	2.3E-05	9.0E-06	kg
Benzene	3.0E-06	1.2E-06	kg
Toluene	1.6E-05	6.2E-06	kg
Xylene	7.5E-06	3.0E-06	kg
Formaldehyde	7.7E-05	3.1E-05	kg
Acetaldehyde	4.2E-05	1.7E-05	kg
Ammonia	5.0E-06	5.0E-06	kg
Dinitrogen monoxide	1.3E-05	8.0E-06	kg
PAH, polycyclic aromatic hydrocarbons	4.0E-10	1.6E-10	kg
Heat, waste	1.6E+01	6.3E+00	MJ
Emissions to Water			
Zinc	5.0E-06	2.0E-06	kg
Copper	1.2E-07	4.7E-08	kg
Cadmium	1.8E-09	7.1E-10	kg
Chromium	8.5E-09	3.4E-09	kg
Nickel	2.3E-08	9.1E-09	kg
Lead	7.3E-08	2.9E-08	kg
Emissions to Soil			
Zinc	5.0E-06	2.0E-06	kg
Copper	1.2E-07	4.7E-08	kg
Cadmium	1.8E-09	7.1E-10	kg
Chromium	8.5E-09	3.4E-09	kg
Nickel	2.3E-08	9.1E-09	kg
Lead	7.3E-08	2.9E-08	kg

Appendix-4d. *Inventory data for Coaster operation*

Emissions to air	Ecoinvent database	Coaster Inventory	Unit
Carbon dioxide, fossil	1.1E+00	4.0E-01	kg
Sulfur dioxide	3.5E-05	2.2E-05	kg
Cadmium	3.7E-09	2.3E-09	kg
Copper	9.9E-07	6.2E-07	kg
Chromium	2.3E-08	1.5E-08	kg
Nickel	3.0E-08	1.9E-08	kg
Zinc	7.5E-07	4.7E-07	kg
Lead	2.8E-08	1.8E-08	kg
Selenium	3.5E-09	2.2E-09	kg
Mercury	7.0E-12	4.4E-12	kg
Chromium VI	3.5E-11	2.2E-11	kg
Carbon monoxide, fossil	3.2E-03	2.6E-03	kg
Nitrogen oxides	1.3E-02	2.7E-03	kg
Particulates, < 2.5 um	4.4E-04	4.1E-04	kg
Particulates, > 10 um	5.7E-05	3.6E-05	kg
Particulates, > 2.5 um, and < 10um	6.2E-05	3.9E-05	kg
NMVOC, non-methane volatile organic compounds, unspecified origin	7.5E-04	3.5E-04	kg
Methane, fossil	2.3E-05	1.4E-05	kg
Benzene	3.0E-06	1.9E-06	kg
Toluene	1.6E-05	9.9E-06	kg
Xylene	7.5E-06	4.7E-06	kg
Formaldehyde	7.7E-05	4.8E-05	kg
Acetaldehyde	4.2E-05	2.6E-05	kg
Ammonia	5.0E-06	8.0E-06	kg
Dinitrogen monoxide	1.3E-05	1.2E-05	kg
PAH, polycyclic aromatic hydrocarbons	4.0E-10	2.5E-10	kg
Heat, waste	1.6E+01	9.9E+00	MJ

Appendix-4d (continuation). *Inventory data for Coaster operation*

Emissions to air	Ecoinvent database	Coaster Inventory	Unit
Emissions to Water			
Zinc	5.0E-06	3.2E-06	kg
Copper	1.2E-07	7.5E-08	kg
Cadmium	1.8E-09	1.1E-09	kg
Chromium	8.5E-09	5.3E-09	kg
Nickel	2.3E-08	1.4E-08	kg
Lead	7.3E-08	4.6E-08	kg
Emissions to Soil			
Zinc	5.0E-06	3.2E-06	kg
Copper	1.2E-07	7.5E-08	kg
Cadmium	1.8E-09	1.1E-09	kg
Chromium	8.5E-09	5.3E-09	kg
Nickel	2.3E-08	1.4E-08	kg
Lead	7.3E-08	4.6E-08	kg

Appendix-5a. *Data for BodaBoda maintenance*

Materials	Ecoinvent database	BodaBoda Inventory	Unit
Aluminium alloy, AlMg3, at plant/RER U	1.5	1.8	kg
Steel, low-alloyed, at plant/RER U	1.1	1.3	kg
Synthetic rubber, at plant/RER U	47.2	20.4	kg
Polyethylene, HDPE, granulate, at plant/RER U	1.9	2.2	kg
Section bar extrusion, aluminium/RER U	1.5	1.8	kg
Turning, chromium steel, conventional, average/RER U	1.1	1.3	kg
Injection moulding/RER U	1.9	2.2	kg
Tap water, at user/RER U	34.4	41.3	kg
Transport, transoceanic freight ship/OCE U	536.6	644.0	tkm
Transport, lorry >16t, fleet average/RER U	54.6	61.9	tkm
Sulphuric acid, liquid, at plant/RER U	0.1	0.1	kg
Lead, at regional storage/RER U	1.3	1.6	kg

Appendix-5a (continuation). *Data for BodaBoda maintenance*

Materials	Ecoinvent database	BodaBoda Inventory	Unit
Waste treatment			
Disposal, plastics, mixture, 15.3% water, to municipal incineration/CH U	1.9	2.2	kg
Disposal, rubber, unspecified, 0% water, to municipal incineration/CH U	23.6	20.4	kg
Disposal, treatment of batteries/GLO U	1.4	1.7	kg

Appendix-5b. *Data for TukTuk maintenance*

Materials	Ecoinvent database	TukTuk Inventory	Unit
Aluminium alloy, AlMg3, at plant/RER U	1.5	6.5	kg
Steel, low-alloyed, at plant/RER U	1.1	4.6	kg
Synthetic rubber, at plant/RER U	47.2	24.0	kg
Polyethylene, HDPE, granulate, at plant/RER U	1.9	8.1	kg
Section bar extrusion, aluminium/RER U	1.5	6.5	kg
Turning, chromium steel, conventional, average/RER U	1.1	4.6	kg
Injection moulding/RER U	1.9	8.1	kg
Tap water, at user/RER U	34.4	148.5	kg
Transport, transoceanic freight ship/OCE U	536.6	2313.5	tkm
Transport, lorry >16t, fleet average/RER U	51.6	222.4	tkm
Sulphuric acid, liquid, at plant/RER U	0.1	0.1	kg
Lead, at regional storage/RER U	1.3	1.3	kg
Waste treatment			
Disposal, plastics, mixture, 15.3% water, to municipal incineration/CH U	1.9	8.1	kg
Disposal, rubber, unspecified, 0% water, to municipal incineration/CH U	23.6	24.0	kg
Disposal, treatment of batteries/GLO U	1.4	1.4	kg

Appendix-5c. *Data for Coaster maintenance*

Materials	Ecoinvent database	Coaster Inventory	Unit
Reinforcing steel, at plant/RER U	55	18.5	kg
Polyethylene, HDPE, granulate, at plant/RER U	1.4	0.5	kg
Synthetic rubber, at plant/RER U	133	246.0	kg
Natural gas, burned in industrial furnace >100kW/RER U	40400	13589.1	MJ
Electricity, low voltage, at grid/CH U	67800	22805.5	kWh
Light fuel oil, burned in industrial furnace 1MW, non-modulating/RER U	40400	13589.1	MJ
Tap water, at user/CH U	484000	162800.0	kg
Lubricating oil, at plant/RER U	824	277.2	kg
Lead, at regional storage/RER U	18	6.0	kg
Paper, woodfree, uncoated, at regional storage/RER U	3	1.1	kg
Transport, freight, rail/CH U	207	69.6	tkm
Transport, lorry 20-28t, fleet average/CH U	52	17.4	tkm
Emissions to Air			
Heat, waste			
Waste treatment	244000	82072.7	MJ
Disposal, used mineral oil, 10% water, to hazardous waste incineration/CH U	824	277.2	kg
Disposal, plastics, mixture, 15.3% water, to municipal incineration/CH U	55	54.9	kg
Treatment, sewage, to wastewater treatment, class 1/CH U	484000	162800.0	kg
Disposal, rubber, unspecified, 0% water, to municipal incineration/CH U	133	246	kg

Appendix-5d. *Data for Kamunye maintenance*

Materials	Ecoinvent database	Kamunye Inventory	Unit
Reinforcing steel, at plant/RER U	54.9	9.1	kg
Polyethylene, HDPE, granulate, at plant/RER U	1.4	0.2	kg
Synthetic rubber, at plant/RER U	133	229.6	kg
Natural gas, burned in industrial furnace >100kW/RER U	40400	6684.4	MJ
Electricity, low voltage, at grid/CH U	67800	11217.8	kWh
Light fuel oil, burned in industrial furnace 1MW, non-modulating/RER U	40400	6684.4	MJ
Tap water, at user/CH U	484000	80080.0	kg
Lubricating oil, at plant/RER U	824	136.3	kg
Lead, at regional storage/RER U	17.9	3.0	kg
Paper, woodfree, uncoated, at regional storage/RER U	3.2	0.52	kg
Transport, freight, rail/CH U	207	34.2	tkm
Transport, lorry 20-28t, fleet average/CH U	51.7	8.6	tkm
Emissions to Air			
Heat, waste	244000	40370.9	MJ
Waste treatment			
Disposal, used mineral oil, 10% water, to hazardous waste incineration/CH U	824	136.3	kg
Disposal, plastics, mixture, 15.3% water, to municipal incineration/CH U	54.9	54.9	kg
Treatment, sewage, to wastewater treatment, class 1/CH U	484000	80080.0	kg
Disposal, rubber, unspecified, 0% water, to municipal incineration/CH U	133.0	229.6	kg

Appendix-6a. *Material recovery rates for Coaster at end of Life (manual dismantling)*

Material	Recycling %	Recycling mass (kg)	Landfilling %	Landfiiling (kg)	Reference
Steel	95	2214.5	5	116.6	(Giannouli, de Haan, Keller, & Samaras, 2007)
Polymer	85	377.4	15	66.6	(Giannouli, de Haan, Keller, & Samaras, 2007)
Aluminium	95	351.5	5	18.5	(Giannouli, de Haan, Keller, & Samaras, 2007)
Copper	95	140.6	5	7.4	(Gradin, Luttropp, & Björklund, 2013)
Glass	90	66.6	10	7.4	(Gradin, Luttropp, & Björklund, 2013)
Other	0	0	100	333	(Gradin, Luttropp, & Björklund, 2013)

Appendix-6b. *Material recovery rates for Kamunye at end of Life (manual dismantling)*

Material	Recycling %	Recycling mass (kg)	Landfilling %	Landfiiling (kg)	Reference
Steel	95	1089.3	5	57.3	(Giannouli, de Haan, Keller, & Samaras, 2007)
Polymer	85	185.6	15	32.8	(Giannouli, de Haan, Keller, & Samaras, 2007)
Aluminium	95	172.9	5	9.1	(Giannouli, de Haan, Keller, & Samaras, 2007)
Copper	95	69.2	5	3.6	(Gradin, Luttropp, & Björklund, 2013)
Glass	90	32.8	10	3.6	(Gradin, Luttropp, & Björklund, 2013)
Other	0	0	100	163.8	(Gradin, Luttropp, & Björklund, 2013)

Appendix-6c. *Material recovery rates for TukTuk at end of Life (manual dismantling)*

Material	Recycling %	Recycling mass (kg)	Landfilling %	Landfiiling (kg)	Reference
Steel	95	228.5	5	12.0	(Giannouli, de Haan, Keller, & Samaras, 2007)
Polymer	85	49.5	15	8.7	(Giannouli, de Haan, Keller, & Samaras, 2007)
Aluminium	95	29.5	5	1.6	(Giannouli, de Haan, Keller, & Samaras, 2007)
Copper	95	14.7	5	0.8	(Gradin, Luttropp, & Björklund, 2013)
Glass	90	7.0	10	0.8	(Gradin, Luttropp, & Björklund, 2013)
Other	0	0	100	34.9	(Gradin, Luttropp, & Björklund, 2013)

Appendix-6d. *Material recovery rates for BodaBoda at end of Life (manual dismantling)*

Material	Recycling %	Recycling mass (kg)	Landfilling %	Landfiiling (kg)	Reference
Steel	95	68.7	5	3.6	(Gradin, Luttropp, & Björklund, 2013)
Polymer	85	9.2	15	1.6	(Gradin, Luttropp, & Björklund, 2013)
Aluminium	95	8.2	5	0.4	(Gradin, Luttropp, & Björklund, 2013)
Copper	95	4.1	5	0.2	(Gradin, Luttropp, & Björklund, 2013)
Other	0	0	100	11.9	(Gradin, Luttropp, & Björklund, 2013)

Appendix-7a. *Energy consumption during manual disassembly for Coaster end of life*

Vehicle	Tonne	Average energy (kWh/t)	Energy consumption (kWh)
Steel	2.331	36.1	84.1491
Polymer	0.444	36.1	16.0284
Aluminium	0.37	36.1	13.357
Copper	0.148	36.1	5.3428
Glass	0.074	36.1	2.6714
Other	0.333	36.1	12.0213
Total (Coaster) (Gradin, Luttropp, & Björklund, 2013)	3.7		133.57

Appendix-7b. *Energy consumption during manual disassembly for Kamunye end of life*

Vehicle	Tonne	Average energy (kWh/t)	Energy consumption (kWh)
Steel	1.1466	36.1	41.39226
Polymer	0.2184	36.1	7.88424
Aluminium	0.182	36.1	6.5702
Copper	0.0728	36.1	2.62808
Glass	0.0364	36.1	1.31404
Other	0.1638	36.1	5.91318
Total (Kamunye) (Gradin, Luttropp, & Björklund, 2013)	1.82		65.702

Appendix-7c. *Energy consumption during manual disassembly for TukTuk end of life*

Vehicle	Tonne	Average energy (kWh/t)	Energy consumption (kWh)
Steel	0.2406	36.1	8.68422
Polymer	0.0582	36.1	2.10102
Aluminium	0.03104	36.1	1.12054
Copper	0.01552	36.1	0.56027
Glass	0.00776	36.1	0.28014
Other	0.03492	36.1	1.26061
Total (TukTuk) (Gradin, Luttropp, & Björklund, 2013)	0.388		14.0068

Appendix-7d. *Energy consumption during manual disassembly for BodaBoda end of life*

Vehicle	Tonne	Average energy (kWh/t)	Energy consumption (kWh)
Steel	0.07236	36.1	2.6122
Polymer	0.0108	36.1	0.3899
Aluminium	0.00864	36.1	0.3119
Copper	0.0043	36.1	0.1552
Other	0.01188	36.1	0.4289
Total (BodaBoda) (Gradin, Luttropp, & Björklund, 2013)	0.108		3.8988

Appendix-8a. *Energy consumption during the shredding and separation of Coaster components*

Vehicle	Tonne	Average energy (kWh/t)	Energy consumption for Coaster (kWh)
Steel	2.331	100	233.1
Polymer	0.444	100	44.4
Aluminium	0.37	100	37
Copper	0.148	100	14.8
Glass	0.074	100	7.4
Other	0.333	100	33.3
Total (Coaster) (Gradin, Luttropp, & Björklund, 2013)	3.7		370

Appendix-8b. *Energy consumption during the shredding and separation of Kamunye components*

Vehicle	Tonne	Average energy (kWh/t)	Energy consumption for Kamunye (kWh)
Steel	1.1466	100	114.66
Polymer	0.2184	100	21.84
Aluminium	0.182	100	18.2
Copper	0.0728	100	7.28
Glass	0.0364	100	3.64
Other	0.1638	100	16.38
Total (Kamunye) (Gradin, Luttropp, & Björklund, 2013)	1.82		182

Appendix-8c. *Energy consumption during the shredding and separation of TukTuk components*

Vehicle	Tonne	Average energy (kWh/t)	Energy consumption for TukTuk (kWh)
Steel	0.24056	100	24.056
Polymer	0.0582	100	5.82
Aluminium	0.03104	100	3.104
Copper	0.01552	100	1.552
Glass	0.00776	100	0.776
Other	0.03492	100	3.492
Total (TukTuk) (Gradin, Luttropp, & Björklund, 2013)	0.388		38.8

Appendix-8d. *Energy consumption during the shredding and separation of BodaBoda components*

Vehicle	Tonne	Average energy (kWh/t)	Energy consumption for BodaBoda (kWh)
Steel	0.07236	100	7.236
Polymer	0.0108	100	1.08
Aluminium	0.00864	100	0.864
Copper	0.00432	100	0.432
Other	0.01188	100	1.188
Total (BodaBoda) (Gradin, Luttropp, & Björklund, 2013)	0.108		10.8

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