A MODELLING APPROACH FOR ASSESSING ENERGY PERFORMANCE AND INFLUENTIAL FACTORS OF VEHICLES POWERED BY BATTERY, FUEL CELL AND ULTRACAPACITOR

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Abstract

This research work aims to assess the performance of electric vehicles and powered by battery, fuel cell, ultra-capacitor and combination of the former. A flexible vehicle simulation model is developed in MATLAB-Simulink and vehicle performance is evaluated in various test cases (e.g. 1 Hz certified cycles) enabling the assessment of SOC, energy consumption/km, overall range and other performance details.

The proposed model accurately estimates energy consumption and range of passenger vehicle with an average absolute error of less than 4% and 2% for the electric bus. The study showed that BEV has the least energy consumption (23%), followed by FCEV (65%) compared to ICE vehicles. The performance analysis showed increasing the battery capacity of BEV by three-fold, the range is extended by 294%, while the battery with higher energy density helps to reduce 2-4% in energy consumption.

Simulation results point out that aggressive driving and higher average speed have a negative influence on vehicle range based on acceleration profiles. Also, the varying atmospheric conditions in northern and southern European countries can result in a range difference of 25-35%. Combination of the battery-fuel cell shows an increase in range by 10%, while combining ultra-capacitor with battery enables a lifetime extension of battery life by 10%, with negligible change in range. For buses, ultra-capacitors are highly recommended for short-frequent trips with a life of 20 years, with the highest cost-benefit ratio. The fuel cell as a primary energy source is recommended for the long-range drive, for coaches and trucks.

1. INTRODUCTION

The overexploitation of natural resources is paving way for an increasing amount of greenhouse gas (GHG) emissions and global warming impacts around the globe[1]. Even though the primary cause is not the automotive field, the former holds a considerable amount of responsibility to the overall emissions. As per the European Commission statistics for 2017, the transportation sector is responsible for around 31% of the final energy consumption in Europe. Facing the challenges on global warming and GHG emissions, the EU claimed cars are responsible for around 12% of EU emission of carbon dioxide (CO_2) to the atmosphere[2]. As a result of this regulatory push, vehicle manufacturers have started focusing on more efficient powertrains with vehicle hybridization and electrification, in an attempt to reduce emissions and also the dependency towards fossil fuels.

It is estimated that on shifting to electric mobility, the energy consumption can be reduced by 75% and 57% when considering the energy production stage [3]. Furthermore, it is expected that the economic competitiveness of electric technologies improves, with a breakeven point between the two technologies to be expected in the next 10 years, even without the presence of governmental incentives.

In the wake of higher demand for the electric powertrain, diverse studies have been carried out based on theoretical and practical experiments. The key technologies that have helped the success of EV and HEV include up to 95% efficient motor drive technology, reliable guidance and vehicle control system, sustainable material technology and energy storage technology. Integration of all these technologies has been a key aspect in the success of EV, resulting in sales of 2919 vehicle in 2010 to 97,687 vehicle in 2015 and 223,284 vehicles in 2018 around the Europe [4].

Due to the different characteristics of energy storage systems for the automotive systems, a single energy source cannot be employed to all vehicle segments. This has been discussed widely over the last couple of years by different manufacturers. Nikola Motors is now developing the fuel cell trucks for the future, claiming the future relies on hydrogen while Tesla Motors are resisting with revolutionising various battery electric vehicle. To test these hypotheses, investing in experimental models can be highly risky due to the uncertainty of the outcome. The optimal option will be to carry out modelling and simulation to validate these comments and realise the facts, without financial and time risking processes.

1.1. OBJECTIVE OF THE STUDY

This work aims to study the energy-efficient and cost-effective powertrain design focusing on different vehicle technologies (focused on energy storage with batteries or hydrogen or ultra-capacitors) and vehicle segments (light-duty vehicles and buses), based on certification and real-world driving cycles. For this purpose, the following tasks were performed:

- Developing and validating the vehicle model in Simulink toolbar in MATLAB, considering a road load model and dimensioning the efficiency of the different components under different real-world driving conditions;
- Model component of the vehicle such as vehicle physical model, motor, battery system, fuel cell system, ultra-capacitor system and regenerative braking system through programming blocks.
- Apply the model both to light-duty vehicles and buses, assessing different powertrain designs to learn the financial benefits with CAPEX and environmental benefits for different types of vehicles.
- Compute and compare the total ownership cost of the light-duty passenger vehicle to understand the long term and short-term benefit associated with different vehicles

With the primary objectives to achieve, this work focused both on light-duty vehicle and also on buses. With the developed model, this research finding will be submitted with simulation evidence.

2. DATA AND METHODS

Numerous simulation and testing software were released in the market. Most of the software was developed and licenced by private institutes. Facing the lack of accessibility and flexibility of software, a new simulation model is required which is adaptable to different vehicle model and energy sources. A model was developed in Simulink toolbox in MATLAB, which satisfies the requirements.

The model comprises of 7 subsystems, namely drive cycle, vehicle model, vehicle physical model, motor, battery system, fuel cell system and ultra-capacitor system. The model allows to simulated different types of vehicles with combination of different energy sources such as battery, fuel cell and ultra-capacitor.

The energy consumption of the vehicle primarily depends upon the drive cycle. The drive cycle data can be obtained by a real-world drive cycle or from a theoretical standard drive cycle. Some of the most commonly used drive cycles for simulation purposes are NEDC drive cycle, WLTP drive cycle, FTP 75 cycle, and HWFET drive cycle [5].

A generic vehicle model is created in Simulink, comprises of mechanical and mathematical principles. Considering a one-dimensional movement vehicle fundamentals, the power requirement of the vehicle in specific drive-cycle depends upon the basic vehicle loads forces as presented in Figure 9.

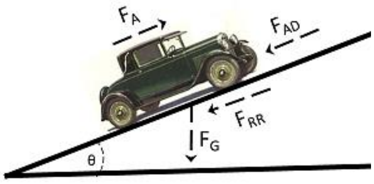

Figure 1: Forces acting on a vehicle

The traction force (F_T) required to move the vehicle is calculated by equation 1.

$$F_T = F_A + F_G + F_{RR} + F_{AD} \qquad \text{Eq. 1}$$

Where F_A is the acceleration force (N), F_G is the gravitational force (N), F_{RR} is the rolling resistance force (N), and F_{AD} is the aerodynamic drag force (N).The acceleration force is defined as the force required to move an object of mass m (kg) with an acceleration of a (m/s^2), as expressed in equation 2.

$$F_A = m*a \qquad \text{Eq. 2}$$

The gravitational force acting on the vehicle depends upon the slope of the road, as expressed as

$$F_G = m*g*\sin\theta \qquad \text{Eq. 3}$$

Where g is the acceleration due to gravity (m/s^2) and θ is the angle of inclination of the surface (degrees). The force that restricts the rolling motion on a surface is termed as rolling resistance force is given by equation 4.

$$F_{RR} = Cr*m*g*\cos\theta \qquad \text{Eq. 4}$$

Where Cr is the coefficient of rolling resistance. Aerodynamic drag is the resistance force developed by the air on the moving direction of the vehicle. The force is given by equation 5.

$$F_{AD} = \frac{1}{2}*Cd*\rho*A_f*v^2 \qquad \text{Eq. 5}$$

Where Cd is the coefficient of drag, v is the velocity (m/s), ρ is the density of air (kg/m^3) and A_f is the frontal area of the vehicle (m^2). Incorporating all the parameters, the total traction force, F_T at the driving wheels is expressed as:

$$F_T\,(N) = m*a + \frac{1}{2}*Cd*\rho*A_f*v^2 + Cr*m*g*\cos\theta + m*g*\sin\theta \qquad \text{Eq. 6}$$

The rotational speed, ω (rpm), of the wheel is calculated using equation 7.

$$\text{Rotational speed, } \omega \text{ (rpm)} = {s*1000}/{l*60} \qquad \text{Eq. 7}$$

Where s is the speed of the vehicle (km/h) and l is the linear distance of the tire (m). Torque is calculated as defined in equation 8.

$$\text{Torque, } \tau \text{ (Nm)} = \frac{P_{wheel}}{\left(\omega*\frac{2\pi}{60}\right)} \qquad \text{Eq. 8}$$

The model is made adaptable and flexible. The ambient temperature is given as input in the vehicle model and the model calculates the required auxiliary power, rolling resistance and air density of the vehicle by itself.

Permanent Magnet Synchronous Motors (PMSM) are integrated into the model due to its high efficiency, power density and popularity in the automotive sector. Based on the literature [6], the motor efficiency curve of Nissan Leaf 80 kW motor was considered as generic efficiency curve. The power required to deliver the traction force to the wheel by the motor is expressed by

$$P_{wheel}\,(W) = \frac{F_T * v}{\eta_m} \qquad \text{Eq. 9}$$

Where η_m (%) is the efficiency of the motor. The efficiency of the motor is determined based on the percentage of motor torque and speed at each second instead of the output power range. Gear ratio, motor torque and motor RPM are defined using the equations as follows:

$$\text{Gear ratio, } Gr = \frac{\pi}{60} * \frac{\omega * t_d}{v} \qquad \text{Eq. 10}$$

$$\text{Motor torque, } \tau_m = \frac{\tau}{G_r} \qquad \text{Eq. 11}$$

$$\text{Motor rotational speed, } \omega_m = \omega * G_r \qquad \text{Eq. 12}$$

Where t_d is the diameter (m) of the tire and G_r is the gear ratio of the vehicle. During regenerative mode, energy extracted from the traction force is sent back to the battery and is expressed as the following

$$P_{regen}\,(W) = F_T * \eta_{regen} \qquad \text{Eq. 13}$$

Where η_{regen} is the regenerative efficiency.

In this model, the High level open-loop control system is developed as the primary controller. Control system controls the energy distribution from the power source and the amount of energy that is withdrawn from the power source, in case of multiple power sources. The primary power source delivers the power till the setpoint if more power is required, the secondary source will deliver the additional required for the acceleration. Also, control system comes in action during regenerative/deceleration mode. If the SOC is less than the setpoint, the regenerative energy is used to charge secondary source first and then the primary source.

For this model, a nonspecific battery system is modelled, calculates the required parameter to determine the state of charge during the ride, energy consumption and range.

Total power required, P_{total} is calculated as

$$P_{total}\,(W) = P_{wheel} + P_{AUX} + P_{loss} \qquad \text{Eq. 14}$$

Where P_{loss} *(W)* is the power loss during energy transmission within the vehicle. The P_{AUX}, auxiliary power is considered to vary between 800 W at 22 ˚C to 2.8 kW at -12.2 ˚C for light-duty vehicles [7]. The total power stored in the battery is defined by

$$P_{bat} = V * I \qquad \text{Eq. 15}$$

Where *V* is the voltage (V) and *I* is the current (*A*). The charging and discharging current of the battery is evaluated by equation 16 during each second of the drive cycle.

$$I\,(A) = \frac{V_t - \sqrt{V_t - 4RP_{wheel}}}{2R} \qquad \text{Eq. 16}$$

Where V_t is the terminal voltage (*V*) of the battery and *R* is the battery internal resistance (0.1 *ohms* [7]). The terminal voltage of the battery to be determined according to equation 18.

$$V_{drop} = I * R \qquad \text{Eq. 17}$$

$$V_t = V_t(t-1) - V_{drop} \qquad \text{Eq. 18}$$

Where *t* is the time in seconds. The power loss (P_{loss}) during the transmission of energy is calculated as

$$P_{loss} = I^2 * R \qquad \text{Eq. 19}$$

The total energy consumed during the drive cycle is estimated by summing the power consumed during all seconds of the drive cycle.

$$E_T = \sum_{t=1}^{T} P_{total} - E_{regen} \qquad \text{Eq. 20}$$

The *Average energy consumption (Wh/km)*, energy consumed to reach each unit distance (*km)* is calculated as follows:

$$\text{Average energy consumption} = {}^{E_T}/_{d} \qquad \text{Eq. 21}$$

Where *d* is the distance travelled in the drive cycle (km). The *Range* (km) of the vehicle is calculated as:

$$\text{Range} = \frac{P_{bat}}{Average\ energy\ consumption} \qquad \text{Eq. 22}$$

State of Charge (SOC) is defined as the level of charge of the battery with respect to its capacity. SOC is calculated at each second by using the coulomb current counting method, equation 28

$$SOC(t) = SOC\,(t-1) \pm {}^{I_t}/_{I} \qquad \text{Eq. 23}$$

I is the maximum current stored and I_t is the current charged or discharges at the time *t.*

For this model, a PEMFC is developed for simulation and for studies. PEMFC is the most commonly used in the automotive sector due to its low operating temperature range, small size and weight, high efficiency and wide operating range.

The fuel cell power (P_{fc}) of a stack is calculated through equation 24,

$$P_{fc}(W) = \frac{P_{fcp}}{1 - BOP} \qquad \text{Eq. 24}$$

Where *BOP is* the balance of plant and P_{fcp} is the maximum output of stack. The area (cm^2) of each cell is the ratio of the maximum output power of the stack to the product of the number of cells and maximum specific power, is presented by

$$A_{fc} = \frac{P_{fc}}{N_c * P_{sfc}} \qquad \text{Eq. 25}$$

Where P_{sfc} is the specific power density of the fuel cell. The stack output voltage (V) of the fuel cell is the total voltage produced by the individual cells,

$$V_{fcp} = N_c * V_{fc} \qquad \text{Eq. 26}$$

Fuel cell electrical efficiency is calculated as the ratio of the electric power output to the energy input from hydrogen. The total efficiency of the module can also be calculated as the product of the factors

$$\eta = \eta_{th} * \eta_v * \eta_F * \mu_F \qquad \text{Eq. 27}$$

Where η_{th} is the thermodynamic efficiency, η_v is the voltage efficiency, η_F is the faradic efficiency, and μ_F is the utilization factor of the fuel cell. The thermodynamic efficiency, faradic efficiency and utilization factor are assumed as 0.83, 0.9 and 1 respectively [8] and voltage efficiency is calculated by equation 28. The fuel mass flow rate of hydrogen (gram/second) is calculated by equation 29

$$\eta_V = \frac{V_{fc}}{1.23} \qquad \text{Eq. 28}$$

$$\dot{m}_{H_2} = \frac{P_{fcp}}{Q * \eta} \qquad \text{Eq. 29}$$

Where Q = 120 MJ/kg or 33.33 kWh, is the lower heating value/specific energy of hydrogen. The amount of fuel used is calculated by adding the fuel consumption (grams) at each second.

$$\dot{m}_{total} = \sum_1^t \dot{m}_{H_2}(t) \qquad \text{Eq. 30}$$

The total energy consumed and the average energy consumption is calculated using equation 20 and 21. Since the power requirements vary each second, the current and voltage produced also changes and it will affect the working of the fuel cell. To avoid that, a DC-DC converter is used with an efficiency of 90%. *Range* (km) of the vehicle is calculated as:

$$Range\ (km) = \frac{M_{H_2} * 33.33 * 1000}{Average\ energy\ consumption} \qquad \text{Eq. 31}$$

Where M_{H_2} is the amount of hydrogen (kg) stored in the vehicle

An ultra-capacitor (UC), also called as super-capacitor, is a capacitor with a high capacitance with lower voltage limit. An electric field is developed between the two charged electrode plates when an electric field is applied to the capacitor. The applied potential difference (*V*) will be equal to

$$V = E * d \qquad \text{Eq. 32}$$

Where E is the electric field and d is the distance between the plates. The charge Q stored in a capacitor of capacitance C (Farads) at a voltage of V (Volts) is given by

$$Q = C * V \qquad \text{Eq. 33}$$

The energy stored in the electric field in a capacitor is given by the equation

$$W = ½ * CV^2 \qquad \text{Eq. 34}$$

While considering a module, the resultant potential difference, V_{eq} is the sum of the potential difference between each UC cell.

$$V_{eq} = V_1 + V_2 + V_3 + ---- + V_n \qquad \text{Eq. 35}$$

When equivalent capacitors are combined in a combination of series and parallel connections, the equivalent capacitance will be equal to

$$C_{eq} = C_{cell} * \frac{N_s}{N_p} \qquad \text{Eq. 36}$$

Where C_{cell} is the capacitance of a single cell, Ns is the number of cells connected in series and N_p is the number of cells connected in parallel. For the modelling purpose, ultra-capacitor pack of 16V, 500 F is considered as the standard module.

During the discharging process, a charge equivalent to the current is drawn from the capacitor. The current, *I* is calculated through equation 16. The terminal voltage during each second is calculated by

$$V_t = V_{oc} - \int \frac{I}{C}\, dt - IR_s \qquad \text{Eq. 37}$$

Where V_{oc} is the open-circuit voltage and R_s is the ESR of the UC. When UC is discharged, the voltage drops from the initial voltage V_1 to the voltage V_2, and change in energy is

$$\Delta W = ½ * C\ (V_2 - V_1)^2 \qquad \text{Eq. 38}$$

The state of charge of the ultra-capacitor is computed using equation 39, the state of charge expressed in terms of terminal voltage becomes:

$$SoC = \frac{W}{W_{max}} = \frac{V^2}{V_{max}^2} \qquad \text{Eq. 39}$$

2.1. APPLICATIONS OF THE MODEL

The study is carried out in two steps, where the factors affecting the range of an electric vehicle is carried out initially. A series of influencing variables in an electric vehicle is analysed and assessed. On the second stage, the future possibilities in powertrains are tested by merging more than one power source (battery + fuel cell, battery + ultra-capacitor, and fuel cell + ultra-capacitor) to learn the benefits. Also, total ownership cost analysis of passenger vehicles is done to carry out a market analysis with current scenarios.

- **PASSENGER CARS**

Due to easy access, comfort and financial assistance from financial institutions encourage individuals to buy BEV. However, as compared with conventional vehicles or hydrogen-powered vehicle, the range of BEV is still comparatively lower for more than 65% of the available vehicles. In this study, the influence of battery capacity, environmental temperature, driving context and driving behaviour on EV range are studied, as explained next:

- **Influence of battery capacity and energy density** - Increasing battery capacity helps to increase the range. However, this has impacts in terms of vehicle weight. Also, as the energy density increases, it helps to reduce the weight of the total battery pack, which results in less pack. For this study, the battery capacity is changed and energy density has altered and tested.
- **Influence of environmental temperature** - To know the dependency of range with climate variations, the model is simulated to a wide range of temperature from -30˚C to 40 ˚C. The model is designed in such a way that as the temperature changes the air density [9], rolling resistance [10] and auxiliary power [7].
- **Influence of average speed**. The driving environment usually refers to whether the vehicle is urban, rural or highway context, typically inferred from average speed. This study covers a range from 10 km/h to 120 km/h to assess the influence in energy consumption.
- **Influence of driving behaviour**. Driving behaviour has a higher influence on the average energy consumption of the vehicle and also the range, which creates the difference of the vehicle performance in real-world with the predicted values. The aggressiveness of the drive cycle is tested to study the relation between the parameters.
- **Influence of combining energy storage source:** The type of power source to the powertrain plays a vital role in vehicle performance. This study intents to analyse how combining different source results in the curb weight of the vehicle and influence vehicle performance and the amount of energy that can be stored without compromising the performance.

Furthermore, the vehicle performance of gasoline vehicle in real-world is compared with an electric passenger vehicle. Table 1 shows the details for the real-world drive cycles.

Table 1: Real-world driving data for passenger vehicle

ID	Period (s)	Distance covered (km)	Average speed (km/hr)	Maximum Speed (km/hr)
1	36000	352	35	115
2	35501	276	28	176
3	35423	325	33	116

- **BUSES**

As of the records in 2017, buses and heavy-duty vehicles emit a total of 235.2 million tonnes CO_2 equivalent [11]. Electric buses are preferred as a replacement due to less maintenance cost, energy loss and are quieter. However, the initial cost is very much higher than the diesel vehicle. Since more battery is stacked for better range, the curb mass is comparatively higher, and also the energy consumption. Other main problems are the time required to charge the batteries.

Due to these, electric buses are still limited and new energy sources are considered. In this study, various energy sources are tested to estimate the most adequate option for the rural and urban public transportation system.

2.2 TOTAL OWNERSHIP COST ANALYSIS

The total ownership cost (TOC) of various passenger vehicle powered by battery, fuel cell and gasoline was estimated for 12 years. The TOC estimated based on three factors; CAPEX, OPEX and the period over these costs have occurred.

Fuel or electricity price is one of the main concerns related to the passenger vehicle sector. For this study, the fuel price and electricity price is estimated for the period based on price change in previous years.

3. RESULTS AND DISCUSSION

For testing the developed model and validation, 7 vehicles from different dominant vehicle manufacturers are selected. The performance variables and specifications are given as inputs in the simulation model to check the reliability of the generated model. Table 2 shows the result of simulation comparison with the certification values.

Table 2: Simulation results (Error, in %)

Vehicle	Energy cons. (Wh/km)	Range (km)
Nissan Leaf S	138.6 (-1.7)	288 (1.4)
Renault Zoe	132.5 (0.4)	392 (-0.8)
Kia Niro	140.2 (3.0)	280 (-3.2)
Kia Soul EV	145.1 (2.1)	271 (-2.2)
Hyundai IONIQ	122.1 (-0.7)	313 (0.6)
BMW i3	129.9 (-2.4)	324 (2.8)
Mini Cooper	121.9 (-1.7)	267 (1.5)

The model was validated through the comparison with the laboratory test performed by independent entities on the different vehicles using WLTP (Worldwide Harmonized Light Vehicles Test Procedure) class 3 drive cycles. It can be observed that results obtained from the simulation are below 2% error in the average of absolute values of energy consumption and range.

Currently there only few numbers of light passenger vehicle in the market which uses fuel cell as the primary power source. Toyota Mirai is tested with the simulation model for validation of FCEV, through comparison with the laboratory test results.

Table 3: Simulation results of Toyota Mirai (error, in %)

variable	FTP 75	HWFET	Combined
Range (km)	496 (- 1.5)	561(10.5)	528 (4.6)
Energy cons. (Wh/km)	323 (- 1.9)	303(4.3)	313 (1.3)

From the results in table 3, it can be observed that simulation model is accurate and reliable with errors below 3% in the average of absolute values of energy consumption and 6% error in the average of absolute values of the range.

The developed model of UC is tested against the ultra-capacitors tested in the laboratory. The literature [12] shows some of the results of laboratory tested ultra-capacitors, shown in figure 2.

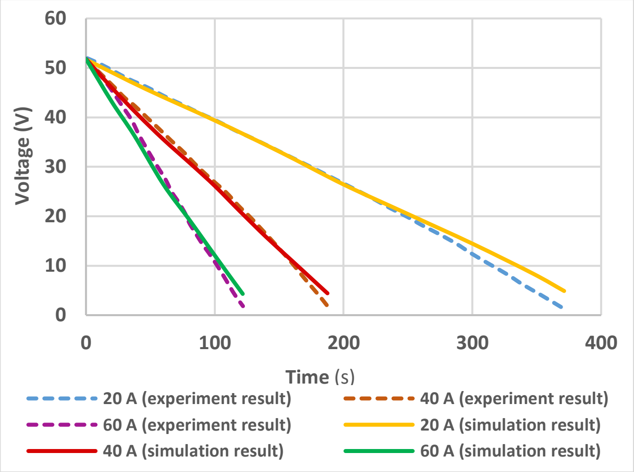

Figure 2: Experimental and simulation result of Ultra-capacitor

The developed model is simulated for constant current output and the voltage change is compared with the experimental results. From the results, it can be observed that the difference in voltage is negligibly small. The average absolute error is 4.8% between the experimental result and simulation results.

From these results, it can observe that the errors are small and negligible. The difference is justified due to the assumptions made in some of the coefficients, motor efficiency and auxiliary power demands.

3.1 PASSENGER VEHICLE

From the last section, the model is tested and marked as accurate and reliable. The proposed study has been carried out to learn the influence of variables in vehicle performance.

- **Influence of battery capacity and energy density on EV range**

The study has done with Nissan leaf for various battery capacity, under the WLTP class 3 drive cycle. Table 4 shows the change in total vehicle mass with battery capacity and the effect on EV range.

Table 4: Battery capacity fraction vs range

Battery capacity (%)	0.25	0.5	0.75	1	1.5	2	2.5	3
Range (km)	46	92	137	181	268	353	434	514
Expec-ted(km)	45	90	136	181	272	363	454	545
Diff. (%)	2.2	1.5	0.7	-	-1.5	-3.0	-4.5	-6.0

The result shows that the range of the vehicle is increased when the capacity is increased to 3 times. However, due to the increase of mass instead of a 300% rise in range, it only reached 294% with a reduction of 6% due to curb mass.

The two Nissan leaf models were tested (157 Wh/kg to 224 Wh/kg). Figure 3 shows the range, average energy consumption and battery capacity with different energy densities.

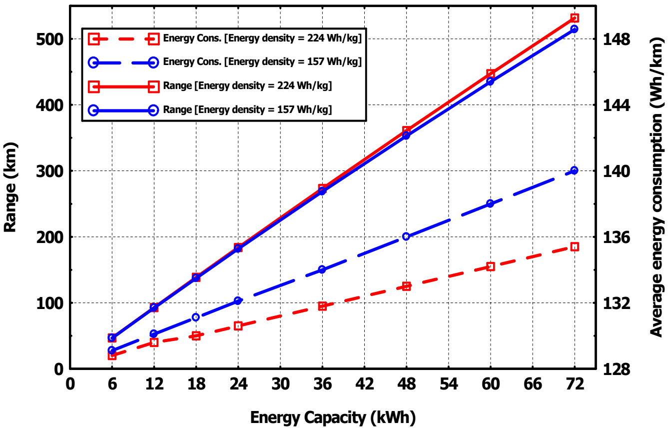

Figure 3: Influence of energy capacity and energy density

We can observe that the energy consumption for battery pack with higher energy density (224 Wh/kg) is lower. While on the range, battery pack with less capacity has negligible difference irrespective to the energy density, higher the capacity of the battery pack, change in the range becomes noticeable.

- **Influence of environmental temperature on EV range**

For this study, the range is determined for ambient temperature ranges from -30 °C to 40 °C for the former vehicle. Figure 4 shows the change in range with temperature.

Results show with a negative temperature average energy consumption is much higher due to the auxiliary devices to maintain indoor comfort conditions. Also, higher rolling resistance and air density increase the traction power required.

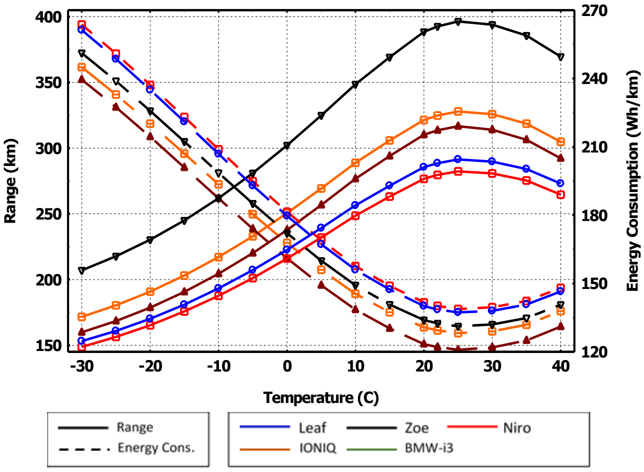

Figure 4: Influence of temperature

As temperature increases, the average energy consumption reduces, and the nominal condition is between 20 ˚C and 30 ˚C where the auxiliary power is minimal, without air conditioning and heaters

- **Influence of the average speed on the range**

Drag force and acceleration forces are a function of vehicle speed. As vehicle speed changes, the energy consumption also varies. Vehicle simulation was done for average speeds from 10 to 120 km/h.

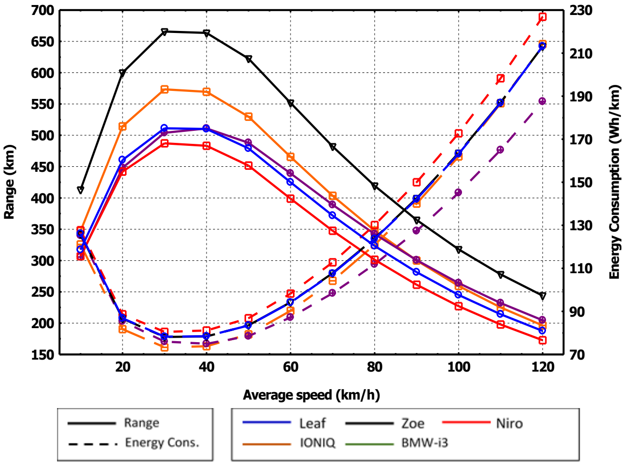

Figure 5: Influence of average speed

From figure 5, We can observe that the energy consumption for unit distance is rapidly increasing when the average speed increases above 20 km/h. The energy consumption below 20 km/h is also increasing rapidly due to the auxiliaries, while above 20 km/h it is due to vehicle speed and the forces that vehicle has to overcome.

- **Influence of driving behaviour on EV range**

Based on the research article [13], the normal aggressiveness of the WLTP class 3 cycle is calculated as 14.44%. To study the influence of aggressiveness, the acceleration points were modified in the WLTP class 3 drive cycle to make it less aggressive by altering the vehicle speed. Figure 6 shows the modified drive cycle with real modified cycle.

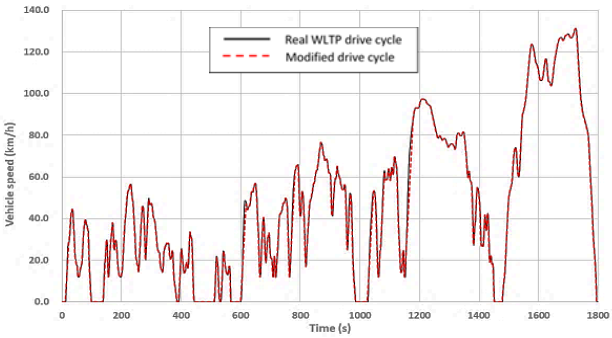

Figure 6: Real and modified WLTP class 3 drive cycle

When the acceleration point is altered with steady and non-aggressive progressive acceleration, the aggressiveness of the modified cycle is reduced to 6.7%. Table 5 shows the parameters with both drive cycles and results from the simulation of the model.

Table 5: Simulation results and comparison of real WLTP drive cycle with the modified drive cycle

Parameters	**Real drive cycle**	**Modified drive cycle**
Duration (s)	1800	1800
Avg speed (km/h)	46.5	46
Max speed (km/h)	131.3 (1724 s)	131.3 (1724 s)
Simulation results (for leaf S 2019)		
Total cons (kWh)	3.225	3.184
Avg cons. (Wh/km)	138.6	136.8
Range	288	292

The results show that limiting aggressiveness driving in acceleration helped to reduce the total energy consumption of the vehicle by 1.3%, thus the average energy consumption is decreased by same and range is increased by 1.4%.

A range of vehicle speed is considered from 60% of the normal drive cycle speed to 140% for the real drive cycle. The aggressiveness is calculated and is tabulated on table 11 within the considered scope.

Table 6: change in the speed of the WLTP cycle and effect in the aggressiveness of driving

Speed (%)	60	70	80	90	100	110	120	130	140
Aggressiveness (%)	3.4	5.9	8.6	11.7	14.5	16.4	18.5	20.6	23.5
Ave. Speed (km/h)	27.9	32.5	37.1	41.8	46.5	51.2	55.8	60.5	65.1

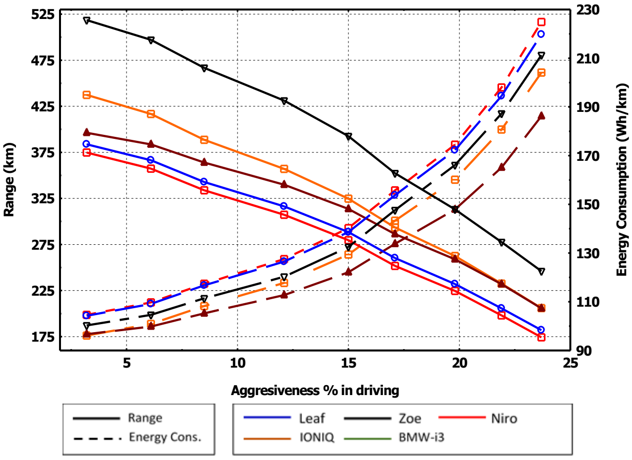

Figure 7: Influence of driving aggressiveness in range

Figure 7 shows the influence of aggressiveness with range. We can observe that as the aggressiveness increases, the energy consumption is also increasing proportionally, and the range of the vehicle decreases. During aggressive driving, the sudden acceleration drains more energy as acceleration force (F_A) and is the reason for the increase in energy consumption.

- **Influence of combining energy source in vehicle performance**

With this study, we will look at the possibilities to extend the life of power source further by combining power sources, which helps to reduce the number of used batteries or fuel cell over time.

For this study, Honda Clarity is chosen as the reference model for the studies. The reason behind this is the availability of the vehicle in both electric and fuel cell version. The results from the simulation are presented in table 7.

Table 7: Simulation results of Honda clarity models in WLTP drive cycle

	Energy Cons. (Wh/km)	Range (km)
Clarity Electric	145.7	175
Clarity Fuel cell	363.2	445

From the simulation results and the assumption that battery lasts 1000 charging cycles, the battery is supposed to replace after 175,000 km. Similarly, for PEMFC fuel cell, the life is considered to be as 5000 hours and replacement is carried out after the vehicle reaches 232,500 km.

The different power source is combined to study the advantages. Table 8 shows the results of with different powertrain option with average energy consumption, range and life of the power source.

Table 8: Simulation results with different power sources

Primary Source (PS)	**Secondary source (SS)**	**Energy cons. (Wh/km)**	**Range (km)**	**Life (PS) (x10^3 km)**	**Life (SS) x10^3 km)**
Battery: 25.5 kWh		146.1	174	175	
Battery: 25.5 kWh	UC : 1.6 kWh	151.7	179	193	7,916
Fuel cell: 103 kW		363.1	442	232	
Fuel cell: 103 kW	Battery : 8 kWh	341.8	556	232	113
Fuel cell: 103 kW	UC : 1.6 kWh	349.6	525	232	7,344
UC: 4 kWh		161.6	25	2,450	

From the results, it can be observed that adding UC helps to improve the charging life of the battery by 10%. For fuel cell vehicles, lifetime is determined by working hours and adding energy source helps to reduce the energy production, but not working hours, consequently, they are not showing any change in total life. However, in fuel cell, adding power source helps to reduce the peak power production point, thus the cell number, weight and cost of the vehicle.

On the contrary, adding more power source has an influence on the curb mass and cost of the vehicle. Figure 27 shows the variation in curb weight and the initial cost of vehicle having different power sources with respect to the Honda Clarity electric model.

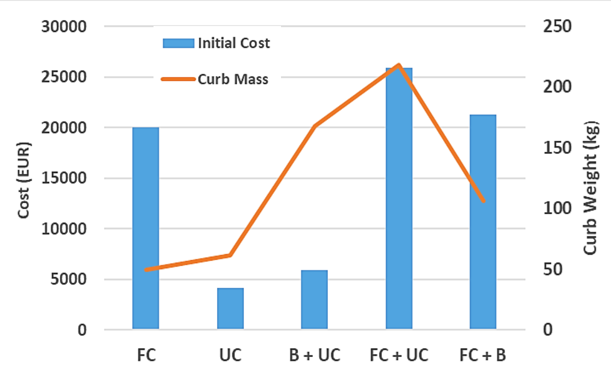

Figure 8: Change in curb weight and initial cost of the Honda Clarity model with different power sources

- **IMPACT IN REAL WORLD DRIVING**

The goal is to investigate the effectiveness of the electric vehicles in the transportation sector and the cost efficiency of EV. The Nissan leaf 24 kWh BEV is simulated with the drive cycle data in table 1 to compare the energy consumption of the vehicle. Table 9 shows the simulation results

Table 9: Energy consumed during driving and estimated consumption in BEV and FCEV

Driver ID	ICE	BEV		FCEV	
	Total cons. (kWh)	Regen energy (kWh)	Total cons.* (kWh)	Regen energy (kWh)	Total cons.* (kWh)
1	212.9	19.5	44.7	1.3	130.7
2	232.4	18.7	46.5	0.9	134.2
3	158.9	18.1	46.5	1.1	130.3

* *Total energy consumption in BEV and FCEV includes regenerative braking*

From the results, it can be seen In BEV, the tank to wheel efficiency is more than 80%, while for FCEV, it around 50% and ICE it's less than 30%. BEV only consumes 28-35 % of the energy consumed by ICE without regenerative braking. The energy capturing from braking through regenerative property help to reduce this even further lower to 20%.

3.2 BUSES

For the studies, due to the easy accessibility of data, Public transportation bus, e.City Gold bus with real-world driving cycle was adopted from a thesis [14]. Performance variables and specifications are given as inputs. The drive cycles cover a total distance of 71.15 km in a duration of 13353. The average speed from the data is calculated as 19.18 km/h with a maximum speed of 74.5 km/h. The simulation results are presented in Table 10, in comparison with the initial results from the real-world testing [14].

Table 10: Simulation results of e.City Gold bus (error, %)

Parameters	Results
Total Energy Cons (kWh)	58.5 (-1.1)
Average energy Cons (Wh/km)*	822.5
Range (km)*	103.3

* *Values are obtained through the simulation*

From the results, we can observe that simulated results were accurate with a very small error of 1%, which is negligible. It points out that the developed model was reliable and can be used to simulate a wide range of electric and fuel cell heavy-duty vehicles.

- INFLUENCE OF DIFFERENT ENERGY SOURCES ON BUSES

To compensate for the weight factor due to battery for energy storage and higher charging times, alternative energy source has been simulated to find the possible substitutes for battery-powered buses.

Table 11 shows the performance of e.City Gold bus with different energy sources.

Table 11: Simulation results of the performance of e.City Gold bus with the different energy source

Energy Source	Energy cons. (Wh/km)	Range (km)	Life (x 10^3 km)	Life* (days)
Battery : 85 kWh	996	86	86	594
Battery : 170 kWh	1038	164	164	1131
Battery : 200 kWh	1053	190	190	1310
FC : 230 kW; 10 kg H_2	3035	98	96	662
FC : 230 kW; 20 kg H_2	3058	195	96	662
UC : 16 kWh	1084	15	1,500	10344
UC : 30 kWh	1189	25	2.500	17241

From the results, it's clear that adding more battery helps to cover more distance. While using the fuel cell, it improves life by 12% compared to the standard specifications. However, the cost-benefit ratio is much lesser than that of the electric vehicle. With ultra-capacitor, even though the range was limited to 15 – 25 km, the ultra-capacitor last to 1.5 million charging cycles within least favourable conditions and it will last for at least 25 years.

However, these advantages of energy sources come with some disadvantages. Figure 9 shows the change in curb mass and initial cost.

From the figure, it can be observed that all battery is the cheapest of all options. While considering mass, one of the noticeable advantages of the fuel cell is that to increase mileage no additional arrangements is required other than the storage tank for more fuel.

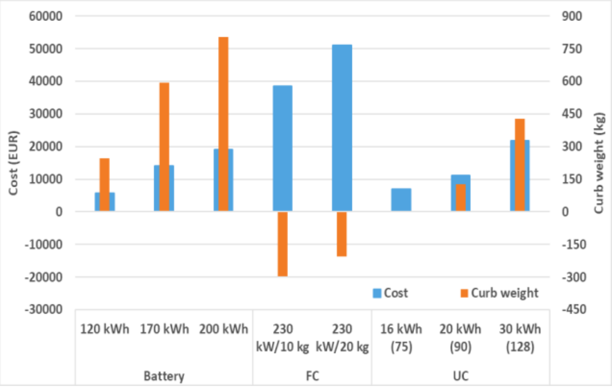

Figure 9: Change in curb mass and the initial cost of the bus for different energy sources (compared to the standard vehicle)

For UC, the expense is similar to 200 kWh battery, however, it has the highest cost-benefit ratio when comparing lifetime. From the analysis, it can certainly tell that ultra-capacitor will be the most beneficial option when considering public transport.

Also, combination of power source is simulated and tested for buses. Table 18 shows the performance of e.City Gold bus with multiple power sources.

Table 12: Simulation results with combination of energy source

Primary Source (PS)	Secondary source (SS)	Energy cons. (Wh/km)	Range (km)	Cost (*10^3 €)	Curb mass (kg)
Battery: 52 kWh	UC : 5.1 kWh	978	58	5.1	73
Fuel cell: 135 kW	Battery : 16 kWh	2702	129	24.6	- 330
Fuel cell: 135 kW	UC : 5.1 kWh	2717	124	32.6	- 40

Comparing the previous results with passenger vehicle and results from the bus, we can observe that combining battery with ultra-capacitor won't bring any benefits in range or energy consumption, apart from the battery life extension. While with the fuel cell, both studies show it is better to combine with a battery than ultra-capacitor, which helps to improve the performance of former than the latter with economic benefits.

3.3 TOTAL OWNERSHIP COST ANALYSIS

The goal of this study is to investigate the effectiveness and cost-efficiency of BEV and FCEV in the transportation sector.

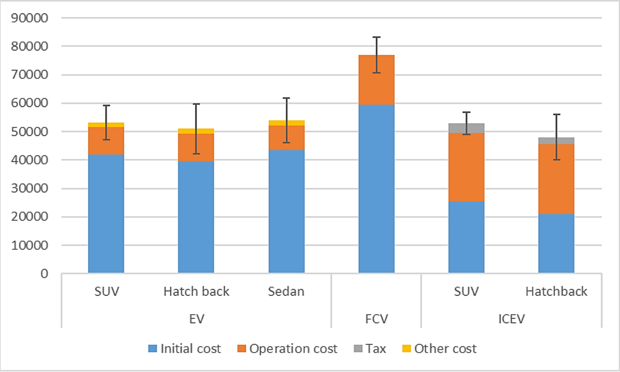

Figure 10: Average price distribution between various vehicle segments

Figure 10 shows the average price range of vehicles from different segments. Vehicle cost includes the initial purchase cost. Operational cost includes maintenance cost and fuel cost and Tax includes yearly and one-time tax. Other costs of EV includes installation of charging station at home.

From the results, it can be observed that conventional vehicles are the least expensive to buy. However, half of the TOC over the period is spent on operational and maintenance cost. While for electric vehicles the initial cost is high which is almost 70% of the TOC is, the operational cost is between 20 – 25%. In the case of fuel cell vehicle, it can be observed that both the initial and operational cost are high, which make it least preferable by the customers

4. CONCLUSIONS

This aim of this research work was to study the energy and cost-effectiveness of powertrains powered by battery, fuel cell and ultra-capacitor for different vehicle segments. A model was developed by considering a road load model and dimensioning the efficiency of different components and to estimate energy consumption. The model for a passenger vehicle is initially tested and the result shows the model is reliable with an average absolute error less than 4% (combined for battery, fuel cell and ultra-capacitor module). For bus, the difference of error is less than 2%, proved that the model is flexible to simulate different types of vehicles.

The analysis in influencing factor on EV range shows that increasing the battery capacity 3 fold increases the range, but not by three-fold. Due to the increase in vehicle mass, energy consumption increases and range is extended to 294% instead of 300%. While the average speed of the vehicle is recommended to maintain between 25-40 km/h, which has the least energy consumption and highest range. The results on aggressive driver behaviour show that EV range can be reduced by 4% based on the driving pattern. However, reducing the average speed of the vehicle along with less aggressive driving can help to increase the range from 10 – 20%.

Analysis of the combination of energy source showed that battery combining with UC helps to increase the life of the battery by 10%. Combining battery with fuel cell helps to cover more distance than combining with UC, but won't result in benefit with the fuel cell operation life, however, the powertrain can be benefited in terms of cost by the reduction of the number of fuel cells in the stack. UC shows positive results with other powertrains, nevertheless, it cannot be used as the primary energy source due to the high initial cost

For buses, batteries are less favourable due to higher charging duration. While increasing the battery capacity increases vehicle mass and energy consumption, which is a disadvantage. Fuel cells are referred in buses and coaches which is intended to cover long-distance trips. Fuel cell vehicles only have to add more storage space for the hydrogen, where the curb mass change is negligible. For short-frequent trips, ultra-capacitor is preferred because of its ability to deliver high power in a short time. The fast-charging property of UC makes it possible charging spots during stops in the bus stations. While the combination of energy sources didn't show any improvement than the former results.

Total ownership cost analysis result shows that battery electric vehicle is preferred till next decade due to moderate initial cost and lower operational and maintenance cost. While fuel cell vehicle will be the most expensive option due to higher initial and operational cost.

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