Application of Fuzzy Logic in Multi-Mode Driving for a Battery Electric Vehicle Energy Management

T.A.T. Mohd[1,4], M.K. Hassan[1,2], Ishak Aris[1], Azura C.S.[1] and B.S.K.K Ibrahim[3]

[1]Department of Electrical and Electronic Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 Serdang, Selangor, Malaysia

[2]Institut Teknologi Maju, Universiti Putra Malaysia, Malaysia

[3]Department of Mechatronic Engineering and Robotics, Faculty of Electrical and Electronics Engineering, Universiti Tun Hussein Onn Malaysia, Malaysia

[4]Politeknik Kuala Terengganu, Malaysia
E-mail: tengkuazman78@gmail.com, khair@upm.edu.my

Abstract— **Energy management system is an area of emerging interest in a full electric vehicle research. With the increasing moves to a more sustainable vehicle, there is a need to extend the battery range that simultaneously satisfying the conflicting demand between battery capacity and vehicle weight or volume. This paper presents a research conducted in the Universiti Putra Malaysia, focusing on the energy management strategy of a battery-powered electric vehicle. Three vehicle driving modes; sport, comfort, and eco have been individually modelled. Each mode is capable to dominate different driving environments; highway, suburban, and urban. In European driving cycle simulation test, comfort and eco modes have shown large extension in driving range with the maximum of 7.33% and 19.70% respectively. However the speeds have been confined by certain specific limits. The proposed of integrated multi-mode driving using fuzzy logic has enabled an adaptive driving by automatically select the driving parameters based on the speed conditions. The results have proven its ability in reducing the energy consumption as much as 32.25%, and increasing the driving range of 4.21% without downgrading the speed performance.**

Keywords— **battery electric vehicle; energy management; fuzzy logic controller; multi-mode driving.**

I. INTRODUCTION

Massive production of conventional internal combustion vehicles (ICEV) in vehicle population has increased worldwide concerns on energy conservation and environment protection. In search for sustainable transportation, battery electric vehicle (BEV) has been identified as one of the potential candidate. BEV does not only offer appropriate solution to emission problems in relation to transportation and energy crisis, but it also offers many advantages in term of performance, energy efficiency, noiseless, less maintenance and can be regulated by power grid operator [1-4]. However, the key challenge in BEV is the limitation in driving range since BEV relies on battery as its sole energy source. The battery therefore, must contain sufficient energy to drive certain range and supply all loads; propulsion and auxiliary loads. By simply increase the size of battery in order to enhance the energy capacity will only imply a penalty to the vehicle weight and volume. A promising way to increase the range is by implementing energy management system (EMS) to manage the energy by

controlling and coordinating the power generation, energy storage and power flow within components to achieve maximum system efficiency [4]. Vehicle driving mode designs are basically based on the driver's driving styles, appropriate driving environments, vehicle types and its EMS strategy. Hybrid EV (HEV) such as BMW i8 [5] and Toyota Prius [6] benefit a wide option in modes as they possess a secondary propulsion power source which is not available in BEV, such as Mitsubishi i-MiEV [7] or Nissan Leaf [8]. Available modes in HEV vary from high performance mode (i.e. sport mode) to high efficiency mode (i.e. eco mode). However in BEV, the mode priority is given to sustain the energy for a better range; varies from standard driving mode to aggressively energy regenerating in braking mode. Examples of driving modes available in the commercial electric vehicle are presented in Table 1. Eco-driving is a driving strategy that maximizes energy efficiency in order to extend the vehicle's range [9]. At this very moment, many researches have put their focus on improving eco-driving mode [9-11]. For instance, Frank, R., G. Castignani, R. Schmitz and T. Engel [9] proposed an eco-driving mode

application for EV using android devices. Kim, Y., I. Lee and S. Kang [10] proposed an eco-assist techniques through real-time monitoring of BEV energy usage efficiency. Later, Vatanparvar, K. and M.A.A. Faruque [11] have proposed an eco-friendly automotive climate control and navigation system to extend battery lifetime and driving range of EV. The deployment of eco-driving in EV has successfully extended the vehicle's range up to approximately 20%; subject to constraints of maximum speed, comfort level, as well as regenerative braking energy.

UPM-EV research team has conducted a research in Universiti Putra Malaysia (UPM), focusing on multi-mode driving of a BEV based on EMS. Unlike other previous works, this research intends to integrate the available driving modes into a multi-mode driving that is automatically triggered by the driving speed limits. It is expected that, the vehicle can benefits the diverse advantages in each mode without downgrading its speed performance. The vehicle, BEV-001 is specifically designed with adaptation to Malaysia local environment and social requirements. The technical specifications of the BEV-001 are as shown in Table II. In this research, the vehicle simulation model was the improved model adopted from our previous research in BEV [2-3]. Four driving modes have been designed and integrated into the vehicle based on the energy management strategy; sport mode, comfort mode, eco mode, and artificial intelligent (AI) mode. Fuzzy logic has been employed in the AI mode to implement a multi-mode driving due to its advantages of having simple structure and small computation time [12]. The significance of each mode towards the extension in range is then tested and compared in simulation test using new European driving cycle (NEDC) [13].

TABLE I
DRIVING MODES OF COMMERCIAL ELECTRIC VEHICLE

Manufacturer /Model	Driving modes
BMW i8 (HEV)	(3): Sport, comfort, eco pro
Toyota Prius Gen 3 (HEV)	(4): Power, normal, eco, EV
BMW i3 (BEV)	(3): Comfort, eco pro, eco pro+
Mitsubishi i-MiEV (BEV)	(3): Drive, eco, B
Nissan Leaf (BEV)	(4): Drive, drive +eco, B-mode, B-mode +eco
BMW i8 (HEV)	(3): Sport, comfort, eco pro

TABLE II
BEV-001 TECHNICAL SPECIFICATIONS

Vehicle Dynamic Parameters		Drivetrain Parameters	
Curb Weight	1380 kg	Drive System	Front wheel drive
Wheel radius, r_w	0.298 m	Drive Battery	Lithium-Ion (2.8V)
Coefficient of drag, C_d	0.3	Modules, cells	3, 180
Coefficient of rolling resistance, C_r	0.015	Rated Voltage	168 V
Frontal Area, A_f	1.627 m^2	Rated Capacity	20.16 kWh, 120 Ah
Air density, ρ	1.202 kg/m^3	Usable Capacity	16.13 kWh (80% DOD)
Performance (NEDC)		Battery Weight	270 kg
Consumption	112 Wh/km	Motor Type	PMAC (YASA-400)
Cruising Speed	80 km/h	Max Output	90 kW
Range (100% DOD)	140 km		from 2400 – 4500 rpm
Range (80% DOD)	110 km	Max Torque	360 Nm
Max Speed	150 km/h		from 0 – 2400 rpm
Acceleration 0-100 km/h	10.5 sec	Transmission	Single speed reduction gear, 3.37:1

II. MATERIALS AND METHODS

A. Simulink modelling of BEV-001

The modelling of BEV-001 has been performed in the Matlab-Simulink environment. The vehicle is configured according to Fig. 1 and consists of; high voltage (HV) battery pack, low voltage (LV) battery, power electronic converter and inverter, onboard charger, propulsion load (electric motor), mechanical transmission, HV auxiliary load and LV auxiliary load. The mathematical equations for HV battery state of charge (SOC) and permanent magnet AC motor (PMAC) are given as follows;

SOC for HV battery cell,

$$SOC = \frac{E_{max}[j] - E_{consumed}[j]}{E_{max}[j]} \times 100\% \qquad (1)$$

where; $E_{max}[j]$ = maximum energy capacity in Joule, and $E_{used}[j]$ = consumed energy in Joule.

PMAC electromagnetic torque,

$$T_{em} = k_e \left[f(\theta_e)i_a + f\left(\theta_e - \frac{2\pi}{3}\right)i_b + f\left(\theta_e - \frac{4\pi}{3}\right)i_c \right] \qquad (2)$$

where; k_e = motor torque constant, θ_e = rotor angle, and i_a, i_b, i_c = phase currents from inverter.

PMAC takes 3-phase input current form inverter and rotor rotational speed from gearing in order to produce torque and power based on motor efficiency map, as shown in the

following Fig. 2. The dynamic model for BEV-001 is based on [3, 14] as in the following equations;

$$M \frac{dV}{dt} = F_t - (F_{rr} + F_{ad} + F_{hc}) \qquad (3)$$

$$F_{rr} = MgC_r \cos\alpha \qquad (4)$$

$$F_{ad} = \frac{1}{2} \rho A_f C_d V^2 \qquad (5)$$

$$F_{hc} = Mg \sin\alpha \qquad (6)$$

where;

M = vehicle curb weight,

$\frac{dV}{dt}$ = vehicle linear acceleration along longitudinal direction,

F_t = traction force, F_{rr} = rolling resistance force,

F_{ad}= aerodynamic drag force, F_{hc}= hill climbing force,

C_r = tire rolling resistance coefficient,

g = gravitational acceleration, α = slope angle of the road,

ρ = air density, A_f= vehicle frontal area,

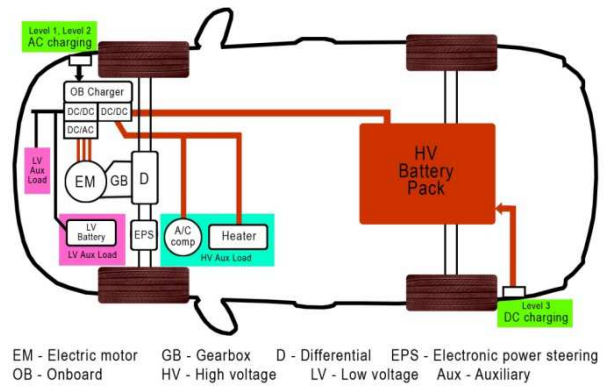C_d = aerodynamic drag coefficient, and V = vehicle speed.

Fig. 1 Component configuration of BEV-001

The complete Simulink model of BEV-001 is presented in following Fig. 3. In order to validate the model performance with the actual commercialized vehicle, performance test has been employed to this model and the performance comparisons are presented in Table III.
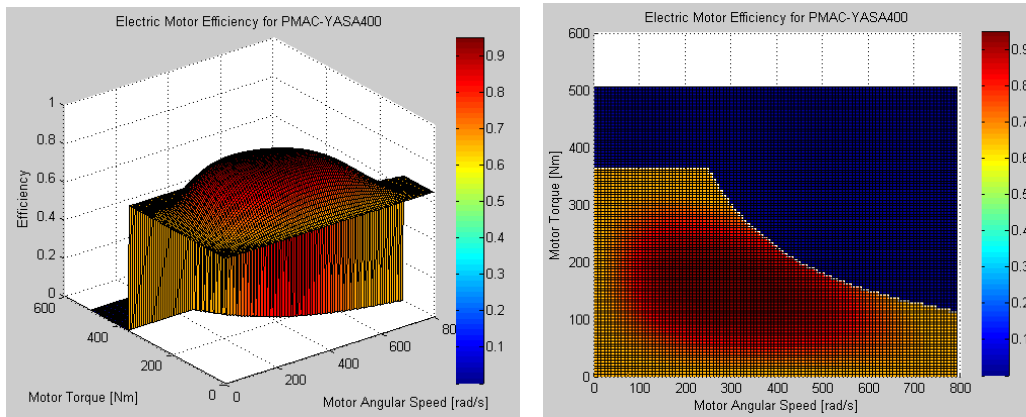

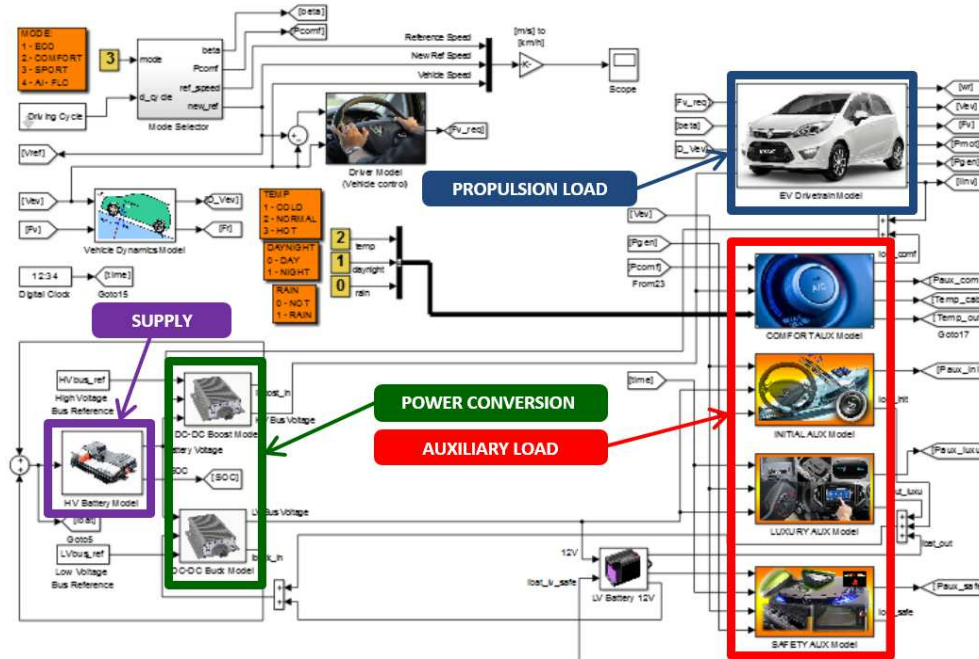Fig. 2 Efficiency map for PMAC YASA-400 model in Matlab [16]

Fig. 3 Simulink model of BEV-001

TABLE III
MODEL PERFORMANCE COMPARISON WITH LG-PROTON IRIZ BEV

Performance Parameter	LG-Proton Iriz BEV	BEV-001
Li-Ion Capacity	39.6 kWh, 100 Ah	20.16 kWh, 120 Ah
Consumption (NEDC)	132 Wh/km	144 Wh/km
Range NEDC (100% DOD)	300 km	140 km
Range NEDC (80% DOD)	240 km	110 km
PMAC Pmax / Tmax	116 kW / 360 Nm	90 kW / 360 Nm
Maximum Speed	150 km/h	150 km/h
Acceleration 0-100 km/h	9 sec	10.5 sec

According to the above table, the performance of our simulation model is closely matched the actual LG-Proton Iriz BEV. Half capacity of Li-Ion batteries in BEV-001 is able to provide half driving range of actual BEV in NEDC. The maximum speed of the model perfectly matched the actual BEV, while the acceleration is slightly better in the actual BEV due to the better rating of maximum power in electrical motor (PMAC) model used. Based on the table, it can be assumed that the simulation model can be further applied for the implementation of energy management system strategy.

B. Modelling of supply-load topology

Regardless any drivetrain layouts, BEV basically consists of three major subsystems; energy source (supply), propulsion load, and auxiliary load [14]. The supply-load topology for our model is as presented in Fig. 4. The HV battery pack is a lithium-ion battery based on Winston Battery model WB-LYP40AHA [15]. The battery pack comprise of three modules, where a module consist of three-parallel and 20-serial (3P, 20S) cells connections. These connections will increase the pack Ah capacity from 40 Ah to 120 Ah and nominal voltage from 56 V to 168 V. The DC-DC converter is to increase or decrease the voltage from the HV traction battery to suit the voltage requirement of the loads. Two types of DC-DC converters are used; boost converter, and buck converter. Both are assumed operating in continuous mode.
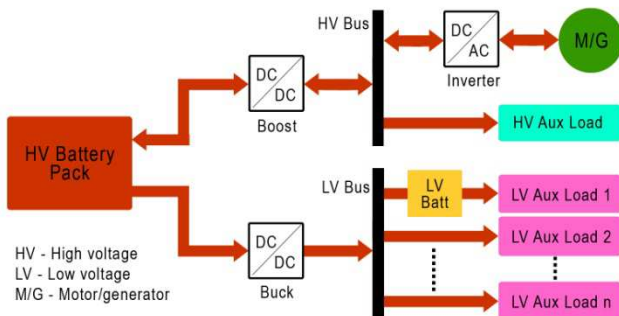

Fig. 4 Supply-load topology of Iriz BEV

The propulsion load is PMAC model YASA-400 from YASA Motors [16]. This motor possesses a high torque and power density capability that suitable for EV applications. This AC motor works together with an inverter, that controls the input and output parameters of the motor. The auxiliary loads are loads that accomplish either necessary or desired aspects of vehicle operation [14]. These loads are clustered into four groups; initial load, comfort load, safety load and luxury load, based on their performed functions as in Fig. 5 below. All auxiliary loads are supplied by the HV battery pack through power buses (HV and LV) except for the safety load, which is fed by the LV battery for safety purposes.
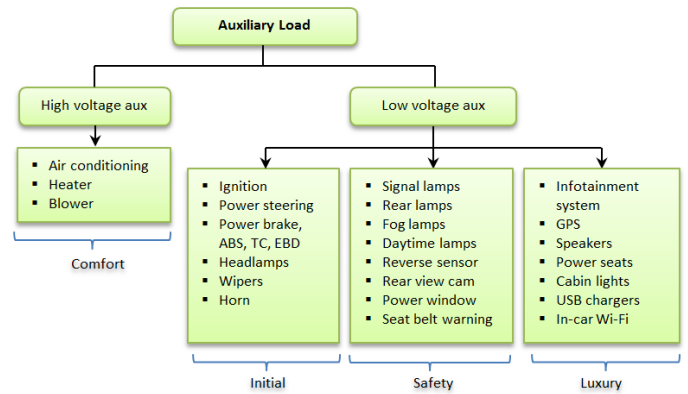

Fig. 5 Auxiliary loads categorization

C. Design of EMS strategy

An energy management strategy for BEV-001 is included in the model in three different driving modes; (1) sport mode, (2) comfort mode, and (3) eco mode. Mode is typically defined by three parameters; the speed or acceleration limit, the regenerative braking (beta) limit, and the comfort power limit. Globally, in European driving cycle, urban limit is at 50 km/h and highway limit is at 120 km/h, while in US driving cycle is ~100km/h and ~60 km/h respectively [13]. Our BEV-001 speed limit is adapted based on Malaysia national speed limit from Ministry of Works [17], highway speed limit is at 110 km/h, federal and state road at 90 km/h while 50 to 70 km/h at urban areas.

Power regenerates as much as 50% from braking in eco mode; the maximum possible for HEV or BEV [18]. Aggressive driving in sport mode will contribute as much as 35% energy while the least is in comfort mode (20%) to ensure smooth driving. Heating, ventilating and air conditioning (HVAC) or comfort load as the second largest power consuming load, is set to maximum in sport mode, is reduced to 60% in comfort mode, and is kept at minimum in eco mode (30%). However, active circulation during comfort and eco mode will assist to preserve the comfort level in comfort mode and minimally in eco mode. The summary of driving modes for BEV-001 is recaps in Table IV below.

Integrated driving mode

Fuzzy logic as one of the artificial intelligence (AI) techniques is employed in AI-Fuzzy mode in order to allow BEV-001 operates in integrated multi-mode driving. Our fuzzy logic controller (FLC) consists of a single input (driving cycle) and three outputs; speed limit (v_{limit}), beta limit (β_{limit}), and comfort level (P_{comf_limit}). The advantage of this mode is that, the vehicle can operates in all range of speeds, beta's, and comfort levels without been confined by certain limit. Since the problem to solve by FLC is a boundary or limit problem, a triangle membership function (MF) is selected for all outputs. The input is a trapezium MF. The design of FLC is as illustrated in Fig. 6 below. The simulation test using NEDC driving cycle as presented in Fig. 7 shows the ability of FLC to produce the required outputs as previously described in Table IV.
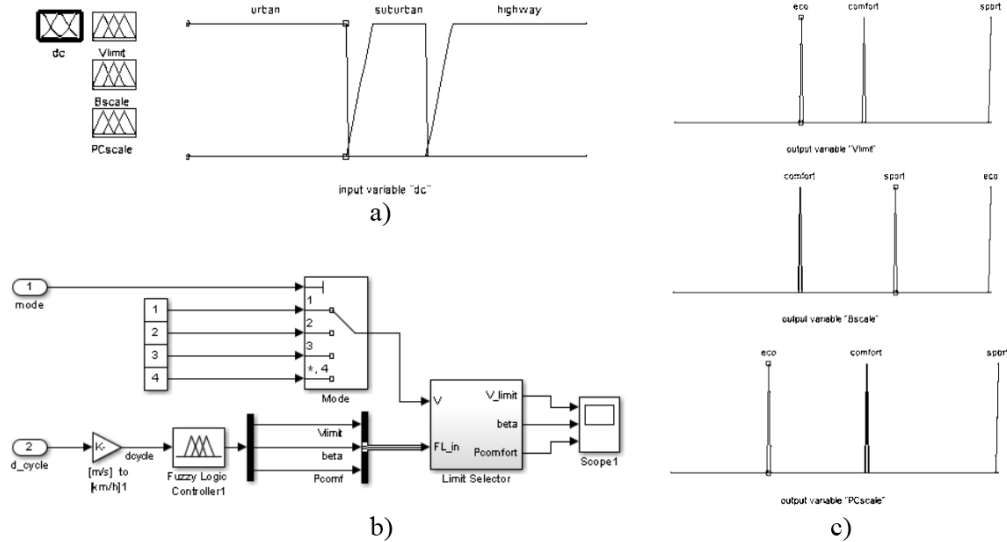

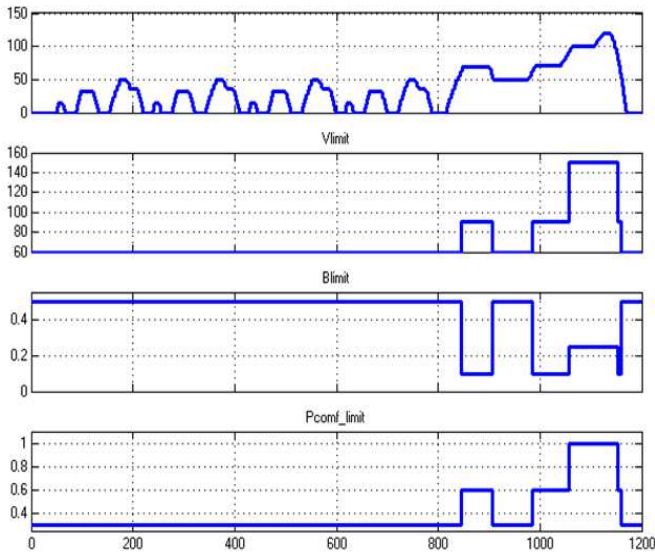Fig. 6 (a) Input MF, (b) FLC in driving mode, (c) output MFs.

Fig. 7 FLC input (NEDC driving cycle) and outputs.

III. RESULTS AND DISCUSSION

The model is tested in NEDC under two weather conditions; (1) day, clear and hot temperature, and (2) night, rain and normal temperature. These two weathers are based on Malaysia average weather conditions throughout the year [19]. The speed plots for BEV-001 in all four driving modes are as displayed in Fig. 8. The complete energy consumption in each load during every mode is compared and summarized in the following Table V (weather 1) and Table VI (weather 2).
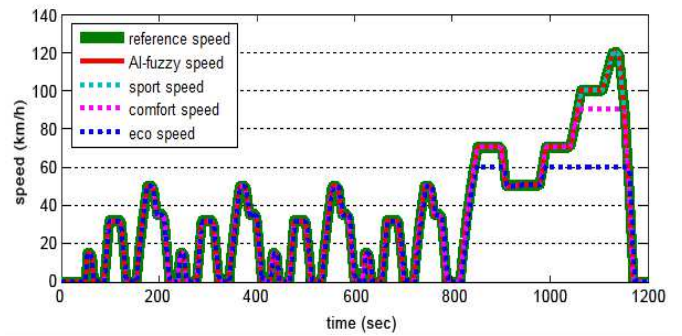

Fig. 8 Speed vs. time response for all modes in NEDC.

Fig. 8 demonstrates the speed-time response of BEV-001 in four driving modes against the reference speed of NEDC. All vehicle mode responses track the reference speed below their speed limits. However, in comfort and eco modes; once the speed limits have been reached, the responses are confined by the limits, and return back tracking after the reference speed is lower than the limits. The figure also

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verified that complete speed tracking only occurs during sport and AI-Fuzzy modes. It is mentioned in the EMS design that selection of speed limits is based on the driving environment. In eco and comfort modes, the user is confined by the speed limit of 60km/h and 90 km/h which is respectively the urban and suburban speed limits. Eco mode is recommended for urban driving, comfort mode is for suburban driving and sport mode is for aggressive and highway driving.

Energy consumption in BEV-001 is calculated based on below equation;

$$E_{consumed} = E_{mot} + \sum E_{aux} - E_{regen} \qquad (7)$$

where;

E_{mot} = propulsion load energy during motoring,

E_{regen} = propulsion load energy during regenerating, and

$\sum E_{aux}$ = total auxiliary loads energy (consist of initial, safety, comfort and luxury auxiliaries).

TABLE V
COMPARISON OF ENERGY CONSUMPTION AND RANGE BETWEEN MODES IN WEATHER 1

Load	Energy (Wh)			
	Sport	Comfort	Eco	AI-Fuzzy
Motoring	1004.00	855.70	636.70	1004.00
Regenerating	64.20	21.82	79.87	96.61
Initial aux	5.44	5.05	4.85	5.44
Safety aux	25.78	25.61	25.46	25.78
Comfort aux	1003.00	601.50	300.80	389.80
Luxury aux	51.87	51.87	51.87	51.87
Energy Consumed	**2000.00**	**1492.00**	**914.00**	**1355.00**
Energy Reduced	-	**508.00**	**1086.00**	**645.00**
% Reduced (relative to sport)	-	**25.40**	**54.30**	**32.25**
Travelled range (km)	10.91	10.51	9.29	10.91
Residual range (km)	72.70	75.17	78.97	76.22
Total range (km)	83.61	85.68	88.26	87.13
Additional range (km)	-	**2.07**	**4.65**	**3.52**
% Increased (relative to sport)	-	**2.48**	**5.57**	**4.21**

TABLE VI
COMPARISON OF ENERGY CONSUMPTION AND RANGE BETWEEN MODES IN WEATHER 2

Load	Energy (Wh)			
	Sport	Comfort	Eco	AI-Fuzzy
Motoring	1004.00	855.70	636.70	1004.00
Regenerating	64.20	21.82	79.87	96.61
Initial aux	78.36	77.97	77.77	78.36
Safety aux	49.08	48.92	48.76	49.08
Comfort aux	192.70	115.60	57.82	73.92
Luxury aux	65.20	65.20	65.20	65.20
Energy Consumed	**1276.00**	**1093.00**	**758.00**	**1125.00**
Energy Reduced	-	**183.00**	**518.00**	**151.00**
% Reduced (relative to sport)	-	**14.34**	**40.59**	**11.83**
Travelled range (km)	10.91	10.51	9.29	10.91
Residual range (km)	115.90	125.60	142.50	117.19
Total range (km)	126.81	136.11	151.79	128.10
Additional range (km)	-	**9.30**	**24.98**	**1.29**
% Increased (relative to sport)	-	**7.33**	**19.70**	**1.02**

The above strategies have decreased the energy consumption of the vehicle as presented in Table 5 and Table 6. Among the three individual modes (eco, comfort and sport), eco mode is the lowest in energy consumption, followed by comfort mode and finally sport mode, in both weather conditions. In relative to sport mode, 54.30% and 40.49% energy reductions in eco mode have produced 5.57% and 19.70% extra ranges during weather 1 and weather 2 respectively. Whilst, in comfort mode; 25.40% and 14.34% energy reduction contributes to 2.48% and 7.33% extra ranges during weather 1 and weather 2. The results uncover that weather conditions is the energy saving influencing factor in BEV; our BEV-001 can run better mileage in weather 2 than weather 1 with about 30-40% increases in driving range. Though there are some increases in luxury, safety and initial loads in weather 2, however the decreases in comfort load (HVAC) energy consumption has significantly increased the driving range. Also, inevitable energy losses in BEV-001 model at DC-DC converter and inverter due to switching and PMAC operation based on its power efficiency map have resulted inefficiency in driving operation. This requires optimization strategy in order to have a better range which will be proposed in further research.

The proposed multi-mode driving (AI-Fuzzy mode) is apparently to improve the range in sport mode without being confined by any speed limit as in comfort and eco mode. The speed response in Fig. 5 demonstrates that this mode not only can perform at par with sport mode, but also produces large energy reduction (32.25%) and 4.21% increases in driving range during weather 1 (Table V). These results prove the significant of multi-mode driving for a BEV in reducing the energy consumption and extending the driving range without downgrading its speed performance. Furthermore, this mode is an adaptive mode that will automatically select the driving parameters according to the vehicle speed. Therefore, this mode is suitable to all driving conditions.

IV. CONCLUSION

This research has proven the significance of employing driving modes in extending the battery range of BEV. Driving mode represents the energy management strategy at supervisory level to increase the energy efficiency and reduce the energy consumption. The three driving modes; sport, comfort and eco employed in the BEV-001 model have their own advantages and suitable for different driving conditions; urban, suburban, and highway. The proposed integrated multi-mode driving based on fuzzy logic is an adaptive mode that suitable for all driving condition as it capable to automatically change the driving parameters based on the speed conditions. The results have proven its ability in reducing the energy consumption, and increasing the driving range without downgrading the speed performance.

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