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Simulation of Energy Consumption in Hybrid Electric Vehicles used in a Semi-Arid Region: A case for Palapye, Botswana

Matthias O. T. Motsomi*, M. Tunde Oladiran
Botswana International University of Science and Technology,
Department of Mechanical, Energy and Industrial Engineering
P/Bag 16, Palapye, Botswana
matthias.motsomi@studentmail.biust.ac.bw

Abstract

Electric vehicles are renowned for their merits such as reduced pollution, no emission and small reliance on non-renewable fossil fuels, yet their adoption is low. The low adoption of electric vehicles is due to their disadvantages such as low range, long charging hours and some potential consumers have the fear of running out of charge while driving. A prediction of the energy consumption of an electric vehicle helps to alleviate such fear. In this work simulation results are presented which compare the energy consumption of a Toyota Prius, a hybrid electric vehicle modeled in ADVISOR simulation package, when used under summer European and Palapye Botswana ambient conditions respectively. The New European Driving Cycle was used and ambient conditions were varied in the input parameters. Results show that the state of charge are respectively 50% and 54% under hotter conditions of Palapye and a European country. The gradient of the state of charge of the battery pack during the simulation period is also steeper for Palapye conditions than for a European country which shows that energy is consumed at a higher rate in the former. Based on the difference in the state of charge for both conditions, results show that there was an 8% higher energy consumption under Palapye's conditions. The results can inform consumers on what to expect when purchasing and operating a hybrid electric vehicle. Results also provide a guide for the design of electric vehicles intended for use in a semi-arid country such as Botswana. It can be concluded that electric vehicles consume more energy under harsher or more hostile environmental conditions owing to the use of auxiliary systems such as air conditioners and other temperature control systems. Future research work needs to develop better battery storage systems and driving cycles that accurately model conditions in hot climate regions.

KEYWORDS: ADVISOR, hybrid electric vehicle, energy consumption, ambient conditions, state of charge

1. Introduction

Transportation plays a pivotal role in the day to day lives of people in society, be it directly, whether they use passenger vehicles to help them to get from one destination to another, or indirectly where vehicles are used to transport goods (Li, 2017). Transportation is important for the economy since it helps to get goods from their places of production to the market and for workers to reach their places of employment (Filip, 2014). Such involvement of transportation in the economy can be taken to imply that, with economic growth comes an increased need for transportation (Filip, 2014). Increased use of transportation is seen through the increase of vehicles on the roads which in turn means that the problems associated with use of internal combustion engine vehicles, such as air pollution and reliance on non-renewable fuel sources, become worse (Kadij, 2016). Table 1 below shows the countries or continent with highest levels of CO_2, it is worth noting also that these are some of the most developed countries and continents in the world. The carbon dioxide is principally from combustion of fossil fuels in transportation vehicles.

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Table 1: Regions with highest levels of CO_2 level in unit Metric tonnes.

Country or continent	China	America	Europe
CO_2 (Mt)	11680	4535	1028

Sources: world population review, euro stat

Research and development efforts by governments and automobile companies have been made to mitigate the problems of using internal combustion engine vehicles for transportation, where the results include development of alternative fuel vehicles such as electric vehicles (EVs) (Bjerkan, 2016). EVs are vehicles that use an electric motor for propulsion, instead of an internal combustion engine, and a battery pack as a source of energy instead of a fuel tank (Ding, 2017). EVs come in two main types being pure electric vehicles, which use an electric motor as the sole source of traction force, and hybrid electric vehicles (HEVs) which use both fuel and a battery as energy sources and a motor as well as an engine for traction (Ding, 2017). In line with the high levels of air pollution as shown from table 1, figure 1 shows how EVs are adopted in high numbers in the same countries.

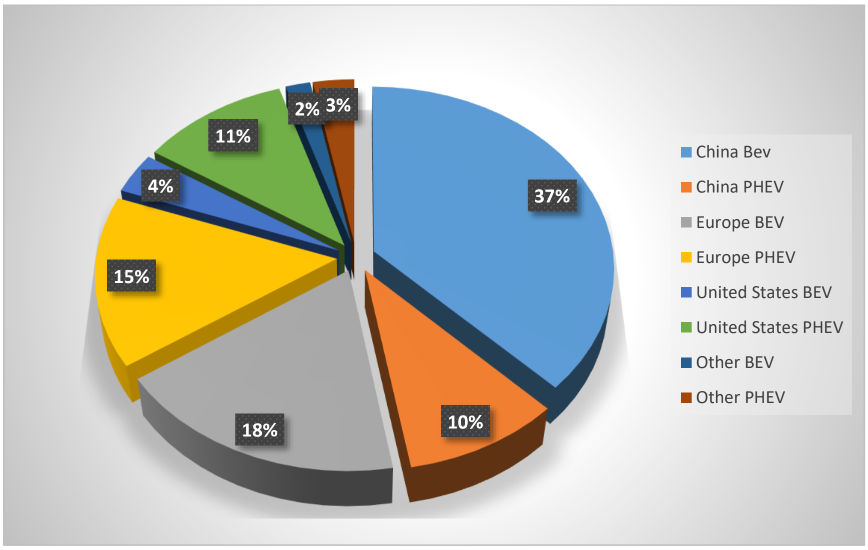

Figure 1: Regions with most EVs worldwide
Source: Global Electric Vehicle Outlook 2022

Most currently available models of electric vehicles use an AC motor for traction, have temperature control technology for both the cabin and the battery pack as well as the features of conventional vehicles including motorized windows, wipers, entertainment features, etc. In a conventional vehicle the 12V battery that runs features using 12V is charged through the alternator while in an electric vehicle the battery is charged through a DC-DC converter which draws power from the traction battery pack that is usually of a higher voltage, to charge it. In this way the traction battery pack is the main energy source for the vehicle.

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Common battery chemistry for the traction battery pack is Li-ion (Faraz, 2021). The battery technology has concerns of thermal runaway which is a situation where the battery self-heats and the result is a release of gas, shrapnel or particulates and extreme heat (Liu, 2017). Thermal runaway occurs when heat generated by the battery exceeds heat dissipated to the battery's surrounding (Golubkov, 2014). Cooling systems for the batteries are thus important and electric vehicles have temperature control systems for the battery packs because over cooling the battery cells also affects their performance (Pandya, 2021). The temperature control systems keep the cells at their optimum performance temperature range. Cabin temperature control through air conditioning is another temperature control system in electric vehicles (Piao, 2020). Now that these systems run on the 12V system, which draws energy from the traction pack, they affect the range of an electric vehicles (Badin, 2013). How much energy they require depends on the effect of the external temperature on the temperature control systems, that is, how much energy is required by the compressor in order to compress the refrigerant so that it may reach a temperature higher than that of the environment in order to dissipate heat from the battery pack. Most EV cooling systems run on a refrigeration cycle (Piao, 2020). For cabin cooling or heating, the energy required to overcome the temperature depends on how hot or cold the cabin air is, where the bigger the difference between the set temperature and the cabin air temperature, the more energy is required to achieve the desired temperature (Moran, 2014). Compressor input work is used to account for the energy consumed by the cooling systems and also to model the system. Equations 7 through 10 show how energy consumed is determined from the compressor input work.

The climate where an electric vehicle is used thus impacts the range of the vehicle because of the energy drawn by the temperature control systems (Badin, 2013). Table 2 shows the climate experienced in the regions that have most EVs, where Norway is the sampled European country since it is the leader in European countries adopting the use of electric vehicles.

Table 2: Climate experienced in different developed countries that adopt EVs.

Country	China	America	Norway
Climate	Tropical in the south and subtropical in the north	Tropical, arctic and alpine	maritime

Sources: NCCS report, Gunnar Ketzler (2022)

Botswana is described as a developing country with a semi-arid climate. To promote adoption of electric vehicles in such a country it is important to predict how an electric vehicle would perform in the conditions of a semi-arid climate. Literature review shows that two-wheel electric vehicles and hybrid electric vehicles are the most suited types of electric vehicles for adoption in developing countries. This work thus presents simulation results and analysis of a hybrid electric vehicle under conditions of Botswana.

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The total energy available after a trip is the sum of energy required by the traction motor, E_{mot}, energy required by the auxiliary components, E_{aux} and energy recuperated through regenerative braking , E_{reg}, as shown in equation 1. For the scope of this work, regenerated energy will be neglected since it is not affected by ambient conditions as shown in equations 2 and 6. Energy as a function of power and time is illustrated in equations 3 through 5, this is because the power rating of components and how long they are in use is relied on to determine the energy they consume.

$$E_{tot} = E_{mot} + E_{aux} + E_{reg} \quad (1)$$

$$E_{req} = E_{mot} + E_{aux} \quad (2)$$

$$E_{req} = \int P\, dt \quad (3)$$

$$= P\int dt \quad (4)$$

$$= P\Delta t \quad (5)$$

Where P is component rated power, t is time, J is joules of energy and s is seconds.

Therefore $E_{req} = J_{mot} + J_{aux}$ 6

$$\dot{W}_c = \dot{m}(h_{out} - h_{in}) \quad (7)$$

$$E_{cool} = \int kW\, dt \quad (8)$$

$$= kW\int dt \quad (9)$$

$$= (kW)^* \Delta t \quad (10)$$

Where $\dot{W}_c$ is compressor input work, $\dot{m}$ is refrigerant mass flow rate, h_{out} is the enthalpy of the refrigerant exiting the compressor and h_{in} is enthalpy of the refrigerant entering the compressor

2. Literature review

Numerous studies on the adoption of electric vehicles in developing countries make mention of electric two-wheelers and hybrid electric vehicles being the types most suited for early adoption (PLotz, 2014). Infrastructure for supporting the use of electric vehicles is expensive to develop (Li Y. , 2016) hence electric two-wheelers and plug-in hybrid electric vehicles are easier to operate because they can be re-charged at home using a house power outlet and a dedicated electric vehicle charger to charge the battery pack of the hybrid electric vehicle.

How far one can travel on a single charge, travel range that is, has been determined to be one of the critical decision making factors for consumers hence need to determine the energy consumption of electric vehicles (Hardman, 2016) (Dua, 2019). Energy consumption of electric vehicles impacts the range of the vehicle because the higher it is, the lower the range of the vehicle. It is influenced by the road type, driving style as well as ambient conditions (Badin, 2013). Temperature has an impact on the energy consumption of the traction motor, where higher temperatures reduce the motor efficiency which then leads to higher energy consumption in order to attain the same results (Khalifa, 2010). It is thus important to investigate the influence of temperature on the energy consumption of EVs in different regions because EVs will perform differently in climates with significantly diverse temperatures.

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EV energy consumption can be determined through road tests where an EV is driven for a known distance and a recording of the vehicle's state of charge is taken at the beginning and end of the trip (Hu, 2017). The expected energy consumption is a function of time and the power rating of the traction motor as shown in equation 1. Simulations are another way to determine the energy consumption of EVs. EV models can be built and simulations ran to predict the energy consumption of an EV (Genikomsakis, 2017). Simulation may be a difficult task in some instances because of the complexity of having to account for the effect of many varying conditions and also the regeneration of power during vehicle braking (Kavalchuk, 2015). Some simulation packages are available for making simulations easier of which they have inbuilt vehicle models and they can run simulation over established test cycles.

3. Methodology

3.1 Chosen Vehicle Model

In line with literature review, a hybrid electric vehicle is modeled and its energy consumption simulated. One of the inbuilt hybrid electric vehicles available in the Advanced Vehicle Simulator (ADVISOR) simulation package is the Toyota Prius hybrid which was chosen for this work.

ADVISOR makes an approximation of the continuous behaviour of a vehicle as a sequence of steps using basic physics calculations and measured component performance. The vehicle is assumed to be at steady state, whereby the effect of changing voltage, current, RPMs and torque are neglected. The simulator takes driving profile, conditions in which the vehicle is to be driven in and vehicle parameters as inputs. It then works backwards using the desired vehicle speed to determine the required torque and speed of each component including the energy source. The required energy to put the vehicle through the chosen cycle is the vehicle's energy consumption.

3.2 Chosen Driving Cycle

A driving cycle or procedure is a description of the velocity and how long a vehicle is to be driven, so as to assess its performance. For most countries, urban areas usually have the most developed infrastructure that supports use of electric vehicle. Urban areas commonly have inhabitants who earn enough to afford an electric vehicle. For these reasons, the New European Driving Cycle (NEDC) is chosen for testing the proposed vehicle. The cycle is a dynamometer test used for passenger vehicle type approval in Europe. It consists of sub-cycles for simulating city driving. Figure 2 shows the velocity vs time graph for the cycle, it shows how the vehicle is accelerated and decelerated.

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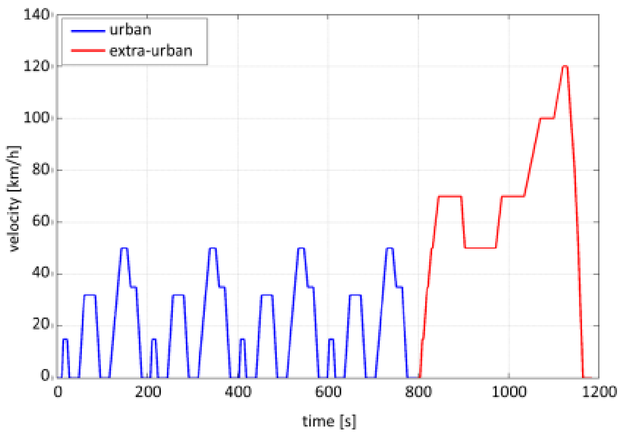

Figure 2: New European Driving Cycle (NEDC)
Source: ResearchGate

3.3 Input parameters

To put the summer temperatures of the Botswana's climate into perspective, a week's temperature recordings for Palapye are shown in table 3. The ambient temperature used as input is the average of the temperature recordings and the inbuilt summer conditions for the vehicle model used are ones used for summer operation of the vehicle under NEDC.

Table 3: Temperature recording taken at 1300 of each day from Saturday October 8th till Friday October 14th 2022.

Day	Mon	Tue	Wed	Thu	Fri	Sat	Sun
Date						08/10	09/10
	10/10	11/10	12/10	13/10	14/10		
Temperature (°C)	35	33	35	35	36	37	34

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4. Results

The energy consumption pattern of the simulated vehicle under the inbuilt normal European conditions is shown in figure 3. Figure 4 shows the energy consumption of the same vehicle but with the input temperature increased.

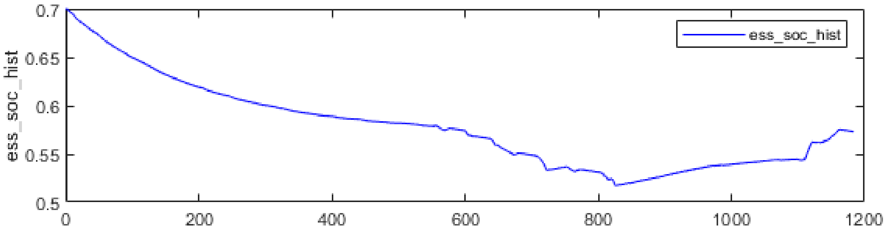

Figure 3. Simulated energy consumption in the hybrid Toyota Prius.

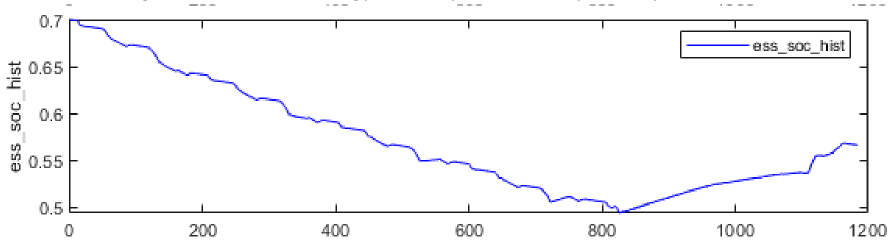

Figure 4. Simulated energy consumption in the hybrid Toyota Prius but under a higher ambient temperature.

It can be observed that just after the 800s mark, the two graphs show approximately 4% difference in state of charge where the graph for normal European use is higher than for use in Palapye's ambient summer conditions. Both graphs rise thereafter which is a representation of the energy recovered by the vehicle during regenerative braking.

5. Conclusion

This work presents the simulation of energy consumption in a hybrid electric vehicle if it were to be used in the conditions of a semi-arid country such as Botswana. The simulation was focused on temperature effects on the energy consumption of an electric vehicle and disregarded difference in humidity among other factors that influence energy consumption of an EV. Potential customers, researchers and automobile developers can expect at least a 4% higher energy consumption from a hybrid EV based on the results presented.

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