

## Impact of Transmission Configuration on Efficiency and Energy Recovery in Electric Vehicles

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### ABSTRACT

This study investigates the regenerative energy efficiency of electric vehicles (EVs) equipped with Continuously Variable Transmission (CVT) compared to those utilizing traditional Single-Speed Transmission (SST). The research employs a simulation-based approach using Permanent Magnet Synchronous Motors (PMSMs), which are known for their high efficiency and responsiveness in EV applications. By simulating vehicle dynamics under standardized driving cycles such as the New European Driving Cycle (NEDC) and the Worldwide Harmonized Light Vehicles Test Cycle (WLTC), the study analyzes key performance indicators including regenerative braking force, energy recovery potential, and the battery's state of charge (SOC). The results reveal that EVs with CVT systems outperform their SST counterparts in terms of energy regeneration, particularly during deceleration and braking phases. CVT not only enables smoother transitions in gear ratios but also maintains optimal operating points for the motor, allowing more effective energy capture during braking. Furthermore, vehicles with CVT demonstrate a more stable SOC profile throughout the driving cycles, contributing to extended battery life and improved driving range. These findings highlight the potential of integrating CVT into EV drivetrains as a strategy to enhance overall efficiency, regenerative performance, and driving safety—making it a promising direction for the development of next-generation electric vehicles.

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### 1. Introduction

Growing concerns over environmental pollution and fossil fuel depletion have accelerated the shift toward electric vehicle (EV) technologies. Most EVs still use single-speed drivetrains for their simplicity, but this design limits torque–speed optimization under varying conditions. Recent studies have therefore focused on improving drivetrain performance through advanced motor control and optimized transmission systems. These developments enhance energy efficiency, reduce operating costs, and improve user experience, helping EVs compete more effectively with conventional internal combustion vehicles in the transition toward cleaner transportation.

Several studies have investigated alternative EV drivetrain configurations by replacing conventional single-speed transmissions (SST) with multi-speed solutions such as dual-clutch transmissions (DCT) or continuously variable transmissions (CVT). The analysis in [1] compared SST, DCT (2–4 speeds), and CVT architectures for pure electric vehicles (PEVs) to optimize energy efficiency, driving range, and battery capacity without increasing motor power. Using a simulation model validated with experimental data, the study evaluated B-Class and E-Class vehicles under the FTP-75 and HWFET driving cycles. The results showed that, relative to SST, a 2-speed DCT improved B-Class efficiency by 16.4%, while CVT achieved the highest improvement of 17.4%, reducing energy consumption to 7.6 kWh/100 km and lowering the required battery capacity from 28 kWh to 18 kWh. For E-Class vehicles, CVT provided a 24% reduction in energy consumption and demonstrated superior regenerative braking performance, offering the greatest economic benefits. In [2], a co-design methodology for EV CVT drivetrains was presented, using convex optimization to simultaneously refine the motor, battery,

transmission, and control strategy (gear ratio and cooling) to minimize total cost of ownership. The results indicated a 5.9% reduction in TCO and a 5.1% decrease in energy consumption compared to a non-optimized CVT system, along with improved compactness and efficiency relative to SST-based configurations.

In this study, the theoretical foundation and simulation of an electric vehicle drivetrain using a Permanent Magnet Synchronous Motor (PMSM) with both a Continuously Variable Transmission (CVT) and a Single-Speed Transmission (SST) are presented. The system is modeled in MATLAB/Simulink with Field-Oriented Control (FOC), a PI controller, and Space Vector PWM (SVPWM) to ensure fast torque response and stable current regulation. Simulations are performed under the FTP-75 and NEDC driving cycles to evaluate torque response, regenerative braking performance, and battery behavior under varying load conditions. The objective is to compare CVT and SST drivetrains and provide a technical basis for applying CVT in EVs to improve drivetrain efficiency and support sustainable transportation development.

## 2. Materials and Methods

### 2.1. Mathematical Modeling of the Drivetrain System

This section outlines the mathematical models used to simulate the electric vehicle drivetrain, including vehicle dynamics, motor control, and energy regeneration. The model is built modularly, incorporating vehicle dynamics, mechanical power transmission, Permanent Magnet Synchronous Motor (PMSM), field-oriented control (FOC), and regenerative braking. The vehicle's longitudinal dynamics are modeled using Newton's Second Law, with total traction force comprising rolling resistance  $F_{rr}$ , aerodynamic drag  $F_{aero}$ , grade resistance  $F_{grade}$ , and inertial force  $F_{acc}$ . These components are used to describe the linear motion behavior of the vehicle under varying driving conditions.[3]

$$F_{total} = F_{rr} + F_{aero} + F_{grade} + F_{acc} \quad (1)$$

The required motor torque is derived based on the principle of mechanical energy conservation and the rotational lever principle, where the gear ratio adjusts the torque transmitted through the drivetrain  $i$  and the mechanical transmission efficiency  $\eta_{trans}$ . In a CVT (pulley–belt) system, the output torque is inversely proportional to the transmission ratio and the effective pulley radius.

$$T_{out} = \frac{T_{in}}{i} \eta_{trans} \quad (2)$$

where  $T_{out}$  is the output torque (delivered to the wheels or load),  $T_{in}$  is the input torque (provided by the motor),  $i$  is the gear ratio of the CVT (the ratio of the driving pulley radius to the driven pulley radius),  $\eta_{trans}$  is the mechanical efficiency of the transmission system.[4]

The electrical dynamic equations of the PMSM, referenced to the synchronous rotor frame with the d-axis aligned to the rotor flux, are derived by applying the Park transformation, which preserves the magnitude of current and voltage

$$\begin{bmatrix} v_d(t) \\ v_q(t) \end{bmatrix} = R_s \begin{bmatrix} i_d(t) \\ i_q(t) \end{bmatrix} + \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_d(t) \\ i_q(t) \end{bmatrix} + \begin{bmatrix} 0 & -\omega_e L_q \\ \omega_e L_d & 0 \end{bmatrix} \begin{bmatrix} i_d(t) \\ i_q(t) \end{bmatrix} + \lambda_m \begin{bmatrix} 0 \\ \omega_e(t) \end{bmatrix} \quad (3)$$

where  $v_d(t)$ ,  $v_q(t)$ ,  $i_d(t)$ , and  $i_q(t)$  are the time-dependent voltage and current  $dq$  components,  $L_d$  and  $L_q$  are the motor inductance at the  $dq$ -axis,  $\lambda_m$  is the flux linkage due to the spinning of the magnets,  $R_s$  is the winding phase resistance and  $\omega_e(t)$  is the time-dependent electrical speed.[5]

At steady-state conditions, the voltage equations are simplified as

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = R_s \begin{bmatrix} I_d \\ I_q \end{bmatrix} + \begin{bmatrix} 0 & -\omega_e L_q \\ \omega_e L_d & 0 \end{bmatrix} \begin{bmatrix} I_d \\ I_q \end{bmatrix} + \lambda_m \begin{bmatrix} 0 \\ \omega_e \end{bmatrix} \quad (4)$$

where  $V_d$ ,  $V_q$ ,  $I_d$  and  $I_q$  are the non-time-dependent voltage and current  $dq$  components,  $\omega_e$  is the non-time-dependent electrical speed [5].

The connection between the mechanical and electrical speeds in a Permanent Magnet Synchronous Motor is represented as

$$\omega_m = \frac{\omega_e}{P} \quad (5)$$

where  $\omega_m$  is the mechanical speed, and  $P$  is the pair of poles of the electric machine.

The electromagnetic torque ( $T_e$ ) is expressed as

$$T_e = \frac{3}{2}p[\lambda_m I_q + (L_d - L_q)I_d I_q] \quad (6)$$

At high rotor speeds, the back electromotive force (EMF) can exceed the inverter's voltage limit. To address this, flux weakening is applied by setting the d-axis current  $i_d < 0$ . This adjustment is guided by the Pythagorean relationship of voltage vectors in the  $dq$  reference frame and the inverter's linear voltage constraint. Optimal values of  $i_d$  and  $i_q$  under flux weakening are determined by solving nonlinear constraints numerically. These computations are implemented in Simulink using Embedded MATLAB Function blocks.[6]

$$V_{max}^2 \geq V_d^2 + V_q^2 \quad (7)$$

The brake regeneration energy can be calculated by the following formula.

$$E_{re} = \int \frac{F_{bm} \cdot v}{\eta} dt \quad (8)$$

where  $v$  represents the vehicle's speed, and  $\eta$  is the energy transfer efficiency within the Braking Energy Recovery System (BERS), which can be influenced by factors such as the battery's state of charge and ambient temperature. In general,  $\eta = 0.85 \sim 0.94$ . [7]

To evaluate the energy savings provided by the Braking Energy Recovery System in pure electric vehicles during deceleration and braking, the regenerative braking energy is expressed in terms of energy per 100 kilometers. The formula is as follows:

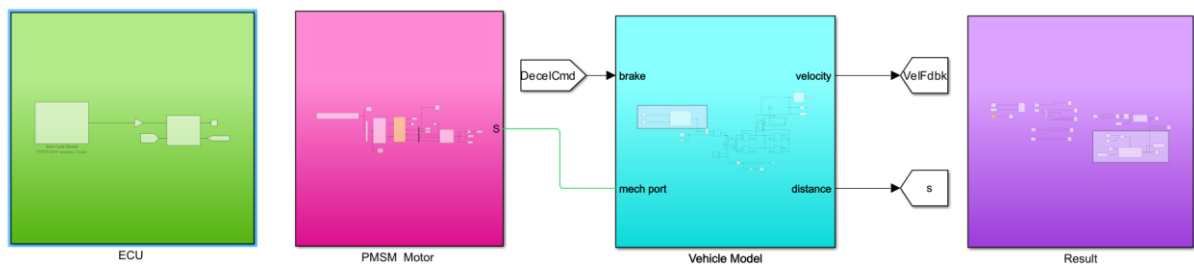
$$R = \frac{E_{re}}{d_{dec}} \cdot 100 \quad (9)$$

where  $R$  is the braking regenerative energy (presented in the form of energy per hundred kilometers) and is the vehicle deceleration braking distance.[7]

The battery state of charge is updated based on the battery's stored energy:[8]

$$SOC(t) = SOC(t_0) - \frac{1}{C_{bat}} \int_{t_0}^t I_{battery}(t) dt \quad (10)$$

## 2.2. System Modeling and Simulation in MATLAB/Simulink



**Figure 1.** Block Diagram of the Electric Vehicle Powertrain Simulation Model.

The electric vehicle drivetrain simulation model was developed on the MATLAB/Simulink platform to evaluate system performance under urban driving conditions using a compact EV configuration. The overall system architecture is illustrated in Figure 1, which integrates the ECU, PMSM motor, vehicle dynamics, and result-processing modules. Velocity profiles from the NEDC and WLTC cycles serve as reference inputs for the torque control unit. A detailed PMSM—whose electrical and mechanical characteristics are listed in Table 1—is controlled through Field-Oriented Control (FOC) in the rotating dq reference frame, enabling independent regulation of  $i_d$  and  $i_q$  currents for precise torque control. Real-time feedback of motor current and rotor speed ensures stable and efficient operation under varying load conditions. A regenerative braking system is also integrated, with the braking controller modulating regenerative current according to the battery's state of charge and charging limits specified in Table 2, thereby enhancing energy recovery while preserving battery health and extending the lifespan of the energy storage system.

**Table 1.** Simulation parameters for small electric vehicle motor.

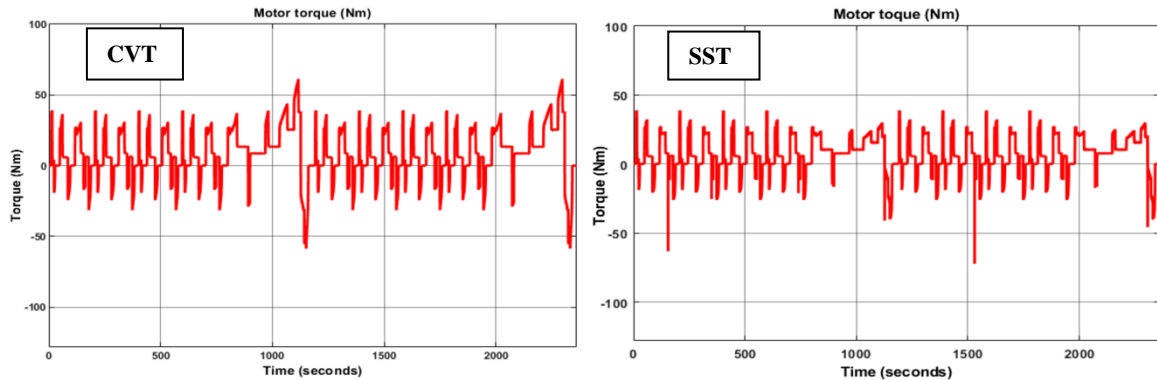
Parameter	Value	Description
$P_{max}$	30 kW	Maximum power of the motor
$P_e$	15 kW	Nominal power of the motor
$T_{max}$	110 Nm	Maximum torque
$T$	55 Nm	Nominal torque
$W_e$	1000 rpm	Nominal speed of the motor
$\omega_{max}$	8000 rpm	Maximum rotational speed of the motor
$L_d$	0.0008524 H	Stator d-axis inductance
$L_q$	0.0009515 H	Stator q-axis inductance
$R_s$	0.0152 $\Omega$	Phase resistance of the stator
$\lambda$	0.173 V·s	Permanent magnet flux linkage
$P$	4	Number of pole pairs
$J$	0.0048 kgm <sup>2</sup>	Rotor moment of inertia
$F$	0.008 Nms	Viscous friction coefficient
$V_{dc}$	358.4 V	The DC bus voltage from the inverter
$I_{max}$	150 A	Maximum allowable current

**Table 2.** Battery specifications (LFP Type).

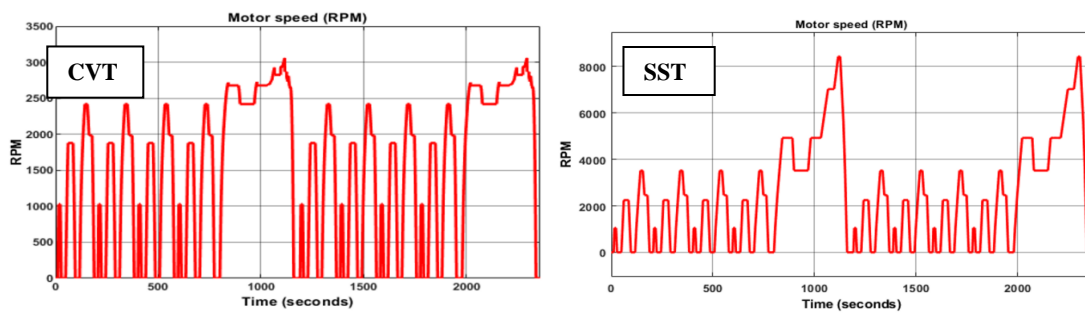
Parameter	Value
<b>Battery type</b>	LFP
$V_{nominal}$	358.4 V
<b>Maximum capacity</b>	52.02 Ah
<b>Cut-off voltage</b>	280 V
<b>Fully charged voltage</b>	450 V
<b>Nominal discharge current</b>	42 A
<b>Internal resistance</b>	0.07 $\Omega$
<b>Usable capacity at nominal voltage</b>	50 Ah
<b>Exponential zone</b>	[380 V 10 Ah]

### 3. Results and Discussion

#### 3.1. Simulation Results for the NEDC Driving Cycle

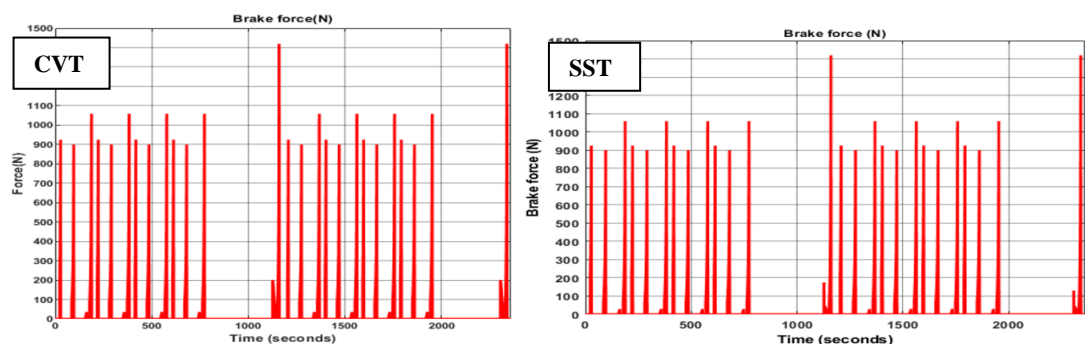


**Figure 2.** Comparison of torque responses between SST and CVT configurations under the NEDC driving cycle.



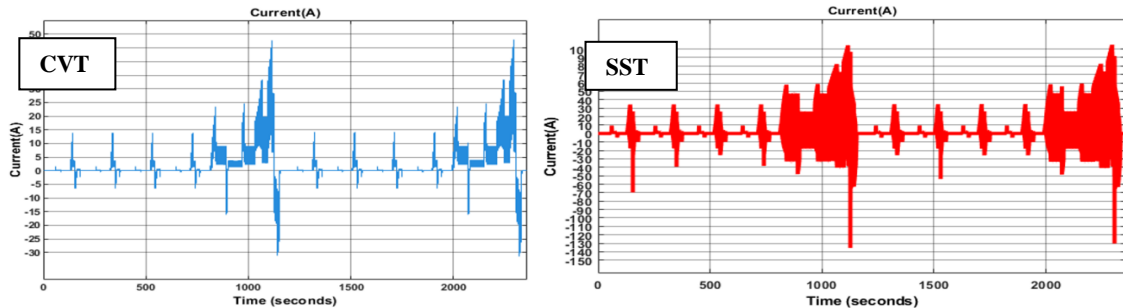
**Figure 3.** Motor speed profiles of SST and CVT configurations during the NEDC cycle.

Under the same NEDC driving cycle conditions, the drivetrain configuration utilizing a SST - a conventional transmission in EV - combination with a PMSM presents noticeably lower operational efficiency when compared to the configuration based on a CVT. This performance gap becomes particularly evident in key performance such as energy regeneration capability, braking force delivery, and the system's ability to maintain the motor within its optimal efficiency range under the different operating conditions. Due to the fixed gear ratio in SST, the motor frequently operates at suboptimal torque-speed points, resulting in increased energy consumption and reduced regenerative energy recovery during deceleration phases. In contrast, the CVT configuration, through its continuously adjustable transmission ratio, enables smoother transitions, maintains closer alignment with the motor's high-efficiency region, and enhances the effectiveness of regenerative braking. Consequently, the SST setup leads to greater fluctuation in motor dynamics and battery SOC, reflecting its limitations in adapting to transient driving conditions, especially under urban-like profiles characterized by frequent acceleration and deceleration events.



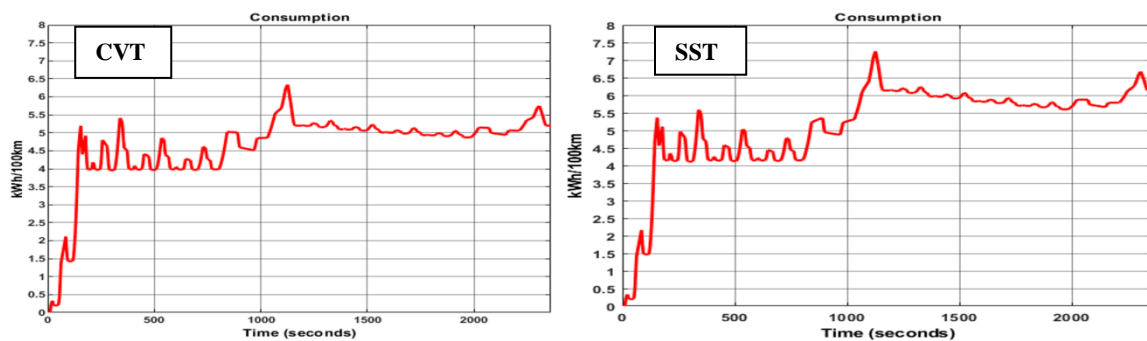
**Figure 4.** Comparison of brake force responses between SST and CVT configurations under the NEDC driving cycle.

**Torque and engine Speed (Figure 2 and 3):** The torque data reveal large oscillations and inconsistent responses throughout the entire driving cycle. Due to the fixed gear ratio operation only, the SST configuration causes the motor to operate at multiple points outside its optimal efficiency region. The RPM figure indicates that the fluctuation amplitude is approximately 18% higher compared to the CVT configuration.

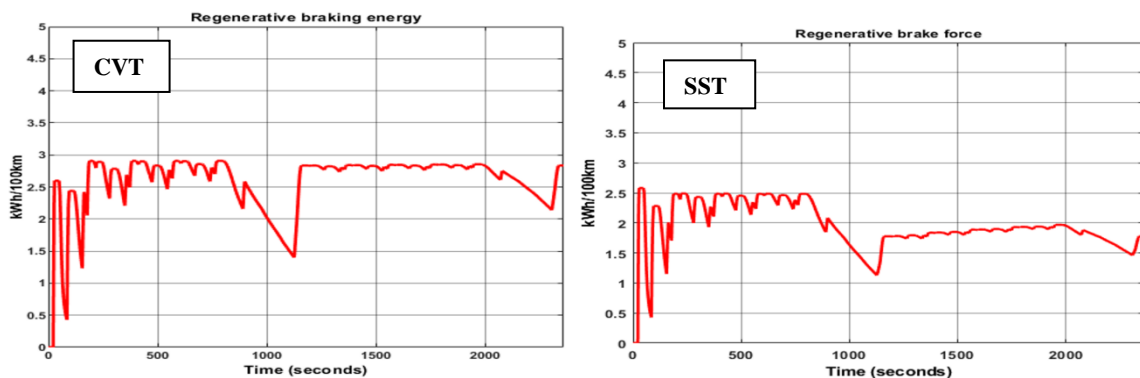


**Figure 5.** Regenerative braking current profiles of SST and CVT configurations during the NEDC cycle.

**Regenerative Braking Current and Force (Figure 4 and 5):** In the CVT and PMSM configuration, the peak regenerative braking current reaches approximately 42A, and the corresponding regenerative braking force reaches around 980N. In contrast, the SST configuration yields a peak braking current of approximately 34A, which is about 19% lower than that of the CVT. The regenerative braking force only reaches 790N, representing a reduction of approximately 19.4%. This indicates a significantly lower ability to recover kinetic energy, particularly during light braking or short deceleration phases.



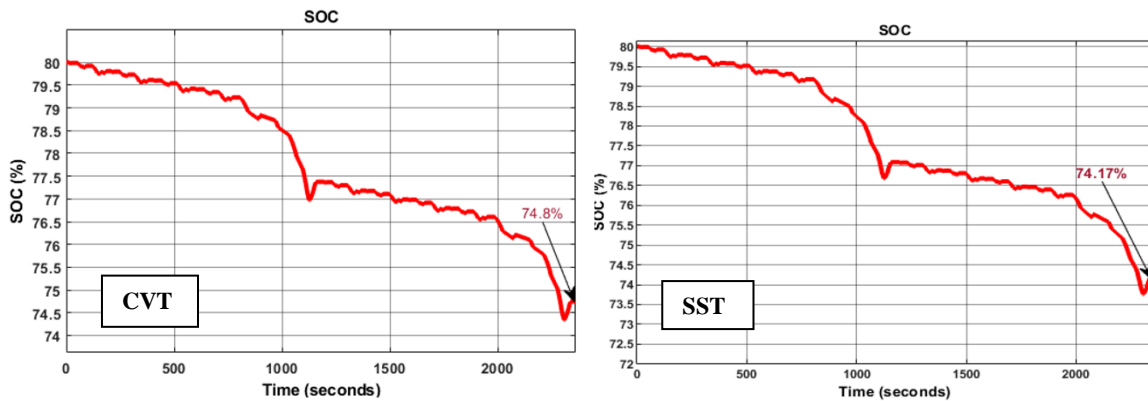
**Figure 6.** Comparison of total energy consumption between CVT and SST configurations under the NEDC driving cycle.



**Figure 7.** Regenerative energy profiles showing superior energy recovery performance of the CVT configuration compared to SST during the NEDC cycle.

**Regenerated and Energy Consumption (Figure 6 and 7):** In the CVT and PMSM configuration, the total regenerated energy reaches approximately 3.21MJ, while the total energy consumption remains at around 11.74MJ. These values indicate high system efficiency and effective utilization of regenerative brake under urban driving conditions. In comparison, the total regenerated energy in the SST configuration is approximately 2.60MJ, which is 23.4% lower than that of the CVT setup. Additionally,

the total energy consumption increases to about 13.33MJ, representing an 11.9% rise, clearly reflecting energy losses caused by the motor operating outside its optimal efficiency range.



**Figure 8.** SOC profiles showing more stable charge retention and better regenerative recovery in the CVT configuration compared to SST during the NEDC cycle.

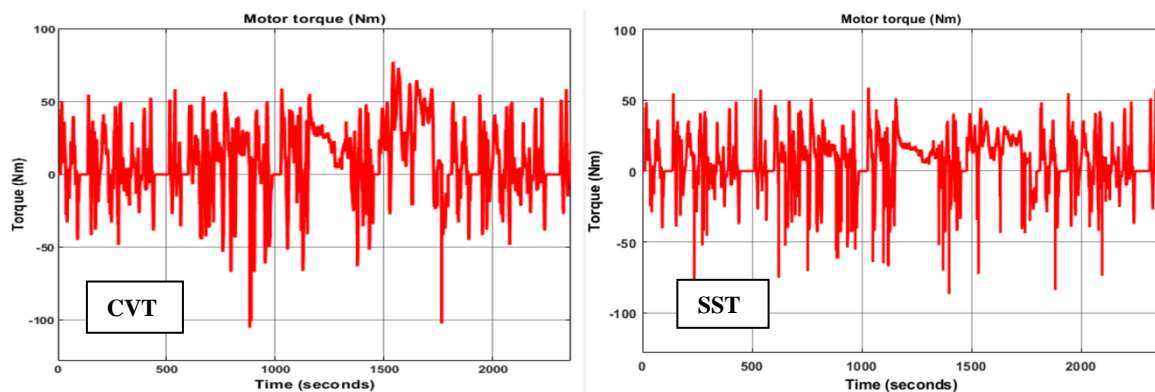
**State of Charge (Figure 8):** The CVT configuration helps maintain a more stable SOC, with noticeable recovery during braking phases, thereby reducing stress on battery discharge. In contrast, the SOC curve for the SST configuration shows a deeper decline with no significant recovery during deceleration periods. The total SOC drop is approximately 6.5% greater compared to the CVT, indicating that the regenerative energy is insufficient to offset consumption.

**Table 3.** Comparison performance between CVT and SST configurations for the NEDC Cycle.

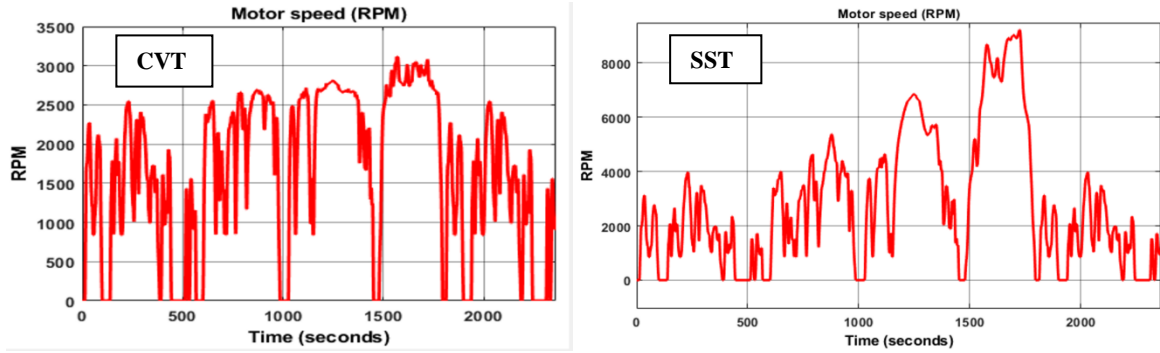
Parameter	CVT	SST	Performance Evaluation with CVT
Energy Consumption (MJ)	11.74	13.33	-11.9%
Regenerated Energy (MJ)	3.21	2.60	+23.4%
Peak Regenerative Braking Current (A)	~42	~34	+19.0%
Peak Regenerative Braking Force (N)	~980	~790	+19.4%
SOC Fluctuation	Low, stable	Wide, deep drop	SST is less efficient in charge retention

### 3.2. Simulation Results for the WLTC Driving Cycle

The simulation results of the PMSM combined with SST configuration reveal significant limitations when compared to the configuration using a CVT and a PMSM under the same WLTC driving cycle. The following technical indicators highlight the performance gap between the two configurations.

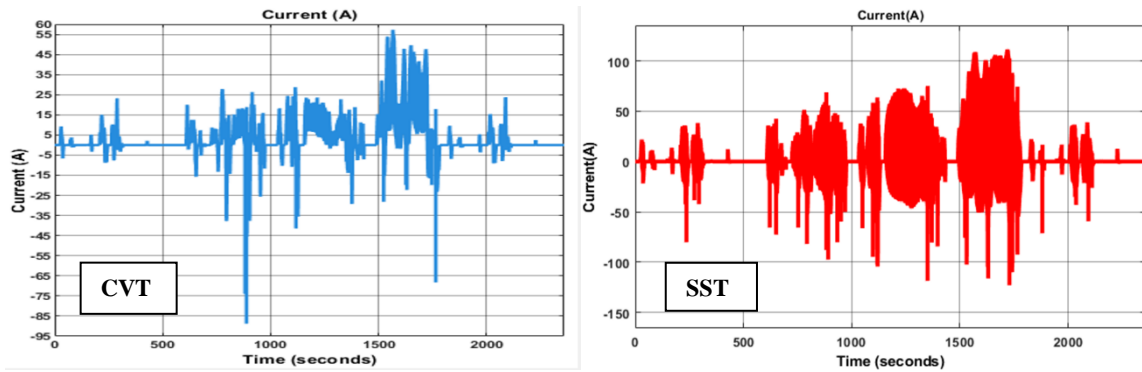


**Figure 9.** Comparison of torque responses between SST and CVT configurations under the WLTC driving cycle.

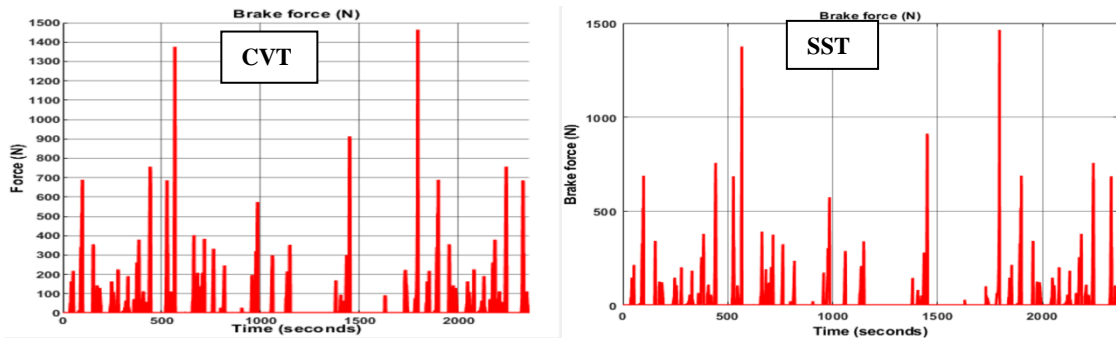


**Figure 10.** Motor speed profiles of SST and CVT configurations during the WLTC cycle.

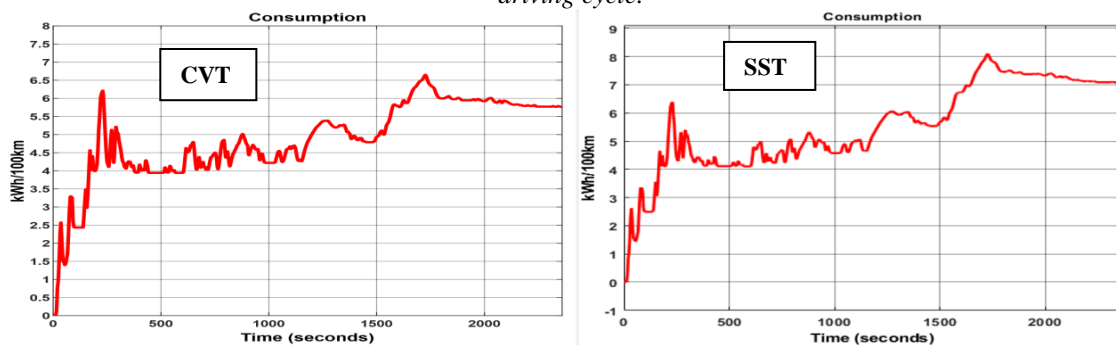
**Torque and engine Speed (Figure 9 and 10):** In the SST configuration, torque exhibits large fluctuations and inconsistent responses, particularly during rapid acceleration and deceleration phases. The RPM varies significantly due to the inability to maintain motor operation within its optimal efficiency range. In contrast, the CVT configuration enables more stable torque delivery and smoother RPM behavior, thanks to its continuously adjustable gear ratio.



**Figure 11.** Regenerative braking current profiles of SST and CVT configurations during the WLTC cycle.

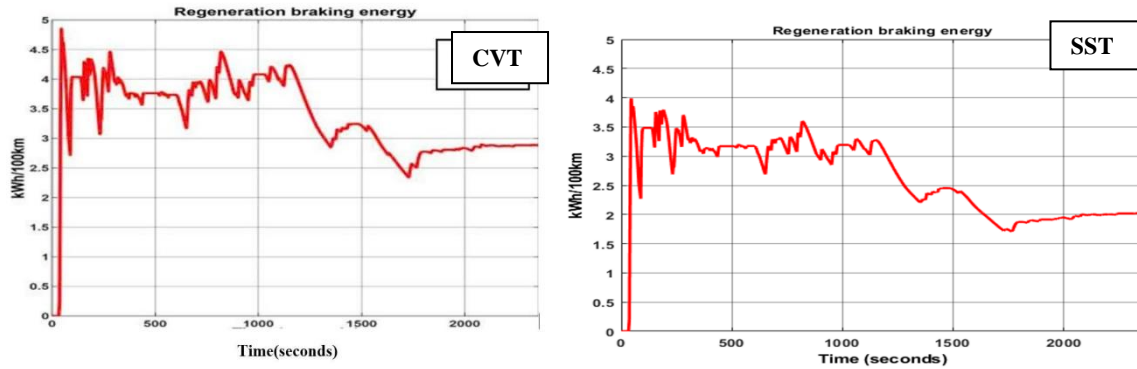


**Figure 12.** Comparison of brake force responses between SST and CVT configurations under the WLTC driving cycle.



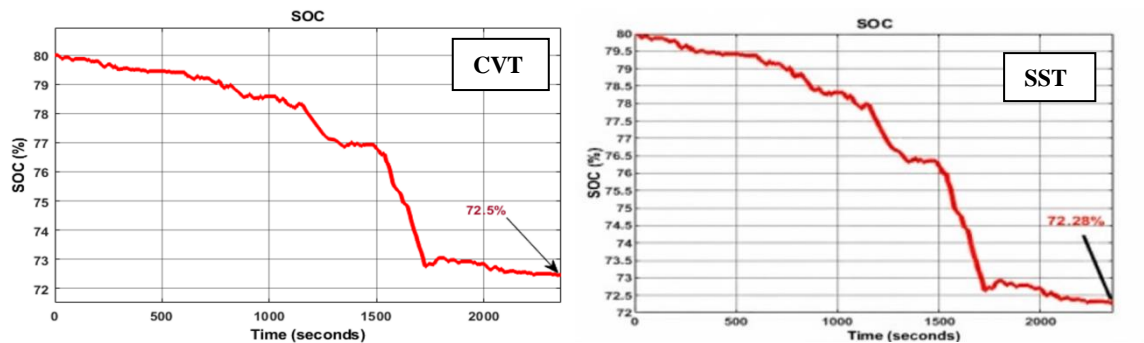
**Figure 13.** Comparison of total energy consumption between CVT and SST configurations under the WLTC driving cycle.

**Regenerative Braking Current and Force (Figure 11 and 12):** The SST configuration registers a 22.6% lower regenerative current compared to the CVT under identical deceleration conditions, with a peak current of approximately 38A versus 49A. The regenerative braking force is also reduced by approximately 19.8%, indicating limited energy recovery capability due to the motor’s inability to synchronize effectively with deceleration demands.



**Figure 14.** Regenerative energy profiles showing superior energy recovery performance of the CVT configuration compared to SST during the WLTC cycle.

**Regenerated and Energy Consumption (Figure 13 and 14):** The total regenerated energy of the SST configuration reaches only ~2.94MJ, while the CVT configuration recovers up to ~3.72MJ, representing an increase of approximately 26.5%. At the same time, the SST configuration consumes ~14.6MJ, which is 13.6% higher than that of the CVT (~12.86MJ), indicating a lower overall drivetrain efficiency.



**Figure 15.** SOC profiles showing more stable charge retention and better regenerative recovery in the CVT configuration compared to SST during the WLTC cycle.

**State of Charge (Figure 15):** In the SST model, SOC decreases almost monotonically with negligible recovery after braking. In contrast, the CVT case presents several short plateaus/shallow-slope segments, suggesting improved charge retention under favourable regenerative conditions. By the end of the cycle, the terminal SOC is ~72.5% (CVT) versus ~72.28% (SST). Assuming an initial SOC near 80%, this corresponds to drops of ~7.5 and 7.72 percentage points, respectively—i.e., the CVT reduces the SOC drop by about 0.22 percentage points ( $\approx 2.8\%$  lower relative drop) compared to the SST.

**Table 4.** Comparison performance between CVT and SST for the WLTC Driving Cycle.

Parameter	CVT	SST	Performance Evaluation with CVT
Energy Consumption (MJ)	12.86	14.60	-13.6%
Regenerated Energy (MJ)	3.72	2.94	+26.5%
Peak Regenerative Braking Current (A)	~49	~38	+22.6%
Peak Regenerative Braking Force (N)	~1060	~890	+19.8%
Final SOC Drop (%)	~14.7%	~13.7%	+2.8%

#### 4. Conclusions

This study developed a comprehensive simulation model of an electric vehicle drivetrain using a Permanent Magnet Synchronous Motor (PMSM) combined with either a Single-Speed Transmission (SST) or a Continuously Variable Transmission (CVT). Simulations were carried out under the NEDC and WLTC driving cycles to assess energy efficiency and regenerative braking capability, with detailed numerical comparisons reported in Table 3 for the NEDC cycle and Table 4 for the WLTC cycle.

As shown in Table 4, under WLTC conditions the CVT reduces total energy consumption from 14.60 MJ (SST) to 12.86 MJ and increases regenerated energy from 2.94 MJ to 3.72 MJ, corresponding to improvements of 13.6% and 26.5%, respectively. Similarly, Table 3 indicates that under NEDC conditions the CVT decreases energy consumption from 13.33 MJ (SST) to 11.74 MJ and raises regenerated energy from 2.60 MJ to 3.21 MJ, improving efficiency by 11.9% and regenerative performance by 23.4%. In both cycles, the CVT helps maintain the motor closer to its optimal operating region, resulting in smoother torque and speed responses and improved driving dynamics. It also supports more stable battery state-of-charge (SOC) behavior, as reflected by the reduced SOC drop values reported alongside the regenerative metrics in both tables.

Overall, the results in Table 3 and Table 4 confirm that integrating a CVT enhances drivetrain efficiency, regenerative braking effectiveness, and adaptability to variable driving conditions, making it a promising approach for future electric vehicle powertrain development.

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#### Conflict of Interest

The authors declare no conflict of interest.

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