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# Model Based Engineering and Realization of the KAYOOLA Electric City Bus Powertrain

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## Abstract

In the race to decrease the well-to-wheels fuel consumption and improve environmental stewardship, automakers and researchers worldwide have moved to electrify the vehicle powertrain for personal and public transportation. The Center for Research in Transportation Technologies at Makerere University is exploring electric vehicle transportation technology as a plausible solution to traffic issues in Uganda's urban centers and cities. Electric vehicle transportation in Africa's cities is a practical solution due to the fact that most of these cities are on a relatively small area; distances involved are small.

This paper presents the technical, operational and functional aspects that were considered in the design of the KAYOOLA Electric City Bus, which has a drive cycle that suits the public transport system in Kampala City in Uganda. Since Battery Electric Vehicles have specific on-board energy, the powertrain for the KAYOOLA electric city bus was designed following the specific road-load requirements of typical city drive cycle from data obtained from actual road measurements in Kampala city. For range extension, On-board solar charging is incorporated. To accurately predict performance, Autonomie-Modeling and simulation tool kit for light and heavy duty vehicles developed by Argonne National Laboratory was used to model and simulate the entire powertrain, noting effects of the grades, range, speed and drive cycles on the battery SOC and voltage. Design iterations are made to meet performance targets. This approach was employed to reduce time between concept development and prototyping while maximizing efficiency. The results shall inform the integration of key powertrain technologies into the KAYOOLA Electric City Bus.

**Key Words**

*KAYOOLA Electric City Bus, Model Based Engineering, Powertrain, City Drive Cycle*

# 1 Introduction

The successful completion of KIIRA EV [1] prototype in November 2011 by the Center for Research in Transportation Technologies (CRTT) at Makerere University paved the way for the development of an Electric City Bus, the KAYOOLA (Fig. 1). The design intent for the KAYOOLA Electric City Bus envisages the integration of on- board solar charging for range extension. While most Ugandans would enjoy driving in electric cars, few people can afford to own a car. It is imperative to note that road transport in Uganda, though not fully developed, contributes to over 95 % of Uganda's transportation means [3]. The KAYOOLA City Bus Project is a pioneer intervention aimed at addressing the urban transportation needs of Uganda with technology enhancing improved environmental stewardship. The Case Study Kampala, is a city located on seven hills; Rubaga, Namirembe, Makerere, Kololo, Kibuli, Kampala, and Mulago. This presents a unique road-load requirement for the bus in terms of gradeability, speed, range and drive cycle. This was the motivation for the implementation of a custom powertrain pulling market tested EV technology.

Building prototypes and hardware using traditional vehicle design paradigms is costly [4]. To reduce costs and improve time to market, it is imperative that greater emphasis be placed on modeling and simulation [5].The use of Model Based Engineering for development of electric vehicles and trucks has been proven [6-8].

The automotive development process for the KAYOOLA Electric City Bus was based on an iterative component sizing process [9]. Autonomie, a Modeling and simulation tool kit for light and heavy duty vehicles developed by Argonne National Laboratory [5] was used. To realize an optimum solution verified against established vehicle requirements, models for motor, battery, transmission, gear boxes, vehicle chassis and vehicle control strategy were simulated in Autonomie.

The subsequent sections of this paper present a synopsis of the vehicle technical definition, drive cycle requirements, the component sizing process, the vehicle propulsion architecture, vehicle level control strategy and analysis of the simulation results.

Figure 1: KAYOOLA Electric City Bus Computer Model

# 2 Vehicle Definition

Typical vehicle powertrain sizing parameters were established through a benchmarking process of production class 6 medium duty electric buses and trucks. Linear extrapolation based on the Vehicle Gross Vehicle Weight (GVW) was used to estimate the logical requirements summarized in the Table 1. The architecture developed is that of a purely BEV as shown in in Fig. 2. On-board charging is by solar and regenerative braking [4].

It is envisaged that the abundance of solar energy in Uganda can contribute significantly to range extension.

## 3 Drive Cycle Requirements

To meet the all-electric range (AER) requirements, the battery is sized to follow specific driving cycle [10].Though standard Environmental Protection agency (EPA) drive cycles based on the Kansas city drive tests were used, a specific Kampala drive cycle was also developed as a means of testing the extent to which the developed concept satisfies the road conditions in Kampala city. To design a drive profile for the envisaged powertrain, a case study route in Kampala was taken. Gradeability measurements were taken for major grades using standard surveying methods. Vehicle speed on a second by second basis was used to develop the speed profile of the drive cycle. Fig. 3 shows the drive cycle developed in Autonomie. Table 2 shows the driving characteristics of the case study route. The specific cycle is characterized by stop and go scenarios with low average speeds.

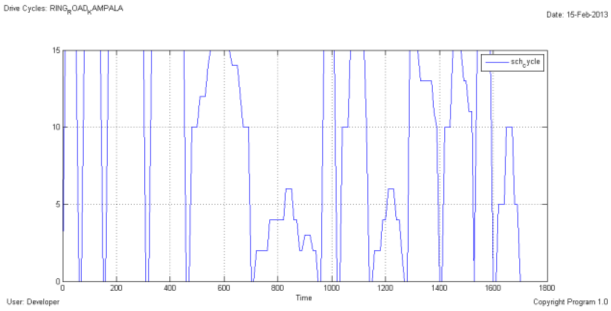

Figure 3: Kampala Ring Road City Drive Cycle

Table 1: KAYOOLA Electric City Bus Parameters

| | |
|---|---|
| GVW | 10,500 kg |
| Range | 100 km |
| Top Speed | < 100 km/hr |
| Coefficient of drag ($C_d$) | 0.35 |
| Bus Frontal Area | 5.46 $m^2$ |
| Wheel Type | 265-75/R22.5 |
| Tyre Radius | 0.3937 |
| Coefficient of rolling resistance ($C_r$) | 0.05 |

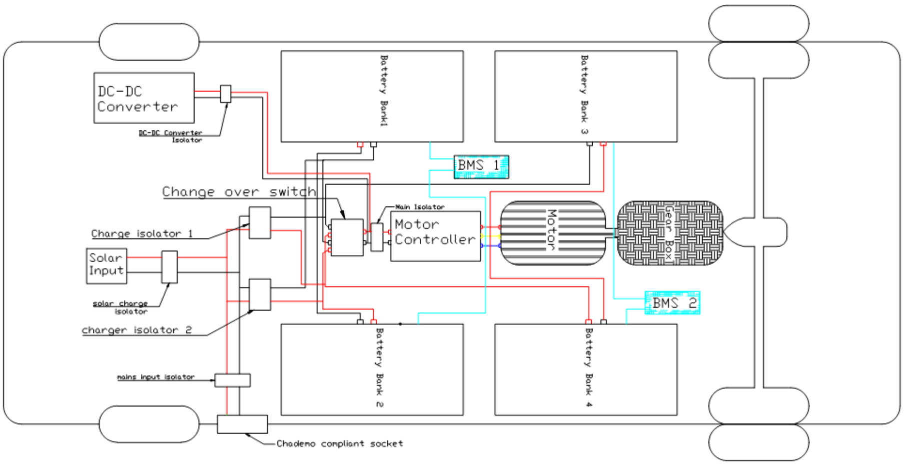

Figure 2: KAYOOLA Bus Architecture

Table 2: Kampala Route Characteristics

| | |
|---|---|
| Maximum Acceleration | 1.5 m/s$^2$ |
| Average Acceleration | 0.1 m/s$^2$ |
| Maximum Deceleration | 1.5 m/s$^2$ |
| Distance | 16.5 km |
| Driving Time | 1700 s |
| Maximum Speed | 54 km/hr |
| Average Speed | 40.2 km/hr |
| Stop Frequency | 0.72 Times Per km |
| Maximum Gradeability | 7.9 % |

# 4 Component Sizing

For light-duty applications, typical sizing requirements are made of four criteria: acceleration (e.g., 0 to 60 mph time), passing (30 to 50 mph time), gradeability at a given speed, and top speed. The same sizing procedure can be applied to trucks and buses [11].Component sizing followed an iterative process presented in earlier studies [1] [9]. The iterative sizing process was modified to suit the project requirements of the KAYOOLA Electricity City bus. Fig. 4 shows the modified iterative process used for component sizing. Road-load equations [1] were used to establish the traction motor power, torque, gear ratios, battery and solar power. Range versus battery capacity was adjusted for optimum performance. The battery rating was optimized to meet the All Electric Range with solar range extension inclusive. Commercial off the shelf components were established for integration of system models into the vehicle architecture in Autonomie. Table 3: summarizes the component specifications

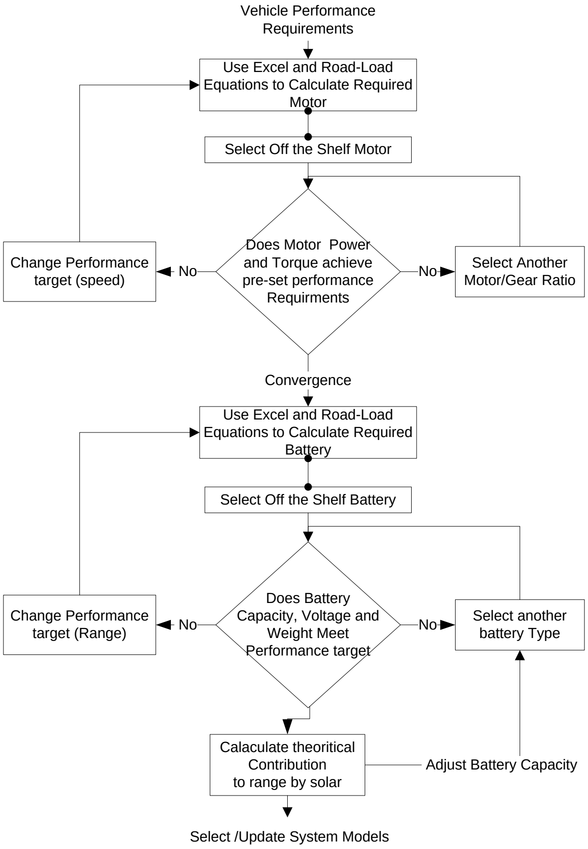

**Figure 4; The Sizing Process**

Table 3: Component Specifications for the KAYOOLA Electric City Bus

| | | |
|---|---|---|
| Motor Max Power | kW | 150 |
| Motor Continuous Power | kW | 100 |
| Max. Torque | Nm | 400 |
| Cont. Torque | Nm | 210 |
| Battery Energy x2 | kWh | 70 |
| Nominal Battery Voltage | VDC | 384 |
| Battery Capacityx2 | AH | 90x2 |
| Roof Top Solar Panel Max. Energy | kWh | 9 |
| Solar Output Voltage | VDC | 144 |
| Range Extension by Solar | km | 12 |
| Maximum Charging Power | kW | 50 |
| Charging | DC and AC CHAdeMO | |
| Transmission | 2 Gear Automatic Transmission 1:1 and 1:3 | |

## 5 Vehicle Propulsion Architecture

Two powertrain architectures were developed, one representing the conventional Battery Electric Vehicle (BEV) without a gearbox and the other with a gearbox. The aim of this was to compare performance results of the two architectures in terms of energy consumption and hill climbing ability to ascertain predictions of improved hill climbing, energy consumption and higher powertrain efficiency as a result of incorporating multi-gear gearboxes into electric powertrain for heavy duty vehicles [12].

## 6 System Models

In Autonomie; driver, environment, vehicle propulsion architecture (vpa), power converter, electrical accessories, final drive, motor drive, torque coupling, gearbox, chassis and wheel plant and controller reusable models in Fig. 5 and Fig. 6 and Table 4 were used to realize the KAYOOLA Electric City Bus.

Figure 5: Propulsion Architecture without multi-gearbox

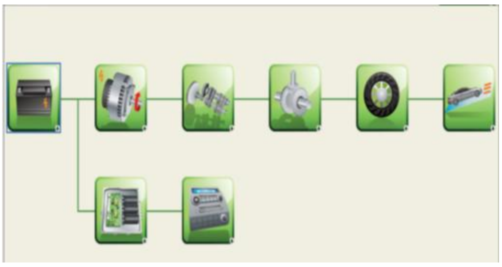

Figure 6: Propulsion Architecture with Mulit-gear box

## 7 Vehicle Level Control Strategy

The vehicle level control strategy implemented is the brake and propulsion control with regenerative braking. For the case of the architecture with the transmission, the 2 gear selection is managed by automatic gear shifting controller with demand and constraints blocks. The battery pack was modularized with two independent modules of each 384 V, 90 AH and 35 kWh specifications to allow for on-board in-transit solar charging. Simulations are performed on one battery pack. It is assumed that the test results for the other battery bank are the same. The energy management strategy enables the switching of modules and solar charging whenever the SOC charge is below 20 %. This ensures that any single module has either a charging or discharging regime and not both.

A set of control requirements is pulled from the controller-component interaction hierarchy. Fig. 7 shows the set of high level control requirements as a result of the control strategy. Detailed control requirements were implemented from the high level requirements identified above

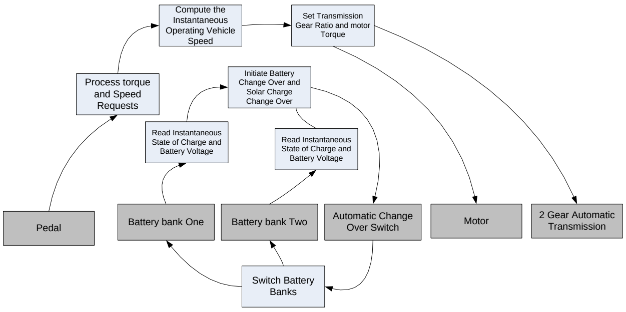

Figure 7: Power Train High Level Control Requirements

Table 4; Power Train Component Specifications and Models

| **System** | **Information** | **Plant Model Used** |
|---|---|---|
| Driver | Normal Driver | *Drv_conv_dm_equation, kp=3000 and ki=50* |
| Environment | Normal Earth Environment | ***Earth Environment Parameters,*** |
| Vehicle Propulsion Architecture | Propel and Brake Controller | |
| Power converter | 2200 Watts | Pc_plant_P2P_constant_eff, pc_plant_V2V_constant_eff,pc_plant_2ess_constant_eff,pc_plant_P2V_constant_eff |
| Electrical Accessories | 2000 Watts Accessories | *Accelec_plant_const_pwrloss_volt_in, accelec_plant_const_pwrloss_pwr_in* |
| Final Drive | Differential 1:5 Ratio | *fd_plant_map_trqloss_funTW* |
| Motor Drive | Remy HVH250-115 DOM | mot_plant_map _pelec_funTW_volt_in, mot_plant_map_pelec_funTW_pwr_in |
| Torque Coupling | Various Gear ratios used<br>1:3 and 1:1 | Tc _plant_map_trqloss_funTW |
| Wheel | 265-75/R22.5 (2 wheel drive mode) | Whl_plant_2wd |
| Chassis | Heavy Duty Class 6 vehicle(Road _load equation losses) | *chas_plant_veh_equation_losses* |
| Gear Box | IEdrives automatic 2 gear 2 Transmission | gb_plant_au_map_trqloss_funTWratio |
| Energy Storage System | WB_LYP90 AHA Winston Lithium ion batteries 90 Ah | *ess_plant_pngv_map_anl_PI controller* |

# 8 Vehicle Level Simulation and Results

Acceleration, gradeability and top speed simulations were performed using the standard EPA cycles implemented in Autonomie. In addition to the above cycles, tests were performed on the Kampala city cycle developed. The SOC of one battery module was also observed under the different drive cycles. The test runs were used to compare the performance of the two vehicle architectures developed based on maximum acceleration gradeability, speed and battery SOC values

## 8.1 Acceleration Test

Based on Table 5 results, the two vehicle models clearly do not achieve the target acceleration of 1.5 $m/s^2$ characteristic of the typical Kampala city ring road. The Maximum acceleration achievable is 1.07 $m/s^2$ which is close to the drive cycle maximum acceleration in Table 2. The Vehicle model with a gearbox is capable of achieving a higher acceleration and also travels a longer distance within the given timeframe of 40 s. As already evidenced by the change in SOC, this higher acceleration value and higher mileage results into a higher energy demand and battery consumption. Both vehicles are capable of reaching the speed mark of 60 mph/97 km/hr which satisfies the speed requirement set in Table 1.

Table 5: Acceleration run Results for Models with and without gearbox

| Parameter | | No Gear box | With Gearbox |
|---|---|---|---|
| Time : 0 to 60 mph | s | 40 | 40 |
| Time: Initial vehicle Movement to 60 m | s | 38.6 | 38.4 |
| Distance Travelled During run | mile | 0.14 | 0.39 |
| Maximum Acceleration during run | $m/s^2$ | 0.36 | 1.07 |
| Distance travelled in 8 s | mile | 0.14 | 0.39 |
| Electrical Consumption | W.h/ mile | 2663.21 | 3373.37 |
| Initial SOC | % | 100 | 100 |
| Final SOC | % | 99.14 | 96.87 |

## 8.2 Gradeability Test

The Kampala ring road drive cycle in Fig. 3 is characterized by a maximum grade of 7.9 %. Initial requirements are set for the bus to do such a grade at a maximum speed of 30 km/hr. gradeability simulations are performed at this speed

In Table 6, clearly the two vehicles fall short of the expected gradeability of 7.9 % at 30 km/hr. The best gradeability achieved at this speed is with a multi-gear box in the vehicle powertrain. Simulation performed using the powertrain architecture with a gear box reveal that the bus can do a grade of up to 10.02% at a speed of 1 km/hr. With better gearing ratios, this can be improved.

It should be observed that the overall vehicle gradeability requirement is set at 14.3 % . It is envisaged that the vehicle shall be able to do such a grade at relatively lower speeds than 30 km/hr. Since gradeability tests are performed on a vehicle starting from rest, the expected performance results of an already mobile bus are expected to be better.

Table 6: Gradeability results for models with and without gearbox

| Parameter | | No Gear Box | With Gear box |
|---|---|---|---|
| Grade | % | 1.5 | 3.75 |
| Cycle Distance | mile | 13.66 | 13.8 |
| Electrical Consumption | W.h/ mile | 1898.73 | 2335.74 |
| Initial SOC | % | 100 | 100 |
| Final SOC | % | 37.01 | 20.64 |
| Delta SOC | % | -62.99 | -79.3 |

## 8.3 Drive Cycle Test Runs

The KAYOOLA Electric City Bus powertrain is designed to have an all electric range capable of traversing the city cycle developed in Fig. 3 for at least 7-8 times . The first battery bank should be able to power the bus around the drive cycle at least four times. The different powertrain architectures developed are tested for single runs and trip runs (4 times) and SOC and other powertrain performance parameters analyzed

In Fig. 8, over one cycle, the SOC of the model developed without transmission decreases by 24.68 % compared to the 10.51 % decrease of the model with a transmission in Fig. 10. The Vehicle without the gear box misses the drive cycle trace by 44.17 % compared to the 16.32 %. Over the four cycles which is the design range for one battery pack of the bus, the vehicle without transmission consumes 91.75 % which is beyond the recommended DoD (80%). The vehicle with gear box achieved the targeted electric range with only 42.74% DoD. The addition of the powertrain gearbox resulted into a saving of up to 49.01 %

of the battery pack for the Kampala City drive. It is important to also note that since the model of the vehicle with transmission missed the drive cycle by a less percentage, more cycle distance is travelled. Kampala city is generally hilly and a powertrain designed with a gearbox addresses the question of implementation of an electric vehicle in typically hilly area. Considering a trip of over four (4) drive cycles through regenerative braking, up to 9.9 kWh of energy is recovered at the battery. In Table 3, theoretical calculations show that up to 9 kWh of energy can be harvested through solar charging in a single full sun day. Regenerative braking and solar can contribute an equal amount of energy to the battery bank which results into a range extension of up to 12 km from each.

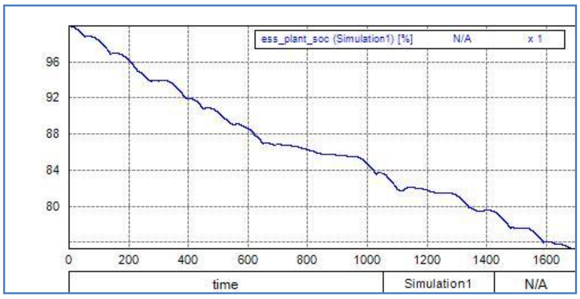

Figure 8:  SOC Vs Time for Model without Transmission Over One Cycle

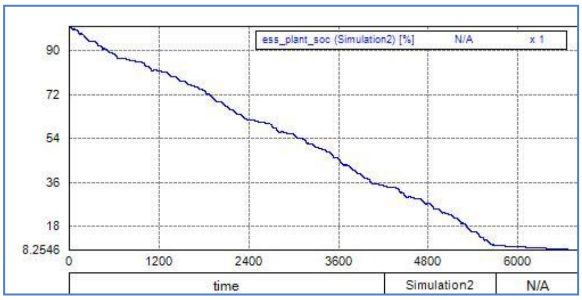

Figure 9: SOC Vs Time for Model without Transmission Over Four Cycles

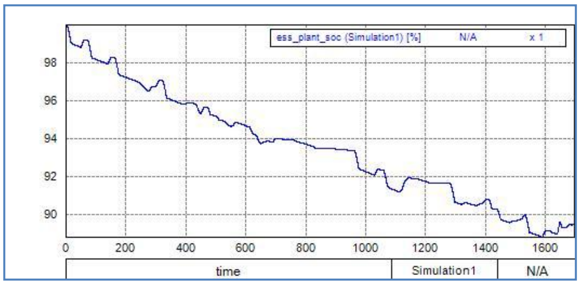

Figure10: SOC Vs Time for Model with Transmission Over One Cycle

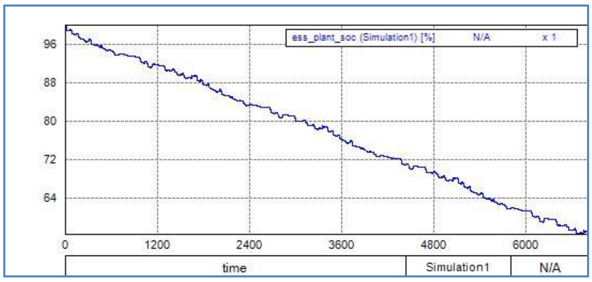

Figure 11: SOC Vs Time for Model with Transmission Over Four Cycles

Table 7:Vehicle Performance Results Over One Drive Cycle

| Over One Cycle | | | |
|---|---|---|---|
| **Ring_Road** | | **No Gear Box** | **Gear Box** |
| Distance Travelled | mile | 8.37 | 10.72 |
| Cycle Distance | mile | 10.26 | 10.26 |
| Percent Time trace Missed by 2mph | % | 44.17 | 16.32 |
| Electrical Consumption | W.h/mile | 1253.35 | 417.74 |
| Initial SOC | % | 100 | 100 |
| Final SOC | % | 75.32 | 89.49 |
| Delta SOC | % | -24.68 | -10.51 |

Table 8: Vehicle Performance Results Over Four Drive Cycles

| **Over Four Cycles** | | | |
|---|---|---|---|
| **Ring_Road** | | **No Gear Box** | **Gear Box** |
| Distance Travelled | mile | 29.0 | 42.8 |
| Cycle Distance | mile | 41.0 | 41.0 |
| Percent Time trace Missed by 2mph | % | 53.5 | 16.3 |
| Electrical Consumption | W.h/mile | 1268.1 | 417.8 |
| Initial SOC | % | 100 | 100 |
| Final SOC | % | 8.25 | 57.2 |
| Delta SOC | % | -91.7 | -42.7 |
| Regenerative Energy Recovered | W.h | -2903.7 | -9911.6 |

# 9 Conclusion

This paper has presented a simulation of a powertrain model of a public transportation bus powertrain for Kampala city in Uganda. A synopsis of the vehicle technical specification, drive cycle requirements, propulsion architecture and control strategy is presented. The Autonomie model development and simulation results have been presented.

The powertrain development was greatly enhanced by reverse engineering with the aim of integrating off the shelf powertrain components. The results of the simulation suggest that the realisation of the KAYOOLA City Bus powertrain would require a motor of peak power 150 kW, and torque of 400 Nm to achieve a maximum speed of 100 km/hr and a maximum gradeability of 10.2 % at 1km/hr from rest. This performance is based on a two speed transmission with gear ratios of 1:1 and 1:3.The requisite total battery bank for the prescribed 100 km is 70 kWh at 384 V. This is modularized to allow for in-transit solar charging.

It has been demonstrated that the energy consumption and mileage along the Kampala drive cycle is greatly improved with a multi-gearbox. On-board solar charging and regenerative braking contribute to range extension in almost equal proportions. The design strategy of modularizing battery banks to harness both regenerative and solar energy contributes significantly to range extension

The key powertrain specifications presented shall address the need for an electric transportation means in a predominantly hilly Kampala city

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