APPLICATION OF SIMCENTER AMESIM IN MODELING AND EVALUATING THE EFFECTIVENESS OF BRAKE BLENDING STRATEGIES ON ELECTRIC VEHICLES

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ABSTRACT

Regenerative Braking technology is the key to improving energy efficiency on electric vehicles. However, managing the interaction between the regenerative braking system and the traditional mechanical braking system requires complex Brake Blending strategies to ensure safety and dynamic stability. This paper applies the 1D system simulation method on Simcenter Amesim software to investigate the operating characteristics of a commercial electric vehicle model (based on Tesla Model 3 specifications). Three brake blending strategies, namely Series (energy optimization), Parallel (simplified control), and Hybrid (balanced), were modeled and evaluated for performance through simulation scenarios. The research results indicate a substantial difference in energy recovery efficiency among the strategies (ranging from ~23.7% to ~69.7%), while simultaneously highlighting the trade-off between control system complexity and practical operational performance. This study provides valuable reference parameters for selecting appropriate brake energy management solutions tailored to specific electric vehicle segments.

Keywords: *Electric vehicle, regenerative braking, brake blending, system simulation, Simcenter Amesim, energy management.*

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1. INTRODUCTION

The rapid proliferation of the electric vehicle (EV) market necessitates the urgent optimization of energy efficiency to mitigate driving range anxiety per charge cycle [1, 7]. Regenerative Braking technology - the process wherein the electric motor operates in the second quadrant (generator mode) to convert the vehicle's kinetic energy into electrical energy and recharge the battery pack - serves as the fundamental key to enhancing global energy efficiency [10]. However, due to stringent physical constraints, including the peak charging power of the battery (which is highly dependent on the State of Charge - SOC and temperature), the non-linear characteristic curve of electromagnetic torque, and the degradation of braking capacity at extremely low-speed ranges [12], the regenerative braking system cannot function independently. To ensure that the actual braking force seamlessly tracks the driver's deceleration demand while maintaining absolute active safety, regenerative braking must be meticulously integrated with the conventional Electro-Hydraulic Brake (EHB) system [9].

The process of dynamically sharing and allocating the driver's instantaneous braking torque demand into these two force components (electro-mechanical and hydraulic) is defined as cooperative control or brake blending [2, 8]. Synthesizing an optimal brake blending strategy constitutes a highly complex multi-objective control problem. The torque allocation algorithm must flawlessly manage the trade-off among three conflicting objectives: (i) Maximizing the amount of recovered electrical energy [10]; (ii) Guaranteeing longitudinal and lateral vehicle dynamics stability, preventing wheel lock-up, and ensuring seamless coordination with active safety systems such as ABS (Anti-lock Braking System) and ESC (Electronic Stability Control) [13, 14]; and (iii) Executing rapid torque compensation to deliver a natural brake pedal feel, eliminating any driveline jerk or torque discontinuity for the driver [4, 11].

Within the modern automotive product development lifecycle - particularly under the Model-Based Systems Engineering (MBSE) paradigm - 1D multi-physics system simulation serves as an indispensable foundational tool for the preliminary analysis and validation of control algorithms during the concept phase [15]. The Siemens Simcenter Amesim software platform demonstrates superior capabilities through its advanced co-simulation architecture, enabling the precise computation of multi-physical domain interactions: spanning chassis longitudinal dynamics, fluid power (hydraulics), electromagnetism (electric motors and battery packs), and complex control logic signals. This paper leverages the robust computational power of Simcenter Amesim to construct a comprehensive plant model of a commercial electric vehicle (parameterized based on Tesla Model 3 specifications). Consequently, the study conducts in-depth simulations to investigate and quantitatively benchmark the operational characteristics of three typical brake blending strategies.

2. THEORETICAL BASIS

To build and verify Brake Blending Strategies within the Simcenter Amesim environment, the first step is to accurately establish the longitudinal force balance equation. The energy recovery capability of an EV depends entirely on the "surplus" kinetic energy after overcoming natural resistance forces.

The general equation describing motion resistance (RRL) consists of three main components: Aerodynamic Drag, Rolling Resistance, and Grade Resistance.

2.1. Aerodynamic Drag

In EV simulation, aerodynamics not only affects energy consumption but also acts as a nonlinear "natural braking force," particularly important at high-speed ranges. When a vehicle moves through the air, it is subjected to dynamic pressure and surface friction. This drag force is proportional to the square of the vehicle velocity.

$$D_A = \frac{1}{2}\rho V^2 C_D A \tag{1}$$

Where: ρ is the air density, C_D is the aerodynamic drag coefficient (usually very low in EVs to optimize range), A is the frontal area, and V is the vehicle velocity.

Significance for braking strategy: At high speeds, D_A creates a large braking force. The regenerative braking control algorithm must account for this force to avoid generating an excessive total braking torque, causing abrupt deceleration (jerk) for the driver.

2.2. Rolling Resistance

For electric vehicles, rolling resistance accounts for a significant proportion of total resistance due to the heavy mass of the battery pack increasing pressure on the road surface. This force is generated mainly due to hysteresis in the tire rubber material as it undergoes continuous deformation under load.

$$R_x = f_r W \tag{2}$$

where W is the vehicle weight and f_r is the rolling resistance coefficient. In high-fidelity system simulation, f_r is not a constant but a function dependent on velocity (f_r increases as velocity increases) and tire pressure.

Significance for braking strategy: At low-speed ranges (where aerodynamic drag is negligible), rolling resistance is the main energy consumption component. The braking strategy needs to precisely manage the transition phase when the vehicle is nearing a stop, where regenerative braking efficiency drops and rolling resistance plays a major role in bringing the vehicle to a standstill.

2.3. Grade Resistance

This is the most critical variable component determining energy recovery potential. It is the component of gravity acting along the vehicle's longitudinal axis when moving on an incline.

$$R_g = W \sin \Theta \tag{3}$$

Significance for braking strategy: When driving downhill, Rg takes a negative value (becoming a propulsive force), and potential energy is converted into kinetic energy. This is the ideal scenario for regenerative braking to operate at high power to maintain a stable speed without using mechanical brakes.

Synthesizing the above factors, the longitudinal force balance equation at the vehicle's center of gravity is established in the Simcenter Amesim model as follows:

$$M_{eff}\frac{dV}{dt} = F_{total\_braking} - (D_A + R_x + R_g) \tag{4}$$

Where, $F_{total\_braking}$ is the sum of two force sources that this study needs to optimize:

- Regenerative Braking Force (F_{regen}): Generated from the Electric Motor (acting as a generator), limited by motor power, battery state (SOC, temperature), and tire grip.

- Friction Braking Force ($F_{friction}$): Generated from the hydraulic system, used to compensate for the deficit during emergency braking or when F_{regen} is limited.

The study will use the above resistance models as a "virtual environment" to verify which blending strategy will recover the most energy into the battery while still ensuring the vehicle stops within a safe distance according to defined physical laws.

3. BUILDING THE SIMULATION MODEL

In this study, parameters based on the Tesla Model 3 vehicle are used as shown in Table 1.

Table 1. Tesla Model 3 Specifications

Parameter	Value	Unit	Parameter	Value	Unit
Gross Vehicle Weight	2192	kg	Battery pack nominal energy	60	kWh
Curb weight (unloaded)	1760	kg	Battery pack nominal voltage	345	V
Rolling resistance coefficient	0.007	-	Cell nominal capacity	5	Ah
Frontal area	2.22	m^2	Cell nominal voltage	3.7	V
Aerodynamic drag coefficient	0.23	-	Motor nominal power	100	kW
Transmission ratio	9.03	-	Motor peak power	194	kW
Tire radius	0.334	m	Motor peak torque	340	Nm
Tire width	255	mm	Motor nominal speed	6000	rev/min
Tire height ratio	40	%	Motor maximum speed	18000	rev/min
Rim diameter	457.2	mm	Motor nominal efficiency	96	%

A single-motor Rear-Wheel Drive (RWD) electric vehicle model has been developed on the Simcenter Amesim platform, utilizing dedicated libraries such as Vehicle Dynamics, Electric Motors and Drives, and Signal, Control. This specific driveline configuration dictates the system's torque allocation logic: the entirety of the regenerative braking torque (T_{regen}) is exclusively controlled and applied to the rear axle, whereas the front axle relies solely on hydraulic friction braking torque ($T_{friction}$). The model comprises the main subsystems as illustrated in Figure 1.

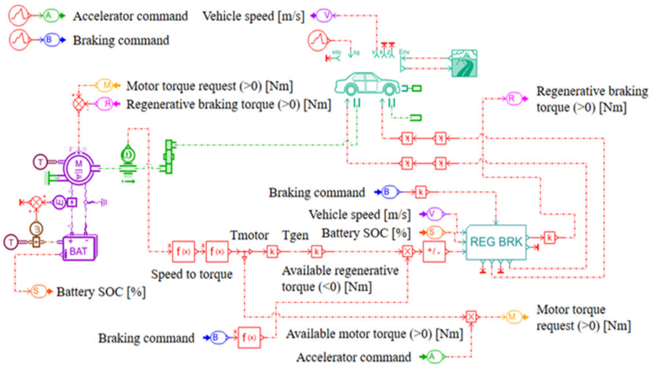

Figure 1. Diagram of the electric vehicle system simulation with brake blending controller

- Electric Drive System: Includes the electric motor model (PMSM) and Li-ion battery pack. The torque/speed limit characteristics of the motor, including the constant torque region and constant power region (flux weakening), are defined based on motor technical specifications [1], as shown in Figure 2. Regenerative braking capability (T_{gen}) is limited by the battery charging power.

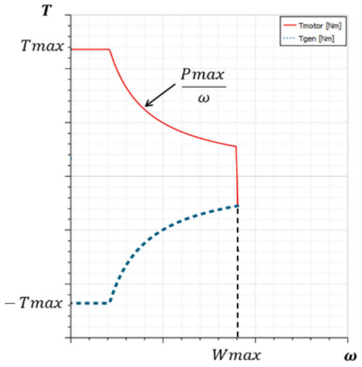

Figure 2. Motor torque/speed limit characteristics in traction and regeneration modes

- Vehicle and Tires: Uses blocks from the Vehicle Dynamics library to simulate vehicle dynamics, based on vehicle dynamics principles described by Gillespie [5]. Tire-road interaction is modeled using the Pacejka Magic Formula [6].
- Brake Blending Controller (REG BRK): This is the central component of the study, modeled using the Signal, Control library. This controller receives the braking demand signal from the driver and vehicle states (speed, SOC, regeneration capability) to calculate and distribute regenerative braking torque and friction braking torque to each wheel.

4. BRAKE BLENDING STRATEGIES

Three brake blending strategies, based on common industry classifications [3, 4], have been implemented and investigated within the model.

In the control unit setup (utilizing the Signal, Control library), the total driver's requested braking torque (T_{req}) is initially distributed between the front axle (T_{req_F}) and the rear axle (T_{req_R}) according to a fixed static split ratio β ($\beta = 60\%$ for the front, 40% for the rear). This simplifies the baseline process, adhering to the static ideal braking force distribution curve. Due to the RWD (Rear-Wheel Drive) configuration, the regenerative braking torque (T_{regen}) is exclusively applied to the rear axle and is continuously bounded by the motor/battery capacity limits $T_{gen\_max}(\omega, SOC)$. The specific strategies are as follows:

Series Strategy: Maximizes the utilization of regenerative braking. Friction (hydraulic) braking is only activated when the braking demand exceeds the regeneration capacity of the electric motor.

Allocation logic equations:

Rear axle: $T_{regen} = \min(T_{req\_R}, T_{gen\_max})$;

$$T_{fric\_R} = T_{req\_R} - T_{regen}$$

Front axle: $T_{fric\_F} = T_{req\_F}$ (Purely hydraulic).

Parallel Strategy: Both regenerative and friction braking are activated simultaneously upon brake pedal application. The ratio between them at the driven axle is a constant k (set to $k = 50\%$ in the simulation).

Allocation logic equations:

Rear axle: $T_{regen} = \min(k \cdot T_{req\_R}, T_{gen\_max})$;

$$T_{fric\_R} = T_{req\_R} - T_{regen}$$

Front axle: $T_{fric\_F} = T_{req\_F}$.

Hybrid Strategy: Combines the two aforementioned strategies, utilizing the brake pedal stroke Z_{brk} as an input signal to route the control logic:

Light braking ($Z_{brk} \leq 20\%$): This threshold represents low deceleration scenarios (under ~0.2g). The system operates under the Series strategy, where the rear axle braking torque is fully fulfilled by T_{regen} to maximize energy recovery.

Heavy braking ($Z_{brk} > 20\%$): The system transitions the logic block to the Parallel strategy. The friction brake T_{fric_R} is immediately blended with T_{regen} via a linear mapping to rapidly respond to large deceleration gradients, preventing wheel lock-up and ensuring vehicle dynamic stability.

5. RESULTS AND DISCUSSION

A simulation scenario was conducted: the vehicle is traveling at an initial velocity of 60km/h, the battery State of Charge (SOC) is initialized at 80%, and the driver applies a ramp braking command increasing from 0% to 100% over a 5-second duration.

Figures 3 ÷ 5 illustrate the braking torque allocation results for each strategy. Specifically, these output signals precisely validate the control algorithms established in Section 4:

Figure 3 (Series): The plot demonstrates that the regenerative torque response curve (T_{regen}) perfectly tracks the braking demand during the initial phase. Only when T_{regen} reaches the saturation limit imposed by the peak power constraints of the motor/battery (indicated by the plateau region of the curve), is the hydraulic valve control signal triggered, causing the friction torque (T_{fric_R}) to increase for error compensation. This verifies the absolute priority given to energy recovery.

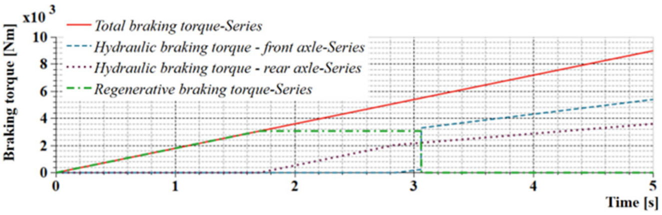

Figure 3. Distribution of regenerative and friction braking torque over time for Series braking strategy

Figure 4 (Parallel): In contrast to the Series strategy, the graph reflects a simultaneous ramp-up of both T_{regen} and T_{fric_R} right from the onset ($t = 0$). The two characteristic curves exhibit constant gradients, verifying that the static split ratio (coefficient k) operates exactly as designed. This early hydraulic blending results in a peak value of T_{regen} that is significantly lower than the actual capacity of the electrical powertrain.

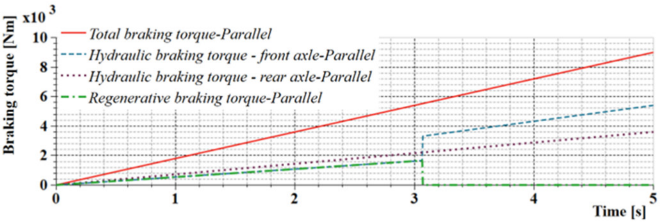

Figure 4. Distribution of regenerative and friction braking torque over time for Parallel braking strategy

Figure 5 (Hybrid): The plot clearly illustrates the non-linear state transition characteristics of the controller. During the initial timeframe, corresponding to a brake pedal stroke $\leq 20\%$, the system exhibits an identical response to the Series strategy ($T_{fric\_R} = 0$). Upon crossing this threshold, the algorithm executes the torque blending process, triggering a sharp increase in T_{fric_R} to share the braking load, thereby securing the high deceleration gradient demanded by the Vehicle Dynamics without overloading the motor.

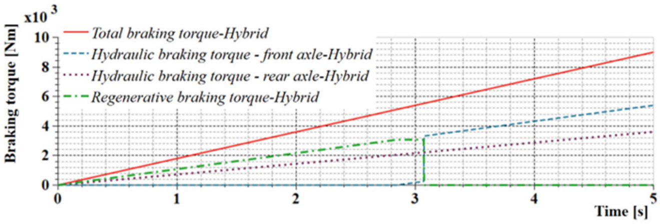

Figure 5. Distribution of regenerative and friction braking torque over time for Hybrid braking strategy

To quantify effectiveness, energy recovery efficiency is calculated using the widely recognized formula [2]:

$$\eta_{reg} = 100\frac{E_{bat}}{E_{kin}}\ (\%) \tag{5}$$

Where E_{bat} is the energy recovered into the battery and E_{kin} is the initial kinetic energy of the vehicle.

The efficiency results are presented in Figure 6.

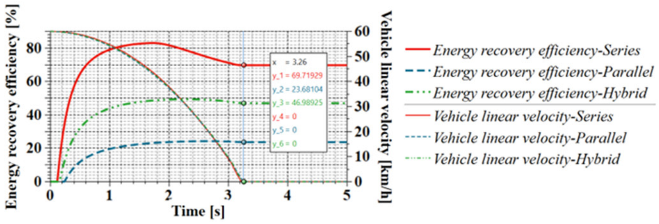

Figure 6. Comparison of energy recovery efficiency of three braking strategies

The results show that the Series strategy achieves the highest efficiency (~69.7%), followed by the Hybrid strategy (~47%), and finally the Parallel strategy with the lowest efficiency (~23.7%). This significant difference affirms the importance of selecting a control strategy. The Series strategy, while most energy-efficient, requires a complex brake-by-wire system and sophisticated control algorithms to ensure smooth brake feel. The Hybrid strategy is a good compromise, balancing energy efficiency and practicality in implementation, thus being most widely applied on modern electric vehicles.

6. CONCLUSION

The study has successfully established a multi-physics system model for electric vehicles on the Siemens Simcenter Amesim platform, fully including subsystems from longitudinal dynamics, tire model (Magic Formula), and electric powertrain to the energy storage unit. This is a reliable platform for quantitatively evaluating the effectiveness of Brake Blending strategies - one of the biggest challenges in EV chassis control.

Based on the simulation results, the following main conclusions are drawn:

- Regarding energy efficiency: The Series Strategy demonstrates absolute superiority with an energy recovery efficiency of ~69.7%, thanks to the ability to maximize regenerative braking characteristics before friction braking intervention. The Hybrid strategy reaches an average level of ~47%, while the Parallel strategy reaches only ~23.7% due to the early and fixed participation of friction braking.

- Regarding practical applicability: Although the Series strategy delivers the highest energy efficiency, it requires complex hardware systems (usually requiring full Brake-by-Wire technology) and sophisticated control algorithms to ensure a smooth blending process, avoiding shock to the driver. The Hybrid strategy presents itself as the best trade-off solution between efficiency and implementation cost for current commercial vehicle lines.

- Future development: The Simcenter Amesim model built in this study is highly scalable. Future studies can expand to integrate a Battery Thermal Model to evaluate regenerative charging current limits based on temperature, or investigate the impact of battery State of Health (SOH) on braking strategy, aiming to comprehensively optimize the Energy Management System (EMS) on electric vehicles under harsh real-world operating conditions.

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