

Article

Operation-Quality-Oriented Energy Management for a Hybrid Electric Tractor in Rotary Tillage–Seeding Operations

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Abstract

Rotary tillage–seeding combined operations require stable power take-off (PTO) speed during rotary tillage and accurate tracking of the prescribed travel speed for seeding. Existing energy management strategies for hybrid electric tractors mainly focus on fuel economy and commonly use fixed objective weights, limiting their ability to adjust control priorities under changing operating conditions. To address this issue, an operation-quality-oriented energy management strategy based on model predictive control, termed OQ-EMS/MPC, is proposed. An equivalent combined-operation condition was constructed using the PTO-side rotary-tillage load, drive-side equivalent traction load, segmented travel-speed reference, and equivalent seeding-quality risk. A condition-severity index integrating the PTO-load coefficient of variation, PTO-load impact intensity, and equivalent seeding-quality risk was developed to distinguish steady, fluctuating, and impact-dominated conditions. Based on the identified condition, the weights assigned to PTO-speed regulation, equivalent seed synchronization, and energy economy were adjusted online. These weights were used in the MPC to optimize torque allocation among the engine, motor-generator 1 (MG1), and motor-generator 2 (MG2). The proposed strategy was validated on a dual-side loading bench and compared with a rule-based energy management strategy and a fixed-weight MPC strategy. The overall PTO-speed root-mean-square error (RMSE) was reduced to 1.76 r/min, representing reductions of 58.40% and 45.66% relative to the two comparative strategies, respectively. The equivalent seed-synchronization RMSE was reduced by 69.15% and 52.66%, respectively. Under the impact-dominated condition, the PTO-speed RMSE decreased to 1.65 r/min. The normalized composite cost decreased by 13.53% and 6.26%, while the equivalent fuel consumption increased by 3.40% and 3.76%, respectively. The results demonstrate that the proposed strategy improves PTO-speed stability and equivalent seed-synchronization performance as operating severity increases while accounting for energy economy.



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Keywords: hybrid electric tractor; model predictive control; adaptive objective weighting; PTO-speed regulation; equivalent seed synchronization; rotary tillage–seeding operation

1. Introduction

The development of agricultural machinery is increasingly shaped by low-carbon powertrains, electrified off-highway platforms, and intelligent control [1–4]. Combined field operations reduce repeated tractor passes, which is directly relevant to mitigating soil

compaction in cropping systems [5,6]. Rotary tillage–seeding combined operation brings together high-PTO-load tillage and speed-sensitive seeding, two processes that have been shown to affect rotary power demand and seed-spacing quality [7–11]. This operation imposes two coupled requirements on the tractor: the power take-off (PTO) branch must maintain the blade-roller speed under irregular soil-cutting loads, while the drive branch must follow the travel-speed requirement that determines seed-meter timing. The energy management strategy (EMS) therefore influences not only fuel consumption, but also the operation quality associated with rotary tillage and seeding.

Hybrid electric tractors provide additional control freedom through the coordinated use of the engine, motor-generator 1 (MG1), motor-generator 2 (MG2), and the battery [12,13]. In a power-split configuration, the engine and electric machines are connected through planetary gear sets, so the speed and torque of the PTO branch and the drive branch are mechanically and electrically coupled [14–16]. This coupling is useful for compensating load disturbances, but it also means that a change in rotary-tillage load or drive-side load can redistribute power across the whole drivetrain. An EMS designed only around fuel economy may therefore overlook transient PTO speed drops and drive-side speed deviations that are directly related to combined-operation quality.

Existing EMS studies for hybrid agricultural machinery have mainly focused on fuel economy, SOC maintenance, and powertrain efficiency [13,17–23]. Rule-based control offers simple implementation, ECMS and dynamic programming provide useful optimization references, and MPC can incorporate constraints and prediction information into real-time control [15,19–24]. Mocera and Somà [13] validated engine–motor power distribution for a parallel hybrid electric tractor under several PTO conditions, while recent tractor EMS studies have further improved equivalent fuel consumption and SOC-sustaining behavior [18–23]. These studies provide the foundation for hybrid tractor energy management, but operation quality is usually treated as an indirect consequence of the power allocation rather than as a control objective that changes with tillage and seeding conditions.

MPC is particularly suitable for this problem because it can handle system dynamics, actuator limits, SOC constraints, and multiple objectives within a receding-horizon framework [24]. Yang et al. [25] showed that directional weighting in guided MPC can reduce the dependence on empirical fixed weights in a power-split hybrid vehicle. For tractor combined operations, the same preview–feedback idea can use measurable bench signals, including PTO speed, drive-side speed, SOC, and load information. The unresolved issue is how to assign objective priorities when the same operation contains steady rotary tillage, strong load fluctuation, and short impact-dominated intervals.

The need for condition-dependent control is supported by the load characteristics of rotary tillage. Field and bench studies have shown that PTO load fluctuation and impact are major causes of PTO speed instability during rotary tillage [8,9,26]. Kim et al. [8] reported that gear selection affects both transmission and PTO loads during rotary tillage, and Kim et al. [9] further showed that rotary tillage can impose much larger PTO-side load severity than transport operation. These observations indicate that PTO-load statistics and local impact features are more informative for quality-oriented energy management than the mean load level alone.

Seeding performance is also sensitive to operating speed, seed-meter rotational speed, seedbed condition, and seed flow stability [10,11,27]. Yang et al. [10] showed in bench tests of a motor-driven maize precision seeding system that higher operating speed reduces the qualified seeding index and increases mis-seeding and spacing variation. Olomitutu et al. [11] similarly reported that increasing planting speed reduced seed-placement quality and increased misses and spacing variability. Therefore, this study describes the seeding-

related operation-quality demand using an equivalent seed-meter synchronization indicator derived from the drive-side speed response and the target seed-metering frequency.

In rotary tillage–seeding combined operations, the PTO side and the drive side are not independent. PTO load disturbances change the operating states of the engine, MG1, and MG2 through the coupled transmission and electric power exchange, while drive-side speed deviations change the travel-distance basis for seed-meter frequency matching [14–16,26]. A controller that treats rotary-tillage load, drive-side load, and seeding requirement separately cannot fully describe this interaction. A unified EMS framework is therefore needed to coordinate PTO-speed stability, drive-side speed response, seed-meter synchronization, and energy economy under the same combined-operation load.

Condition identification and adaptive control provide a practical route for assigning these objectives under different operating states [28,29]. Chen et al. [28] used driving-cycle recognition to improve the fuel economy of hybrid electric vehicles, while Yin et al. [29] employed online working-condition recognition to adapt the energy management strategy of a hybrid tractor. These studies show the value of matching the control strategy to the working condition. However, rotary tillage–seeding operation requires a finer distinction within a single operation, because stable, fluctuating, and impact-dominated intervals impose different priorities on PTO-speed regulation, seed-meter synchronization, and energy use.

Bench-load replay offers a repeatable way to evaluate such control strategies before field deployment. Mocera [1] used an eddy-current brake and a hardware-in-the-loop bench to simulate PTO loads for a parallel hybrid electric tractor. For rotary tillage–seeding combined operation, the same principle can be extended to a dual-side loading bench, where the PTO-side loading device replays the rotary-tillage load and the drive-side dynamometer replays the equivalent driving load. This arrangement allows different EMS strategies to be compared under identical rotary-tillage load, drive-side load, speed reference, and seeding-risk inputs.

Against this background, this study develops an operation-quality-oriented energy management strategy (OQ-EMS) based on MPC for a power-split hybrid electric tractor under rotary tillage–seeding combined operation. The strategy builds a bench-equivalent combined-operation input from PTO load, drive-side load, segmented travel-speed reference, and a seeding-risk sequence derived from calibration data. It then identifies the current condition severity and adjusts the relative priorities of PTO-speed regulation, equivalent seed-meter synchronization, and energy economy. Engine, MG1, and MG2 torque commands are optimized online through receding-horizon control and validated under the same load replay sequence used for the comparison strategies.

The main contributions of this paper are as follows:

First, a bench-equivalent description of rotary tillage–seeding combined operation is established. The PTO rotary-tillage load, drive-side equivalent load, segmented travel-speed reference, and seeding-risk sequence are organized as a common input for bench replay and controller computation, which makes the tillage and seeding requirements comparable within one EMS framework.

Second, a condition-severity identification and priority-scheduling method is developed for combined-operation quality control. PTO-load fluctuation, PTO-load impact, and the seeding-risk feature are used to distinguish steady, fluctuating, and impact-dominated intervals, and the control priorities are adjusted smoothly among PTO-speed regulation, equivalent seed-meter synchronization, and energy economy.

Third, an OQ-EMS/MPC controller is implemented on a hybrid electric tractor bench with PTO-side and drive-side loading and compared with a rule-based EMS and a fixed-weight MPC-EMS under identical equivalent rotary tillage–seeding loads. The validation

focuses on PTO-speed stability, equivalent seed-meter synchronization based on drive-side speed, power-source allocation, and equivalent fuel consumption, allowing the operation-quality gain and energy cost to be evaluated together.

2. Materials and Methods

This section describes the hybrid electric tractor bench, the bench-equivalent representation of rotary tillage–seeding combined operations, the powertrain prediction model, the operation-quality indicators, the condition-severity identification method, and the operation-quality-oriented energy-management framework.

2.1. Hybrid Electric Tractor Bench, Control System, and Rotary Tillage–Seeding Operation Equivalence

Rotary tillage–seeding combined operations impose two distinct but coupled demands on the tractor powertrain. The PTO-side load originates primarily from the interaction between the rotary blades and the soil and directly affects PTO-speed stability [8,30]. The drive-side load mainly represents the equivalent traction resistance acting on the drive axle. In addition to these physical load demands, the prescribed travel speed defines the drive-side speed-tracking requirement, while the seed-meter synchronization requirement is evaluated from the relationship between the travel-speed response and the equivalent seed-metering frequency [10,11]. For a power-split hybrid electric tractor, the PTO-side and drive-side loads jointly influence the power distribution among the engine, MG1, and MG2 through the mechanical coupling mechanism and the electrical power path [14].

The bench experiments were conducted in April 2026 on a power-split hybrid electric tractor powertrain platform at the College of Engineering, Nanjing Agricultural University. The experimental platform comprised a diesel engine, motor-generator 1 (MG1), motor-generator 2 (MG2), a customized dual-planetary power-coupling gearbox, a battery pack, a PTO-side magnetic-powder brake, a drive-side eddy-current dynamometer, torque–speed sensors, programmable logic controllers, data-acquisition equipment, and a host computer. The rotary tiller and seeder shown in Figure 1 represent the corresponding combined-operation power demands rather than physical implements directly mounted on the bench. During the tests, the PTO-side magnetic-powder brake and the drive-side eddy-current dynamometer reproduce the equivalent rotary-tillage and traction loads, respectively, while the seeding requirement is represented by the prescribed travel speed and the equivalent seed-meter synchronization relationship. Figure 1 illustrates the corresponding power-flow topology and combined-operation equivalence.

The physical test bench consisted of a diesel engine, MG1, MG2, a customized coupling gearbox, a PTO-side magnetic-powder brake, a drive-side eddy-current dynamometer, torque–speed sensors, a PLC control cabinet, an industrial computer, and a host computer. The engine and MG1 were connected to the PTO-related branch, whereas MG2 mainly supplied the drive-side branch and contributed to travel-speed regulation. Their torque outputs were coordinated through the coupling gearbox to meet the PTO-speed and equivalent travel-speed requirements.

The PTO-side magnetic-powder brake reproduced the rotary-tillage load, while the drive-side eddy-current dynamometer reproduced the equivalent traction load. Torque–speed sensors installed on the key shafts measured the rotational speed, torque, and power responses of the PTO-side and drive-side branches. The manufacturers, models, rated specifications, units, and functions of the principal bench components and experimental settings are summarized in Table 1. The overall configuration and principal components of the physical test bench are shown in Figure 2.

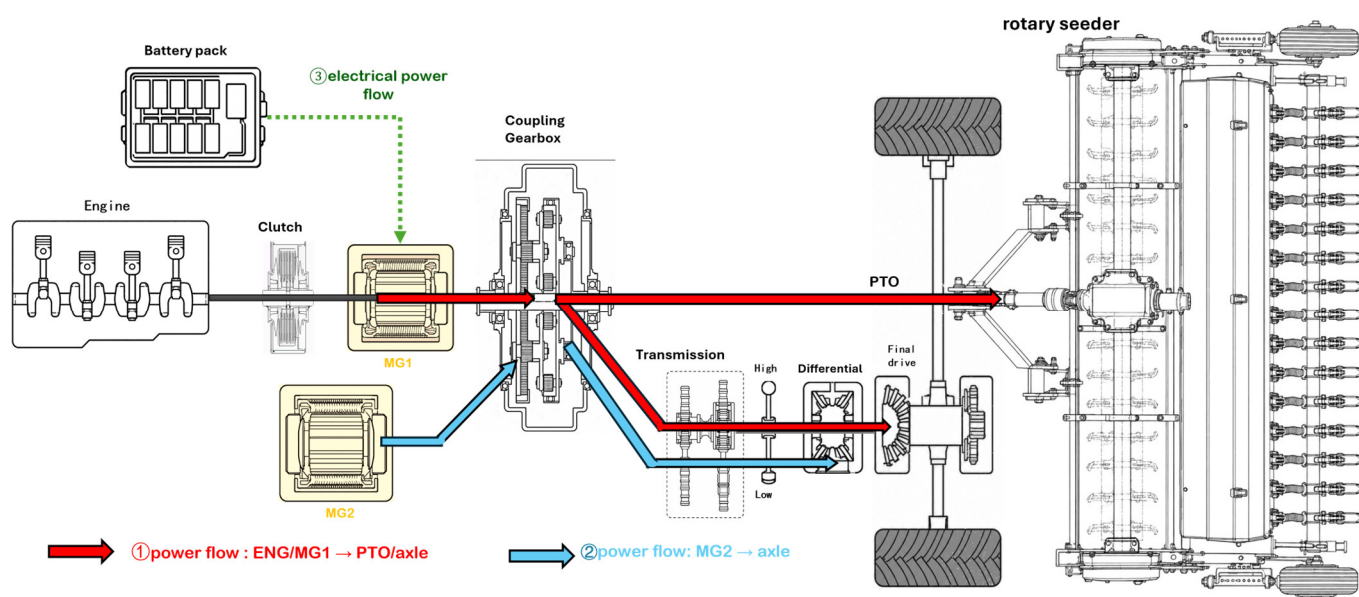


Figure 1. Power-flow structure of the hybrid powertrain test bench.

Table 1. Main parameters of the hybrid electric tractor bench and tests.

Category	Parameter	Manufacturer and Model	Value	Units	Purpose
Engine	Rated power	YTO, LR4A3LR-T67	90	kW	Primary power source constraint
Engine	Rated speed	YTO, LR4A3LR-T67	2200	r/min	Engine operating region reference
Engine	Maximum torque	YTO, LR4A3LR-T67	520	N·m	Engine torque upper limit
MG1	Rated power	Lu'an Jianghuai, TYP200L-8-40-55KW-B3	55	kW	PTO-related branch compensation
MG1	Rated torque	Lu'an Jianghuai, TYP200L-8-40-55KW-B3	131	N·m	MG1 torque constraint
MG2	Rated power	Lu'an Jianghuai, TYP225M-8-24-75KW-B3	75	kW	Drive-side power compensation
MG2	Rated torque	Lu'an Jianghuai, TYP225M-8-24-75KW-B3	280	N·m	MG2 torque constraint
Loading device	Drive-side eddy-current dynamometer rated power	Jiangsu Lanling, CW-1000B	160	kW	Drive-side equivalent load replay
Loading device	PTO-side magnetic-powder brake rated speed	Jiangsu Lanling, FZ630.J/Y or FZ1000.J/Y	2000	r/min	PTO-side rotary-tillage load replay
Measurement Controller	Analogue output range PLC	ZJ-A torque-speed sensor Siemens S7-1200 CPU 1214C	0–5 —	V —	Signal transmission Bench coordination
Test setting	PTO reference speed	—	540	r/min	Rotary tillage operation-quality reference
Test setting	Steady condition speed reference	—	7.5	km/h	Equivalent forward speed reference
Test setting	Fluctuating condition speed reference	—	7.0	km/h	Equivalent forward speed reference
Test setting	Impact-dominated condition speed reference	—	6.8	km/h	Equivalent forward speed reference
Test setting	Reference plant spacing	—	0.35	m	Seed-synchronization frequency calculation
Battery system	Initial SOC	—	0.65		Strategy initial state

Table 1. Cont.

Category	Parameter	Manufacturer and Model	Value	Units	Purpose
Battery system	SOC constraint	—	0.40–0.80		Battery state constraint
Planetary gear set	First planetary characteristic parameter k_1	—	2.92	—	Engine/MG1 and coupling shaft speed relation
Planetary gear set	Second planetary characteristic parameter k_2	—	1.84	—	MG2 and drive-side output speed relation
Transmission	Final drive ratio	—	4.54	—	Drive-side speed conversion
Transmission	Wheel-side reducer ratio	—	6.4	—	Drive-side speed conversion

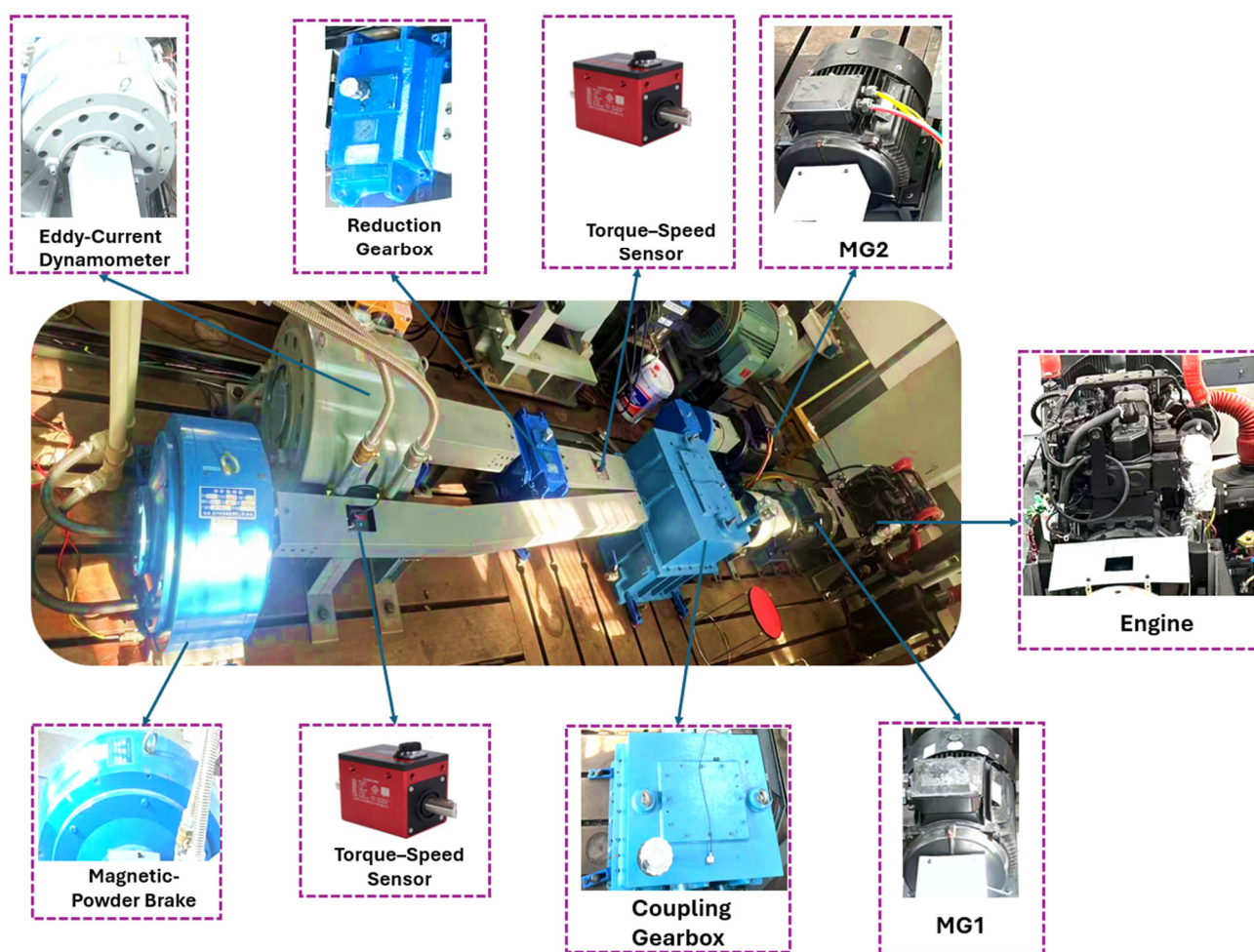


Figure 2. Overall configuration and key components of the hybrid electric tractor test bench with PTO- and drive-side loading.

The PTO-side and drive-side dynamometers replay the equivalent rotary-tillage load torque and the equivalent drive-axle traction load torque, respectively:

$$\mathbf{T}_{\text{load}}(k) = [T_{\text{PTO}}(k), T_{\text{drive}}(k)]^T \quad (1)$$

where $T_{\text{load}}(k)$ is the bench-equivalent load-torque vector at the k -th sampling instant; $T_{\text{PTO}}(k)$ is the PTO-side rotary-tillage load torque; and $T_{\text{drive}}(k)$ is the drive-side equivalent traction load torque. The superscript T denotes the transpose of a vector or matrix. Unless otherwise stated, k denotes the discrete sampling instant, whereas t denotes continuous time.

The instantaneous PTO power is calculated from the PTO load torque and PTO speed:

$$P_{\text{PTO}}(k) = \frac{T_{\text{PTO}}(k)n_{\text{PTO}}(k)}{9550} \quad (2)$$

where $P_{\text{PTO}}(k)$ is the instantaneous PTO power in kW; $T_{\text{PTO}}(k)$ is the PTO load torque in N·m; and $n_{\text{PTO}}(k)$ is the PTO rotational speed in r/min.

The equivalent rotary tillage–seeding combined-operation task is described by:

$$q(k) = [T_{\text{PTO}}(k), T_{\text{drive}}(k), v_{\text{ref}}(k), R_{\text{seed}}(k)]^T \quad (3)$$

where $q(k)$ is the combined-operation task descriptor; $v_{\text{ref}}(k)$ is the prescribed equivalent travel-speed reference; and $R_{\text{seed}}(k)$ is the calibration-based equivalent seeding-quality risk. The PTO-side and drive-side torque spectra characterize the external load disturbances acting on the two power branches. The travel-speed reference and seeding-quality risk are incorporated on the same time axis to describe the corresponding speed-tracking and operation-quality requirements. In the control framework, $T_{\text{PTO}}(k)$ and $T_{\text{drive}}(k)$ are used in the powertrain prediction model and replayed by the corresponding loading devices. The prescribed travel-speed reference determines the drive-side tracking target and the reference equivalent seed-release frequency, while $R_{\text{seed}}(k)$ participates in condition-severity identification. The synchronized task descriptor therefore connects bench-load replay, operating-condition identification, and MPC calculation within a common combined-operation sequence. It also enables the controller to distinguish operating segments with similar mechanical load levels but different travel-speed and seeding-quality requirements.

The bench test combined dynamometer load replay with host-computer-based online control. At each 0.1 s control cycle, the host computer acquired the PTO speed, drive-side shaft speed, reconstructed equivalent travel speed, battery SOC, and load information. The OQ-EMS/MPC was then solved online, and the resulting torque commands were issued to the engine, MG1, and MG2.

The test control system shown in Figure 3 consists of a host computer, an industrial Ethernet switch, an industrial computer, a PLC control cabinet, the engine ECU, motor controllers, and loading-device controllers. The host computer runs the OQ-EMS/MPC program and calculates the condition severity, operating-condition class, adaptive objective weights, and torque commands online. It communicates with the industrial computer through the Ethernet switch using bidirectional TCP/IP communication and a LabVIEW-based monitoring interface. The bench control system was coordinated by Siemens S7-1200 CPU 1214C programmable logic controllers. The 55 kW and 75 kW permanent-magnet synchronous motors were operated using LD350 motor drives. Torque and rotational-speed signals from the key shafts were acquired using ZJ-A torque–speed sensors, and analog signals were collected through a USB5633 data-acquisition unit. The eddy-current dynamometer was interfaced through a TR-5 acquisition unit, whereas the magnetic-powder brake was regulated by a dedicated tension controller. Communication among the host computer, PLCs, and supervisory devices was implemented through TCP/IP. RS485/Modbus was used for the motor drives and loading devices, while the engine ECU and battery management system communicated through the CAN bus. Analog sensor signals were transmitted mainly through 0–5 V and 4–20 mA interfaces.

The industrial computer serves as the field-control and data-acquisition node. It receives the torque and load commands from the host computer and transmits them to the PLC control cabinet. The PLC coordinates the engine ECU, MG1 and MG2 controllers, the PTO-side magnetic-powder brake controller, and the drive-side eddy-current dynamometer controller. The engine, MG1, and MG2 receive torque commands, while the two loading devices receive the corresponding load-replay commands. Torque, speed, SOC, and loading-

device states are collected and transmitted to the host computer for state prediction and receding-horizon optimization in the next control cycle.

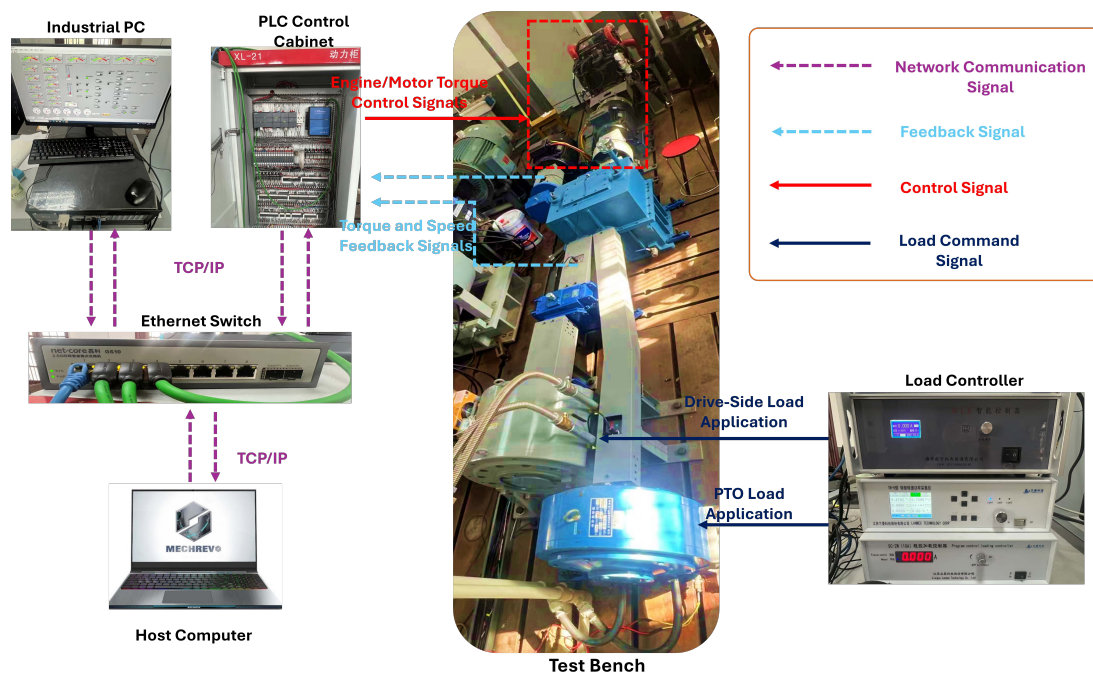


Figure 3. Control architecture and signal flow of the hybrid electric tractor test bench with PTO-side and drive-side loading.

The condition-identification module uses the PTO-load fluctuation feature, PTO-load impact feature, and equivalent seeding-quality risk. The PTO speed, equivalent travel speed, SOC, and load states are used to update the prediction model. The PTO-side magnetic-powder brake and the drive-side eddy-current dynamometer replay the prescribed load profiles. All three EMS strategies use the same load profiles, initial SOC, and travel-speed references. The stage intervals shown in the figures are used for performance statistics and graphical annotation.

The bench tests employed the same equivalent rotary tillage–seeding task sequence as the simulation. The sequence consisted of the PTO-side rotary-tillage load, drive-side equivalent traction load, segmented travel-speed reference, and equivalent seeding-quality risk. During the test, the condition-severity index was calculated online from the PTO-load fluctuation, impact intensity, and equivalent seeding-quality risk, and the operating condition was updated according to Equation (18). Changes in the identified condition occurred at approximately 78 s and 112 s. These time points are marked in Figure 8 to distinguish the steady, fluctuating, and impact-dominated stages for graphical presentation and performance statistics. The PTO-side magnetic-powder brake applied the prescribed rotary-tillage load torque, while the drive-side eddy-current dynamometer applied the equivalent traction-load torque. The segmented travel-speed reference was supplied to the controller for drive-side speed regulation.

Before each test, the engine, MG1, MG2, loading devices, and torque–speed sensors were checked. Communication among the host computer, industrial Ethernet switch, industrial computer, and PLC control cabinet was established through TCP/IP, and the transmission of control commands and feedback signals was verified in LabVIEW. After the bench reached a stable operating state, the rule-based EMS, fixed-weight MPC-EMS, and proposed OQ-EMS were tested sequentially using the same initial SOC, load-torque profiles, travel-speed reference, and sampling frequency. LabVIEW recorded the bench

states at 10 Hz, including PTO speed, equivalent travel speed, engine power, MG1 power, MG2 power, SOC, equivalent fuel consumption, and equivalent seed-synchronization error.

2.2. Hybrid Powertrain Prediction Model

Based on the kinematic relationships of the dual-planetary power-coupling mechanism, the angular velocities of the engine, MG1, MG2, the first planetary carrier, and the drive-side output shaft satisfy [14,15]:

$$\begin{cases} \omega_{\text{MG1}} = (1 + k_1)\omega_{c1} - k_1\omega_e, \\ \omega_{\text{out}} = \frac{\omega_{\text{MG2}} + k_2\omega_{c1}}{1 + k_2} \end{cases} \quad (4)$$

where $\omega_e, \omega_{\text{MG1}}, \omega_{\text{MG2}}, \omega_{c1}$, and ω_{out} are the angular velocities of the engine, MG1, MG2, the first planetary carrier, and the drive-side output shaft, respectively; and k_1 and k_2 are the characteristic parameters of the two planetary gear sets. All angular velocities are expressed in rad/s, and k_1 and k_2 are dimensionless characteristic parameters.

Under the selected bench operating mode, the transmission configuration remains fixed. Therefore, the dependent shaft speeds can be algebraically determined from the planetary-gear kinematic relationships and the fixed transmission relationships. The engine and MG2 angular velocities are selected as the independent mechanical states:

$$x_m(t) = [\omega_e(t), \omega_{\text{MG2}}(t)]^T \quad (5)$$

where $x_m(t)$ is the continuous-time mechanical state vector. The engine speed represents the PTO-side speed response through the fixed engine–PTO transmission relationship, whereas the engine-side and MG2 speeds jointly determine the drive-side output speed through the power-coupling mechanism. The remaining shaft speeds, including the MG1 speed and the first planetary-carrier speed, are calculated from the corresponding kinematic constraints.

After reflecting the component inertias and the external load torques into the selected mechanical coordinates, the continuous-time powertrain dynamics are expressed as:

$$J_{\text{sys}}\dot{x}_m(t) = H_{\text{sys}}u(t) - C_L^T T_{\text{load}}(t), \quad u(t) = [T_e(t), T_{\text{MG1}}(t), T_{\text{MG2}}(t)]^T \quad (6)$$

where J_{sys} is the powertrain equivalent inertia matrix; H_{sys} is the torque-input mapping matrix that relates the engine, MG1, and MG2 torques to the mechanical states; C_L^T is the load-torque mapping matrix; $u(t)$ is the control-torque vector; and T_e, T_{MG1} , and T_{MG2} are the engine, MG1, and MG2 torques, respectively. $T_{\text{load}}(t)$ contains the PTO-side rotary-tillage load torque and the drive-side equivalent traction load torque. The elements of $u(t)$ and $T_{\text{load}}(t)$ are expressed in N·m.

The powertrain equivalent inertia matrix is expressed as:

$$J_{\text{sys}} = \begin{bmatrix} I_e + I_{\text{MG1}} & \frac{k_2 I_{c2}}{(1+k_1)(1+k_2)} \\ \frac{k_2 I_{c2}}{(1+k_1)(1+k_2)} & I_{\text{MG2}} + I_{s1} \end{bmatrix} \quad (7)$$

where I_e, I_{MG1} , and I_{MG2} are the moments of inertia of the engine, MG1, and MG2, respectively; I_{c2} and I_{s1} are the equivalent moments of inertia of the relevant components in the power-coupling mechanism; and the identical off-diagonal terms represent the mechanical coupling between the two power branches. All moments of inertia are expressed in kg·m².

After discretization of the mechanical model, the battery SOC and the reconstructed equivalent seed-metering frequency are incorporated as auxiliary prediction states. The augmented state vector is defined as:

$$x_a(k) = \left[x_m^T(k), \text{SOC}(k), f_{\text{seed,eq}}(k) \right]^T \quad (8)$$

where $x_a(k)$ is the augmented state vector at the k th sampling instant; $\text{SOC}(k)$ is the battery state of charge; and $f_{\text{seed,eq}}(k)$ is the bench-reconstructed equivalent seed-metering frequency. This equivalent state is used to characterize the speed–frequency synchronization requirement and does not represent a directly measured seed-meter speed or field seeding-quality indicator.

The augmented prediction model is formulated as:

$$x_a(k+1) = \begin{bmatrix} A_m x_m(k) + B_m u(k) - \Delta t J_{\text{sys}}^{-1} C_L^T \mathbf{T}_{\text{load}}(k) \\ \text{SOC}(k) - \frac{\Delta t}{3600 E_{\text{bat,nom}}} \left[\frac{P_{\text{bat}}^+(k)}{\eta_{\text{dis}}} - \eta_{\text{chg}} P_{\text{bat}}^-(k) \right] \\ f_{\text{seed,eq}}(k) + \frac{\Delta t}{\tau_{\text{seed}}} \left[K_{\text{seed}} v_{\text{out}}(k) - f_{\text{seed,eq}}(k) \right] \end{bmatrix} \quad (9)$$

where A_m and B_m are the state and input matrices obtained after discretization of the mechanical sub-model; Δt is the sampling period in seconds; $E_{\text{bat,nom}}$ is the battery nominal energy in kWh; P_{bat}^+ and P_{bat}^- are the battery discharge and charge powers, respectively; η_{dis} and η_{chg} are the battery discharge and charge efficiencies; τ_{seed} is the equivalent seed-release response time constant; and K_{seed} converts the drive-side output speed into the equivalent seed-release frequency.

The drive-side equivalent speed and the PTO speed are computed from the mechanical states:

$$\begin{bmatrix} v_{\text{out}}(k) \\ \omega_{\text{PTO}}(k) \end{bmatrix} = \begin{bmatrix} c_{v,e} & c_{v,m2} \\ i_{\text{PTO}} & 0 \end{bmatrix} x_m(k) \quad (10)$$

where $v_{\text{out}}(k)$ is the equivalent travel speed reconstructed from the drive-side output speed; $\omega_{\text{PTO}}(k)$ is the PTO angular velocity; $c_{v,e}$ and $c_{v,m2}$ are the speed-conversion coefficients determined by the powertrain kinematic relationships; and i_{PTO} is the fixed engine-to-PTO speed-conversion coefficient, defined as $i_{\text{PTO}} = \omega_{\text{PTO}}/\omega_e$.

2.3. Rotary Tillage–Seeding Operation–Quality Indicators and Condition Identification

The reference equivalent seed-release frequency is determined from the prescribed travel-speed reference and the target plant spacing:

$$f_{\text{ref}}(k) = \frac{v_{\text{ref}}(k)}{l_{\text{seed,ref}}} \quad (11)$$

where $f_{\text{ref}}(k)$ is the reference equivalent seed-release frequency; $v_{\text{ref}}(k)$ is the prescribed travel-speed reference; and $l_{\text{seed,ref}}$ is the target plant spacing. This relationship represents the required seed-release frequency per unit time corresponding to the prescribed travel speed.

The equivalent seed-release frequency is reconstructed from the drive-side speed response [10,11]:

$$f_{\text{seed,eq}}(k+1) = f_{\text{seed,eq}}(k) + \frac{\Delta t}{\tau_{\text{seed}}} \left[K_{\text{seed}} v_{\text{out}}(k) - f_{\text{seed,eq}}(k) \right], \quad K_{\text{seed}} = \frac{1}{l_{\text{seed,ref}}} \quad (12)$$

where $f_{\text{seed,eq}}(k)$ is the reconstructed equivalent seed-release frequency in Hz; $v_{\text{out}}(k)$ is the equivalent travel speed in m/s; K_{seed} is the speed-to-frequency conversion coefficient

in m^{-1} ; and τ_{seed} is the equivalent response time constant in s. For $l_{\text{seed,ref}} = 0.35 \text{ m}$, $K_{\text{seed}} = 2.857 \text{m}^{-1}$. The sampling period was $\Delta t = 0.1 \text{ s}$, and τ_{seed} was set to 0.5 s , corresponding to a discrete update coefficient of $\Delta t / \tau_{\text{seed}} = 0.2$. This value limits the influence of sample-to-sample speed fluctuations while retaining the short response delay considered in the equivalent seed-frequency model. In Equations (10)–(13), v_{out} and v_{ref} are expressed in m/s for the seed-frequency calculation. For graphical presentation and travel-speed RMSE evaluation, they are converted to km/h .

The equivalent seed-synchronization error is defined as:

$$\epsilon_{\text{seed}}(k) = \frac{f_{\text{seed,eq}}(k) - f_{\text{ref}}(k)}{f_{\text{ref}}(k) + \epsilon_f} \quad (13)$$

where $\epsilon_{\text{seed}}(k)$ is the dimensionless equivalent seed-synchronization error, and ϵ_f is a small positive constant used to avoid division by zero. This indicator characterizes the relative deviation between the reconstructed equivalent seed-release frequency and its reference value. The vehicle-speed RMSE is used to check drive-side speed-tracking performance.

The PTO speed error is defined as [8,30]:

$$e_{\text{PTO}}(k) = n_{\text{PTO}}(k) - n_{\text{PTO,ref}} \quad (14)$$

where $e_{\text{PTO}}(k)$ is the PTO-speed error; $n_{\text{PTO}}(k)$ is the measured or predicted PTO speed; and $n_{\text{PTO,ref}}$ is the target PTO speed. This indicator characterizes the PTO-speed regulation performance under rotary-tillage load disturbances.

The equivalent seeding-quality risk is constructed from speed-grouped seeding calibration data [10,11,27]:

$$R_{\text{seed}}(k) = 0.70 \frac{p_{\text{abn}}(v_{\text{ref}}(k))}{100} + 0.20 \frac{p_{\text{miss}}(v_{\text{ref}}(k))}{100} + 0.10 |e_{\text{cal}}(v_{\text{ref}}(k))| \quad (15)$$

where $R_{\text{seed}}(k)$ is the equivalent seeding-quality risk; p_{abn} is the abnormal plant spacing rate; p_{miss} is the mis-seeding rate; and e_{cal} is a synchronization error proxy obtained from seeding calibration. This risk sequence, held constant across different control strategies, characterizes the influence of operating speed on seeding-quality risk.

The PTO load fluctuation and shock characteristics are defined as [8,30]:

$$CV_T(k) = \frac{\sigma[T_{\text{PTO}}(\mathcal{W}_k)]}{|\mu[T_{\text{PTO}}(\mathcal{W}_k)]| + \epsilon_T}, \quad I_T(k) = \frac{\max_{j \in \mathcal{W}_k} |\Delta T_{\text{PTO}}(j)|}{|\mu[T_{\text{PTO}}(\mathcal{W}_k)]| + \epsilon_T} \quad (16)$$

where $CV_T(k)$ is the PTO-load coefficient of variation; $I_T(k)$ is the PTO-load impact intensity; $\mathcal{W}_k$ is the sliding window preceding the current instant; $\mu[\cdot]$ and $\sigma[\cdot]$ denote the mean and standard deviation, respectively; $\Delta T_{\text{PTO}}(j)$ is the PTO-load variation between adjacent sampling points; and ϵ_T is a small positive torque constant used to avoid numerical singularity.

The condition-severity index is defined as:

$$SI(k) = \gamma_1 \tilde{CV}_T(k) + \gamma_2 \tilde{I}_T(k) + \gamma_3 \tilde{R}_{\text{seed}}(k) \quad (17)$$

where $SI(k)$ is the condition-severity index; $\tilde{CV}_T(k)$, $\tilde{I}_T(k)$, and $\tilde{R}_{\text{seed}}(k)$ are the normalized PTO-load fluctuation feature, PTO-load impact feature, and equivalent seeding-risk feature, respectively; and γ_1 , γ_2 , and γ_3 are their weighting coefficients. The normalization bounds were determined from an independent calibration dataset and fixed for all subsequent analyses to reduce the effects of differences in units and value ranges. The three features describe load fluctuation, load impact, and seeding-related quality risk, which jointly

characterize the severity of the combined operation. Accordingly, $\gamma_1 = \gamma_2 = \gamma_3 = 1/3$ was adopted, assigning the same contribution to the three features in the calculation of $SI(k)$.

The operating condition class is determined by the severity thresholds:

$$c(k) = \begin{cases} C1, & SI(k) < \theta_1, \\ C2, & \theta_1 \leq SI(k) < \theta_2, \\ C3, & SI(k) \geq \theta_2 \end{cases} \quad (18)$$

where $c(k)$ is the current condition class; C1, C2, and C3 denote steady, fluctuating, and impact-dominated conditions, respectively; and θ_1 and θ_2 are the severity thresholds determined from an independent calibration sequence.

2.4. Operation-Quality-Oriented Energy Management Control Framework

Figure 4 illustrates the closed-loop control framework of the proposed OQ-EMS/MPC. The controller receives the combined-operation task information. The PTO-load fluctuation and impact features, together with the equivalent seeding-quality risk, are used for condition-severity identification. The drive-side load enters the prediction model, while the prescribed travel speed defines the drive-side tracking reference and constraint. Meanwhile, the PTO-side and drive-side loads are replayed by the corresponding dynamometers, ensuring consistency between the disturbances used in the prediction model and the physical bench loads.

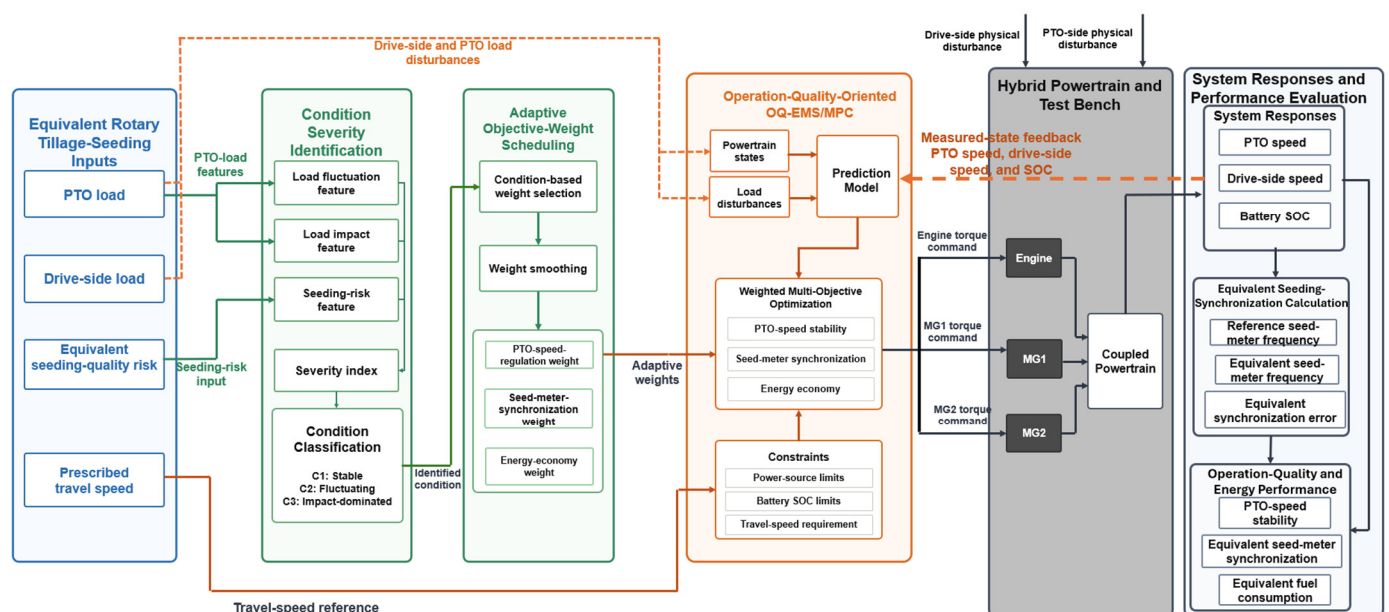


Figure 4. Overall framework of the proposed OQ-EMS/MPC.

Within each control cycle, the condition-identification module calculates the severity index and classifies the operating state as steady, fluctuating, or impact-dominated. The identified condition is then sent to the objective-weight scheduling module, where the corresponding target weights are smoothed and supplied to the OQ-EMS/MPC. Using the feedback of PTO speed, equivalent travel speed, and SOC, the controller updates the predicted states and optimizes the torque distribution among the engine, MG1, and MG2 under the power-source torque, SOC, and travel-speed constraints.

The first control action is applied to the bench. The PTO speed is used to evaluate PTO-speed regulation performance, the equivalent travel speed is used to update the equivalent seed-synchronization error, and the SOC represents the battery energy state.

These feedback signals are returned to the prediction model for the next control cycle, forming the closed-loop control process.

2.5. Operation-Quality-Oriented Energy Management Optimization Problem

The OQ-EMS/MPC adjusts the target weights of PTO-speed regulation, equivalent seed synchronization, and energy economy according to the identified operating condition. The target weights are smoothed during condition transitions before entering the receding-horizon objective function [28]:

$$w_i(k) = \alpha_w w_i(k-1) + (1 - \alpha_w) w_{i,c(k)}, \quad i \in \{\text{PTO}, \text{seed}, \text{energy}\} \quad (19)$$

where $w_i(k)$ is the smoothed weight of the i -th objective at the k -th sampling instant; $w_{i,c(k)}$ is the target weight corresponding to the identified condition class $c(k)$; and α_w is the weight-smoothing coefficient. In this study, α_w was set to 0.85 to suppress abrupt weight changes during condition transitions.

The MPC receding-horizon objective function is defined as:

$$J(k) = \sum_{j=0}^{N_p-1} [w_{\text{PTO}}(k) J_{\text{PTO}}(k+j|k) + w_{\text{seed}}(k) J_{\text{seed}}(k+j|k) + w_{\text{energy}}(k) J_{\text{energy}}(k+j|k)] + J_{\text{ter}}(k) \quad (20)$$

where $J(k)$ is the total objective function over the prediction horizon; N_p is the prediction-horizon length, set to 10 steps, corresponding to 1.0 s at a sampling period of 0.1 s. The prediction horizon was selected according to the duration scale of the PTO-load impact in the replay sequence. During the representative impact transition at approximately 113.3–114.4 s, the commanded PTO-load torque increased from about 706 to 904 N·m, while the measured torque increased from about 684 to 907 N·m. The corresponding 10–90% rise times were approximately 0.7 and 0.9 s, respectively. Therefore, the 1.0 s prediction horizon covers the principal rising interval of the representative load impact within one prediction window. J_{PTO} , J_{seed} , and J_{energy} are the PTO-speed regulation, equivalent seed-synchronization, and energy-economy sub-objectives, respectively; and J_{ter} is the terminal SOC penalty.

The three sub-objectives are defined as:

$$\begin{aligned} J_{\text{PTO}}(k+j|k) &= \left[\frac{n_{\text{PTO}}(k+j|k) - n_{\text{PTO,ref}}}{n_{\text{PTO, scale}}} \right]^2, \\ J_{\text{seed}}(k+j|k) &= \left[\frac{\epsilon_{\text{seed}}(k+j|k)}{e_{\text{seed, scale}}} \right]^2, \\ J_{\text{energy}}(k+j|k) &= \left[\frac{\dot{m}_{\text{eq}}(k+j|k)}{\dot{m}_{\text{eq, scale}}} \right]^2 + q_{\text{SOC}} \left[\frac{\text{SOC}(k+j|k) - \text{SOC}_{\text{ref}}}{\text{SOC}_{\text{scale}}} \right]^2 \end{aligned} \quad (21)$$

where $n_{\text{PTO, scale}}$, $e_{\text{seed, scale}}$, $\dot{m}_{\text{eq, scale}}$, and $\text{SOC}_{\text{scale}}$ are normalization scales; $\dot{m}_{\text{eq}}$ is the equivalent fuel rate; SOC_{ref} is the SOC reference value; and q_{SOC} is the SOC deviation penalty coefficient.

The power and equivalent-fuel-rate relationships among the engine, the two electric machines, and the battery are expressed as [13,14]:

$$\begin{aligned} P_e(k) &= \frac{T_e(k) \omega_e(k)}{1000}, \\ P_j(k) &= \frac{T_j(k) \omega_j(k)}{1000}, \quad j \in \{\text{MG1}, \text{MG2}\}, \\ P_{\text{bat}}(k) &= \sum_j \left[\frac{P_j^+(k)}{\eta_{j, \text{mot}}} - \eta_{j, \text{gen}} P_j^-(k) \right] + P_{\text{aux}}, \\ \dot{m}_{\text{eq}}(k) &= F_f[\omega_e(k), T_e(k)] + \lambda_{\text{dis}} P_{\text{bat}}^+(k) - \lambda_{\text{chg}} P_{\text{bat}}^-(k) \end{aligned} \quad (22)$$

where P_e is the engine power; P_j is the power of the j -th electric machine; P_{bat} is the battery power; and P_{aux} is the accessory power. All power variables are expressed in kW. The parameters $\eta_{j,mot}$ and $\eta_{j,gen}$ are the motoring and generating efficiencies of the j -th electric machine, respectively; $F_f(\cdot)$ is the engine fuel-rate model in kg/h; and λ_{dis} and λ_{chg} are the fuel-equivalent coefficients for battery discharge and charge in kg/kWh. The positive and negative power components are defined as $P^+ = \max(P, 0)$ and $P^- = \max(-P, 0)$.

The fuel-equivalent coefficients for battery discharge and charge were both set to 0.23 kg/kWh, and the same values were applied to all comparative EMS strategies.

The terminal SOC constraint term is [20,31]:

$$J_{ter} = q_{ter} \left[\frac{SOC(k + N_p | k) - SOC_{ref}}{SOC_{scale} + \varepsilon} \right]^2 \quad (23)$$

where q_{ter} is the terminal SOC penalty coefficient and $SOC(k + N_p | k)$ is the predicted SOC at the end of the prediction horizon. Equation (23) penalizes the terminal SOC deviation, while Equation (24) imposes the allowable SOC bounds. ε is a small positive dimensionless constant used to avoid numerical singularity.

The control constraints are expressed as [21,31]:

$$\begin{cases} u_{min} \leq u(k + j|k) \leq u_{max}, \\ \Delta u_{min} \leq \Delta u(k + j|k) \leq \Delta u_{max}, \\ SOC_{min} \leq SOC(k + j|k) \leq SOC_{max}, \\ |v_{out}(k + j|k) - v_{ref}(k + j)| \leq \Delta v_{max} \end{cases} \quad (24)$$

where u_{min} and u_{max} are the lower and upper torque limits of the power sources; Δu_{min} and Δu_{max} are the torque-rate limits; SOC_{min} and SOC_{max} define the allowable SOC range; Δv_{max} is the maximum allowable equivalent travel-speed deviation; and j is the step index within the prediction horizon.

The nonlinear constrained MPC problem was solved using the sequential quadratic programming algorithm implemented with MATLAB 2020 fmincon. The shifted optimal control sequence obtained at the previous sampling instant was used as the initial guess for warm starting. The decision variables were the engine, MG1, and MG2 torque-command sequences over the control horizon N_c . The battery power was decomposed into non-negative discharge and charge components according to $P_{bat}^+ = \max(P_{bat}, 0)$ and $P_{bat}^- = \max(-P_{bat}, 0)$. The maximum number of iterations was set to 200, and the convergence tolerance was set to 10^{-6} . The average and maximum computation times were 18 ms and 42 ms, respectively, both below the 0.1 s control period, demonstrating the real-time computational feasibility of the proposed controller.

2.6. Comparative Strategies and Performance Evaluation Metrics

Three strategies are compared in this study: a rule-based EMS, a fixed-weight MPC-EMS, and the proposed OQ-EMS. All three strategies use the same equivalent rotary tillage-seeding task, initial SOC, load profiles, prescribed travel-speed reference, and evaluation metrics. The fixed-weight MPC-EMS and the proposed OQ-EMS share the same prediction model, constraints, and optimization solver. The fixed-weight MPC-EMS adopts the best-performing fixed target weights obtained from the predefined full-process weight sweep: $w_{fixed} = [0.49, 0.35, 0.16]$ corresponding to the PTO-speed regulation, equivalent seed-synchronization, and energy-economy objectives, respectively. The proposed OQ-EMS schedules the three objective weights according to the identified operating condition.

The full-process equivalent fuel consumption is [13,18]:

$$m_{eq} = m_f + \lambda_{dis} E_{bat}^{dis} - \lambda_{chg} E_{bat}^{chg} \quad (25)$$

where m_{eq} is the equivalent fuel consumption over the complete operating process; m_f is the engine fuel consumption; E_{bat}^{dis} and E_{bat}^{chg} are the battery discharge and charge energies, respectively; and λ_{dis} and λ_{chg} are the corresponding fuel-equivalent coefficients.

The performance metrics for PTO-speed stability, equivalent travel-speed tracking, and equivalent seed synchronization are defined as:

$$\begin{aligned} RMSE_{PTO} &= \sqrt{\frac{1}{N} \sum_{k=1}^N [n_{PTO}(k) - n_{PTO,ref}]^2}, \\ \sigma_{PTO} &= \sqrt{\frac{1}{N-1} \sum_{k=1}^N [n_{PTO}(k) - \bar{n}_{PTO}]^2}, \\ RMSE_v &= \sqrt{\frac{1}{N} \sum_{k=1}^N [v_{out}(k) - v_{ref}(k)]^2}, \\ RMSE_{seed} &= \sqrt{\frac{1}{N} \sum_{k=1}^N \epsilon_{seed}^2(k)} \end{aligned} \quad (26)$$

where $RMSE_{PTO}$ is the PTO-speed root-mean-square error; σ_{PTO} is the standard deviation of PTO speed; $RMSE_v$ is the equivalent travel-speed RMSE; $RMSE_{seed}$ is the equivalent seed-synchronization RMSE; N is the number of evaluation samples; and $\bar{n}_{PTO}$ is the mean PTO speed.

The comprehensive performance metric is defined as:

$$J_{raw} = \beta_1 \frac{RMSE_{PTO}}{S_{PTO}} + \beta_2 \frac{RMSE_{seed}}{S_{seed}} + \beta_3 \frac{m_{eq}}{S_{fuel}}, \quad \sum_{i=1}^3 \beta_i = 1, \quad J_N = \frac{J_{raw}}{J_{raw,RB}} \quad (27)$$

where J_{raw} is the composite cost; J_N is the composite cost normalized relative to the rule-based EMS; and $J_{raw,RB}$ is the composite cost of the rule-based EMS. Because the three indicators differ in physical units and numerical ranges, they were normalized using fixed engineering reference values before weighted aggregation, following commonly used multi-criteria evaluation procedures [32,33]. $S_{PTO} = 10$ r/min corresponds to the deviation between the nominal PTO speed of 540 r/min and the lower limit of the adopted operating range. $S_{seed} = 0.10$ represents a 10% relative equivalent seed-synchronization error, whereas $S_{fuel} = 0.45$ kg represents the characteristic full-cycle equivalent fuel consumption of the test sequence. The same normalization scales were applied to all strategies.

The evaluation weights were set to $\beta_1 = 0.20$, $\beta_2 = 0.15$, and $\beta_3 = 0.65$. These coefficients determine the contributions of the three normalized indicators to the composite performance index. PTO-speed RMSE and equivalent seed-synchronization RMSE were also reported separately to characterize operation quality. A relatively high coefficient was assigned to equivalent fuel consumption so that the energy cost associated with improving operation quality was adequately reflected in the composite comparison. Within the operation-quality terms, PTO-speed RMSE was assigned a slightly higher coefficient because it directly characterizes the stability of the rotary-tillage power input, whereas the equivalent seed-synchronization error was calculated from the drive-side speed response. A lower J_N indicates better composite performance.

3. Results

3.1. Simulation of Condition-Severity Identification and Adaptive Weight Scheduling

An equivalent rotary tillage–seeding condition was constructed using the PTO-side load, drive-side load, segmented travel-speed reference, and equivalent seeding-quality risk. The condition includes steady, fluctuating, and impact-dominated stages. During the simulation, the condition-severity index was calculated from PTO-load fluctuation, impact intensity, and equivalent seeding-quality risk, and the operating condition was identified according to Equation (18).

Figure 5 presents the condition-severity index, identified condition, and adaptive objective weights. Under steady conditions, the energy-economy weight remained relatively high. As the load entered the fluctuating stage, the weights of PTO-speed regulation and equivalent seed synchronization increased. During the impact-dominated stage, the PTO-speed regulation weight increased further, while the weight-smoothing mechanism ensured a gradual transition between different weight combinations.

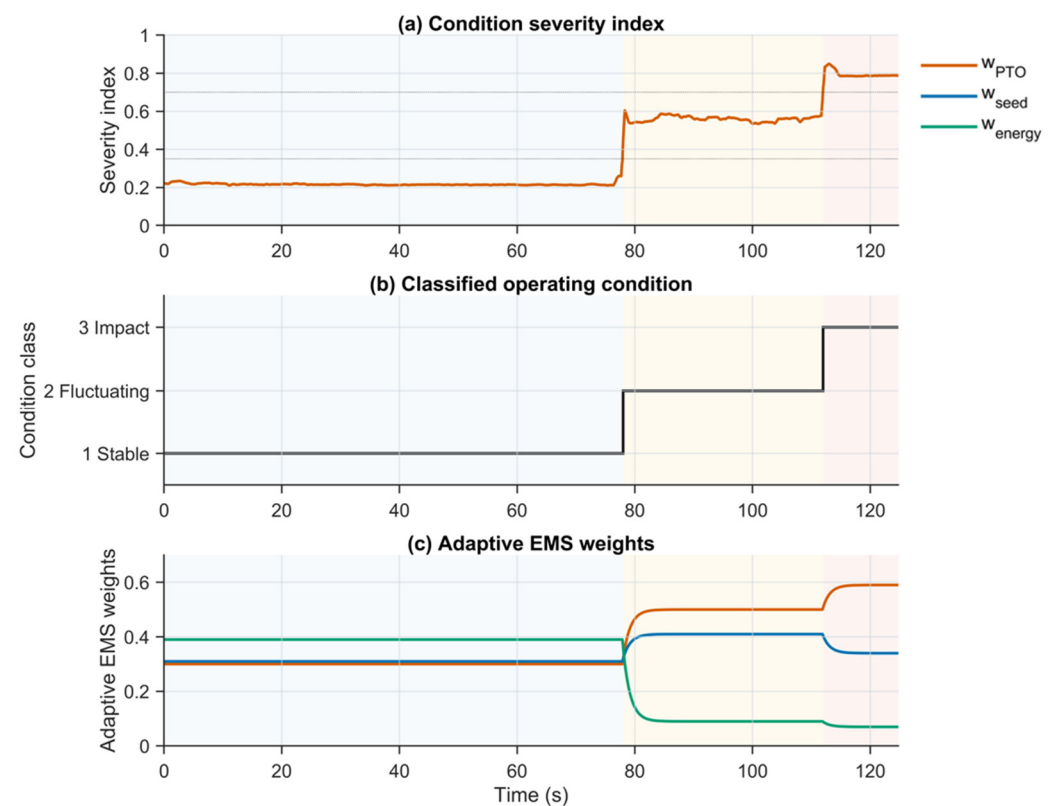


Figure 5. Condition-severity identification and adaptive EMS weights.

The results show that the proposed condition-identification method can reflect changes in combined-operation severity and adjust the priorities of the three control objectives accordingly. Energy economy is emphasized under mild loading, whereas PTO-speed stability and equivalent seed synchronization receive greater attention as load fluctuation and impact intensity increase.

3.2. Target-Weight Sensitivity and Rationality Analysis

To analyze the influence of objective weights on control performance, a systematic weight sweep was conducted under steady, fluctuating, and impact-dominated conditions. The candidate weights satisfied the non-negativity and sum-to-unity constraints. For each weight combination, the PTO-speed RMSE, equivalent seed-synchronization RMSE, and

equivalent fuel consumption were calculated and normalized using fixed scales before entering the composite objective.

Figure 6 presents the sensitivity results for the three operating conditions. Under the steady condition, the adopted weights were $w_{\text{PTO}} = 0.30$, $w_{\text{seed}} = 0.31$, and $w_{\text{energy}} = 0.39$, maintaining a relatively high priority for energy economy. Under the fluctuating condition, the weights were $w_{\text{PTO}} = 0.50$, $w_{\text{seed}} = 0.41$, and $w_{\text{energy}} = 0.09$, increasing the priorities of PTO-speed regulation and equivalent seed synchronization. Under the impact-dominated condition, the weights were $w_{\text{PTO}} = 0.59$, $w_{\text{seed}} = 0.34$, and $w_{\text{energy}} = 0.07$, further strengthening PTO-load disturbance rejection. The three weight combinations are located within the low-cost regions of their corresponding condition-specific response distributions.

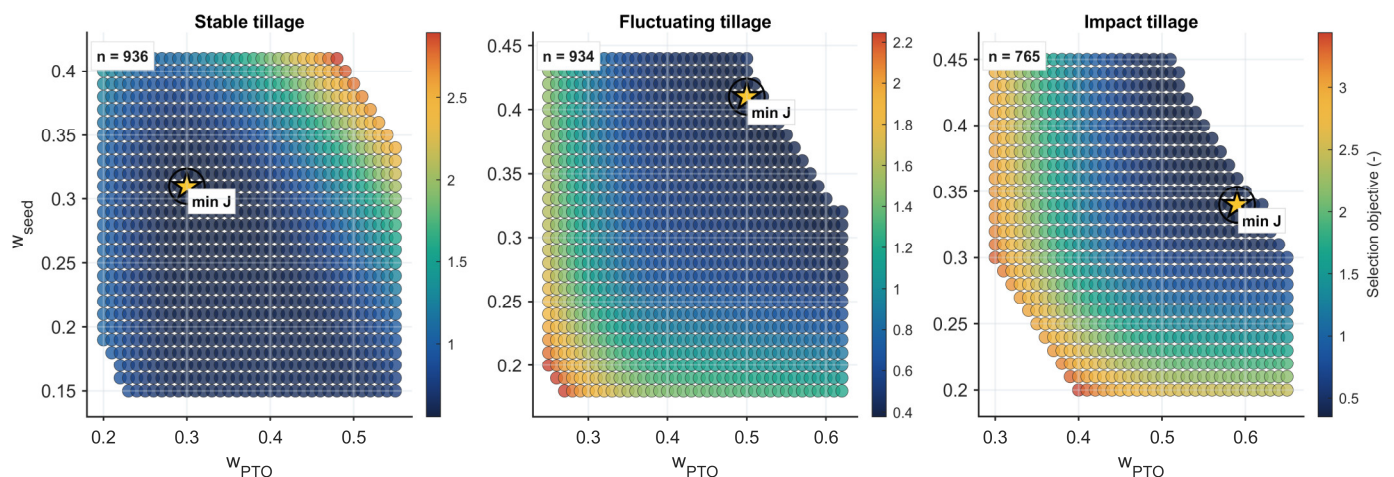


Figure 6. Weight-sweep evaluation under different rotary tillage–seeding conditions. The label “min J” denotes the weight combination with the minimum composite cost within the predefined sweep grid for each operating condition.

Figure 7 illustrates the effects of w_{PTO} and w_{seed} on the three sub-objectives and the composite objective. Increasing w_{PTO} generally reduces the PTO-speed RMSE, while increasing w_{seed} improves equivalent seed synchronization. A higher energy-economy weight reduces equivalent fuel consumption but weakens the priorities assigned to PTO-speed regulation and seed synchronization. The best-performing fixed-weight combination within the predefined full-process sweep grid was $w_{\text{PTO}} = 0.49$, $w_{\text{seed}} = 0.35$, and $w_{\text{energy}} = 0.16$, and this combination was adopted for the fixed-weight MPC-EMS baseline.

The sensitivity results show that the required balance among the three objectives changes with operating severity. Energy economy receives greater emphasis under steady loading; PTO-speed regulation and equivalent seed synchronization become more important under fluctuating loading; and PTO disturbance rejection becomes dominant under impact-dominated loading. This weight-allocation pattern supports the condition-dependent scheduling mechanism used in the proposed OQ-EMS.

3.3. Hybrid Electric Tractor Bench Test Validation

3.3.1. Equivalent Load-Replay Characteristics

Figure 8 presents the calculated loading power during a representative equivalent load-replay test. During the steady stage, the mean PTO-side loading power was 55.16 kW, and the mean drive-side loading power was 53.79 kW, with relatively small fluctuations. For the representative impact transition, the measured PTO-load torque had a 10–90% rise time of approximately 0.9 s, which was within the 1.0 s MPC prediction horizon. During the fluctuating stage, the mean PTO-side loading power decreased to 37.28 kW, with a standard deviation of 2.05 kW, while the mean drive-side loading power was 42.19 kW. During the

impact-dominated stage, the mean PTO-side loading power increased to 52.02 kW, and its standard deviation increased to 4.86 kW, reflecting the rapid load transition and intensified fluctuations. The three stages provide distinct loading characteristics for evaluating the condition adaptability and power-allocation performance of the three EMS strategies.

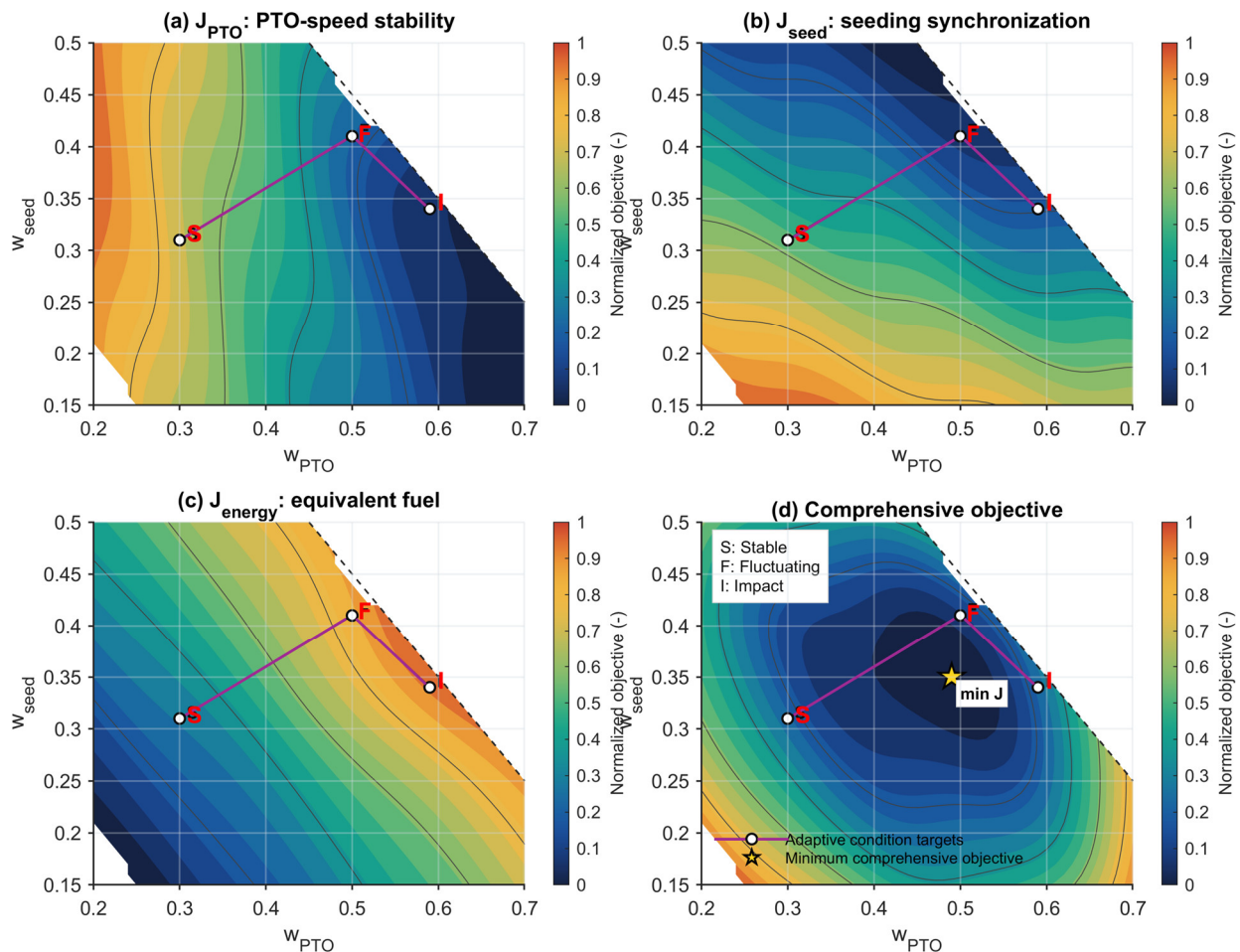


Figure 7. Two-dimensional response surface of OQ-EMS objective weights.

3.3.2. Bench Time-Domain Responses

Figure 9 compares the time-domain responses of the three EMS strategies under identical bench-load replay conditions. During the steady stage, all strategies maintained the PTO speed near its reference value. As the operating condition changed to the fluctuating and impact-dominated stages, the rule-based EMS exhibited larger PTO-speed and equivalent travel-speed deviations. The fixed-weight MPC-EMS reduced these deviations, while the proposed OQ-EMS achieved the smallest PTO-speed fluctuation and maintained the equivalent travel speed closest to its reference. The corresponding equivalent seed-synchronization error also remained lower under the OQ-EMS.

The overall PTO-speed RMSE of the proposed OQ-EMS was 1.76 r/min, compared with 4.23 r/min for the rule-based EMS and 3.24 r/min for the fixed-weight MPC-EMS, corresponding to reductions of 58.40% and 45.66%, respectively. The equivalent seed-synchronization RMSE decreased from 0.0817 and 0.0532 to 0.0252, representing reductions of 69.15% and 52.66%. The equivalent travel-speed RMSE was reduced from 0.540 km/h and 0.325 km/h to 0.115 km/h, consistent with the improvement in equivalent seed-synchronization performance.

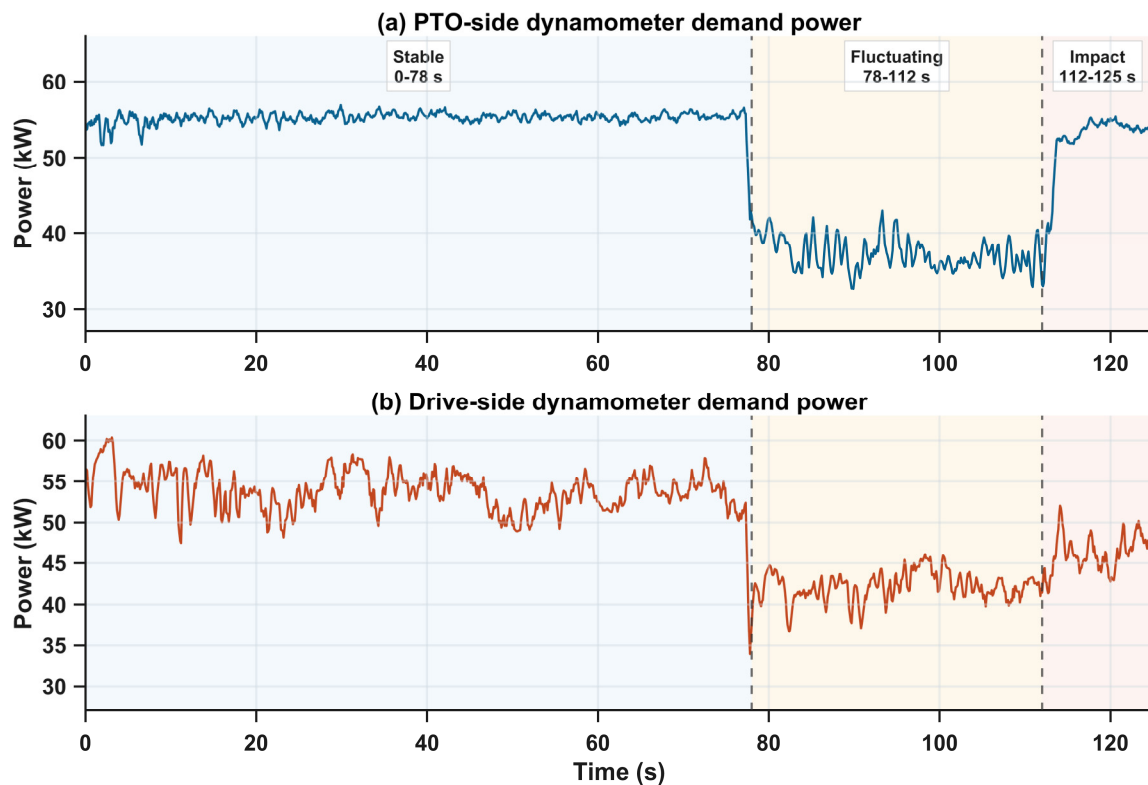


Figure 8. Calculated loading power during equivalent rotary tillage–seeding load replay.

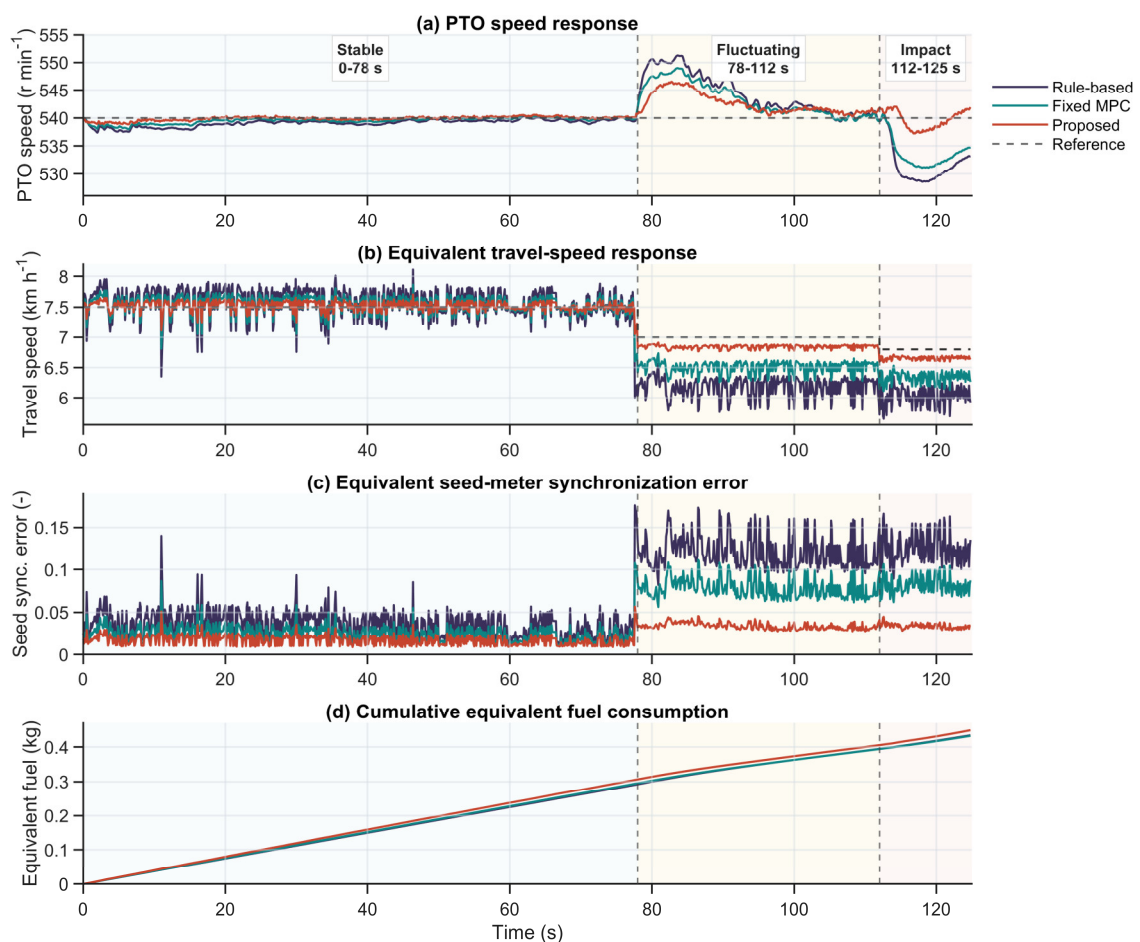


Figure 9. Time-domain responses of different EMS strategies during bench-load replay.

Figure 9d shows that the improved operation-quality performance of the OQ-EMS was accompanied by a small increase in cumulative equivalent fuel consumption. This result reflects the increased use of engine and electric-machine power for PTO-speed regulation and drive-side speed tracking under severe load disturbances. Overall, the OQ-EMS achieved a favorable balance between PTO-speed stability, equivalent seed synchronization, and energy economy.

3.3.3. Condition-Segmented Operation-Quality Evaluation

Figure 10 compares the condition-wise and overall bench-test performance of the three EMS strategies. PTO-speed RMSE was used to evaluate PTO-side regulation performance, travel-speed RMSE was used to assess drive-side speed tracking, and equivalent seed-synchronization RMSE was used to characterize the seeding-side equivalent operation quality. The condition-wise composite cost was calculated using Equation (27).

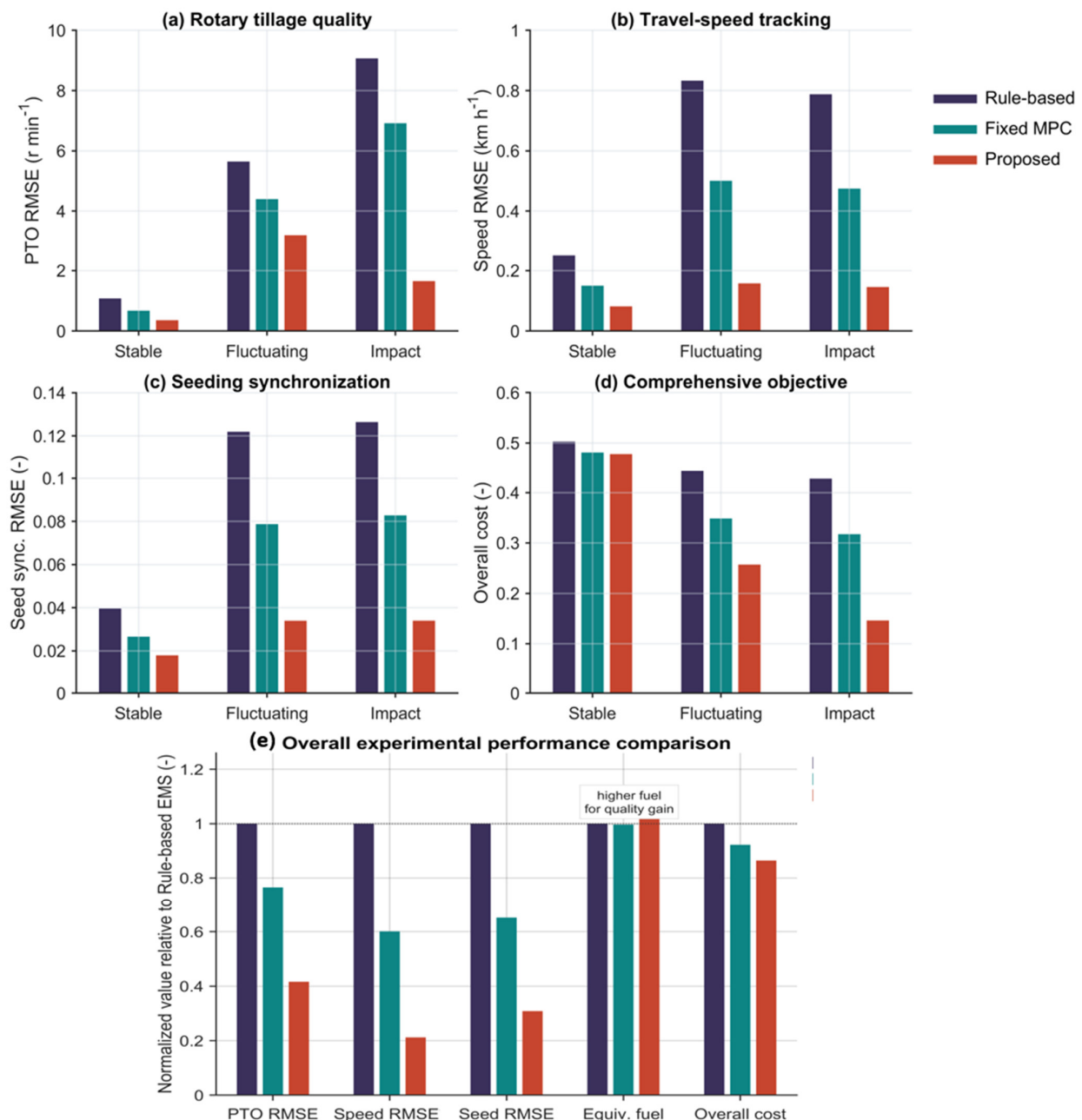


Figure 10. Condition-wise and overall bench-test performance comparison of the three energy management strategies.

Under the steady condition, the proposed OQ-EMS achieved a PTO-speed RMSE of 0.36 r/min and an equivalent seed-synchronization RMSE of 0.0180. Under the fluctuating condition, the corresponding values were 3.17 r/min and 0.0340, compared with 5.64 r/min and 0.1219 for the rule-based EMS and 4.40 r/min and 0.0787 for the fixed-weight MPC-EMS. During the impact-dominated stage, the PTO-speed RMSE of the OQ-EMS was 1.65 r/min, whereas those of the rule-based EMS and fixed-weight MPC-EMS were 9.07 and 6.92 r/min, respectively. The travel-speed tracking results in Figure 10b showed a similar reduction in error for the proposed strategy.

As shown in Figure 10d, the fixed-weight MPC-EMS and OQ-EMS exhibited similar composite performance under steady loading. Under fluctuating and impact-dominated conditions, the OQ-EMS reduced the condition-wise composite cost by 26.25% and 53.97%, respectively, relative to the fixed-weight MPC-EMS. The corresponding reductions in PTO-speed RMSE, equivalent seed-synchronization RMSE, and composite cost are further summarized in Table 2. These results show that the benefit of condition-dependent weight scheduling is mainly reflected under fluctuating and impact-dominated loading.

Table 2. Performance reductions achieved by OQ-EMS relative to the fixed-weight MPC-EMS.

Operating Condition	PTO-Speed RMSE Reduction (%)	Seed-Sync RMSE Reduction (%)	Condition-Wise Composite-Cost Reduction (%)
Steady	46.97	32.48	0.63
Fluctuating	27.90	56.81	26.25
Impact-dominated	76.11	58.91	53.97

For the complete test cycle, Figure 10e shows that the normalized composite costs of the rule-based EMS, fixed-weight MPC-EMS, and OQ-EMS were 1.000, 0.922, and 0.865, respectively. The OQ-EMS therefore reduced the overall composite cost by 13.53% relative to the rule-based EMS and by 6.26% relative to the fixed-weight MPC-EMS. Its equivalent fuel consumption was 0.449 kg, which was 3.40% and 3.76% higher than those of the rule-based EMS and fixed-weight MPC-EMS, respectively. The proposed strategy therefore improved PTO-speed regulation, travel-speed tracking, and equivalent seed synchronization, with a modest increase in equivalent fuel consumption.

Table 2 further quantifies the condition-wise performance improvement of the OQ-EMS relative to the fixed-weight MPC-EMS. Under the steady condition, the PTO-speed RMSE and seed-synchronization RMSE were reduced by 46.97% and 32.48%, respectively, whereas the condition-wise composite cost decreased by only 0.63%, indicating similar overall performance between the two strategies. Under the fluctuating condition, the corresponding reductions were 27.90%, 56.81%, and 26.25%. The greatest improvements were obtained under the impact-dominated condition, with reductions of 76.11% in PTO-speed RMSE, 58.91% in seed-synchronization RMSE, and 53.97% in the composite cost. These results indicate that the benefit of condition-dependent weight scheduling becomes more pronounced as the load fluctuation and impact intensity increase.

3.3.4. Operation-Quality-Oriented Power Distribution and Energy Trade-Off Analysis

Figure 11 presents the power responses of the engine, MG1, and MG2 under the three EMS strategies. Positive electric-machine power denotes motoring operation. During the fluctuating and impact-dominated stages, the proposed OQ-EMS increased the power contribution of MG1 and MG2 according to the identified operation severity. This reduced the reliance on rapid engine-power adjustment and provided faster compensation for the PTO-side and drive-side load variations. Over the complete test cycle, the mean engine

power of the OQ-EMS was 56.61 kW, compared with 58.20 kW for the rule-based EMS and 57.32 kW for the fixed-weight MPC-EMS, while the mean MG1 and MG2 powers increased to 17.38 kW and 52.60 kW, respectively.

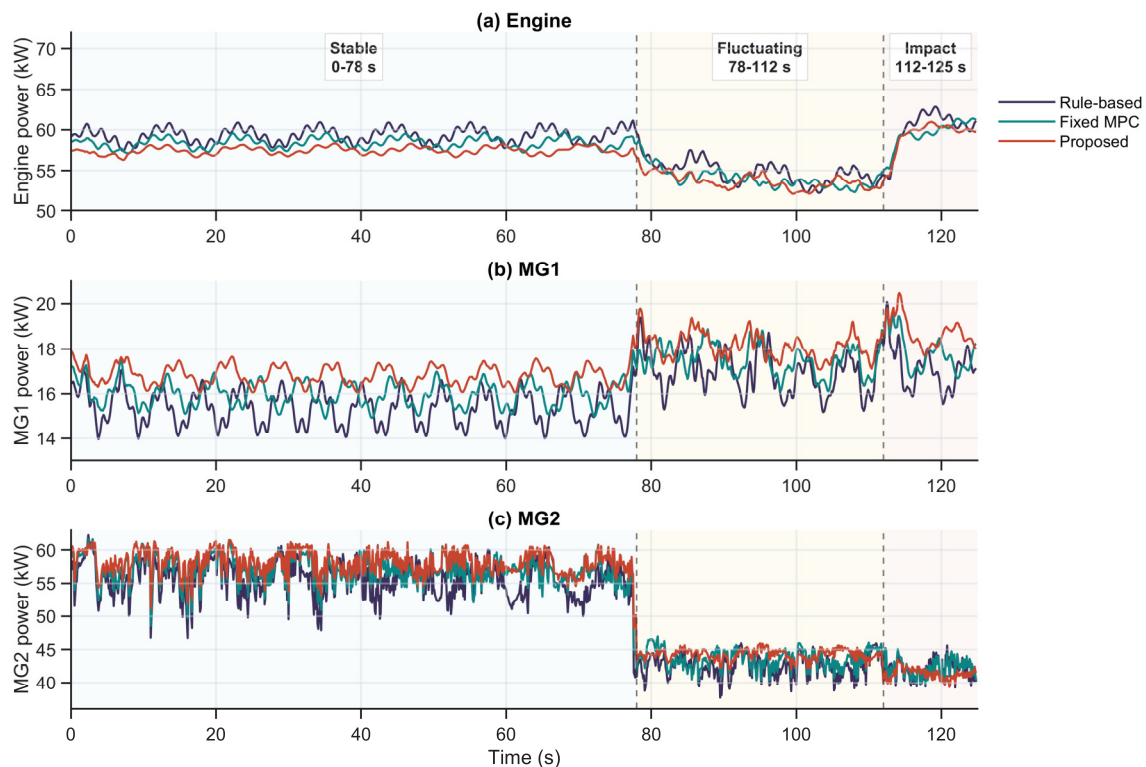


Figure 11. Power responses of the engine, MG1, and MG2 in the bench-load replay experiment.

The redistributed power contribution explains the improvement in the operation-quality indicators. The increased electrical-machine compensation reduced the PTO-speed deviation under fluctuating and impact-dominated loads, thereby improving the PTO-side operation quality. Meanwhile, the improved drive-side speed response reduced the equivalent seed-synchronization error and enhanced the seeding-side equivalent operation quality. Under steady loading, the higher energy-economy weight maintained a more balanced engine–motor power distribution.

The increased electrical-machine contribution changed the battery energy balance and resulted in a moderate increase in equivalent fuel consumption. The power-distribution results therefore show that the OQ-EMS reallocates engine and electric-machine power according to the operation-quality demand: energy economy receives greater emphasis under steady loading, while PTO-speed stability and equivalent seed synchronization receive higher priority as load fluctuation and impact intensity increase. This mechanism supports the improvement in equivalent rotary tillage–seeding combined-operation quality observed in Figures 9 and 10.

Figure 12 compares the torque responses of the engine, MG1, and MG2 under the three operating conditions. During the steady stage, all three strategies maintained relatively regular torque distributions, while the OQ-EMS assigned slightly more torque to MG1 and MG2 and reduced the corresponding engine torque. Under the fluctuating condition, the OQ-EMS increased the MG1 contribution and reduced the torque fluctuations of both motors compared with the rule-based EMS and fixed-weight MPC-EMS. During the impact-dominated stage, the increase in MG1 torque was more pronounced than that of MG2, whereas MG2 continued to provide relatively stable drive-side torque support. These results indicate that MG1 mainly undertakes rapid compensation for PTO-side load variations,

while MG2 maintains the drive-side power demand. The differentiated torque coordination reduces the engine torque requirement and improves the response to fluctuating and impact loads.

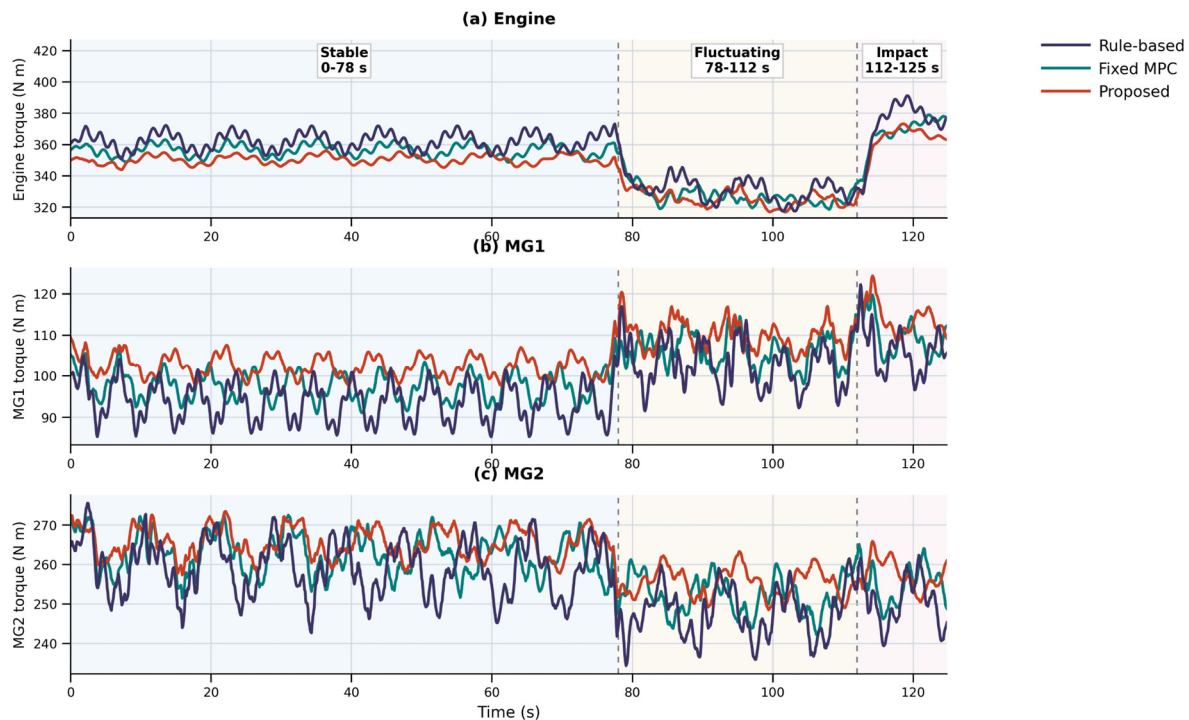


Figure 12. Torque responses of the engine, MG1, and MG2 under different operating conditions.

4. Discussion

4.1. Positioning of Operation-Quality-Oriented Energy Management

Existing energy management studies for hybrid electric tractors mainly focus on fuel economy, SOC sustenance, and powertrain efficiency, using methods such as rule-based control, ECMS, DP, and MPC [13,18–20,34]. Rotary tillage–seeding combined operations impose additional requirements on the powertrain. PTO-speed fluctuation affects the operating stability of the rotary blade system [8,30], while travel-speed fluctuation changes the matching relationship between seed-release frequency and travel distance [9,10]. In this study, powertrain-level operation quality is therefore characterized by PTO-speed stability and equivalent seed synchronization.

The proposed OQ-EMS/MPC incorporates PTO-speed regulation, equivalent seed synchronization, and energy economy into a unified objective function. The relative priorities of these objectives are adjusted according to the identified operating severity. Energy economy receives greater emphasis under steady loading; PTO-speed regulation and equivalent seed synchronization receive higher weights under fluctuating loading; and PTO disturbance rejection is further strengthened under impact-dominated loading.

Compared with fixed-weight MPC strategies [20,21], the proposed method links power-allocation priorities to changes in combined-operation severity. This mechanism extends hybrid tractor energy management from energy-economy optimization toward coordinated optimization of operation quality and energy consumption, thereby better matching the powertrain requirements of rotary tillage–seeding combined operations.

4.2. Role of Condition-Severity Identification in Adaptive Weight Scheduling

Rotary-tillage loads exhibit random fluctuations and localized impact disturbances. Previous studies have shown that load amplitude variation, fluctuation intensity, and

transient impacts influence PTO-speed stability [8,30]. Based on these characteristics, the proposed condition-severity index combines the PTO-load coefficient of variation, PTO-load impact intensity, and equivalent seeding-quality risk. The resulting C1, C2, and C3 classes represent steady, fluctuating, and impact-dominated combined-operation conditions, respectively.

During bench operation, the condition-severity index is updated online from the PTO-load fluctuation feature, PTO-load impact feature, and equivalent seeding-quality risk within the sliding window. The time points marked at 78 s and 112 s in the figures are used for stage presentation and condition-wise performance statistics. The identified condition is then supplied to the weight-scheduling module, which updates the priorities of PTO-speed regulation, equivalent seed synchronization, and energy economy.

The influence of adaptive scheduling becomes more evident as the operating severity increases. Under steady loading, the fixed-weight MPC and OQ-EMS achieve similar overall performance. Under fluctuating and impact-dominated loading, the OQ-EMS increases the operation-quality-related weights and strengthens the power contribution of MG1 and MG2. This reduces PTO-speed deviation and improves equivalent travel-speed tracking, thereby enhancing PTO-side operation quality and seeding-side equivalent operation quality. The response-surface analysis and bench results jointly show that condition-severity identification and adaptive weight scheduling redistribute the powertrain control priorities according to the combined-operation demand.

4.3. Trade-Off Among Rotary Tillage Stability, Equivalent Seed-Synchronization, and Energy Consumption

PTO-speed stability is used to characterize the PTO-side operation quality of rotary tillage. A stable PTO speed supports consistent rotary-blade operation under varying soil resistance [8,30]. The proposed OQ-EMS reduced the overall PTO-speed RMSE to 1.76 r/min, corresponding to reductions of 58.40% and 45.66% relative to the rule-based EMS and fixed-weight MPC-EMS, respectively. During the impact-dominated stage, the PTO-speed RMSE decreased from 9.07 r/min and 6.92 r/min to 1.65 r/min. These results show that the adaptive increase in the PTO-speed regulation weight improves PTO-side operation stability under severe load disturbances.

The seeding-side equivalent operation quality is characterized by the equivalent seed-synchronization error reconstructed from the drive-side speed response. The reference equivalent seed-release frequency is calculated from the prescribed travel speed and target plant spacing, while the actual equivalent seed-release frequency is reconstructed from the drive-side output speed and the equivalent response lag. The proposed OQ-EMS reduced the overall equivalent seed-synchronization RMSE to 0.0252, representing reductions of 69.15% and 52.66% relative to the rule-based EMS and fixed-weight MPC-EMS. The improved equivalent travel-speed tracking therefore resulted in a closer match between the required and reconstructed seed-release frequencies, enhancing the seeding-side equivalent operation quality.

The equivalent fuel consumption of the OQ-EMS was 0.449 kg, which was 3.40% and 3.76% higher than those of the rule-based EMS and fixed-weight MPC-EMS, respectively. The power-distribution results show that the OQ-EMS reduced the average engine power and increased the power contribution of MG1 and MG2 under fluctuating and impact-dominated loads. The rapid response of the electric machines strengthened PTO-side disturbance compensation and drive-side speed regulation, while the associated battery energy variation increased the equivalent energy cost [13]. Despite this moderate increase in equivalent fuel consumption, the normalized composite cost decreased by 13.53% and 6.26% relative to the two comparative strategies. The results indicate that the OQ-EMS

achieves a favorable trade-off by improving PTO-side operation stability and seeding-side equivalent operation quality while maintaining an acceptable energy-consumption level.

4.4. Applicability of Bench-Load Replay Validation

The dual-side loading bench provides a repeatable experimental environment for evaluating energy management under equivalent rotary tillage–seeding combined operations [23]. The PTO-side magnetic-powder brake replays the rotary-tillage load, while the drive-side eddy-current dynamometer replays the equivalent traction load. The engine, MG1, MG2, coupling gearbox, loading devices, controllers, communication network, and sensor-feedback system are all included in the closed-loop test process. The bench results therefore reflect the implementation and control performance of the OQ-EMS/MPC under actual hardware actuation, communication, loading, and measurement conditions.

All three EMS strategies were evaluated using the same PTO-side load, drive-side load, travel-speed reference, initial SOC, and equivalent seeding-quality risk sequence. These controlled input conditions support a direct comparison of the rule-based EMS, fixed-weight MPC-EMS, and OQ-EMS and reveal the influence of condition-dependent weight scheduling on PTO-side operation stability, seeding-side equivalent operation quality, and energy consumption [12,20].

The bench-equivalent indicators describe powertrain-level operation quality. PTO-speed stability characterizes the PTO-side response to rotary-tillage disturbances, while equivalent seed synchronization characterizes the matching between travel-speed response and the required seed-release frequency. Field operation quality is also affected by soil conditions, wheel–soil interaction, implement vibration, seed flow, and seedbed characteristics. The bench results therefore provide a repeatable basis for controller comparison and hardware validation, while field experiments are required to extend the evaluation to actual tillage and seeding outcomes.

4.5. Methodological Limitations and Future Research

The first limitation concerns the representation of seeding-side operation quality. The equivalent seeding-quality risk is constructed from speed-grouped calibration data, and the equivalent seed-synchronization error is reconstructed from the drive-side speed response [10,11,27]. The bench test does not reproduce tire–soil interaction; therefore, the equivalent travel speed used in the synchronization calculation does not include the effect of driving-wheel slip. Under field conditions, the actual travel speed can be expressed as $v_{\text{act}} = (1 - s)v_w$, where s is the driving-wheel slip ratio and v_w is the wheel-peripheral speed. Consequently, the bench-equivalent travel speed may be higher than the actual field speed, leading to an underestimation of the seed-synchronization error when appreciable slip occurs. For example, a slip ratio of 0.10 results in an approximately 10% difference between the wheel-peripheral speed and the actual travel speed. Future work will integrate measurements of wheel speed, actual ground speed, and seed-meter speed, together with seed-flow sensors, photoelectric detection, or high-speed imaging, to establish relationships among powertrain response, driving-wheel slip, mis-seeding rate, multiple-seeding rate, and plant-spacing variation.

The second limitation concerns the coverage of the load spectrum. The bench tests include steady, fluctuating, and impact-dominated stages, representing three typical levels of combined-operation severity. Field loads vary with soil type, moisture content, tillage depth, operating speed, and implement engagement [8,30,35]. Expanding the load database and conducting repeated tests under different operating parameters will support further evaluation of the condition-identification thresholds and weight-scheduling rules.

The third limitation concerns the energy-evaluation horizon. Equivalent fuel consumption and SOC variation are used to compare the short-duration energy-management performance of the three strategies [18,20]. Over longer operating periods, battery temperature, charge–discharge efficiency, SOC-sustaining control, and battery aging will affect the energy balance. Future research will incorporate operation-quality objectives, fuel economy, battery thermal states, and battery health into a long-horizon energy-management framework and validate the strategy under field combined-operation conditions.

5. Conclusions

This study developed an operation-quality-oriented energy management strategy based on MPC for a power-split hybrid electric tractor under equivalent rotary tillage–seeding combined operations. The PTO-side rotary-tillage load, drive-side equivalent traction load, prescribed travel-speed reference, and equivalent seeding-quality risk were used to describe the combined-operation task. Condition-dependent objective-weight scheduling was then applied to coordinate PTO-speed regulation, equivalent seed synchronization, and energy economy. Simulation, weight-sensitivity analysis, and dual-side loading bench tests led to the following conclusions.

1. The condition-severity index integrated PTO-load fluctuation, PTO-load impact intensity, and equivalent seeding-quality risk to identify steady, fluctuating, and impact-dominated operating conditions. The corresponding weight scheduling retained a higher energy-economy priority under steady loading and increased the priorities of PTO-speed regulation and equivalent seed synchronization as operating severity increased.
2. The weight-sensitivity results revealed clear trade-offs among PTO-speed stability, equivalent seed synchronization, and energy consumption. Increasing w_{PTO} reduced the PTO-speed RMSE, increasing w_{seed} reduced the equivalent seed-synchronization RMSE, and increasing w_{energy} reduced equivalent fuel consumption. The adopted condition-specific weights were located within the low-cost regions of the corresponding response distributions, supporting the rationality of the weight-scheduling pattern.
3. The proposed OQ-EMS/MPC improved both PTO-side operation quality and seeding-side equivalent operation quality. Compared with the rule-based EMS and fixed-weight MPC-EMS, the overall PTO-speed RMSE was reduced by 58.40% and 45.66%, respectively, while the equivalent seed-synchronization RMSE was reduced by 69.15% and 52.66%. The equivalent travel-speed RMSE decreased by 78.79% and 64.72%, respectively. Under the impact-dominated condition, the PTO-speed RMSE was reduced to 1.65 r/min, showing improved PTO-side disturbance regulation under severe loading.
4. The normalized composite cost of the OQ-EMS/MPC was 0.865, representing reductions of 13.53% and 6.26% relative to the rule-based EMS and fixed-weight MPC-EMS, respectively. The corresponding equivalent fuel consumption increased by 3.40% and 3.76%. The power-distribution results showed that the increased contribution of MG1 and MG2 strengthened PTO-side load compensation and drive-side speed regulation, thereby improving the equivalent combined-operation quality at a moderate energy cost.

Overall, the proposed OQ-EMS/MPC adjusted power-allocation priorities according to the severity of rotary tillage–seeding combined operations and achieved coordinated improvement in PTO-speed stability, equivalent seed synchronization, and comprehensive performance.

The conclusions of this study are limited to the 125 s equivalent bench-load conditions and the powertrain configuration considered in the present tests. Future work will implement the OQ-EMS on a complete hybrid electric tractor and conduct rotary tillage–seeding field tests under different soil conditions and load levels. Actual travel speed, driving-wheel slip, PTO torque and speed, seed-meter shaft speed, seed spacing, fuel consumption, and battery SOC will be measured synchronously to evaluate the long-duration robustness of the condition-severity identification and adaptive weight scheduling and to recalibrate the relevant thresholds and model parameters.

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Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Definition
EMS	Energy management strategy
OQ-EMS	Operation-quality-oriented energy management strategy
MPC	Model predictive control
PTO	Power take-off
MG1	Motor-generator 1
MG2	Motor-generator 2
SOC	State of charge
RMSE	Root-mean-square error
ECU	Engine control unit
PLC	Programmable logic controller
TCP/IP	Transmission Control Protocol/Internet Protocol
CAN	Controller Area Network

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