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# Development of backward model of REEV and its subcomponents

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Abstract: As an alternative to battery electric vehicles, range-extended electric vehicles offer a reliable solution for extending driving range on a single charge. This study focuses on the development of a REEV simulation model. The main components including the electric machine, battery, and auxiliary power unit are modeled to evaluate the overall system performance under various operating conditions. To ensure the reliability of the developed model, simulation results were compared with experimental data.

Keywords: REEV, electric machine, auxiliary power unit, generator, internal combustion engine, battery

## 1. Introduction

Due to the depletion of fossil fuel resources and the increasing emissions from transportation systems, battery electric vehicles (BEVs) have gained significant attention as a sustainable alternative. However, BEVs have certain drawbacks, including limited driving range, a lack of charging infrastructure, and the relatively short lifespan of batteries. Range extended electric vehicles (REEVs) represent a practical solution to mitigate the range limitations of BEVs and reduce the environmental impact of traditional internal combustion engine vehicles. In contrast to BEVs, REEVs are equipped with an auxiliary power unit consisting of a generator and a small internal combustion engine. The architecture of REEVs is based on a series hybrid configuration [1], in which all propulsion power is supplied by an electric machine. This paper focuses on developing a REEV simulation model to evaluate overall vehicle performance.

In vehicle simulation, backward and forward modeling approaches are commonly used to calculate fuel consumption over a specified driving cycle. The forward modeling approach, often called the “dynamic” or “cause-effect” method, models interconnected powertrain components and variables, capturing their impact on vehicle performance [2]. Although this approach requires more computational effort to solve a limited number of differential equations or maps, it is generally more accurate than the backward modeling approach [3]. The dynamic approach also includes a driver model to establish the starting point for calculations. Conversely, backward modelling approach does not include the driver model and it is called as “quasi static” or “effect to cause” method [2,3]. The imposed speed profile (v_x) is used to determine the required traction force at the wheels. In order to calculate the energy consumption or fuel consumption of the vehicle, the acting force at the wheels is directly translated to the required torque (T_req) that has to provided by energy source blocks for traction. In REEVs, the backward modelling approach is widely used for component sizing and the performance evaluation of control strategies under predefined driving conditions. Figure 1 shows the powertrain structure of REEV using backward modelling approach.

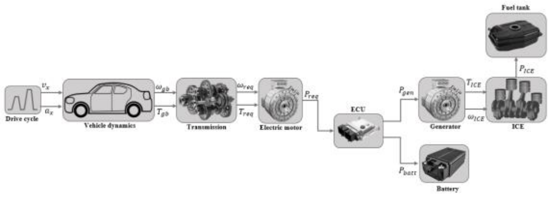


**Fig. 1. Backward modelling approach for REEV**

The next sections present a detailed development of the REEV subcomponents, focusing on the modeling of the battery, electric motor, generator, and auxiliary power unit, as well as their contribution to overall system performance. The drive cycle, vehicle dynamics, and transmission subsystems were adopted from previously validated models in the literature [4].

## 2. Research methodology

**Component modelling and performance analysis**

**Electric machine model**

The required power for the movement of REEV model is supplied by an electric machine, which draws energy from both the electric battery and a generator connected to the internal combustion engine. The electric machine performs two distinct functions: it drives the wheels as a motor and charges the electric battery as a generator. Depending on the requested torque ($T_{req}$) and angular speed ($\omega_{req}$) of electric machine’s shaft, to calculate the required power for traction as an output or charging the battery for braking are considered as the main task of electric machine block. The efficiency of the electric machine during traction ($\eta_{em}$) and braking ($\eta_{gen}$), dependent on the demanded torque ($T_{em}$) and angular velocity $\omega_{em}$, can be expressed as:

$$\begin{cases} \eta_{em} = f(T_{em}, \omega_{em}) \rightarrow \text{traction} \\ \eta_{gen} = f(T_{gen}, \omega_{gen}) \rightarrow \text{braking} \end{cases} \tag{1}$$

The original characteristics of the electric machine as function of angular speed and torque, derived from experimental results of BMW i3 REX 2014, are illustrated in Figure 2. In the figure, the efficiencies of the electric motor are represented as discrete points.

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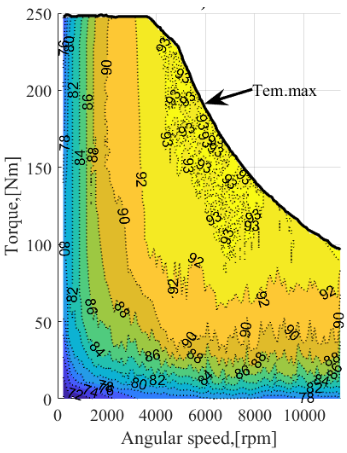


**Fig. 2. Electric machine characteristics**

The required electric power is considered as an output of electric machine block, so it is calculated according to the traction ($P_{em}$) or braking ($P_{gen}$) modes as equations below:

$$\begin{cases} P_{em} = T_{em} * \omega_{em} / \eta_{em} \\ P_{gen} = T_{gen} * \omega_{gen} * \eta_{gen} \end{cases} \quad (2)$$

**Energy management unit**

The energy management unit consists of control rules that receive operational commands from the driver and make decisions regarding the appropriate operational modes. In the REEV, the control unit is responsible for managing the distribution of the required traction motor power based on the received commands. Specifically, it splits this power between the auxiliary power unit and the electric battery, ensuring optimal performance and efficiency under different driving conditions.

$$P_{em} = P_{APU} + P_{batt} \quad (3)$$

For the design of the energy management controller, a rule-based control strategy derived from the authors' previous work is employed [5]. In this approach, engine speed and engine torque are discretized into three and two levels, respectively. Furthermore, within the charge-sustaining region of the battery SOC, six operating modes are established as a function of SOC and vehicle speed.

**Auxiliary power unit**

The auxiliary power unit (APU) in a REEV consists of an internal combustion engine, a starter-generator (ISG), and power electronics, including an AC/DC invertor and a DC/DC converter. The engine block converts the thermal energy generated by fuel combustion into mechanical energy, which drives the coupled generator. The generator including converters subsequently produces electrical power, which is utilized to supply the electric machine for propulsion and/or to recharge the electric battery, thereby enhancing the vehicle's overall energy efficiency and extending its driving range.

*Internal combustion engine model*

The mathematical model of the internal combustion engine is established using a fuel consumption map as a lookup table or by analytically solving polynomial equations. Experimental data are employed to evaluate the required engine output torque, angular speed, and fuel mass flow rate for both approaches. The fuel consumption map of BMW i3 REX 2014 is used for analysis in this study.

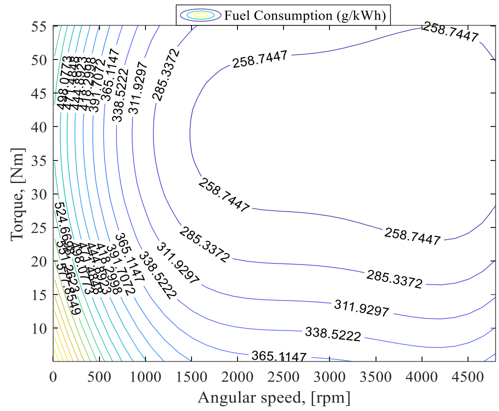


**Fig. 3. Fuel consumption map of BMW i3 REX 2014**

*Generator model*

The generator model includes an AC/DC inverter that converts mechanical energy generated by the engine into electrical energy and using it to either power the traction motors directly, or recharge the battery in REEV. For a given angular speed $\omega_{gen}$ and a mechanical torque $T_{gen}$, the generator calculates produced electrical power consumed by traction motor or battery. The generator efficiency ($\eta_{gen}$) can be described as a function of generator angular speed and torque in Equation (4). The electrical power produced by the generator, denoted as the power of the auxiliary power unit $P_{apu}$, is calculated as the product of the mechanical engine power $P_{ice}$ and the generator efficiency $\eta_{gen}$ in Equation (5).

$$\eta_{gen} = f(\omega_{gen}, T_{gen}) \quad (4)$$

$$P_{apu} = \eta_{gen} * P_{ice} \quad (5)$$

Similar to the electric machine model, the generator's maximum operating torque is constrained by its torque characteristics, as illustrated by the efficiency map in Figure 4.

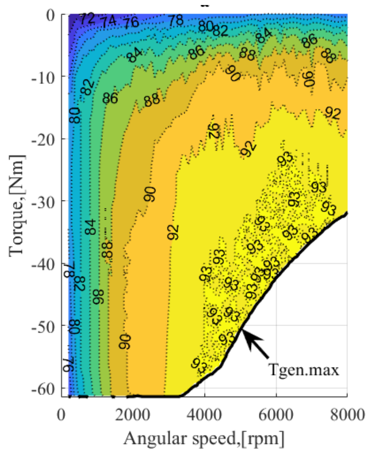


**Fig. 4. The generator static efficiency map of BMW i3 REX 2014 along with its maximum torque characteristic ($T_{gen.max}$)**

The fuel consumption rate $\dot{m}_{fuel}$ depends on the engine efficiency characteristics (through the brake specific fuel consumption), the required APU power, and the generator efficiency is expressed by Equation (6).

$$\dot{m}_{fuel}(t) = BSFC(P_{ice}, \eta_{ice}) * \frac{P_{apu}(t)}{\eta_{gen}(t)} \quad (6)$$

**Electric battery model**

The electric battery model receives the demanded power as an input from control unit, and determines the operational voltage, current and the state of the charge (SOC) by considering its charging and discharging characteristics. The battery model is developed using the Thevinen modelling technique [6] that is a famous Equivalent Circuit Network (ECN) modelling approach. According to the law, the terminal voltage is equal to the difference voltage between internal voltage source and the voltage across the charging resistance and discharging resistance as Equation (7).

$$V_t = \begin{cases} V_{OCV} - R_{chg} * I_{chg}, \ charging \\ V_{OCV} + R_{dchg} * I_{dchg}, \ discharging \end{cases} \quad (7)$$

The value of current flow $I_{chg}$ and $I_{dchg}$ through the battery terminals in charging process can be found as Equation (8) and Equation (9).

$$I_{chg} = \frac{-V_t + \sqrt{V_t^2 + 4 * R_{chg} * P_t}}{2 * R_{chg}} \quad (8)$$

$$I_{dchg} = \frac{V_t - \sqrt{V_t^2 - 4 * R_{chg} * P_t}}{2 * R_{chg}} \quad (9)$$

The SOC of the battery is defined as the level of charge of the battery relative to its capacity. It is computed through Coulomb counting method by measuring the input and output current at each time step and the estimation of an initial state. The expression of SOC is shown in Equation (10) for discharging and charging processes.

$$SOC\ (t) = \begin{cases} SOC(t_0) - \frac{1}{C_{nom}} * \int_{t_0}^{t} I_{dchg}(t)dt \quad - \ discharging \\ SOC(t_0) + \frac{1}{C_{nom}} * \int_{t_0}^{t} I_{chg}(t)dt \quad - \quad charging \end{cases} \quad (10)$$

where $SOC(t)$ - the SOC at time $t$, $SOC(t_0)$ - an initial state at $t_0$ and $C_{nom}$- nominal capacity.

## 3. Results and Discussions

The developed model was implemented and simulated in MATLAB/Simulink to evaluate the performance of the proposed system. For validation of the proposed model, experimental test data were obtained from publicly available sources [7]. Key performance indicators, including vehicle speed, battery power, battery state of charge (SOC), range extender power, and fuel consumption, were compared with experimental results under UDDS driving cycle in Figure 5**.**

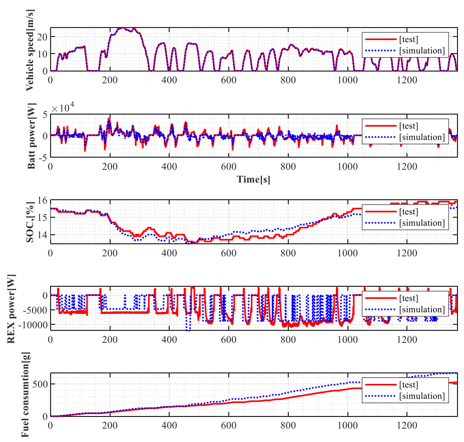


**Fig. 5. Comparative results of vehicle performaces under UDDS driving cycle**

According to the comparative results, the discrepancy between the simulation and experimental data does not exceed 5%–6% in most cases. Furthermore, as shown in Figure 5, the vehicle speed, battery power, battery state of charge (SOC), range extender power, and fuel consumption exhibit well match between the simulation and experimental results.

## 4. Conclusion

A backward-facing simulation model of the REEV was developed in MATLAB/Simulink for performance evaluation. The control unit was designed using a rule-based control strategy adopted from previously reported studies. To validate the proposed model, experimental test data obtained from a BMW i3 REX 2014 were utilized as a benchmark for comparison. The comparison results indicate that the deviations between simulation and experimental data for various performance metrics fall within an acceptable range. Based on the obtained results, the model was validated and demonstrated reliable performance.

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