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Modelling and Optimization of Energy Range Extended Electric Bus Strategy Management System Using Dynamic Programming

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***Abstract*—The number of motor vehicle increases at each year in Indonesia involve much negative impact on human life such as traffic jam. People choose to go by bus to avoid the traffic jam. Another negative impact is an increase amount of carbon dioxide (CO2) emissions in the air. Replacing motor vehicle to electric vehicle is the better way to decrease amount of carbon dioxide emissions. Range extended electric bus is a type of electric bus which use electric and fuel for energy source. On the basis of a typical Japanese driving cycle, optimal control strategy is designed according to the state of charge (SOC) consumption trend, which is optimized by the dynamic programming (DP) algorithm. The SOC value determines the mileage and fuel consumption, it will be the main goal of energy management. The result show that when REEB go through distance as long as the distance of BRT UNDIP – UNNES bus route, the amount of Japanese driving cycle are 11 cycles. The energy and fuel consumption that optimized by DP strategy can reach 121.66 MJ and 0.0143 L/Km. Compared with the conventional bus, the fuel consumption reach 0.212 L/Km.**

***Keywords*—range extended electric bus, state of charge, dynamic programming, fuel consumption, and energy management**

I. INTRODUCTION

Motorized vehicles in Indonesia are increasing every year. The number of motor vehicles reached 67.3 million in 2009 and has reached 129.2 million in 2016 [1]. The negative impact of the increase in the number of motorized vehicles is traffic jam in several major cities in Indonesia. This causes people, especially in big cities to take alternative transportation for travel, such as using public transportation. Buses are public transportation that is easy to find, easy to access, and inexpensive. Buses and other motor vehicles that commonly used by the people in indonesia still use combustion engines that require fuel. This causes an increase in fuel consumption in Indonesia which can cause negative impacts, such as the increase in the amount of carbon dioxide (CO2) emissions in the air. Therefore, public transportation that uses environmentally friendly fuels are needed, such as electric cars. Electric cars have several advantages over oil-fueled cars, it does not produce much emission that make it more environmentally, fuel costs are relatively cheaper, higher engine efficiency. However, electric cars have the disadvantage of not having a station charging facility that supports long trips in Indonesia so that it becomes difficult if the battery car runs out in the middle of the trip. Seeing these impacts, in this study there are innovations to make public transportation in the form of buses that use batteries as the main energy. This bus uses the concept of Range Extended Electric Vehicle (REEV) which also called the Range Extended Electric Bus (REEB). REEB is a powertrain system consisting of a combination of pure electric drive models and hybrid power drives. The schematic of the REEB circuit is shown in Figure 1. The circuit consists of an Auxilary Power Unit (APU), battery, motor traction, transmission, and final drive. The battery and APU provide power to the traction of the motor through electricity. Motor traction drives the wheels directly through the transmission and final drive. The entire power system is connected in series. One of the features of REEB is a large battery capacity, this will provide more power to REEB thereby reducing fossil fuel consumption and emissions. The APU consists of an engine, generator, and rectifier. The generator is mechanically coupled to the engine's output shaft, so the generator and engine have the same relative efficiency. The APU converts diesel power into electricity which is then used by traction motors or as charging batteries. In addition, if the bus power demand is higher than what is provided by the battery, the APU will fill the less power [2].

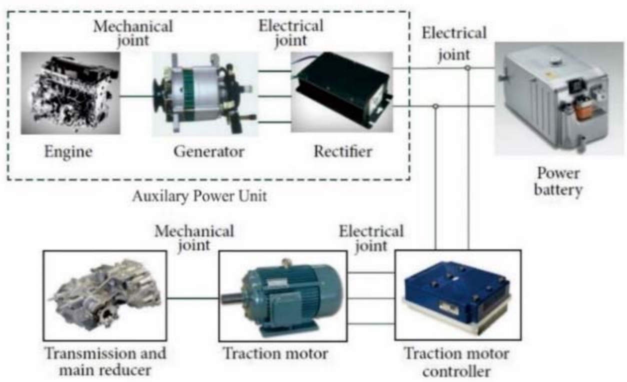


Fig.1. REEB *powertrain system structure* [2].

All vehicle displacement forces are driven by a motor drive system. The engine only works to drive the generator without providing direct driving power. As a result, engine speed is not the same as vehicle speed. The engine can continue to work in the high frequency zone to reduce fuel consumption. In addition, battery power provides power output. Energy management is one of the core problems for REEB. Its main task is to coordinate the distribution of power between the APU and the battery. The state of charge (SOC) of the battery must be maintained within a reasonable range, the output power must meet the required power. Because SOC performance affects driving distance and fuel consumption, so this will be the and the battery. The state of charge (SOC) of the battery must be maintained within a reasonable range, the output power must meet the required power. Because SOC performance affects driving distance and fuel consumption, so this will be the main goal of energy management [3]. It is necessary to implement an optimal strategy in the vehicle energy management system to minimize energy consumption. At present, optimal strategies are grouped into three namely, rule-based strategies, modern control theory-based intelligent strategies, and optimal strategies. In this study, researchers used dynamic programming (DP) as the optimal strategy. DP is one good optimal strategy for overcoming the optimal nonlinear optimal problem. Operated using Matlab software, this strategy significantly reduces computational time, as well as maintaining the accuracy of the desired results [2].

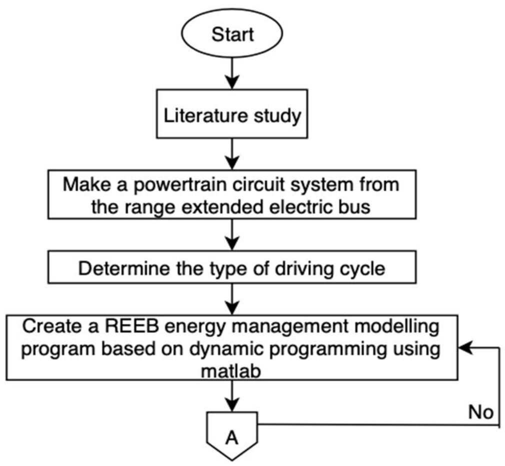
II. OBJECTIVES

The overarching objectives of this paper are to get the REEB energy management strategy model based on dynamic programming, to get the results of optimization of REEB fuel consumption based on dynamic programming, and REEB energy flow.

III. METHODOLOGY

A. *Flowchart of Methodology*

Diagrams are needed to illustrate the course of the research process from the beginning to the end that has been done. Figure 2 is a flowchart of this research.



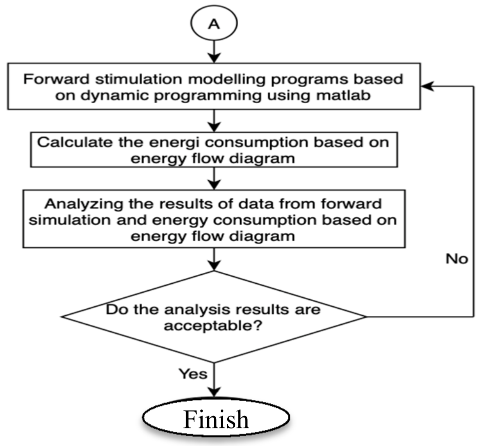


Fig.2. Flow diagram of research methodology

B. *Range Extended Electric Bus Model System*

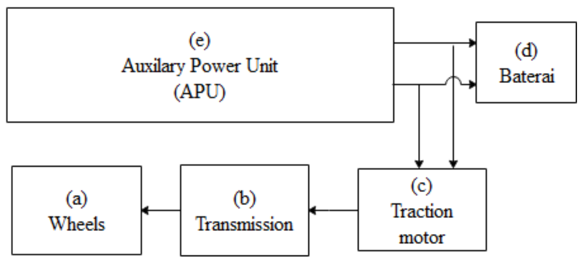


Fig.3. REEB circuit model system [2]

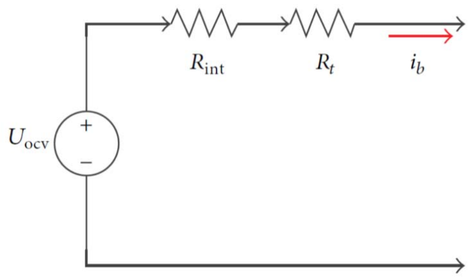


Fig.4. Battery model [2].

Figure 3 explains the 5 main components in the REEB modeling system namely, Wheels, transmission, Traction motor, Battery, and APU. The REEB modeling system includes a serial multistage decision with a final value problem type, where the known value is the final value, which is the driving cycle. So, the REEB modeling program is done in reverse, besides giving a name to each component is also reversed from large to small.

1) Wheels: The wheel is a moving component driven by the rotational speed of the transmission. In this study the wheels provide the vehicle speed input value as a reference value that must be met by the transmission. On the wheels there are values of wheel angle speed, wheel acceleration, and wheel torque. Equation 1 is an equation to get the wheel angular velocity.

$$\boldsymbol{w_v} = \frac{\boldsymbol{v(k)}}{\boldsymbol{r}} \tag{1}$$

Where w_v is the wheel angle, v(k) is the vehicle speed value, and r is the wheel spokes value. Equation 2 is an equation to get the acceleration of the wheel angle.

$$dw_v = \frac{a(k)}{r} \quad (2)$$

Where dw_v is the acceleration of the wheel angle, a(k) is the value of the vehicle acceleration. Then the wheel torque is obtained from vehicle dynamics multiplied by the spokes of the wheel, which can be seen in Equation 3.

$$T_v = (F_f + F_\omega + F_i + F_j)r \quad (3)$$

Where T_v is wheel torque, f_f is rolling force, f_w is air force, f_i is gradient force, and f_j inertia force.

2) *Transmission:* Transmission is a system that has a function as the conversion of torque to rotational speed. In this study, the power generated by transmission through rotational speed becomes the power that must be met. Transmission has the value of the transmission angle speed, transmission angle acceleration, and transmission torque. Angular velocity, angular acceleration, and torque are obtained from the shaft rotation. Equation 4 is the shaft angular velocity. change the default, adjust the template as follows.

$$dw_g = g(k) x\, r_{gear} x\, dw_v \quad (4)$$

Where w_g is the shaft angular velocity, g(k) is the vehicle gear number value, while r_{gear} is the gear ratio value. Equation 5 is the shaft angle acceleration.

$$dw_g = g(k) x\, r_{gear} x\, dw_v \quad (5)$$

Where dw_g is the shaft angle acceleration and equation 6 is an equation to get the shaft torque.

$$T_g = \left(\frac{(g(k)>0)\, x\, (T_v>0)\, x\, T_v}{r_{gear}\, x\, e_g}\right) + \left(\frac{(g(k)>0)\, x\, (T_v \le 0)\, x\, T_v}{r_{gear}} x e_g\right) \quad (6)$$

Where T_g is the gear torque, dan e_g is the gear efficiency value.

3) *Traction motor*: The motor has a function to continue the power from the battery and or from the APU to the transmission to meet the required power, by converting electrical energy into motion energy. The value of the power entering from the battery and / or from the APU must be in accordance with the power required by the transmission in Equation 7.

$$P_m = P_{APU} + P_b \quad (7)$$

Where P_m is motor power, P_{APU} is APU power, and P_b is battery power (Wu, dkk., 2014). In this study, the APU power is a control variable where the value has been determined as a limit of (0.50) kW.

4) *Battery*: In REEB systems, batteries have a major role in providing power to the motor or transmission rather than the APU. The battery model can be seen in Figure 4. There are Rint, Rt, Ib, and UOCV. This model focuses on charge / discharge resistance and the open circuit voltage of the battery. Considering the DP strategy, Equation 8 explains the form of state of charge used on the battery model.

$$SOC = -\frac{I_b(k)}{Q_{bat}} \quad (8)$$

Where SOC is the value of the state of charge, I_b (k) is the current of the battery, Q_{bat} is the charge of the battery. to find out the value of I_b (k) you can see Equation 9.

$$I_b = v - \frac{\sqrt{v^2 - 4P_bR_b}}{2R_b} \quad (9)$$

5) *Auxiliary power unit (APU)*: The APU has a function as an additional power to help the battery complete the power needed by the motor when the battery cannot complete it. The APU consists of an engine and a generator. The generator is considered to have the same efficiency value as the engine, because the generator is mechanically connected by the engine to the shaft. By knowing the APU power value we can calculate the mass value of the fuel flow through Equation 10.

$$m_{fuel} = \frac{P_{APU}}{e_{th}\, x\, 42800000} \quad (10)$$

Where m_{fuel} is the mass value of the flow of diesel fuel consumption, P_{APU} is the APU power, e_{th} is the engine efficiency value, and 42800000 is the low heat value of diesel in units of J/kg.

The characteristics of the buses used, from the design of the bus, motor, engine, generator, and battery. This study extracts powertrain parameters from UNDIP-UNNES BRT buses, BLDC motors, and Lithium-Polymer batteries as shown in Table 1.

TABLE I. POWERTRAINS REEB CHARACTERISTIC [4]

Component	Parameter	Value
Bus	Dimension (l x w x h)	7700 x 2100 x 3330
	Bus mass (kg)	5400
	Passanger mass (kg)	1750
	Air sectional area (m^2)	6.19
	Air resistance coefficient (C_A)	0.7
	Rolling resistance coefficient (f)	0.017
Engine	Power (kW)	50
	Torque (Nm)	220
	Machine mass (kg)	430
Transmission	Gear ratio	1 and 3.5
Motor	Voltage (Volt)	380 - 540
	Power (kW)	100
	Peak power (kW)	220
	Speed (RPM)	5000
	Rate torque (Nm)	191
	Peak torque (Nm)	400
	Current (A)	289.3
	Peak current (A)	590

	Motor mass (kg)	270
Baterai	Nominal voltage (V)	12.8
	Nominal capacity (Ah)	100
	Charge cut-off (V)	14.6
	Discharge cut-off (V)	10
	Cont. discharge current (A)	100
	Charge current (A)	22
	Baterry mass (kg)	10
Cell soecification	Voltage (V)	3.2
	Capacity (Ah)	3.3
	Cell combination	30 paralel, 4 series
	Cell quantity	120

C. *Driving Cycle*

The type of driving cycle that used in this research is the Japanese driving cycle with JN 10-15 type. This cycle is commonly used to certify vehicle emissions and fuel consumption in Japan by simulating urban and highway cycles, including idling, acceleration, cruising and decelerations (Nicolas, 2013). The driving cycle displays information in the form of speed (speed vector) as shown in Figure 5, and the characteristics of the JN1015 cycle as shown in Table 2.

TABLE II. CYCLE MAIN CHARACTERISTIC JN1015 [5]

Distance	4.16 km
Duration	660 s
Average speed	6.3 m/s

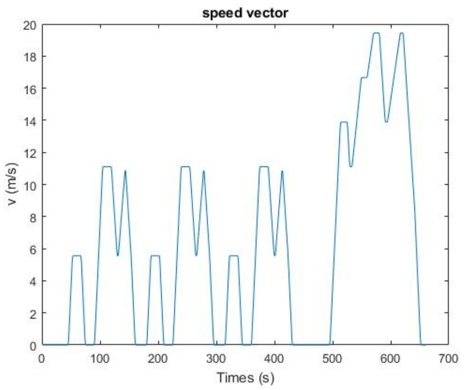


Fig.5. Speed cycle JN1015.

D. *Energy Management Strategies based on Dynamic Programing*

The REE electric vehicle model is a discrete time model. This model contains the power requirements of the vehicle to travel the specified distance. This modeling contains of the motor modellings, engines, and batteries in accordance with the mentioned characteristics. While vehicle modeling is based on vehicle dynamics such as friction force, air force, gradient force, and inertia force. Figures 5 and 6 are the efficiency contour charts of REEB motors and generators. The modeling equation can be seen in Equation 11.

$$X_{k+1} = f(x_k, u_k, v_k, a_k, i_k) + x_k \qquad (11)$$

Where x_k is SOC as state variable, u_k APU power as control variable, v_k is vehicle speed, a_k is vehicle acceleration, and i_k is gear number. Because the driving cycle has been assumed, the vehicle speed, vehicle acceleration, and gear number are known. The modeling equation as follows:

$$X_{k+1} = f(x_k, u_k) + x_k \quad k = 0, 1, \dots, N-1 \qquad (12)$$

This modeling has restrictions on these variables, as shown in the following Equation:

$$\begin{cases} SOC_{min} \le SOC(t) \le SOC_{max} \\ P_{APU\_min} \le P_{APU}(t) \le P_{APU\_max} \\ P_{b\_min} \le P_b(t) \le P_{b\_max} \\ dP_{APU\_min} \le \frac{P_{APU}}{dt} \le dP_{APU\_max} \end{cases} \qquad (13)$$

The following equation is an optimization equation to minimize fuel consumption.

$$J = \sum_{k=0}^{N-1} \Delta m_f(u_k, k) \qquad (14)$$

This study uses JN1015 as a driving cycle. Equations 15-20 are the optimal control equations of REEB.

$$\begin{gathered} \min_{u_k \in U_k} \sum_{k=0}^{N-1} \Delta m_f(u_k, k) \\ x_{k+1} = f_k(x_k, u_k) + x_k \\ x_0 = 1 \\ x_N \ge 1 \quad (= x_{f,min}) \\ x_k \in [0.2, 1] \\ N = \frac{7270}{T_s} + 1 \end{gathered} \qquad (15)$$

During using the optimal control equation such as Equation 3.17 - 3.22 which is solved using dynamic programming with the driving cycle JN1015. This modeling is illustrated in matlab using a function developed by Sundstrom and Guzella in 2009.

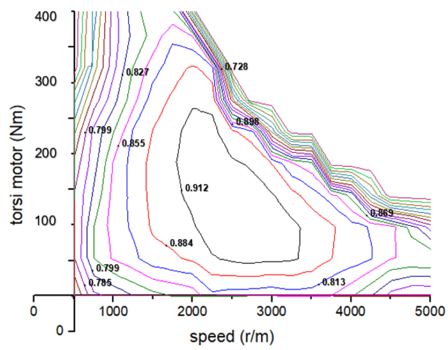


Fig.6. Motor efficiency contour graph.

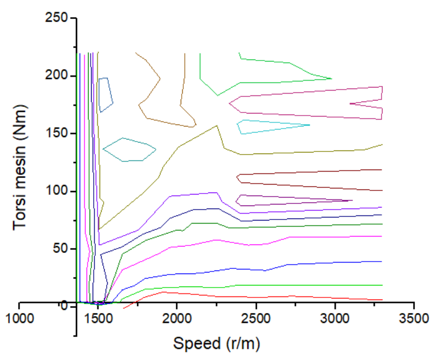


Fig.7. Machine efficiency contour graph.

E. REEB Energy Consumption Based on Flowchart

This section contains an analysis of energy conversion from electricity or battery networks and fuel used by the wheels. The energy efficiency of the powertrain system and other components is involved in energy calculation. Equation 3.23 shows the equation to calculate the total power needed [2].

$$\begin{aligned} P_{dem}(t) &= P_f(t) + P_\omega(t) + P_i(t) + P_j(t) \\ &= F_f(t)u_r + F_\omega(t)u_r + F_i(t)u_r + F_j(t)u_r \end{aligned} \quad (21)$$

The energy from the wheels and the incoming motor energy can be calculated using Equation 3.24. In this study braking energy was not considered. Wheel energy can be calculated by using positive-valued wheel power (Wu, et al., 2014).

$$\begin{aligned} E_{dem} &= \int_{P_{dem}(t)>0} \frac{P_{dem}(t)}{1000} dt, \\ E_{motor,inp} &= \frac{E_{motor,out}}{\eta_m} \\ &= \int_{P_{dem}(t)>0} \frac{P_{dem}(t)}{1000\eta_{tran}(t)\eta_m(t)} dt, \end{aligned} \quad (22)$$

Where $E_{motor,out}$ is the power out of the motor, η_{tram} is the efficiency of the transmission, and η_m is the efficiency of the motor [2]. Equation 23 shown the calculation of battery energy.

$$E_b = \int_{P_b(t)>0} \frac{P_b(t)}{1000} dt, \quad (23)$$

Where E_b is energy from the battery, and P_b is battery power. Outgoing battery energy can be obtained by integrating P_b which is positive. Equation 24 displays the calculation of the grid energy (E_{grid}). Where Q is the charge from the battery, V is the voltage from the battery [2].

$$E_{grid} = \int \frac{3.6(SOC(t)-SOC(t-1))QV(t)}{1000\eta_{chg}(t)} dt \quad (24)$$

The calculation of the energy sent from the APU to the battery or $E_{b,g}$ shown in the following Equation 25.

$$E_{b,g} = \int_{P_b(t)<0} \frac{P_b(t)}{1000} dt, \quad (25)$$

Negative battery power value is used to find $E_{b,g}$. Power from the APU will complement the required power from insufficient battery power. Equation 3.28 shows a calculation of the energy lost from a battery.

$$\begin{aligned} E_{loss,b} &= E_{grid}(1-\eta_{chg}) + \int_{P_b(t)<0} \frac{P_b(t)(1-\eta_{chg}(t))}{1000} dt, \\ &+ \int_{P_b(t)>0} \frac{P_b(t)(1-\eta_{dis}(t))}{1000} dt \end{aligned} \quad (26)$$

This research focuses on energy lost during charging and discharging, including charging batteries with the grid, charging batteries with APU, and discharging batteries to the motor. Energy from APU is calculated based on Equation 27. Where P_{APU} is the APU power value.

$$E_g = \int \frac{P_{APU}(t)}{1000} dt, \quad (27)$$

Energy from the engine can be calculated using Equation 28. Where η_{gen} is the efficiency value of the generator.

$$E_{eng} = \int \frac{P_{APU}(t)}{1000\eta_{gen}} dt, \quad (28)$$

Energy from fuel consumption can be calculated using Equation 29.

$$E_{fuel} = \int \frac{P_{APU}(t)\, be(t)}{\eta_{gen}(t)\rho_{diesel}} \rho_{LHV} dt, \quad (29)$$

Where b is the specific fuel consumption of the engine (kg/kWh), ρ_{diesel} is the density value of diesel, and ρ_{LHV} is the lowest heating value of diesel (42800000 J/L). Fuel efficiency can be calculated using formula as shown in Equation 30 [2].

$$\begin{aligned} \eta_{fuel} &= \eta_{eng}\eta_{gen}x\left(\frac{E_{b,g}}{E_g}\eta_{chg}\eta_{dis} + \frac{E_g - E_{b,g}}{E_g}\right)\eta_m\eta_{tran}, \\ \eta_{eng} &= \frac{E_{eng}}{E_{fuel}}, \\ \eta_{gen} &= \frac{E_g}{E_{eng}}, \\ \eta_m &= \frac{E_{motor,inp}}{E_{motor,out}}, \\ \eta_{grid} &= \eta_{chg}\eta_{dis}\eta_m\eta_{tran}, \end{aligned} \quad (30)$$

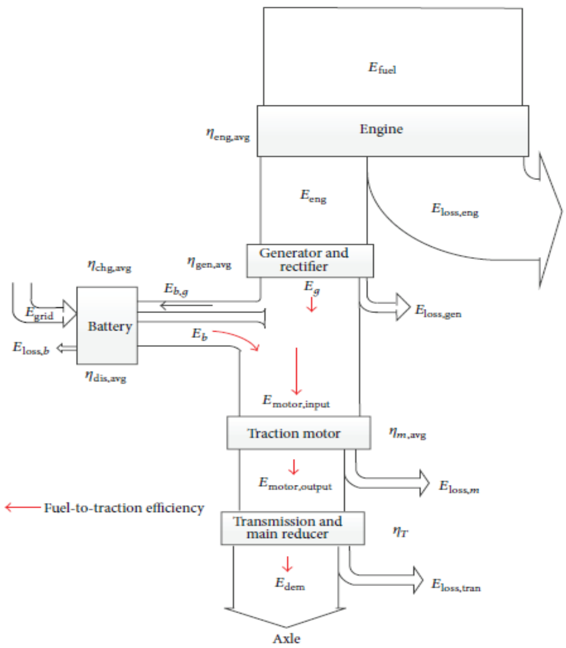


Fig.8. Energy flow diagram REEB [2].

After getting the value of energy and efficiency of each system, these values are entered into the energy flow diagram, according to their position. The goal is to find out the energy flow and its value. Figure 8 shows the energy flow diagram.

IV. RESULT AND DISCUSSION

A. Distance

Based on the survey results, the distance traveled by buses on the UNDIP-UNNES route is 22.9 km, and the distance of UNDIP-UNNES-UNDIP is 45.8 km. This study uses a driving cycle type JN1015, to cover the distance of UNDIP-UNNES-UNDIP required as many as 11 cycles of JN1015. Because in one cycle JN1015 can only cover a distance of 4.16 km. Cycle JN 1015 with 11 cycles can be seen in Figure 9.

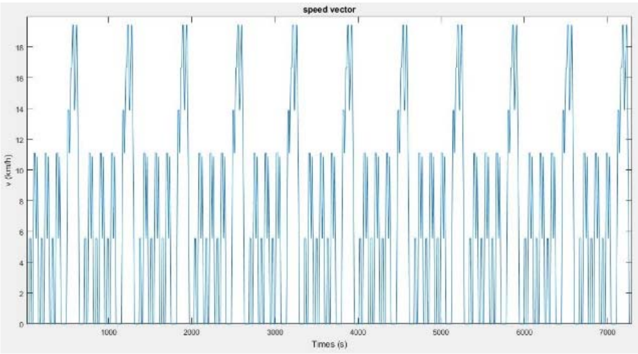


Fig.9. Cycle speed 11 cycles JN1015.

B. Energy Management Strategy Results Based on Dynamic Programming

The results of the energy management strategy based on dynamic programming are obtained from the forward simulation modeling program, the main program, and the dpm program. The results obtained can be seen in Table 3.

TABLE III. ENERGY MANAGEMENT STRATEGY RESULTS BASED ON DYNAMIC PROGRAMMING

Number of driving cycles	11	5	1
Driving distance (km)	45.8	20.8	4.16
Early SOC	1	1	1
Final SOC	0.229	0.637	0.927
Fuel consumption (L)	0.646	0.366	0
Fuel consumption each km (L/km)	0.0141	0.0176	0

SOC in this research is a state variable with a limit [0.2, 1]. Figure 9 explains the optimal SOC path. The SOC bus reaches 1 on the beginning of the bus departs from its original place. At the end of the trip the SOC reaches 0.229.

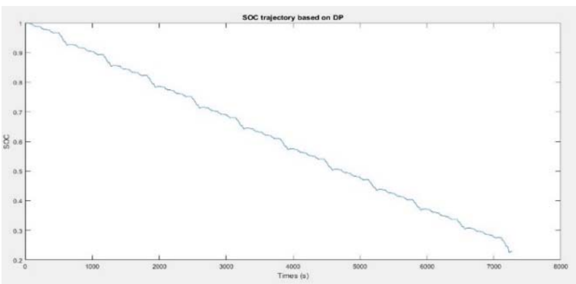


Fig.10. SOC bus berdasarkan *dynamic programming*.

There are three power obtained from the results of this simulation, including motor power, APU power, battery power. Figure 10 explains the motor power of the bus. This motor power is the power needed by the bus to run the system. From this graphic, the largest motor power value is 102.73 kW. Figure 11 explains the battery power of the bus. Battery power is the power needed by the bus to meet the needs of motor power to run the system. From this graphic, the biggest battery power value is 131.43 kW. While the lowest value of the battery power is -39,218. The positive value of this battery power indicates the battery is supplying power to the motor (discharging mode), while the negative value of this battery power indicates that the battery is being supplied by APU and or grid (charging mode). Figure 12 explains the APU power from the bus. APU power is the power generated by the APU to help the battery meet the motor power requirements to run the system. This power is the control variable in this simulation with a limit of [0.50000]. From this graphic, the largest battery power value is 50 kW. The results of the three power can be connected based on the amount of power expended to complete the motor power requirements. Figure 13 is a relationship of the three forces. The graphic explains that the motor gets power from the battery and APU. The battery works more dominantly than the APU, this is marked by the power expended by the battery more dominant than the APU.

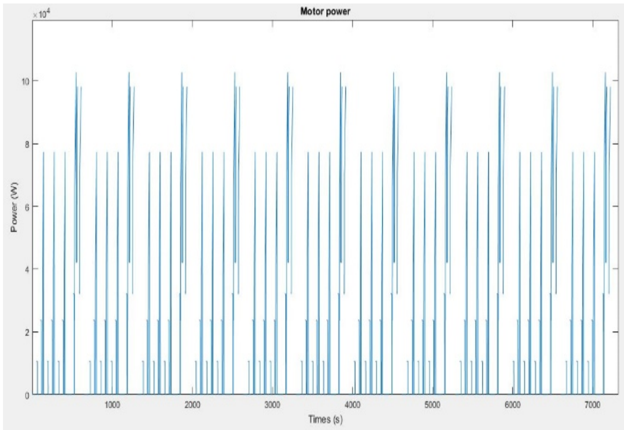


Fig.11. Bus motor power based on dynamic programming.

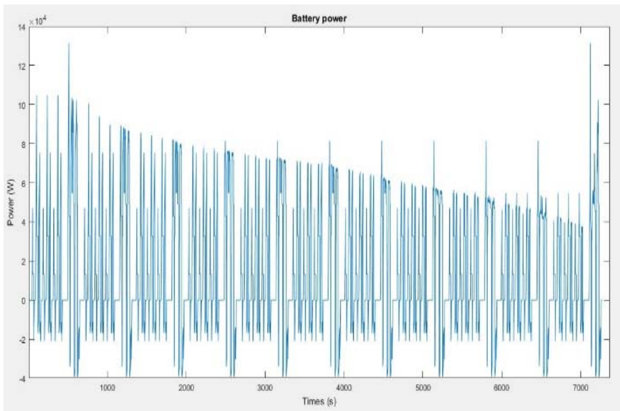


Fig.12. Bus battery power based on dynamic programming.

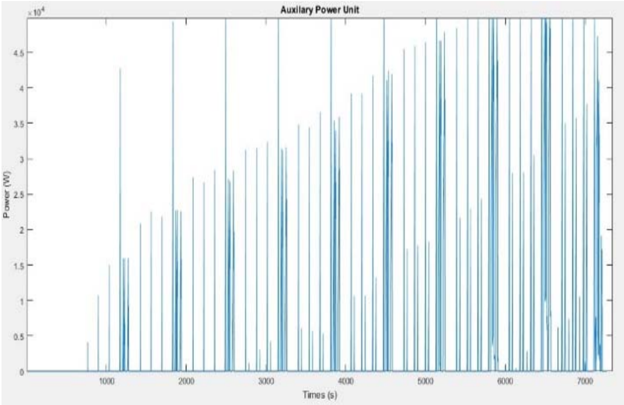


Fig.13. Bus APU power based on dynamic programming.

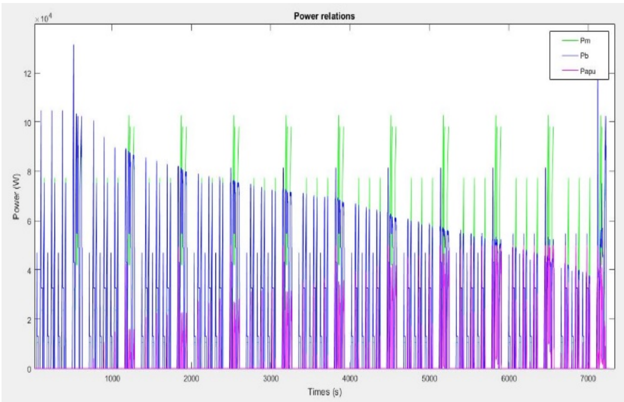


Fig.14. The relationship between motor battery power, battery power , and bus APU power based on dynamic programming

Figure 15 shows a fuel mass flow graph of the UNDIP-UNNES REEB BRT bus. The amount of fuel mass flow bus is 0.538 kg. From these values the fuel consumption value is obtained as follows.

$$Fc = \frac{fuel\ mass\ flow}{0.832\,\frac{kg}{L}}$$

$$= \frac{0.543\ kg}{0.832\frac{kg}{L}} = 0.646\ L$$

$$Fc = \frac{0.653\ L}{45.8\ km} = 0.0143\ L/km$$

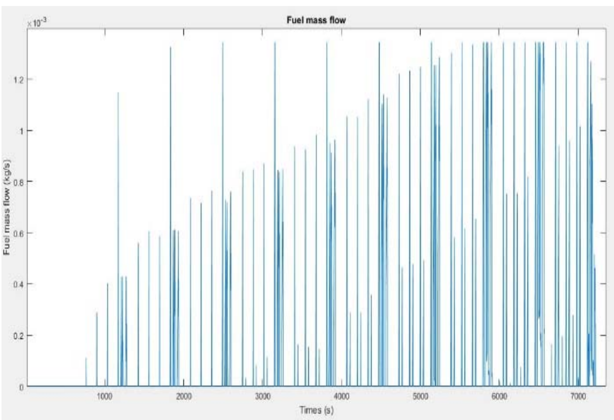


Fig.15. Mass flow of fuel consumption based on dynamic programming

From the results of the fuel consumption calculation, the value of fuel consumption is obtained as 0.014 L / km. Based on observations, Figure 16 is a comparison of REEB buses and conventional buses based on fuel consumption. The value of conventional bus fuel consumption is greater than the fuel consumption of REEB buses. Conventional buses have a total fuel consumption of 58.25 L a day or IDR 300,000 in 2017, with 6 operations [4].

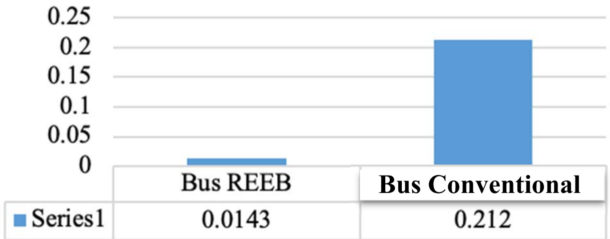


Fig.16. Comparison of fuel consumption.

C. *REEB Energy Consumption Flowchart*

After conducting a forward simulation, an energy consumption calculation is performed on the REEB bus based on the energy flow diagram using Equation 21-30. Figure 17 is a energy consumption flow chart of the REEB bus.

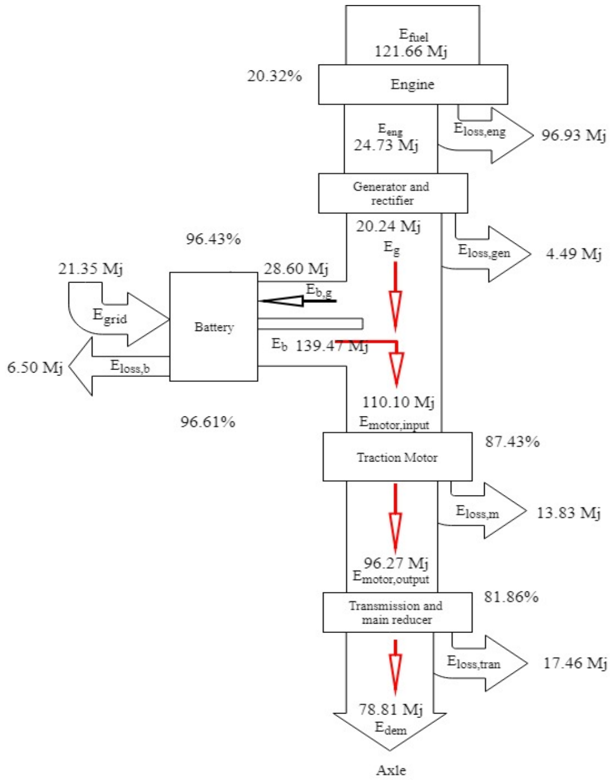


Fig.17. REEB energy flow diagram of UNDIP-UNNES BRT bus

V. CONCLUSION

- Researchers have succeeded in modelling the REEB energy management strategy based on dynamic programming. The results of forward simulation from modelling using Matlab prodeuce SOC values, motor power output, battery power, APU power, and fuel consumption.

- Based on the results of REEB energy management strategy modelling using dynamic programming, batteries are the biggest power supply for motor power requirements compared to the APU. Where the biggest power from the battery is 231.43 kW, the biggest power from the APU is 50 kW, and the biggest power of the motor is 102.73 kW.
- The REEB energy management strategy based on dynamic programming produces a REEB fuel consumption of 0.014 L / Km.
- Using the energy flow diagram, the flow of energy consumption needed by the REEB bus can be seen which is 78.81 MJ.

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