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Sustainable Urban Transportation Approaches: Life-Cycle Assessment Perspective of Passenger Transport Modes in Qatar

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Abstract

Transportation is one of the most responsible sectors for human health impact and greenhouse gas emissions. The transportation mode in Qatar is primarily passenger car; consequently, the significant amount of environmental impact can result. Metro system has been introduced as a strategy to transition urban environments into low carbon by reducing emissions from passenger cars. This study compares the environmental impacts of the metro, passenger car, and bus transportation modes using a life-cycle assessment method from cradle to gate for the case of Qatar. GaBi 6.0 software was used to model and quantify the environmental impacts per functional unit of passenger-kilometer. Our analysis demonstrates that metro is more sustainable concerning all impact categories when compared to buses and cars. Most importantly, the metro transport is vital in addressing the critical environmental impacts in the transportation sector, namely global warming, human health particulate matter, and smog. A metro line can reduce approximately 12.3 Mton of CO_2 emissions, 457.13 ton of human health particulate matter, and 0.061 Mton of smog air annually. Electricity is the prime contributor to the environmental impact of the metro system; therefore, its impact can be further improved by using a cleaner energy source from renewables.

Keywords: Transportation; Life-Cycle assessment; Sustainability; Environmental Impact

1. Introduction

Transportation has become ubiquitous in today's life by providing mobility to industrial, commercial and social services. The share of the global transport sector in total energy consumption has increased from 23% in 1973 to 28% in 2013, mainly due to the increased passenger cars [1]. Today's transportation system is primarily dependent

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on fossil fuels; consequently, the transportation sector is responsible for much of the global warming impact and depletion of non-renewable resources [2]. For example, transportation is the second largest contributor to the total greenhouse gas (GHG) emissions of the USA [3].

The transportation sector is responsible for nearly 20% of the total global GHG emissions [4]. Besides to climate change impact, transportation causes water and other resources depletion. A significant amount of water is consumed either directly for cooling and heating purposes, or indirectly in the infrastructure production as embodied material [5]. Previous research has examined the life-cycle energy and environmental impacts of transportation systems from a cradle to grave in order to improve metro design and passenger transportation [6]–[8]. These studies identified the hot spots for environmental and energy impacts by capturing the whole vehicle life-cycle from the material acquisition, manufacturing, and use, through the end-of-life life-cycle stages. The results demonstrate that the operation stage (or use stage) was the main contributor to the total environmental impact. The operation life-cycle stage of transportation modes accounted for 86-98% of the total energy consumption and 70-92% of the total GHG emissions [7]–[9]. Other studies compared the environmental impact of different transportation modes [10]–[12]. Commuter and light rail systems were found to be better than buses and aircraft concerning energy and environmental performance [13]. The relative performance of a transportation mode is profoundly influenced by the Vehicle Occupancy (VO) and the number of passengers [14]. Furthermore, it is reported that the transportation system results in water depletion. However, the direct water requirements for the cooling system and car washing are insignificant when compared to the indirect water requirement for material production, electricity generation, infrastructure, and other facilities operation [14].

The environmental impact of transportation systems differs geographically because each region has different characteristics with respect to energy supply mix, transport infrastructure, and travel behaviours [7]. To our knowledge, no life-cycle assessment (LCA) study has been done that represents Qatar’s actual setting. Besides, most of these LCA studies were performed based on secondary data which can affect the actual result. It is essential to create a life-cycle inventory for the fast growth of Qatar's urban development. On the other hand, previous transportation studies focused on a single environmental indicator of global warming potential and energy consumption. Environmental indicators such as air pollution and human health which are particular concerns of the transportation sector are ignored.

Doha metro project strongly aligns with *Qatar vision 2030*, which focuses on the human, social, economic, and environmental sustainability of development [15]. Qatar has been ranked one of the highest countries with carbon footprint and power consumption per capita [16]; therefore, the project is seeking sustainability through attaining four stars GSAS rating (Global Sustainability Assessment System) in the design and construction phase to reduce the environmental impact of transportation [17]. Assessing the environmental impacts of alternative transportation options is critical to making an informed decision on new transportation investments with respect to addressing sustainable development and transitioning to a low carbon urban development. Most importantly, Qatar represents a unique position in terms of mobility and transportation modes when compared to the rest of the world. With the highest GDP per capita, it is essential to examine the significance and implication of shifting passenger cars from the road to an alternative metro transportation system.

The objective of this research is elucidating a new perspective on how to support urban transitions to a low carbon sustainable development by examining the environmental life-cycle impacts of planned transportation modes with the conventional automobile passenger car transportation system.

2. Methodology

Life-Cycle Assessment (LCA) is a standardized method for quantifying the environmental impacts of a product or service throughout its life-cycle [18].

2.1. Goal and scope definition

Transportation in Qatar is categorized into private and public transport. The majority of the population in Qatar depend on private, while public transportation is rarely used. Private cars ownership and dependence are extensively dominating in Qatar; consequently, there is heavy traffic congestion. The government's approach to resolving traffic congestions issues is primarily through infrastructure expansion of roads that will include 8,500km with 200 new bridges and 30 new tunnels by the year 2020. These expansions attain to solve the traffic congestion but will not reduce the ownership of the car knowing that the annual growth rate of automobile ownership in 2010 and 2015 reached to 7%; consequently, it leads to inefficient land use, low air quality as well as human health impact [19]. On the other hand, the current public transportation service provided by the government with minimum fees is buses; therefore, it is inconvenient for the majority of the public to use it with limited routes. The drive to conduct this study is the traffic congestions in Qatar which leads to GHG emissions, human health impact, air pollution, noise, and discomfort. The results of this research will support the MOTC (Ministry of Transport and Communication) to address Qatar Vision2030 and National Development Strategy. It will also inform policy-makers in producing relevant policies that promote public health and sustainable transportation.

Qatar government has considered increasing the public transportation options through unique projects in the region such as the metro and trams. As part of Qatar's national vision of 2030, the government has been investing on infrastructural projects such as rail and metro system to diversify its transportation system, reduce the public dependency on cars, and promote sustainable living habits. Public transport meets a tiny portion of the transportation demand. This research investigates the life-cycle environmental impacts of the metro, bus, and private automobile transportation services using a functional unit of 1000 passenger-kilometers (pkm). We related all the input and output flows of the reference flow with the functional unit in our calculation. According to the Qatar Rail annual Report, Phase 1 of the metro project will be launched in 2020 with the expectation of the reduction in traffic congestions by 190,000 cars per day [17]. This project consists of three main lines and a total of 37 stations, 65 trains running along 76km in the first phase. The phase1 metro project consists of three main lines: Red, Gold, and Green. This study focuses on the Gold line due to its essential location where it passes through several hubs in the city as well as the traffic congestions in the old city center. The total number of the stations in the gold line is 11 underground stations passing through Msheireb primary station [17]. Figure 1 illustrates the schematic routes of the three lines of Doha metro for phase 1.

This study evaluates the operation (or use) stage for Qatar metro project as an alternative for vehicles and buses transport services in a gate-to-gate system boundary. The material acquisition and manufacturing (including infrastructure construction) have been excluded from the system because their impact is insignificant when compared to the operation phase, and those stages have been already put in place during the study period. TRACI 2.1 impact assessment method was applied to quantify the environmental impacts of transportation services [20]. A process flow diagram of the studied systems is drawn (Figure 2). The figure illustrates the entire lifecycle of different transportation modes from cradle-to-grave splits into three main systems: upstream, core-stream and downstream whereas the doted enclosed area of the core-stream in Figure 2 represents the significant gate to gate system boundary of the LCA.

Figure 1: Schematic routes of Doha Metro Project Phase 1 [17]

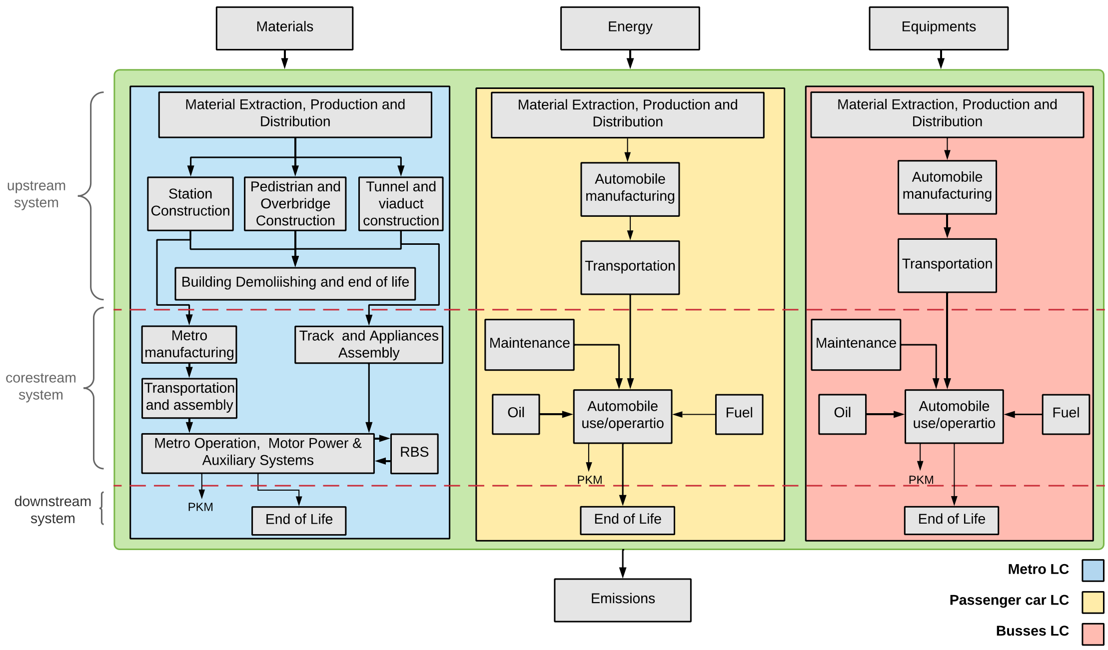

Figure 2: Process flow diagram of the transportation systems studied

2.2. Life-cycle inventory

The life-cycle energy, material, and emission flows to and from the product system were compiled and quantified per functional unit. These elementary flows were tracked and modelled using GaBi software package. Most unit processes were obtained from primary data and constructed manually into GaBi [21].

Primary data were collected from Qatar rail project inventory and Ministry of Development Planning and Statistics. In case primary data was missing, secondary data was collected from literature, reports, and the databases in GaBi software [21], [22]. Moreover, assumptions were made in aspects such as stating the occupancy of transportation mode based on observations and types of cars based on licences distribution for the year of 2018.

In the metro system, electricity is supplied by the dominant local loads. The first load feeds the stations, tunnels, and bridges; however, the scope focus on the tunnels traction systems. The second load represents the non-traction power that feeds into the metro cars. AC supply from the station is converted to 675 V DC supply to power the train. The train load consists of the DC motors, cars interior AC and lighting, as well as auxiliary systems. Furthermore, the Regenerative Braking System (RBS) recover a portion of the energy which would otherwise be lost as heat in conventional braking systems, enhancing the energy management and sustainability of the system.

The metro train consumed approximately 3.42 kWh of electricity per kilometer (km). As for passenger cars and busses, they consume gasoline and diesel as they represent different modes of automobiles. Cars of different categories such as SUV, sedan and pick-up truck consume an average of 290.73 kWh for the functional unit selected. On the other hand, public transport buses consume an average of 192.17 kWh as per 1000 pkm traveled.

3. Results and discussion

A comparative life-cycle environmental impact was carried out for the different transportation modes using TRACI 2.1 method. As shown in Figure 3, the metro transportation mode reduces the impacts for all categories as compared to passenger car and bus transportation systems. The impact at system level demonstrates that the metro transport is vital in addressing the critical environmental impacts that are commonly associated with the transportation sector, namely global warming, human health particulate matter, and smog [23], [24]. On the other hand, the bus transportation system was the second-best alternative when compared to passenger car overall. The source of impact on most impact categories is due to the electricity for the metro, and fuel consumption for the passenger car and bus transportation systems. The power consumed for the metro is driven by electricity from a relatively clean energy source of natural gas. Nevertheless, the environmental impact of the metro system can be further improved by using a cleaner energy source from wind or solar power energy.

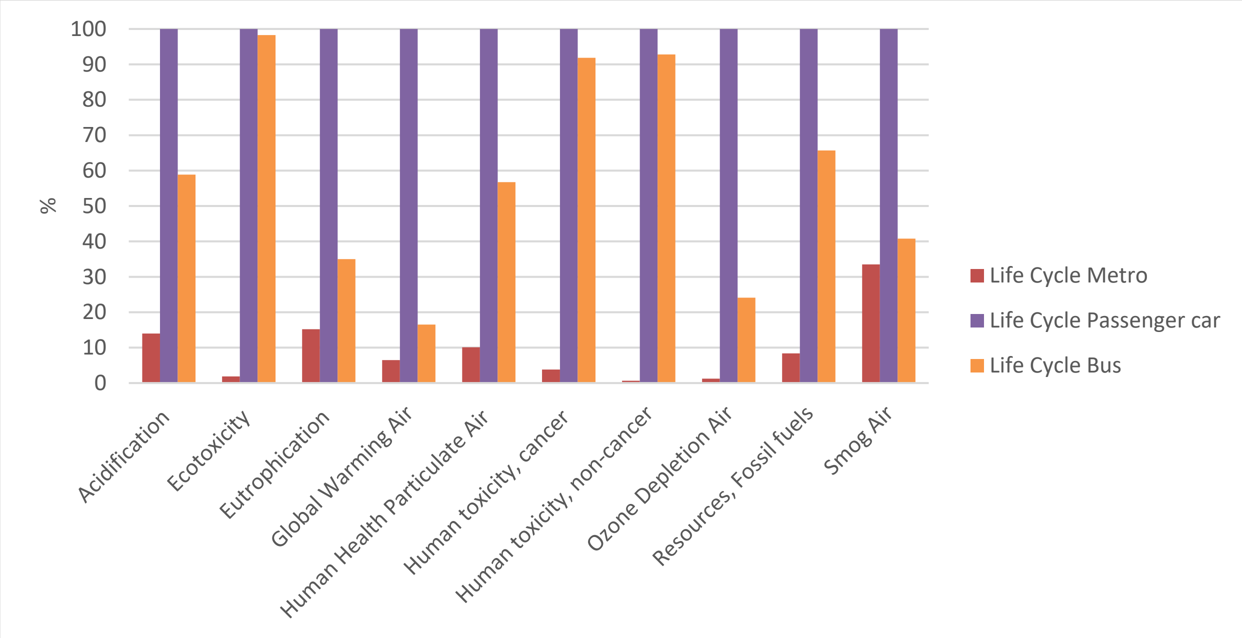

Figure 3: Comparative LC environmental impact per 1000 p-km of transportation modes

The metro project has drawn interest in addressing Qatar's vision 2030 of sustainable development due to the higher passenger occupancy. To this effect, Qatar Railways Company aims to switch nearly 19600 passenger cars off the road through the metro transportation system. Considering the environmental impact of the metro and passenger car systems per FU, we examined the amount of emission reduction per year. Thus, the metro project will reduce approximately 12.3 Mton (megaton) of CO2 emissions for global warming, 457.13 ton of human health particulate matter, and 0.061 Mton of smog air annually. This is critical in profoundly addressing the higher emission per capita of the state of Qatar.

4. Conclusion

The reported results show the significance of environmental benefits of LCA of different transportation modes during its operational phase. According to the study, the metro is more conveniently sustainable concerning all impact categories compared to buses and cars. Most importantly, the metro transport is key in addressing the critical environmental impacts in the transportation sector, namely global warming, human health particulate matter, and smog. Electricity is the prime contributor to the environmental impact of the metro system, and fuel consumption for the passenger car and bus transportation systems. The environmental impact of the metro system can be further improved, considering the harsh environment of Qatar, by using a cleaner energy source from wind or solar power energy as synthetic eFules produced photovoltaics.

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