Hybrid Battery-Diesel Strategy for Reducing Fuel Dependence in Diesel-Electric Locomotives

Lawrence Nizah Mutambo
School of Electrical Engineering
Southwest Jiaontong University
Chengdu, China
nizahlm@gmail.com

Jewad Mohammed Sadik
School of Electrical Engineering
Southwest Jiaontong University
Chengdu, China
jewadsadik@gmail.com

Wei Wenfu
School of Electrical Engineering
Southwest Jiaontong University
Chengdu, China
wfwei@home.swjtu.edu.cn

***Abstract*-Diesel-electric locomotives remain the backbone of freight rail transport in Zambia. However, ageing fleets operating under low-speed duty cycles suffer from high fuel consumption and inefficient dissipation of braking energy. This paper investigates a battery-assisted hybridization strategy focused on regenerative braking energy recovery for Zambia Railways Limited (ZRL) diesel-electric locomotives operating along the 890 km Kitwe–Livingstone corridor. A MATLAB/Simulink co-simulation framework integrating traction demand, route gradients, battery dynamics, diesel fuel mapping, and a rule-based energy management strategy is developed and calibrated to ZRL operating conditions. A 7.5 MWh lithium iron phosphate (LFP) Battery Energy Storage System (BESS) installed on a tender wagon is evaluated based on realistic regenerative energy availability and State-of-Charge constraints. Simulation results indicate that regenerative braking capture and traction power smoothing reduce diesel fuel consumption by 15.4% per trip. The associated fuel cost savings demonstrate economic viability under conservative assumptions and can be reinvested into rail infrastructure and rolling stock maintenance, supporting improved operational reliability. The findings show that regenerative hybridization alone offer a practical, infrastructure-light pathway for improving energy efficiency and reducing fuel dependence on moderate-gradient freight corridors in developing railway networks.**

Keywords—Diesel-Electric Locomotives, Battery Energy Storage (BESS), Traction Energy Recovery, Hybrid Locomotive Retrofit, Regenerative Braking, Energy Management System, MATLAB/Simulink.

I. INTRODUCTION

Rail freight transport remains a strategic component of Zambia's logistics and economic infrastructure, providing a critical link between the Copperbelt mining region and southern export corridors through the 890 km Kitwe–Livingstone mainline operated by Zambia Railways Limited (ZRL). Despite its importance in transporting copper, coal, cement, and agricultural commodities, ZRL continues to rely heavily on ageing diesel-electric locomotives, including the GT36CU, U20C, and U15C series, many of which have exceeded three decades of service. These locomotives operate predominantly under low-speed freight duty cycles (typically 20–30 km/h) and moderate gradients, conditions under which fuel efficiency is inherently limited and braking energy is routinely dissipated through resistor grids [1], [2], [3]. Fig. 1 illustrates a representative elevation and gradient profile.

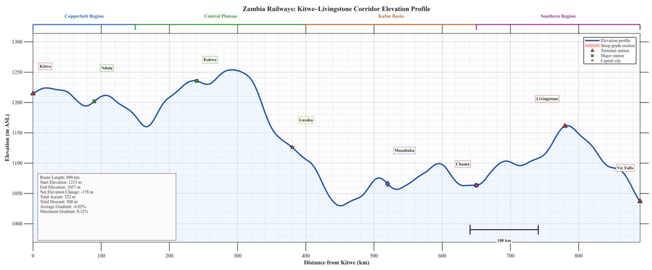

Fig. 1. Representative gradient profile for the Kitwe-Livingston

Hybridization of diesel-electric locomotives using onboard Battery Energy Storage Systems (BESS) has emerged as a practical approach for improving energy efficiency without requiring full network electrification. By capturing regenerative braking energy and smoothing traction power demand, BESS-assisted hybrid locomotives can reduce fuel consumption, emissions, and mechanical stress on diesel engines [4]-[7]. Previous studies have reported fuel savings ranging from 10% to over 30%, depending on route characteristics, braking intensity, and control strategy, particularly in electrified railways, steep-gradient corridors, or newly designed hybrid platforms [8]-[11].

However, the applicability of these findings to developing railway networks operating under moderate gradients and low-speed freight conditions remains insufficiently explored. In particular, limited research has quantified the realistic regenerative braking potential achievable on long-haul, non-electrified freight corridors such as ZRL's Kitwe–Livingstone route, where braking events are less intense and more dispersed than in mountainous or urban rail systems [5] [12]. As a result, the extent to which regenerative hybridization alone can deliver meaningful fuel savings under such operating conditions is not well established.

This paper addresses this gap by developing a MATLAB/Simulink-based co-simulation framework tailored to ZRL operating conditions, integrating traction demand, route gradients, regenerative braking behavior, battery dynamics, and diesel fuel consumption mapping. A 7.5 MWh lithium iron phosphate (LFP) Battery Energy Storage System (BESS), installed on a tender wagon, is evaluated with emphasis on regenerative energy recovery and traction power smoothing. The principal contributions of this study are summarized as follows:

1. Development of a ZRL-specific hybrid locomotive simulation framework incorporating realistic freight duty cycles and route gradients.
2. Quantification of regenerative braking energy recovery and its impact on diesel fuel consumption under moderate-gradient, low-speed freight operation.

3. Physics-based justification of BESS sizing constrained by regenerative power and State-of-Charge limits rather than cumulative trip energy.
4. Demonstration that regenerative hybridization alone can achieve a fuel reduction of approximately 15.4% per 890 km trip.

II. METHODOLOGY

This section describes the development of the proposed hybrid diesel-electric locomotive model for ZRL. The methodology integrates four main components, namely: *(i)* hybrid locomotive architecture, *(ii)* ZRL-specific traction and duty-cycle modelling, *(iii)* BESS and regenerative braking modelling, and *(iv)* a rule-based Energy Management Strategy (EMS) governing power flow between the diesel generator and the BESS. All subsystems were implemented and co-simulated in MATLAB/Simulink to ensure consistent interaction between mechanical dynamics, electrical power flow, and diesel fuel consumption.

A. Hybrid Locomotive System Architecture

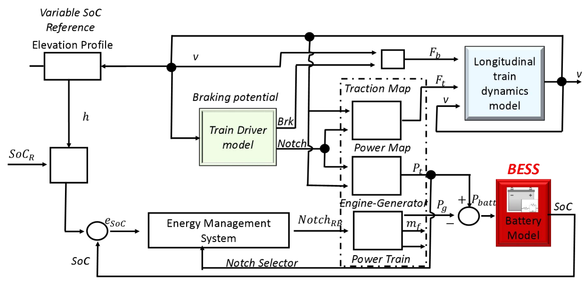

Fig. 2 Hybrid Diesel-Electric Locomotive architecture with battery-assisted regenerative baking

The hybrid architecture consists of a diesel-electric locomotive coupled to a 7.5 MWh lithium iron phosphate (LFP) Battery Energy Storage System (BESS) installed on a dedicated tender wagon and interfaced with the locomotive DC link through a bidirectional DC–DC converter. The traction motors operate bidirectionally, enabling regenerative braking energy recovery during deceleration and downhill operation.

In the hybrid configuration, regenerative braking energy that would otherwise be dissipated in resistor grids is partially captured by the BESS, subject to battery State-of-Charge (SOC) and power constraints. During traction demand, the BESS can provide limited power assistance to smooth transient diesel loading. The architecture, therefore, enables fuel reduction through regenerative energy recovery and traction power smoothing.

B. ZRL Duty Cycle and Traction-Braking Representation

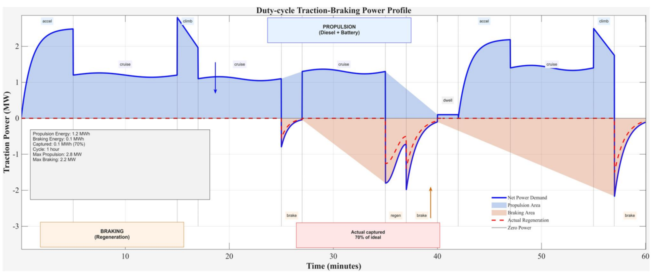

Fig. 3. Duty-cycle traction-braking power profile

The traction and braking power demand along the Kitwe–Livingstone corridor was modelled to reflect ZRL freight operating conditions, characterized by low average speeds (20–30 km/h), heavy train mass, and moderate gradients. The duty cycle consists of repeated phases of acceleration, cruising, gradient traversal, coasting, and braking [13], [14].

Fig. 3 illustrates the representative traction–braking power profile used as input to the hybrid locomotive simulation. Positive power corresponds to propulsion demand supplied by the diesel generator and, where permitted, the BESS, while negative power corresponds to braking events during which traction motors operate as generators. The negative power regions represent the upper bound of available regenerative braking energy prior to efficiency and SOC constraints

C. Traction Load Modelling

The traction demand is computed for a representative 1, 200-Ton freight consist over the 890-km corridor with low operating speeds.

Train resistance (Davis equation) [13]:

$$\boldsymbol{R}_{total}(\boldsymbol{v}) = \boldsymbol{A} + \boldsymbol{B}v + \boldsymbol{C}v^2 + Mg\,sin\theta \qquad (1)$$

Where: A = 2400N (Resistance Coefficient), B = 3.33N/(m/s) (Speed-linear), and C = 0.0463N/(m/s)2 (Squared-speed) are rolling and aerodynamic resistance coefficients, M = (1.2 ×10) ^6 kg is the consist mass, v is train speed (up to 30 km/h), and θ is track gradient.

Mechanical traction power:

$$P_{mech}(\boldsymbol{t}) = R_{total}(\boldsymbol{t}) \times \boldsymbol{v}(t) \qquad (2)$$

Electrical traction power:

$$P_{traction}(t) = \frac{\boldsymbol{P_{mech(t)}}}{\boldsymbol{\eta}_{drive}} \qquad (3)$$

Where drivetrain efficiency ($\boldsymbol{\eta}_{\text{drive}}$) is typically 86-92% for diesel-electric locomotives.

D. Battery Energy Storage and Regenerative Braking Modelling

1. BESS model (LFP Thevenin equivalent)

The BESS is modelled using a first-order Thevenin equivalent suitable for LFP dynamics [15] [13].

Terminal voltage:

$$\boldsymbol{V}_{batt} = \boldsymbol{V}_{oc}(\text{SOC}) - \boldsymbol{I}_{batt}\boldsymbol{R_o} - \boldsymbol{V_{pol}} \qquad (4)$$

Polarization branch:

$$V_{pol} = -\frac{1}{\boldsymbol{R}_1\boldsymbol{C}_1}\boldsymbol{V}_{pol} + \frac{1}{\boldsymbol{C}_1}\boldsymbol{I}_{batt} \qquad (5)$$

SOC evolves:

$$SOC = -\frac{\boldsymbol{I}_{batt}}{\boldsymbol{Q}_{nom}} \qquad (6)$$

Where: $\boldsymbol{Q}_{\text{nom}}$ is the nominal battery capacity.

2. Regenerative braking model

During braking, traction motors operate as generators, and regenerative power is:

$$P_{regen}(t) = \eta_{regen} \times P_{brake}(t) \quad (7)$$

With:

$$P_{brake}(t) = \frac{R_{total}(t) \times v(t)}{\eta_{drive}} \quad (8)$$

Regenerative acceptance constraint:

$$SOC(t) < SOC_{max}, |I_{batt}| < I_{max} \quad (9)$$

E. Route-level recoverable energy and BESS sizing

The required Battery Energy Storage System (BESS) capacity was determined based on route-specific regenerative energy availability and State-of-Charge (SOC) operating constraints along the Kitwe–Livingstone corridor. Although the total recoverable braking energy per trip is approximately 4.66 MWh, BESS sizing is governed by the most demanding continuous downhill segment rather than cumulative trip energy[5], [9].

The longest braking-intensive section occurs between Kapiri Mposhi and Kafulafuta (79 km at an average gradient of approximately 1.75%), where the peak regenerative power is about 1.19 MW over a duration of 2.63 h, yielding approximately 3.13 MWh of recoverable energy. Considering a practical SOC operating window of 45–95%, corresponding to 50% usable capacity, the minimum rated battery capacity required to absorb this energy is approximately 6.26 MWh.

To account for conversion losses, control limitations, and operational uncertainty, a 20% design margin was applied, resulting in a selected BESS capacity of 7.5 MWh. This capacity ensures effective capture of peak downhill regenerative energy without SOC saturation while avoiding unnecessary oversizing that would reduce economic viability.

TABLE I: BATTERY SELLECTION KEY FACTORS

Key Selection Factor	Relevance to ZRL Operations
High thermal stability	Ambient temperatures of 24-40 °C.
Long Cycle Life	Frequent shallow charge/discharge cycles.
Cost per kWh	MWh-scale storage affordability.
Vibration and Shock Tolerance	Freight locomotives operate on uneven tracks.
Wide SOC Operating window	Hybrid duty cycle flexibility

TABLE II: BATTERY CHEMISTRY COMPARISON FOR TAIL TRACTION APPLICATION [15], [16]

Parameter	LFP	NMC	LTO	Lead-Acid
Energy Density (Wh/kg)	90-160	150-250	60-110	30-50
Cycle Life	3,000-6,000	1,000-2,000	10,000+	500-1,000
Safety	Excellent	Moderate	Excellent	Good
Cost 2025 (USD/kWh)	100-130	120-180	300-500	50-80
Operating Temp. (°C)	-20 to 60	0 to 45	-40 to 60	-20 to 50

F. Energy Management Strategy(EMS)

A rule-based EMS is implemented to prioritize fuel reduction while maintaining SOC within a safe window (45-95%). The EMS inputs include traction demand $\boldsymbol{P}_{dem}$, braking status, and SOC [4].

Traction Assist (Battery Discharge)

$$P_{batt} = \min(\boldsymbol{P}_{dem}, P_{batt,max}), \; if\ SOC > SOC_{min} \quad (10)$$

Regenerative Capture:

$$P_{batt} < \mathbf{0}\ during\ braking\ if\ SOC < SOC_{max} \quad (11)$$

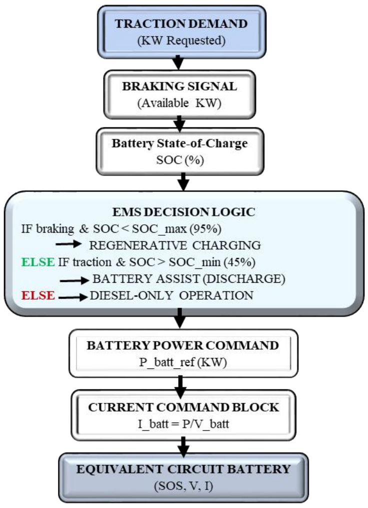

Fig. 4. Rule-based EMS decision logic for regenerative braking capture and traction smoothing under SOC constraints.

The Energy Management Strategy (EMS) is implemented as a supervisory controller designed to maximize regenerative braking energy capture while maintaining battery State-of-Charge (SOC) within safe operating limits. The EMS governs power flow between the diesel generator and the Battery Energy Storage System (BESS) based on traction demand, braking status, and battery constraints [12].

During braking events, when the traction power demand becomes negative, the EMS prioritizes regenerative energy capture by commanding battery charging, subject to SOC upper limits and converter power constraints. If the battery reaches its maximum allowable SOC or power limit, excess braking energy is dissipated through the conventional dynamic braking resistors [17], [18].

During traction operation, limited battery discharge is permitted to smooth transient diesel loading and reduce peak diesel power demand. Battery assistance is constrained by the minimum SOC threshold and maximum discharge power, ensuring battery protection and long-term operational reliability.

The EMS maintains SOC and ensures that traction demand is always satisfied, either by the diesel generator alone or through coordinated diesel–battery operation. The rule-based structure emphasizes robustness, transparency, and ease of implementation, making it suitable for retrofit application on legacy diesel-electric locomotives operating under ZRL freight conditions.

G. Economic Analysis

Capital expenditure is estimated from BESS, integration, and tender-wagon retrofit:

$$C_{capex} = C_{batt} + C_{tender} + C_{integration} \quad (12)$$

Annual fuel savings:

$$S_{fuel} = \Delta F_{,trip} \times N_{trips} \times C_{diesel} \quad (13)$$

With N_{trips} = 100 trips/year.

The payback and ROI:

$$T_{pb} = \frac{C_{capex}}{S_{fuel}}, \; ROI = \frac{S_{fuel}}{C_{capex}} \times 100\% \quad (14)$$

III. RESULTS AND DISCUSSION

A. Battery Power and State-of-Charge Response Under Regenerative Braking.

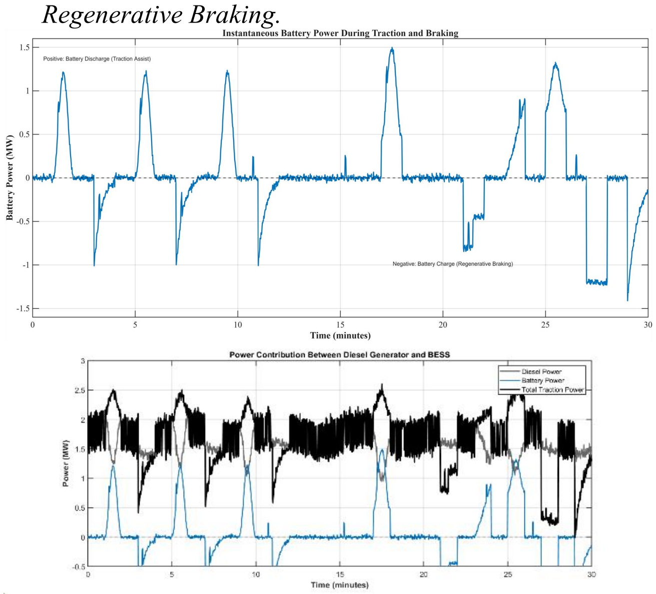

Fig. 5. Hybrid power response over the duty cycle: (a) instantaneous battery power during traction and braking; (b) diesel-battery power contribution

Fig. 5 illustrates the hybrid power response over the representative duty cycle. Positive battery power indicates discharge during traction assistance, while negative power corresponds to energy capture during regenerative braking. The associated diesel–battery power contribution demonstrates that regenerative charging and limited traction support reduce instantaneous diesel loading during braking and high-demand events, confirming effective coordination between the diesel generator and the BESS under imposed power and SOC constraints. [8], [19].

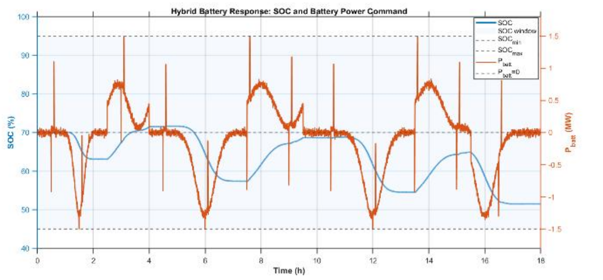

Fig. 6 Battery energy storage (BESS) response over the representative duty cycle

Fig. 6 presents the energy-domain response of the onboard BESS over the representative duty-cycle. The combined SOC and battery power command plots show stable bidirectional operation, with charging during regenerative braking and controlled discharge during traction assistance. The SOC trajectory remains within the prescribed 45-95% operating window throughout the trip, confirming that the selected 7.5 MWh battery capacity is sufficient to absorb regenerative energy without saturation or depletion. The charge and discharge power distribution further indicates that battery operation is concentrated within bound power levels, consistent with converter limits and SOC protection constraints, validating the robustness of the energy management strategy under realistic ZRL operating conditions.

B. Fuel Consumption Characteristics

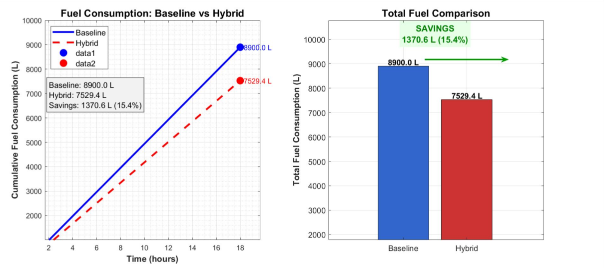

Fig. 7. Baseline vs Hybrid Fuel Consumption comparison

Fig. 7 compares cumulative diesel fuel consumption for conventional diesel-only operation and the hybrid configuration operating with regenerative braking. The hybrid case exhibits a reduced fuel consumption rate during braking and traction smoothing intervals, reflecting partial substitution of diesel energy by recovered electrical energy. Over the full 890 km duty cycle, regenerative braking yields a diesel fuel reduction of approximately 15.4% relative to baseline operation. While this value is lower than savings reported for steep-gradient or electrified routes, it reflects realistic operating conditions for low-speed freight corridors and demonstrates that regenerative hybridization alone can deliver measurable efficiency gains without changes to operational practices or infrastructure.

TABLE III: TRIP-LEVEL FUEL SAVINGS AND EMISSIONS (ZRL, 890 KM)

Parameter	Diesel-only	Hybrid (Regenerative)
Trip Distance	890 km	890 km
Traction fuel (L)	8,900	7,529
Fuel saved (L/trip)	-	1,371
Fuel saving (%)	-	15.4%
CO_2 Reduced (t/trip)	-	3.67
Trips per year	-	100
Annual fuel saved (L)	-	**137,100**

CO_2 Factor = 2.68 kg/L (IPCC)

Annual Economic and Environmental Impact (Per Locomotive)

Assuming diesel price =USD 1.25/L. Annual savings per locomotive (100 trips/year) amount to:

- Fuel saved: 137,100 L/year
- Cost saved: USD 171,375/year
- CO2 reduction: 367 t/year

TABLE IV: CAPITAL COST ASSUMPTIONS (7.5 MWh SYSTEM)

Component	Estimated Cost (USD)
LFP Battery (7.5 MWh)	585, 000
Tender Wagon & Housing	85, 000
Power Electronics & EMS	45, 000
Total CAPEX	**715, 000**

Economic Indicators:
Using the annual fuel saving of USD 171,375:

$$Payback = \frac{715{,}000}{171{,}375} = 4.2\ years$$

$$ROI = \frac{171{,}375}{715{,}000} \times 100\% = 24\%$$

C. *Implications for ZRL Implementation*

The results indicate that regenerative braking–based hybridization represents a technically viable and economically conservative retrofit option for ZRL. Under the moderate-gradient operating conditions of the Kitwe–Livingstone corridor, the hybrid configuration achieves an average fuel reduction of approximately 15.4%, demonstrating that meaningful efficiency gains can be realized without network electrification or changes to operational practices [19],[20], [7].

From an implementation perspective, the use of a tender-wagon-mounted Battery Energy Storage System (BESS) provides a flexible and minimally invasive retrofit pathway that avoids extensive locomotive redesign while extending the useful life of ageing diesel-electric assets. The economic analysis shows that, even when considering regenerative braking alone, the system yields acceptable payback periods and returns on investment, making it suitable for deployment under constrained capital environments.

At the policy level, incremental adoption of regenerative hybrid locomotives can contribute to reduced fuel expenditure, lower exposure to fuel price volatility, and measurable reductions in greenhouse gas emissions. These benefits align with national transport efficiency and decarbonization objectives, positioning regenerative hybridization as a practical transition technology toward longer-term rail electrification strategies [21].

IV. Conclusion

This paper developed a Zambia Railways Limited (ZRL)–calibrated MATLAB/Simulink co-simulation framework to evaluate a tender-mounted 7.5 MWh Lithium Iron Phosphate (LFP) Battery Energy Storage System (BESS) retrofit for diesel-electric freight locomotives operating on the Kitwe–Livingstone corridor. Simulation results show that regenerative braking yields an average diesel fuel reduction of 15.4% over the representative 890 km duty cycle, despite the moderate gradients and low-speed operating conditions characteristic of the route.

The selected BESS capacity was shown to be sufficient to absorb peak downhill regenerative energy while maintaining battery State-of-Charge (SOC) within safe operating limits, validating the route-specific sizing approach adopted in this study. The associated fuel cost savings translate into economically viable payback periods of 4.2 years and returns on investment of 24% under conservative assumptions, making regenerative hybridization suitable for deployment in capital-constrained operating environments.

Importantly, the fuel savings achieved through regen braking can be redirected toward the maintenance of rail infrastructure and rolling stock, supporting improved track condition, locomotive availability, and long-term operational reliability at ZRL. In conclusion, the findings establish regenerative braking–based hybridization as a practical, infrastructure-light transitional pathway for reducing fuel dependence and emissions in ageing diesel-electric freight fleets, without requiring network electrification or changes to existing operational practices.

A. *Future Research Direction*

Future work may extend this study by:

1. Incorporating predictive EMS using GPS-based gradient anticipation.
2. Comparing tender-wagon vs onboard battery integration strategies.
3. Evaluate renewable-assisted charging scenarios for further emissions reduction.
4. Assessing long-term maintenance and lifecycle impact of regenerative hybrid operations.

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