

TECHNICAL SPECIFICATION

Development of thermal and electrical simulation models for a modular railway traction battery system under railway-specific duty cycles

DIGAS, SIA

Project context: Modular battery system and flexible energy management system (EMS) for railway rolling stock hybridization

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Version	1.5 (05.10.2026) – Annex 2 to procurement specification DIGAS-ZKC-2026/1. Changes from v1.4 after MASOC KC comments of 05.10.2026: requirements on the simulation models worded as model requirements (“software”/“tool” replaced by “model”); every input is either mandatory or “may be left empty” (new §4.4, Appendix A); unclear wording (“if available”, “if applicable”, “optional”, “preferred”, “one or more”) replaced by explicit requirements; number of battery branches (§8), acceptance tolerances (§28.1) and run time (§29) fixed; user manual replaced by a model description and verification report (§30). Earlier changes (v1.4, 02.10.2026): on-vehicle EMS/BMS control software excluded (§1); no training session and no warranty; general “or equivalent” clause (§1). A Latvian translation is provided; in case of discrepancies the English text prevails.
Procurement title	Development of thermal and electrical simulation models for a modular railway traction battery system under railway-specific duty cycles
Primary users	DIGAS battery, BMS/CMS, thermal-management and vehicle-integration engineering teams
Expected result	Editable, documented and validated thermal and electrical simulation models with user interface, machine-readable interfaces, model source files and calculation documentation
Configuration philosophy	Chemistry-independent and topology-independent. All topology, cell, cooling and vehicle values shall be user-configurable.
Acceptance philosophy	Acceptance based on reproducible numerical verification, synthetic reference cases, user-supplied datasets and cross-checks against analytical solutions or controlled source data.

Abbreviations

Abbreviation	Meaning
AFE	Analog front end / cell monitoring front end
BMS	Battery Management System
CMS/CMU	Cell/Module Monitoring System / Cell Monitoring Unit
BDU	Battery Disconnect Unit
BTMS	Battery Thermal Management System
DCIR	Direct-current internal resistance
ECM	Equivalent Circuit Model
EMS	Energy Management System
EOL	End of life
HV	High voltage
HVIL	High-voltage interlock loop
IMD	Insulation Monitoring Device
OCV	Open-circuit voltage
PCM	Phase-change material
RMS	Root mean square
SOC	State of Charge
SOE	State of Energy
SOH	State of Health
SOP	State of Power
TMS	Thermal Management System

Abbreviation	Meaning
VCU	Vehicle Control Unit

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1. Purpose, scope and engineering end result

The procurement covers development, verification, documentation and handover of a set of coupled thermal and electrical simulation models for modular railway traction battery systems. The models shall be generic and parameter-driven, not a fixed calculator tied to one product. The user shall be able to create a new cell, module, pack, battery-system and vehicle configuration from parameter data, connect that configuration to a measured or synthesized railway duty cycle, and obtain time-domain electrical, thermal, energy, BMS/CMS and vehicle-performance results.

The models shall cover the full chain from cell characterization to vehicle route simulation. They shall combine cell electrochemical/electrical behavior, topology, bus and contact resistance, pack limits, BMS/CMS limits, thermal generation and heat transfer, coolant hydraulics, power electronics, traction demand, regenerative braking, environmental conditions, faults and uncertainty within one synchronized calculation framework.

The EMS dispatch strategies (§14.2) and the BMS/CMS calibration outputs (§9) are simulation and calibration-data functions of the simulation environment. Development of embedded EMS or BMS control software for on-vehicle use is not part of this procurement.

Any reference in this Technical Specification to a specific standard, technology, file format, programming language, software, manufacturer or brand shall be read as followed by the words “or equivalent”; an equivalent solution with at least the same functionality is acceptable.

1.1 Required engineering uses

- Create and maintain a library of arbitrary battery cells and chemistries using supplier data, laboratory data or user-defined engineering assumptions.
- Create arbitrary modules using any series/parallel arrangement supported by the selected cell-monitoring architecture, including cells in series, parallel cell groups, parallel strings, or other user-defined grouping logic.
- Create arbitrary packs from modules, submodules, trays, subpacks or other hierarchical units; the hierarchy shall not be limited to a fixed number of levels.
- Create multi-pack vehicle systems containing from 1 up to at least 12 independently protected battery branches connected in series, parallel, through DC/DC converters, or as independently switched sources to a common DC bus.
- Simulate acceleration, cruise, coasting, dwell, charging, regenerative braking, dynamic/rheostatic braking, repeated cycles, route reversals, gradients, environmental extremes and degraded operating states.
- Derive BMS/CMS limits and calibration maps from cell data and engineering margins rather than entering only a single maximum current or voltage.
- Calculate thermal-management requirements including cell heat generation, module temperature gradients, cold-plate loading, coolant flow, pressure drop, heater power, chiller/refrigeration load, time to operational readiness and daily auxiliary-energy demand.
- Parametrize a battery for a selected vehicle and route and quantify range, usable energy, continuous and transient power capability, regenerative acceptance, thermal limitations, DC-bus behavior and reserve margins.
- Compare alternative cells, topologies, cooling concepts, insulation concepts and control strategies using identical duty cycles and acceptance metrics.
- Export the results listed in §26 for subsequent detailed battery design, BMS/CMS configuration, supplier communication and testing.

1.2 Required end result

The final deliverable shall be a reusable engineering application with editable source models/code, parameter files, calculation documentation, user interface, batch/API capability and validation cases. A protected spreadsheet, a collection of disconnected calculation sheets, or a black-box executable without editable models and source code is not acceptable.

The models shall be deterministic for deterministic inputs. Every simulation shall be reproducible from a scenario file containing the model version, cell dataset version, topology, vehicle/route dataset version, solver settings, calibration version and, for probabilistic runs (§22), the random seed.

2. General functional architecture and calculation philosophy

The model set shall be organized as coupled but independently testable submodels. Each submodel shall expose defined inputs, outputs, units and validity ranges. The user shall be able to execute individual submodels for engineering checks and execute the complete coupled model for vehicle-duty simulations.

2.1 Functional submodels

Submodel	Primary purpose	Principal coupled variables
Cell data and parameter identification	Convert raw supplier/laboratory curves into validated model parameters and maps	OCV, capacity, DCIR, RC parameters, thermal properties, current limits, ageing data
Electrical cell ECM	Calculate cell terminal voltage, polarization, SOC/SOE and losses dynamically	Current, voltage, SOC, temperature, state variables
Topology/electrical network	Scale cell behavior to modules/packs and solve branch currents and losses	Series/parallel topology, conductor resistance, contactors, fuses, pack branch states
BMS/CMS model	Calculate dynamic allowable charge/discharge/regen power and protection responses	Cell/pack voltage, current, temperature, SOC/SOH/SOP, sensor states
Thermal model	Calculate heat generation and temperature states	Cell losses, coolant temperature/flow, ambient, conduction/convection/radiation
Coolant/hydraulic model	Calculate flow distribution, pressure drop, pump operating point and thermal transport	Flow, pressure, coolant properties, channel geometry, heat load
Rail duty model	Generate or replay time-resolved traction/braking demand	Speed, grade, mass, acceleration, wheel power, auxiliary loads
Power electronics model	Convert wheel/shaft and source powers to DC-bus/battery powers	Efficiency maps, torque/speed limits, bus voltage, current limits
Vehicle/EMS model	Dispatch battery and other energy sources	Requested traction power, SOC targets, charging strategy, generator/fuel-cell limits
Fault/uncertainty model	Apply component faults, sensor errors, parameter dispersion and degraded modes	Fault state, derating, isolation, branch availability, uncertainty distributions

2.2 Coupling and time base

- The master simulation clock shall support a user-selectable base step from 0.05 s to at least 10 s, with smaller internal substeps where required by numerical stability or fast protection logic.
- Imported telemetry timestamps shall be preserved. Any resampling shall be explicit, user-selectable, logged and reversible.
- Electrical states, thermal states, BMS limits, power-electronics limits and vehicle power demand shall be exchanged at every coupling step. The model shall not apply a thermal limit only after completion of an electrical simulation.
- Event-driven logic shall be supported for contactor operation, precharge completion, trip thresholds, hysteresis, debounce timers, fault latching, pack isolation, pack reconnection and mode transitions.
- All internal calculations shall use SI units. The user interface may present engineering units such as km/h, kWh, L/min, bar, °C and %.

3. Generic cell-module-pack topology and configuration engine

The topology engine is a central requirement. No fixed series count, module count, cell count, pack count or pack voltage shall be embedded in the model source files. A user shall create a topology by defining hierarchical components and connectivity. The model shall calculate all derived nominal and limiting electrical quantities from the user-defined structure.

3.1 Supported hierarchy

At minimum the hierarchy shall support: Cell → parallel cell group → module → subpack/tray → pack → vehicle battery branch → common DC bus. The user shall be able to omit unused hierarchy levels. Additional hierarchy levels shall be possible through generic nested component definitions or an equivalent approach.

3.2 User-configurable topology parameters

- Number of cells in series within each electrical group.
- Number of cells in parallel within each group and number of parallel strings.
- Number of modules connected in series and/or parallel.
- Number of subpacks/trays and their series/parallel connection.
- Number of complete packs or branches installed on the vehicle.
- Connection mode of packs: direct parallel, direct series, series-parallel network, independent DC/DC branches, switched branches, or user-defined connection graph.
- Presence and location of pack fuses, module fuses, main contactors, precharge circuits, manual service disconnects, current sensors, busbars, connectors, cable segments and isolation devices.
- Module isolation or bypass devices (the model shall support them; the user decides for each configuration whether they are present), including rules for recalculating active series count and compatible connection of parallel branches.
- Cell-monitor channel grouping, temperature-sensor grouping and communication hierarchy for BMS/CMS calculations.
- Distributed installations in which physically separate packs or subpacks experience different ambient/coolant conditions.

3.3 Derived topology calculations

$N_{s,eq}$ = total number of electrically active cell voltage elements in series

$N_{p,eq}$ = equivalent number of cells sharing branch current in parallel

$V_{nom,pack} = \sum V_{nom,cell,k}$ across the active series path

$Q_{nom,pack} = Q_{nom,cell} \times N_{p,eq}$ [Ah]

$E_{nom,pack} = \sum (V_{nom,group} \times Q_{nom,group})$ [Wh]

$I_{cell} = I_{branch} / N_{p,local}$

The current division shall be resolved at the local parallel-group level. Parallel cells or strings with non-identical resistance shall not be forced to equal current unless the user selects an idealized mode.

$P_{pack}(t) = V_{pack}(t) \times I_{pack}(t)$

For non-identical parallel strings, the model shall solve current sharing from the branch open-circuit voltages and dynamic impedances. Capacity, resistance, SOC, SOH and temperature dispersion between strings shall therefore influence current sharing and thermal loading.

3.4 Topology validity checks

- Warn if the configured maximum pack voltage exceeds user-entered component voltage ratings.
- Warn if BMS/CMS channel count is insufficient for the configured number of monitored cell groups.

- Warn if series-connected packs/modules have incompatible nominal capacities or configured SOC windows.
- Warn if hard-parallel branches can be connected with a user-defined voltage/SOC mismatch above a configurable permissive.
- Calculate the minimum and maximum DC-bus voltage for the topology over the user-defined cell voltage range and active-module states.
- Calculate current carried by every fuse, contactor, conductor, connector and bus segment for all defined branches.
- Calculate topology-dependent short-term and continuous power limits and identify the limiting component.
- Retain both physical topology and active topology so isolated/bypassed modules remain monitored even when excluded from the traction path.

4. Engineering data model, parameter governance and traceability

All calculation inputs shall be stored in a schema-driven parameter database. A chemistry name is metadata only; model behavior shall be determined by numeric properties, maps, equations and limits supplied for the selected cell. A new cell shall be addable without source-code changes.

4.1 Data status and provenance

Data status	Definition	Required treatment
Measured	Direct laboratory or vehicle measurement	Store source file, test condition, sample count, test date and uncertainty (uncertainty may be left empty).
Supplier specification	Published or directly supplied manufacturer value	Store source document and validity conditions.
Fitted	Parameter derived by model fitting	Store fitting method, objective function, dataset and goodness-of-fit metrics.
Derived	Calculated from other controlled values	Store formula and source parameter versions.
Assumed	Engineering assumption due to missing data	Require explicit user acknowledgement; include in reports and sensitivity analysis.
Estimated from analogous component	Borrowed or scaled from another design	Keep separate from measured data and require a confidence grade.

4.2 Required metadata for every parameter/map

- Parameter name and unique internal key.
- Description and physical meaning.
- SI unit and display unit.
- Source type and source reference.
- Applicable chemistry/cell/component.
- Test or operating conditions.
- Valid range for each of SOC, temperature, voltage, current, C-rate, frequency and time on which the parameter or map depends.
- Interpolation method and extrapolation rule.
- Uncertainty/tolerance or probability distribution (may be left empty; if empty, the value is treated as exact in the uncertainty analysis of §22).
- Revision/version and change history.

4.3 Interpolation and extrapolation

Interpolation shall be bounded and transparent. For two-dimensional or three-dimensional maps, the model shall identify the interpolation algorithm (e.g., bilinear, bicubic, Delaunay or piecewise

linear). Extrapolation outside the validated map shall be disabled by default. If the user enables extrapolation, the model shall mark all affected time samples and quantify the fraction of simulated operating time outside the validated domain.

4.4 Mandatory inputs and inputs that may be left empty

The Contractor shall implement every input, function and output described in this Technical Specification. For each input, this Technical Specification states whether it is mandatory or “may be left empty” by the user (see in particular §5.1, §11.1, §12.2 and Appendix A). When the user leaves an input empty, the model shall apply the default stated in this Technical Specification or, where no default is stated, switch off the dependent calculation, and shall state this in the results. The words “may be left empty” and “may be set to zero” refer only to the data entered by the user, never to the Contractor’s obligation to implement the function.

5. Cell characterization, test-data processing and parameter identification

The cell-data module shall accept both summarized cell specifications and raw test time series. It shall convert supplier and laboratory data of the types listed in §5.1 and Appendix A into the parameters needed by the electrical, BMS and thermal models. The model shall not require a specific chemistry and shall not assume that a cell has a flat or monotonic voltage curve.

5.1 Minimum supported cell data

- Nominal and rated capacity [Ah], nominal energy [Wh], nominal voltage and usable voltage range.
- Charge and discharge voltage limits, warning/protection limits (may be left empty), and the supplier’s recommended operating SOC window.
- OCV-SOC data for charge and discharge at any number of temperatures (minimum one), including hysteresis (may be left empty; if empty, a single OCV curve is used).
- Capacity retention versus temperature and versus discharge/charge rate.
- DC resistance versus SOC, temperature, current direction and pulse duration.
- AC resistance or impedance data, including EIS spectra (may be left empty).
- Charge-current capability versus SOC and temperature, including continuous and pulse limits.
- Regenerative-charge current capability (may be left empty; if empty, the ordinary charge capability is used).
- Discharge-current capability versus SOC and temperature for continuous operation and for any number of pulse durations (minimum one).
- Cell mass, dimensions, surface areas, material construction (may be left empty), heat capacity, effective thermal conductivity and anisotropy parameters (anisotropy may be left empty; if empty, isotropic conductivity is used).
- Entropic coefficient $dOCV/dT$ versus SOC (may be left empty; if empty, reversible heat is zero and the results state this, see §16.1).
- Self-discharge, coulombic efficiency, energy efficiency and hysteresis data (each may be left empty; defaults: self-discharge 0, coulombic efficiency 1.0, energy efficiency calculated from the ECM, no hysteresis).
- Cycle-life and calendar-life data, including test temperature, DOD, SOC window, C-rate, rest periods and end-of-life criterion.
- Abuse-test observations may be stored for engineering reference, but the standard operating model shall not infer safe operating limits directly from abuse-test endpoints without explicit user calibration.

5.2 Raw test-data import

The user shall be able to import CSV/XLSX or equivalent tabular time series containing time, current, voltage, temperature and optional additional channels. The importer shall support multiple test sheets/files and a mapping wizard. Sign convention, units, sensor offsets and test metadata shall be explicitly defined before data are accepted.

5.3 OCV-SOC extraction

The model shall support OCV-SOC import from supplier tables and extraction from low-rate or relaxation tests. When separate charge and discharge OCV curves are supplied, both shall be stored. A single averaged OCV curve may only be used as a user-selectable simplification.

$$SOC(t) = SOC(t_0) - (1/Q_{ref}) \int \eta_I(T, SOC, I) \cdot I(t) dt$$

Positive current is discharge. Charge current is negative. The sign convention shall be globally consistent.

5.4 DCIR and pulse characterization

$$R_{DC}(\Delta t) = [V(t_0-) - V(t_0+\Delta t)] / \Delta I$$

The model shall allow resistance extraction at user-defined pulse durations. The sign and time reference shall be recorded.

Where charge and discharge resistances differ, separate maps shall be retained. The model shall support resistance as a function $R_0(SOC, T, SOH, dir, |I|)$; if the data contain no current dependency, R_0 is used without $|I|$ and the results state this. Sparse datasets shall be interpolated with visible confidence limits.

5.5 Equivalent-circuit parameter identification

A two-RC Thevenin model is the minimum primary dynamic electrical model. The fitting routine of the model shall identify R_0 , R_1 , C_1 , R_2 and C_2 against pulse or dynamic data. A one-RC model may be retained for computational comparison, but the delivered default model shall support two dynamic polarization states. The contractor may provide higher-order or physics-based alternatives if they remain user-configurable and do not replace the required transparent ECM.

- Fitting shall be possible independently at multiple SOC and temperature points.
- Optimization shall report RMSE, maximum voltage residual, normalized error and confidence intervals.
- The model shall provide parameter smoothing across SOC and temperature as a user setting (default: off); raw fitted points shall always be preserved.
- Fitted parameters shall be constrained to physically meaningful signs and ranges.
- The model shall flag parameter regions supported only by extrapolation or insufficient data.
- Validation shall use test data not used for fitting wherever such data are provided.

6. Cell electrical equivalent-circuit model and state equations

6.1 Required primary ECM

$$V_t = OCV(SOC, T, SOH, h) - I \cdot R_0(SOC, T, SOH, dir) - V_1 - V_2$$

$$dV_1/dt = -V_1/(R_1 \cdot C_1) + I/C_1$$

$$dV_2/dt = -V_2/(R_2 \cdot C_2) + I/C_2$$

$$dSOC/dt = -\eta_I(SOC, T, I, SOH) \cdot I / Q_{avail}(T, SOH)$$

The implementation shall support separate charge/discharge efficiency and shall permit the OCV function to include hysteresis state h when hysteresis data are entered (§5.1). SOC shall be bounded according to the configured capacity definition but protection logic shall be based primarily on voltage, current and temperature rather than on SOC alone.

6.2 Numerical solution

- Use numerically stable exact discretization for linear RC branches or a validated ODE integration method.
- Allow user-selectable electrical integration step and automatic sub-stepping under fast transients.
- Preserve state continuity through current sign changes, dwell periods and regenerative events.

- Initialize polarization states from rest assumptions or from a user-provided previous-state file.
- Support warm restart of a simulation from a saved electrical/thermal/BMS state.

6.3 Loaded-voltage constraints and power availability

The solver shall calculate allowable current from the combined current map, loaded-voltage constraints, hardware limits and thermal/BMS derating. It shall not simply use nominal pack voltage to translate a power request into current.

$$V_{\min} \leq V_t(I, SOC, T, \text{state}) \leq V_{\max}$$

$$P_{\text{req}} = V_t(I) \cdot I$$

For a requested power the solver shall solve the nonlinear or quadratic relationship between current and loaded voltage. If no feasible solution exists, power shall be curtailed to the maximum feasible value and the limiting constraint recorded.

6.4 Energy accounting

$$E_{\text{terminal}} = \int V_t I \, dt$$

$$E_{\text{OCV}} = \int \text{OCV} I \, dt$$

$$E_{\text{loss,ohmic}} = \int I^2 R_0 \, dt$$

$$E_{\text{loss,pol}} = \int I(V_1 + V_2) \, dt$$

Energy accounting shall close numerically over each simulation and shall expose residual error. Charge and discharge efficiencies shall be available at cell, module, pack, DC-bus and route level.

7. Module, pack and high-voltage electrical network model

The electrical network model shall transform cell behavior into a complete battery branch while retaining local current, voltage, power and loss information. Lumped scaling is acceptable only where the configuration is electrically homogeneous and the user explicitly selects it. For heterogeneous branches, the network shall solve local states.

7.1 Component models

Component	Minimum representation
Busbars / cables	Temperature-dependent or user-defined resistance; length/section/material option; I^2R losses.
Connectors	Contact resistance plus current and temperature rating.
Fuse	Cold resistance, temperature dependence (may be left empty), continuous current rating and I^2t / time-current characteristic (may be left empty).
Main contactor	Closed resistance, current/voltage rating, auxiliary state and opening/closing logic.
Precharge contactor/resistor	Resistance, power/energy rating, timing and thermal energy per event.
Manual service disconnect	Series resistance and state.
Current sensor	Range, accuracy, offset, noise and delay (delay may be set to zero).
Voltage sensor	Range, accuracy, bias and filtering (filter time constant may be set to zero).
IMD/HVIL	Logical safety input with configurable delay and response.
Module bypass / isolation	Electrical state, auxiliary feedback, allowable switching sequence and active-topology update.

7.2 Pack voltage and branch resistance

$$V_{\text{pack}} = \sum V_{\text{group}} - I_{\text{pack}} \cdot R_{\text{distribution}} - \sum V_{\text{component_drop}}$$

$$R_{distribution} = R_{bus} + R_{cable} + R_{connector} + R_{contactors} + R_{fuse} + R_{service} + \dots$$

Distribution loss shall be included in both terminal voltage and thermal load. The user shall be able to assign a fraction of component heat to the battery enclosure, to external cable space, or to another thermal node.

7.3 Precharge

$$V_{bus}(t) = V_{pack} \cdot [1 - \exp(-t/(R_{pre} \cdot C_{bus}))] \quad \text{for the ideal reference case}$$

$$I_{pre}(t) = (V_{pack} - V_{bus})/R_{pre}$$

The full model shall include pack internal resistance, DC-link capacitance, parallel branch states and converter leakage where configured. It shall calculate peak precharge current, resistor energy, precharge time, delta-voltage permissive, timeout and fault cases such as welded contactor or open resistor.

7.4 Cell and parallel-group dispersion

The user shall be able to assign distribution or deterministic offsets to capacity, R0, OCV, self-discharge and initial SOC. For parallel cells/strings, current sharing shall be solved from electrical states. For series cells, the model shall track individual cell voltage if the user enables cell-resolved simulation, allowing identification of the first cell reaching a protection threshold.

8. Parallel packs, multi-branch battery systems and DC-bus coupling

The model shall support from 1 up to at least 12 independently protected battery branches connected to a common DC bus. Each branch may have a different cell type, topology, capacity, SOC, SOH, temperature, resistance and state of availability. The purpose is to model both normal parallel operation and mismatch/degraded cases (§8.3, §20).

8.1 Direct parallel branch solution

For direct parallel branches the common-bus voltage shall satisfy Kirchhoff current balance. A branch shall not be assigned a fixed fraction of total current unless the user selects an idealized equal-sharing mode.

$$V_{bus} = E_k - I_k \cdot Z_k \quad \text{for each connected branch } k$$

$$\sum I_k = I_{bus}$$

The branch equivalent E_k and dynamic impedance Z_k shall include OCV/polarization, pack distribution resistance and applicable power-electronics elements. Current reversal between branches shall be permitted when physically possible and shall be reported as internal circulation.

8.2 Pack connection permissives

- Check polarity and topology compatibility.
- Check bus/pack voltage difference and calculate prospective equalization current before contactor close.
- Check SOC, temperature and active-series-count mismatch against configurable permissives.
- Check insulation/HVIL/contactors/precharge status.
- Execute precharge independently for each branch that is configured with its own precharge circuit.
- Reject or delay connection when predicted equalization current exceeds the pack or contactor limit.
- Log connection reason, inhibition reason and timing.

8.3 Degraded multi-pack operation

If one pack is isolated, the simulation shall recalculate current and thermal loading of remaining branches, the new continuous/peak power capability, usable energy, route completion margin and DC-bus voltage. If branches have unequal active series count because of module bypass, the model shall determine whether direct parallel connection remains permissible and shall not assume it is safe.

9. BMS/CMS limit derivation, protection and calibration-output generator

This submodel shall convert cell capability data, topology, sensor capability, hardware limits, thermal capability and project safety margins into BMS/CMS calibration data. Its output shall contain all calibration families listed in §9.2 and Appendix C, not only nominal values.

9.1 Dynamic current and power limits

The model shall calculate independent discharge, ordinary charge and regenerative-charge limits. Each shall be a function of at least SOC and cell temperature and additionally of SOH, cell voltage, pulse duration, coolant state and hardware limits (the model shall support all of these dependencies; the user selects which are active).

```
I_dis,max = min(I_cell,map, I_Vmin, I_thermal, I_hardware, I_branch, I_sensor,  
I_user_margin)
```

```
I_chg,max = max(I_cell,chg,map, I_Vmax, I_thermal, I_hardware, I_user_margin)  
[negative sign convention]
```

```
P_dis,max = V_loaded(I_dis,max) · I_dis,max
```

```
P_regen,max = |V_loaded(I_chg,max) · I_chg,max|
```

The BMS limit calculation shall operate at the most restrictive cell/module/pack state where cell-resolved data are enabled. Pack-average temperature or SOC shall not mask a single-cell limitation.

9.2 Required BMS/CMS calibration families

- Cell overvoltage: warning, derating start, controlled stop, protective trip and latched trip (the model shall provide all five levels; the user may switch off individual levels for a project); each with hysteresis and debounce/release time.
- Cell undervoltage: warning, derating start, controlled stop, protective trip and latched trip (the model shall provide all five levels; the user may switch off individual levels for a project).
- Cell overtemperature and undertemperature separately for charge, regenerative charge and discharge.
- Pack/module overtemperature and temperature-spread thresholds.
- Charge current, regenerative-charge current and discharge current limit maps.
- Charge/discharge/regen power limit maps.
- Cell voltage rate-of-change and temperature rate-of-change diagnostic thresholds.
- Pack overcurrent thresholds for continuous, short-time and instantaneous protection, with delay/energy criteria.
- Short-circuit coordination values and interface to fuse/pyro-fuse/contactors strategy (calculated when the hardware data are entered; otherwise the results state that they were not calculated).
- Balancing enable/disable SOC and voltage ranges, delta-voltage start/stop thresholds, balance current, maximum duty cycle and thermal inhibit thresholds.
- SOC operating windows, reserve SOC, limp-home reserve and charge target windows.
- SOE and SOP reporting parameters and time horizons.
- Sensor plausibility, open-wire diagnostics and redundant-measurement disagreement limits.
- Pack-to-bus precharge delta-voltage permissive, precharge timeout, minimum/maximum current and welded/open contactor diagnostics.
- Pack parallelization voltage/SOC/temperature/active-topology mismatch permissives.

- Coolant inlet/outlet temperature limits, minimum flow, abnormal pressure/drop diagnostics, chiller/heater request thresholds and thermal derating curves.
- IMD, HVIL, isolation, contactor, communication and BMS/CMS loss responses.
- Fault severity, debounce, hysteresis, latching, reset permissions and safe-state action for every modeled diagnostic.

9.3 Safety margin handling

Supplier absolute limits, recommended operating limits and project-calibrated BMS limits shall be stored separately. The user shall apply margin by absolute offset, percentage, lookup table or rule set. Reports shall show the original source limit and the resulting calibrated limit so that engineering margin is auditable.

9.4 Map generation and export

The model shall generate arbitrary-resolution SOC-temperature maps, not fixed 21×13 tables. The user shall choose breakpoints and interpolation. Maps shall be exportable to CSV/XLSX/JSON or equivalent formats and to a documented machine-readable representation suitable for subsequent BMS supplier implementation. Every exported calibration shall include units, version, source dataset and margin configuration.

10. SOC, SOE, SOH and SOP estimation models

10.1 SOC

The model shall implement coulomb counting with temperature/SOH-adjusted capacity and OCV-based rest correction, and an extended Kalman filter, unscented Kalman filter or equivalent observer.

- User-configurable initial SOC and uncertainty.
- Coulombic efficiency by charge/discharge direction.
- Capacity dependence on temperature and SOH.
- OCV correction only when relaxation conditions are satisfied or through a validated observer.
- Sensor offset/noise influence and drift analysis.
- Parallel-string SOC mismatch handling.

10.2 SOE

$$\text{SOE} = E_{\text{remaining}} / E_{\text{available,reference}}$$

SOE shall account for the actual usable voltage/SOC window, loaded-voltage limits and temperature-dependent capacity. The model shall distinguish nominal stored energy from usable deliverable energy under the current duty and power level.

10.3 SOH

The model shall support capacity SOH, resistance SOH and composite SOH as separate indicators. The model shall not force a single SOH scalar to represent both capacity fade and resistance growth. User-entered measured SOH values shall be usable without an ageing model.

10.4 SOP

SOP shall be calculated for selectable horizons, e.g. instantaneous, 10 s, 30 s, 60 s and continuous. The limiting current shall account for loaded-voltage prediction over the horizon, current maps, temperature, RC polarization, hardware and thermal constraints.

11. Railway measured-duty-cycle import and telemetry replay

The duty-cycle subsystem shall accept real vehicle telemetry and externally prepared duty-cycle files. The model shall not require a specific DIGAS logger format. A mapping layer shall convert source columns to a canonical engineering schema.

11.1 Minimum accepted measured-duty inputs

- Time/timestamp.
- Vehicle speed.
- GPS/route position or chainage.
- Elevation or gradient (may be left empty; if empty, level track is assumed).
- Traction power, DC-bus power or battery power.
- Motor torque/speed or tractive effort (may be left empty).
- Brake command and/or regenerative power.
- Battery voltage/current.
- Cell/module/pack temperatures.
- SOC/SOH/SOP reported by existing system.
- Auxiliary power.
- Generator/fuel-cell/charger power (may be left empty for vehicles without these sources).
- Ambient temperature.
- Coolant inlet/outlet temperature, flow, pressure, pump/heater/chiller states (may be left empty).
- Driver/notch/mode state (may be left empty).

11.2 Data-quality treatment

- Detect gaps, duplicate timestamps, out-of-order samples, impossible values, saturation and flat-lined sensors.
- Allow user-approved interpolation, hold-last-value, deletion or flag-only treatment of gaps.
- Calculate sample-time statistics and preserve the original dataset unchanged.
- Allow synchronization of channels logged at different rates.
- Allow user-entered time offset between data systems.
- Provide data-quality flags in the canonical ledger and exported results.

11.3 Power-driven replay

At minimum, timestamp plus requested battery/DC-bus power shall be sufficient to execute the battery model. If only wheel/traction power is supplied, the model shall apply the configured motor/inverter/DC/DC efficiency and auxiliary-load model to calculate battery demand. If measured battery current/voltage are supplied, the replay shall support model-versus-measurement validation.

12. Route, train and duty-cycle synthesis model

The route synthesizer shall calculate a physically transparent longitudinal railway load profile from vehicle and route data. It shall support both quick feasibility-grade calculations and higher-resolution engineering simulations. The user shall be able to replace any internally generated route/speed/gradient data with surveyed or operator data.

12.1 Vehicle/train inputs

- Vehicle type and identifier.
- Tare mass, payload/passenger mass and gross train mass.
- Rotating-mass factor or equivalent inertia.
- Adhesive mass.
- Wheel diameter and gear ratio.
- Number of powered axles.

- Maximum tractive effort and speed.
- Motor/inverter torque-speed/power maps.
- Continuous and peak traction power.
- Maximum service/regenerative braking effort.
- Auxiliary power profile.
- Drag/running resistance coefficients.
- Curve-resistance formulation (may be left empty; if empty, curve resistance is zero).
- Adhesion coefficient or speed/environment map.
- Allowed acceleration/deceleration and jerk limits.
- Station dwell and operational delays.

12.2 Route inputs

- Start and end points or an imported chainage profile.
- Distance/chainage.
- Point elevation and/or gradient.
- Speed limits.
- Curve radius (may be left empty; if empty, curve resistance is zero).
- Stations/stops and dwell times.
- Direction-specific restrictions.
- Timetable/pathing constraints (may be left empty).
- Ambient temperature/weather profile.
- Charging locations or electrified segments.
- Regenerative-braking restrictions imposed by infrastructure or vehicle configuration.

12.3 Running resistance

$$F_{\text{run}}(v) = A + B \cdot v + C \cdot v^2$$

The generic Davis form shall be available with user-defined coefficients. Coefficients may apply to the complete consist or be built from locomotive and wagon groups. A specific-resistance formulation in N/kN shall also be supported.

$$r(v_{\text{kmh}}) = a + b \cdot v_{\text{kmh}} + c \cdot v_{\text{kmh}}^2 \quad [\text{N/kN}]$$

$$F_{\text{run}} = r(v) \cdot W_{\text{kN}}$$

The model shall include a configurable feasibility reference law and shall allow users to save operator- or vehicle-specific coefficient sets. No single resistance equation shall be hard-coded as universally valid.

12.4 Gradient and curve resistance

$$F_{\text{grade}} = m \cdot g \cdot \sin(\arctan(i/1000)) \approx m \cdot g \cdot i/1000$$

$$F_{\text{curve}} = f(R, \text{gauge}, \text{vehicle}) \quad \text{or} \quad r_{\text{curve}}(R) \cdot W_{\text{kN}}$$

Positive gradient is uphill. Return-direction simulation shall reverse gradient sign from the physical route profile unless an independent return profile is supplied.

12.5 Acceleration and dynamic force

$$m_{\text{eq}} = m \cdot (1 + \lambda_{\text{rot}})$$

$$F_{\text{acc}} = m_{\text{eq}} \cdot a$$

$$F_{\text{req}} = F_{\text{run}} + F_{\text{grade}} + F_{\text{curve}} + F_{\text{acc}}$$

$$P_{\text{wheel}} = F_{\text{req}} \cdot v$$

12.6 Adhesion limitation

$$F_{\text{adh,max}} = \mu(v, \text{weather}, \text{rail condition}) \cdot m_{\text{adh}} \cdot g$$

Traction and electric braking shall be limited by adhesion. The user shall be able to use a scalar coefficient, a speed-dependent curve, separate traction/braking values, or an environment-specific map.

12.7 Speed-profile calculation

Three modes shall be available: measured speed replay, imported target speed profile and calculated speed profile. In calculated mode, a forward/backward integration algorithm shall enforce line speed, vehicle acceleration, braking, traction-power/tractive-effort limits and stop points. The spatial resolution shall be user configurable; values down to 10 m or finer shall be supported for short routes and station approaches.

12.8 Negative mechanical energy and regenerative opportunity

$$E_{\text{kin}} = 0.5 \cdot m_{\text{eq}} \cdot v^2$$

The model shall identify negative wheel power from downhill surplus and deceleration. Mechanical braking opportunity shall then be passed through adhesion, motor-generator, inverter, DC-bus, battery and BMS acceptance limits. The following energy terms shall be reported separately: theoretical mechanical negative energy; electrically convertible regenerative energy; battery-accepted regenerative energy; energy rejected because of battery limits; energy rejected because of power-electronic/adhesion limits; rheostatic/dynamic-brake dissipation; friction-brake energy.

12.9 Repeated cycles and operating schedule

The user shall be able to define repeated round trips, terminal dwell, charging opportunities, shift/day schedules and overnight soak. The resulting battery SOC and temperature shall carry over between cycles. The model shall calculate whether a periodic steady state is reached and report the daily energy balance.

13. Traction motor, inverter, DC/DC, charger and braking models

13.1 Traction motor

- Input torque-speed envelope with continuous and peak curves.
- Efficiency map $\eta_{\text{motor}}(\omega, \text{Torque}, T)$ or scalar fallback.
- Field-weakening region.
- Regenerative torque envelope independently from motoring envelope.
- Motor thermal derating shall be entered as a limit map or as an external power limit (may be left empty).
- Mechanical speed from wheel diameter and gear ratio.

13.2 Inverter

The inverter model shall accept efficiency as a function of DC voltage, output power/torque and speed. If only a scalar efficiency is entered, the model shall use it and state the simplification in the results. DC-bus current shall be solved from actual bus voltage rather than nominal voltage.

$$P_{\text{DC}, \text{trac}} = P_{\text{motor}, \text{electrical}} / \eta_{\text{inv}}$$

$$P_{\text{DC}, \text{regen}} = P_{\text{motor}, \text{generator}} \cdot \eta_{\text{inv}, \text{regen}}$$

13.3 DC/DC converter

Bidirectional DC/DC models shall support voltage/current limits on both ports, efficiency maps, standby consumption and direction-dependent efficiency. This permits simulation of multiple battery packs at different voltage levels or battery/fuel-cell hybrid architectures.

13.4 External charger

- AC/DC or DC charging power limit.
- Charger efficiency versus power.
- Grid power cap.
- Charge-current/voltage control interface with BMS limits.
- Charge tapering.
- Charging-station dwell window.
- Thermal-management auxiliary energy during charging.

13.5 Brake blending

The model shall split requested braking between regenerative electric braking, rheostatic/dynamic braking and friction braking. The split shall be recalculated dynamically as battery acceptance, bus voltage, motor speed, adhesion and BMS limits change.

14. Hybrid source, generator and charging strategy representation

For hybrid railway vehicles, the battery cannot be sized correctly without representing other energy sources. The model shall therefore include configurable source blocks for engine-generator sets, fuel cells, catenary/shore charging or other DC sources. Detailed combustion/fuel-cell electrochemistry is not required unless separately supplied; however, power/efficiency and operating-state behavior shall be modeled.

14.1 Generator/range extender

- Minimum/maximum generator power.
- Target high-efficiency operating band.
- Ramp rate and start/stop delay.
- Fuel or source efficiency map versus power.
- Warm-up and minimum run-time constraints (may be set to zero).
- EMS target SOC band.
- Battery assist during peak demand.
- Battery recharge during low demand/dwell.

14.2 EMS dispatch strategies

At minimum the user shall be able to select or script: charge-depleting, charge-sustaining, fixed-SOC-band, route-aware SOC target, peak-shaving, generator-constant-power, battery-only geofenced section and externally charged duty. The dispatch logic shall always respect the instantaneous BMS/SOP limits returned by the battery model.

15. Battery sizing and vehicle/route parametrization

The sizing module shall determine whether a proposed topology can satisfy the route and vehicle requirements and shall search the integer topology/design space (§15.2). Sizing shall consider energy, power, voltage, regenerative acceptance, thermal behavior, mass, volume and current-carrying hardware simultaneously.

15.1 User-defined design constraints

- DC-bus minimum/nominal/maximum voltage.
- Maximum and target pack voltage.
- Required battery-only distance or operating time.
- Required continuous traction power.
- Required peak power and duration.
- Required regenerative-braking power and duration.
- Minimum SOC reserve at route end.
- Permitted SOC operating window.

- Maximum cell, module and coolant temperatures.
- Minimum temperature for unrestricted charge/discharge.
- Available pack envelope(s).
- Maximum battery mass and axle-load constraints.
- Number and location of pack envelopes.
- Maximum cable/current rating.
- Charging power and time window.
- Target lifetime or equivalent full cycles if ageing is enabled.

15.2 Integer topology search

The model shall be able to enumerate or optimize discrete combinations of cell series/parallel counts, module series/parallel counts and pack-branch counts. Candidate solutions violating voltage, channel-count, current, power, energy or user-defined physical constraints shall be rejected with a documented reason.

15.3 Required sizing outputs

- Total cell/module/pack quantity.
- Nominal and minimum/maximum voltage.
- Gross and usable energy.
- Continuous and transient charge/discharge power capability by SOC/temperature.
- Expected maximum traction and regen current.
- Mass and volume from user-supplied component geometry/mass.
- Expected route SOC profile and terminal SOC.
- Thermal peak and time to thermal limitation.
- Cooling/heating requirement.
- Regeneration accepted/rejected.
- Power reserve and energy reserve margins.
- Route feasibility verdict based on explicit constraints, not a qualitative score.

16. Transient thermal model and heat-generation calculation

The thermal model shall be a real transient heat-balance model coupled to electrical behavior. A lookup table that assigns temperature only from C-rate is insufficient. The model shall represent cell thermal mass, internal heat generation, conduction to neighboring structures, heat transfer to a cold plate or air, coolant transport, enclosure/insulation heat transfer and ambient conditions.

16.1 Cell heat generation

$$Q_{\text{dot_irr}} = I \cdot (OCV - V_t) \approx I^2 R_0 + I \cdot (V_1 + V_2)$$

$$Q_{\text{dot_rev}} = -I \cdot T \cdot (\partial OCV / \partial T)_{\text{SOC}}$$

$$Q_{\text{dot_cell}} = Q_{\text{dot_irr}} + Q_{\text{dot_rev}} + Q_{\text{dot_additional}}$$

Reversible entropic heat shall be calculated from the entered dOCV/dT data; if this input is empty, it is zero and the results state this. The model shall also include heat from balancing resistors, busbars, contactors and local electronics; each of these may be set to zero.

16.2 Thermal network equation

$$C_i \cdot dT_i / dt = Q_{\text{dot_i}} + \sum_j G_{ij} \cdot (T_j - T_i) + Q_{\text{dot_conv},i} + Q_{\text{dot_rad},i}$$

Thermal capacitance C_i and conductance G_{ij} shall be parameterized from material properties, geometry, contact resistance and calibrated effective values. The thermal network shall provide at least one cell-core node and one surface/cold-plate interface node per thermally representative cell group. The user shall be able to increase model granularity.

16.3 Spatial temperature distribution

- Calculate minimum, maximum, mean and standard deviation of cell temperature.
- Calculate temperature spread within each module and pack.
- Identify hottest cell/group and time of occurrence.
- Allow different cells/modules to see different coolant or ambient boundary conditions.
- Allow thermal asymmetry from manifold position, enclosure edges, electronics/BJB heat, neighboring equipment or partial coolant blockage.
- Provide node-level time histories for selected cells/modules.

16.4 Thermal material stack

The user shall define cell-to-TIM, TIM, cold-plate, structural plate, thermal barrier/insulation, enclosure and ambient thermal paths. Material parameters shall include thickness, area, thermal conductivity, heat capacity, density and contact resistance (contact resistance may be set to zero). The model shall support alternative internal insulation concepts and quantify their effect on warm-up, cool-down, hot-spot temperature and energy consumption.

17. Cold plate, coolant circuit and hydraulic model

17.1 Coolant energy balance

$$\dot{Q}_{\text{coolant}} = \dot{m} \cdot c_p(T, x) \cdot (T_{\text{out}} - T_{\text{in}})$$

$$dT_{\text{coolant}}/dx = q_{\text{prime}}(x)/(\dot{m} \cdot c_p)$$

Coolant properties shall be temperature-dependent (the temperature-dependent data may be left empty; if empty, constant properties are used). The user shall define water/glycol ratio or another coolant and its density, heat capacity, viscosity, conductivity and freezing point.

17.2 Cold-plate heat transfer

The cold-plate model shall represent thermal resistance from cell surface through TIM to plate and convective resistance from plate wall to coolant. The user shall enter or import effective heat-transfer coefficient from CFD/test data, or define channel geometry so that the model calculates a correlation-based coefficient.

$$R_{\text{th, total}} = R_{\text{cell-contact}} + t_{\text{TIM}}/(k_{\text{TIM}} \cdot A) + R_{\text{plate}} + 1/(h_{\text{coolant}} \cdot A_{\text{wet}})$$

17.3 Hydraulic pressure drop

$$\Delta p_{\text{fric}} = f \cdot (L/D_h) \cdot \rho v^2 / 2$$

$$\Delta p_{\text{minor}} = K \cdot \rho v^2 / 2$$

$$\Delta p_{\text{branch}} = \Sigma \Delta p_{\text{fric}} + \Sigma \Delta p_{\text{minor}}$$

The model shall calculate Reynolds number, friction factor and branch pressure drop. For laminar flow the laminar friction relation for the channel cross-section, documented by the Contractor ($f = 64/Re$ for circular channels), shall be used. For turbulent flow, Colebrook, Swamee-Jain or an equivalent validated correlation shall be used. User-entered empirical pressure-drop curves shall be supported.

17.4 Parallel branch flow distribution

For parallel module/cold-plate branches, flow shall be distributed by equal pressure-drop solution, not by an assumed equal split unless the branches are identical. The model shall solve manifold and branch losses or permit calibrated branch-flow coefficients.

17.5 Pump operating point

The user shall supply a pump pressure-flow curve and electrical power/efficiency curve or a fixed flow/pressure source. The actual operating point shall be found at the intersection of pump and

system curves. Pump speed control may target flow, pressure, coolant delta-T, cell temperature or BMS request.

$$P_{\text{pump,electrical}} = \Delta p \cdot \dot{V} / \eta_{\text{pump}}$$

17.6 Minimum flow and cooling-loss cases

The model shall determine minimum coolant flow required to keep all modeled cells below the selected temperature limit for the duty cycle. It shall simulate reduced-flow and zero-flow faults, quantify time to derating/trip and determine whether the cell temperature stays below the trip limit until a controlled stop is completed.

18. Heating, cooling, insulation and environmental boundary models

18.1 Cold soak and battery preconditioning

The user shall set initial cell/module/coolant/enclosure temperature or execute a prior soak simulation. The model shall calculate heater energy and time required to reach user-defined release temperatures for discharge, charge and regenerative braking. Power availability shall be progressively released according to BMS maps as cells warm.

$$E_{\text{heat,ideal}} = \sum m_i c_{p,i} (T_{\text{target}} - T_{\text{initial}})$$

The actual electrical heating energy shall additionally include heat losses to ambient, coolant loop, enclosure and other masses. Heater efficiency and control strategy shall be user-defined.

18.2 Heater model

- Electrical heater power limit.
- Voltage dependence of heater power (may be left empty; if empty, heater power is constant).
- Efficiency.
- Control hysteresis/PID or on-off logic.
- Heater placement: coolant loop, plate, air or direct element.
- Power drawn from battery, external supply or another source.
- Maximum coolant or component temperature.

18.3 Chiller / radiator / heat exchanger

The thermal-management plant shall support a radiator/ambient heat exchanger and/or refrigeration chiller. Chiller input power shall be modeled from a COP map versus heat load and temperature lift.

$$\text{COP} = \dot{Q}_{\text{removed}} / P_{\text{chiller}}$$

The model shall calculate chiller, pump, fan and heater auxiliary energy over a trip/day. It shall distinguish traction energy from BTMS auxiliary energy.

18.4 Ambient and enclosure heat transfer

$$\dot{Q}_{\text{conv}} = h_{\text{ext}} \cdot A \cdot (T_{\text{ambient}} - T_{\text{surface}})$$

$$\dot{Q}_{\text{rad}} = \epsilon \sigma A [(T_{\text{surroundings}} + 273.15)^4 - (T_{\text{surface}} + 273.15)^4]$$

The user shall be able to define stationary, underbody and roof-mounted convection coefficients or correlations. The model shall support solar load as a boundary condition for roof/enclosure studies (may be set to zero).

18.5 Environmental scenarios

- Cold ambient/soak with no charging until temperature criteria are reached.
- Hot ambient/high solar load.
- High continuous traction power.
- Repeated acceleration/regen cycles.
- Depot charging in hot or cold conditions.

- Cooling-system partial blockage.
- Pump failure.
- Chiller failure.
- Heater failure.
- Temperature-sensor bias causing delayed control response.

19. Coupled electro-thermal solver and numerical requirements

Electrical and thermal models shall be solved iteratively in one time-domain loop. Cell resistance/current capability depends on temperature, while temperature depends on electrical losses. The model shall therefore update cell/pack electrical parameters from the current temperature state and update thermal heat generation from the solved electrical current and voltage at every coupling step.

19.1 Calculation sequence per time step

1. Read route/telemetry power demand and current vehicle mode.
2. Update environmental, coolant and component boundary conditions.
3. Update cell parameter maps from SOC, temperature, SOH and current direction.
4. Calculate BMS charge/discharge/regen current and power limits.
5. Calculate power-electronics and vehicle limits.
6. Solve battery current(s), common DC-bus voltage and branch sharing.
7. Update electrical ECM states, SOC/SOE and component losses.
8. Calculate cell and component heat generation.
9. Solve coolant flow/pressure and thermal-network state.
10. Apply protection timers, derating, contactor or mode events.
11. Write canonical result channels and proceed to next step.

19.2 Conservation checks

- Electrical KCL residual for parallel branches.
- Electrical energy balance residual.
- Thermal energy balance residual.
- Coolant enthalpy balance residual.
- SOC/coulomb-count balance.
- Mechanical-to-electrical energy conversion balance through motor/inverter (calculated when the motor/inverter data are entered; otherwise the results state that it was not calculated).

The model shall report residuals and configurable tolerances. A simulation that exceeds tolerance shall be flagged rather than silently accepted.

20. Fault, degraded-mode and safe-state simulation

Fault simulation shall be integrated with the same BMS/thermal/electrical logic as normal operation. The model shall support scheduled faults at a specified time/route location and condition-triggered faults.

20.1 Electrical and BMS faults

- Cell capacity reduction.
- Cell resistance increase.
- Cell SOC imbalance.
- Open voltage-sense wire.
- Shorted or biased temperature sensor.
- Current-sensor offset and scale error.
- Pack-voltage sensor bias.
- CMU communication loss.
- Pack-master communication loss.
- Contactor fails open.

- Contactor welded closed.
- Precharge contactor/resistor fault.
- Fuse/open branch.
- Insulation/HVIL fault input.
- Module isolation/bypass event for configurations with module isolation or bypass devices (§3.2).
- Any number of pack branches unavailable (from 1 up to all but one).

20.2 Thermal faults

- Pump stopped.
- Reduced pump speed.
- Partial branch restriction.
- One branch fully blocked.
- Coolant leak represented by flow/pressure reduction.
- Chiller unavailable.
- Radiator/fan degraded.
- Heater unavailable.
- Incorrect thermostat/control threshold.
- Thermal interface degradation represented by increased contact resistance.

20.3 Required safe-state outputs

For every fault the model shall report detection time, warning time, derating start, trip/isolation time, maximum cell/module temperatures, maximum/minimum cell voltages, remaining available power, route consequence and safe-state action. The user shall be able to determine whether the vehicle can continue at reduced power, complete a limited segment, or requires immediate pack/traction isolation.

21. Ageing, degradation and lifetime-energy assessment

A full electrochemical ageing model is not required. The model shall support user-defined degradation laws so that duty-cycle effects can be evaluated. The ageing calculation shall be a user setting (default: off); if the ageing inputs of Appendix A are empty, it is switched off and the results state this.

21.1 Cycle ageing

The user shall be able to define capacity-fade and resistance-growth functions against equivalent full cycles, DOD, mean SOC, temperature and C-rate. Rainflow counting or an equivalent cycle-segmentation method shall be used for complex railway duty.

21.2 Calendar ageing

Calendar ageing shall be represented as a function of storage time, temperature and SOC. The model shall permit independent capacity and resistance evolution.

21.3 Lifetime outputs

- Equivalent full cycles per day/year.
- Energy throughput.
- Time at high SOC.
- Time at high/low temperature.
- Time above selected C-rate thresholds.
- Estimated capacity SOH and resistance SOH versus time under the selected degradation model.
- Projected date/cycles to user-defined end-of-life criterion.
- Sensitivity to reduced SOC window or reduced peak-power strategy.

22. Sensitivity, uncertainty and Monte Carlo analysis

The model shall permit uncertainty analysis because supplier parameters, route gradients, vehicle mass, resistance and thermal contact values are not exact. Deterministic sensitivity and probabilistic Monte Carlo modes shall be available.

22.1 Minimum uncertain parameters

- Cell capacity.
- Cell R0 and dynamic RC parameters.
- Initial SOC.
- Cell-to-cell dispersion.
- Ambient temperature.
- Vehicle/train mass.
- Running-resistance coefficients.
- Motor/inverter efficiency.
- Regenerative-braking efficiency.
- Coolant flow and pump performance.
- TIM/contact thermal resistance.
- Heat-transfer coefficient.
- Auxiliary load.
- Route gradient/speed-profile uncertainty.
- Sensor bias.

22.2 Statistical outputs

- Mean, standard deviation and percentile bands for route energy, terminal SOC, peak temperature and power capability.
- Probability/fraction of cases reaching a limit.
- Sensitivity ranking by standardized regression, variance decomposition or another documented method.
- Scatter/correlation plots.
- Reproducible random seed.
- Export of every individual run or a configurable subset.

23. Optimization and design-space exploration

The model shall support comparing many candidate configurations using consistent constraints. Optimization may be exhaustive, heuristic or mathematical, but all accepted candidates and rejection reasons shall remain auditable.

23.1 Possible objective functions

- Minimize total installed cell count.
- Minimize battery mass.
- Minimize pack volume.
- Minimize peak cell temperature.
- Minimize BTMS energy.
- Minimize current stress / RMS current.
- Maximize regenerative-energy acceptance.
- Maximize usable route energy margin.
- Maximize route completion under degraded pack count.
- Minimize estimated life-cycle degradation.
- Multi-objective Pareto optimization.

23.2 Design variables

- Cell selection.

- Series/parallel cell counts.
- Module grouping.
- Pack branch count.
- SOC operating window.
- Generator/EMS power target.
- Cooling flow/pump control.
- Coolant inlet target.
- Heater/chiller control thresholds.
- Insulation thickness/thermal resistance.
- Regenerative-braking strategy.
- Charge-power limit.

24. User interface and engineering workflow

The user interface shall be suitable for engineering work by battery, thermal and vehicle engineers. It shall not require editing source code for normal parameter changes. Every UI value shall map to a documented parameter key and be exportable.

24.1 Required workspaces

Workspace	Minimum functions
Cell Library	Import/create cell datasets, visualize OCV/DCIR/current maps, fit ECM, validate data ranges.
Topology Builder	Graphical or structured definition of modules, subpacks, packs, parallel branches and HV components.
BMS/CMS Calibration	Protection thresholds, current/power maps, balancing, derating, diagnostics and calibration export.
Vehicle Library	Mass, resistance, wheel/gear, traction motor/inverter, braking, auxiliary loads, hybrid source.
Route Editor	Chainage, elevation/gradient, speed limits, stops, dwell, environmental profile and charging points.
Telemetry Import	Column mapping, units, sign convention, data-quality review, resampling and validation.
Thermal Builder	Thermal nodes, cold plate, TIM, insulation, coolant, pump, heater/chiller and boundaries.
Scenario Manager	Initial SOC/T, route/duty, faults, environment, repeated cycles and solver settings.
Results Dashboard	Time-series, maps, energy balance, limit reasons, thermal/hydraulic results and comparisons.
Batch/Optimization	Scenario sweeps, design-space search, Monte Carlo and export.

24.2 Usability requirements

- All inputs shall show units and allowed range.
- Tooltips or help text shall define engineering meaning.
- Invalid/incomplete configurations shall be identified before simulation starts.
- The user shall be able to duplicate a cell/topology/vehicle/route/scenario as a new revision.
- Comparisons shall preserve common axes and units.
- A run shall not overwrite another run unless explicitly confirmed.
- Long calculations shall expose progress and allow cancellation without corrupting project data.
- All plots shall support CSV (or equivalent) export of underlying data.

25. Input/output schemas and interoperability

25.1 Required import formats

- CSV or equivalent

- XLSX or equivalent spreadsheet format
- JSON or equivalent structured format
- Route profile as CSV/XLSX or equivalent

25.2 Model execution

Each simulation shall be executable from a scenario file without manual intervention and without the graphical user interface, and shall return a run status and machine-readable result files. The execution method (script, command line or equivalent) shall be documented.

25.3 Scenario file

A scenario file shall identify all referenced dataset versions and all user inputs required to reproduce the run. Relative project paths or unique dataset IDs shall be used so a project can be archived and rerun.

25.4 Result channels

Result exports shall permit full time-series output at the simulation resolution and a compact summary. The user shall choose which cell/module channels are retained to manage file size.

26. Model results and engineering exports

26.1 Electrical results

- Cell/module/pack voltage extrema and selected traces.
- Branch and pack currents.
- DC-bus voltage/current/power.
- SOC/SOE/SOH/SOP.
- Charge/discharge/regen limit and actual operating point.
- Limit reason at each time sample.
- Ohmic/polarization/distribution losses.
- Fuse/contactors/cable current and loss.
- Precharge traces.
- Parallel-branch sharing and circulation current.

26.2 Thermal/hydraulic results

- Cell/module/pack min/max/mean temperature.
- Temperature spread.
- Cold-plate and coolant inlet/outlet temperatures.
- Branch coolant flows.
- Pressure drop and pump operating point.
- Pump/heater/chiller power.
- Heat removed and stored.
- Time to discharge/charge/regen availability after cold soak.
- Time to derating/trip after cooling fault.
- Daily BTMS auxiliary energy.

26.3 Route/vehicle results

- Wheel power and force.
- Battery terminal/DC-bus power.
- Gross traction energy.
- Auxiliary energy.
- Theoretical negative mechanical energy.
- Converted regenerative energy.
- Battery-accepted regenerative energy.
- Rejected/rheostatic/friction-brake energy.

- Trip and round-trip net energy.
- Specific energy per train-km and tonne-km.
- Peak traction and braking demand.
- Route segment causing each limiting condition.

26.4 BMS/CMS engineering outputs

The model shall generate a structured calibration package containing all selected thresholds, maps, margins, units, source references, breakpoint axes and version information. It shall also generate an engineering report explaining which cell/hardware/thermal constraint produces each major limit.

27. Verification, validation and model credibility

The contractor shall provide evidence that every submodel reproduces either an analytical solution, a controlled reference dataset or a documented expected behavior. Validation shall not consist only of showing visually plausible plots.

27.1 Verification hierarchy

1. Unit verification of formulas and component models against analytical calculations.
2. Submodel verification against synthetic deterministic test cases.
3. Parameter-identification verification against supplied cell test data.
4. Integrated electrical/thermal verification for a controlled duty cycle.
5. Route-model verification against a supplied route ledger or independent hand calculation.
6. Replay validation against measured battery/vehicle telemetry supplied by the Purchaser.
7. Regression test cases so accepted numerical results remain stable across future changes to the model source files.

27.2 Required error metrics

- Voltage RMSE and maximum error.
- Temperature RMSE and maximum error (calculated when measured temperature data are supplied by the Purchaser).
- SOC error at end of cycle.
- Energy-balance residual.
- Current-sharing KCL residual.
- Pressure-drop/flow error against analytical or test case.
- Route energy difference against reference ledger.
- Parameter-fitting goodness-of-fit and residual plots.

28. Acceptance test suite

Acceptance shall be performed using a mixture of Purchaser-supplied datasets and synthetic tests defined below. Test vectors are verification configurations only and do not define the product architecture. The models shall pass the same logic for arbitrary alternative configurations created by the Purchaser during acceptance.

Acceptance test	Required demonstration
Cell import and provenance	Import a cell dataset containing OCV, capacity, resistance and current maps. Verify units, metadata, interpolation, domain checks and source traceability.
Arbitrary topology A	Create a module/pack with a user-selected series/parallel structure not present in contractor templates. Verify nominal voltage, Ah, Wh, cell count and branch currents analytically.
Arbitrary topology B	Create a second topology with parallel strings and multiple pack branches. Verify current sharing and KCL against independent calculation.
Topology modification	Change module series count and pack branch count after the model is built. No changes to the model source files are permitted; all derived electrical values shall update automatically.

Acceptance test	Required demonstration
2-RC ECM pulse	Run a prescribed current pulse/rest profile with known R/C parameters and compare against closed-form/reference response.
SOC integration	Run constant current charge/discharge and verify coulomb-count result within numerical tolerance.
Loaded-voltage SOP	Force operation near Vmin/Vmax and verify automatic current/power reduction from loaded-voltage prediction.
Precharge	Use a synthetic R-C DC-link and verify precharge voltage/time/current/energy against analytical solution.
Parallel mismatch	Connect two pack branches with different OCV/SOC/resistance. Verify prospective equalization current and connection permissive behavior.
Pack isolation	Open one branch during traction. Verify redistribution of current and recalculated available power/thermal loading.
Measured-duty replay	Import a CSV/XLSX (or equivalent) power-time duty and verify energy integral and electrical/thermal response.
Route force calculation	Run a constant-speed constant-gradient case and compare resistance, grade force and wheel power with hand calculation.
Acceleration case	Run a constant-acceleration case and verify equivalent-mass kinetic energy and peak power.
Regenerative-braking case	Apply a deceleration/downhill event and verify mechanical negative energy, electric conversion, battery acceptance and rejected energy split.
Motor/inverter efficiency	Use a constant efficiency case and verify power conversion exactly; then repeat with an efficiency map.
Thermal lumped case	Single thermal node with constant heat and convection; verify transient temperature against analytical first-order solution.
Thermal network case	Two-node cell/cold-plate test with known conductance/capacitance; verify response against independent numerical reference.
Hydraulic branch	Known channel geometry and flow; verify Reynolds number, friction factor and pressure drop.
Parallel coolant branches	Use branches with different hydraulic resistance and verify non-equal flow distribution and common pressure-drop solution.
Cold-soak readiness	Start below charge/regen release temperature. Verify heater energy, warm-up time and gradual power release according to configured maps.
Cooling-loss fault	Set coolant flow to zero during high-power duty. Verify thermal rise, derating and trip timing.
BMS calibration export	Generate charge, regen and discharge current/power maps plus voltage/temperature/protection thresholds with units, source limits and margins.
Chemistry substitution	Replace the cell dataset with a chemically different cell and rerun without changes to the model source files.
Route repeated cycle	Run repeated round trips with dwell/charging. Verify SOC and temperature state carry-over and daily energy balance.
Monte Carlo reproducibility	Run a probabilistic case twice with the same seed and verify identical output; change seed and verify statistical variation.
Regression package	Execute the Contractor-provided automated model test cases and verify the documented expected results against the tolerances of §28.1.

28.1 Acceptance tolerances

Acceptance tolerances: (a) analytical synthetic cases: relative error ≤ 0.5 % for each compared quantity; (b) energy-balance residual ≤ 0.1 % of the total energy throughput of the cycle; (c) KCL current residual ≤ 0.1 % of the branch current at each coupling step; (d) validation against measured data supplied by the Purchaser: cell-voltage RMSE ≤ 20 mV and temperature RMSE ≤ 2 K.

29. Model computational performance and model-file quality

- A single-route simulation of 8 hours of vehicle operation at 1 s output resolution shall complete in ≤ 10 minutes on a PC with an 8-core CPU and 32 GB RAM (no GPU required).
- Cell-resolved and Monte Carlo runs may take longer; the model shall run independent cases in parallel on all available CPU cores and write the run progress to a log file.
- Model source files shall be modular, commented and delivered with their version history (Git repository or equivalent).
- All physical and calibration constants shall be defined in parameter files, not inside model source files.
- All third-party libraries and licenses shall be listed.
- The delivered models shall not require an undisclosed recurring cloud service to perform standard calculations.
- The delivered models shall not require DIGAS to purchase or renew any licence. Any third-party component shall be open-source or licensed to DIGAS on a perpetual basis without recurring fees, with all costs included in the contract price.
- Automated model verification tests (test cases with expected results and the tolerances of §28.1) shall be included and runnable by DIGAS.

30. Contractor deliverables and handover

The technical deliverables below are mandatory because they are necessary for independent continued use of the models.

1. Operational simulation models including the graphical user interface (§24).
2. Complete editable model source files, parameter files and scenario files, with build and run instructions.
3. Model description and verification report: equations, assumptions, validity ranges and the results of the acceptance tests (§28).

Appendix A. Cell input parameter dictionary

The model shall support all fields below. The input status of each field is given in brackets: [mandatory] or [may be left empty] (§4.4). For fields left empty the model applies the stated default or switches off the dependent calculation and states this in the results.

Family	Fields [input status]	Unit / format
Identity	Manufacturer, model, chemistry label, revision, source documents [mandatory]	Text / metadata
Geometry	Length, width, height, terminal locations, surface areas [mandatory]	m, m ²
Mass	Cell mass [mandatory]	kg
Nominal electrical	Nominal voltage, nominal/rated capacity, nominal energy [mandatory]	V, Ah, Wh
Voltage limits	Recommended/usable min and max; charge/discharge cutoff; supplier protection limits (may be left empty) [mandatory]	V
SOC definition	Capacity reference condition, 0/100% definition [mandatory]	metadata
OCV	OCV vs SOC for charge/discharge and temperature [mandatory]	V map
Capacity	Available Ah vs T, C-rate, SOH [mandatory]	Ah map
R0 / DCIR	Charge and discharge DC resistance vs SOC/T/pulse duration/current [mandatory]	Ω map
R1,C1,R2,C2	Dynamic ECM parameters vs SOC/T/direction/SOH [mandatory]	Ω, F maps
Coulombic efficiency	Charge/discharge efficiency vs conditions [may be left empty]	dimensionless
Energy efficiency	Cycle energy efficiency [may be left empty]	dimensionless
Current limits	Continuous and pulse charge, regen and discharge vs SOC/T/time [mandatory]	A or C-rate maps
Pulse durations	Supported current/power horizons [mandatory]	s
Thermal mass	Specific heat / effective heat capacity [mandatory]	J/kg-K or J/K
Thermal conductivity	Directional or effective conductivity [mandatory]	W/m-K
Thermal contact	Interface/contact resistance [may be left empty]	K/W or m ² K/W
Entropic coefficient	dOCV/dT vs SOC [may be left empty]	V/K
Self-discharge	SOC loss vs time/T [may be left empty]	%/time
Cycle ageing	Capacity fade and resistance growth test data [may be left empty]	dataset/model
Calendar ageing	Storage SOC/T/time degradation data [may be left empty]	dataset/model
Safety/diagnostic notes	Supplier operational restrictions and special conditions [may be left empty]	text
Uncertainty	Tolerance/distribution for selected parameters [may be left empty]	value/distribution

Appendix B. Module/pack/topology parameter dictionary

Parameter family	Required fields
Hierarchy	Component levels and parent-child structure
Electrical connectivity	Series/parallel graph and active states
Cell grouping	Series cells, parallel cells, strings
Module count	Any integer supported by project
Pack count	Any integer supported by project
Pack interconnection	Series / parallel / DC/DC / switched
Busbar/cable	Material, length, cross-section, resistance, temperature coefficient
Connector	Resistance, rating, location
Fuse	Resistance, rating, time-current/I ² t data

Parameter family	Required fields
Contactors	Rclosed, voltage/current rating, coil/state/feedback
Precharge	Rpre, Cbus, contactor, timeout, delta-V limit
Current sensor	range, accuracy, offset/noise
Voltage sensor	range, accuracy, offset/noise
BMS channels	cell-voltage channels, temperature channels, CMU grouping
Balancing	type, current, resistor/power, enable rules
Bypass/isolation	switch resistance, state logic, auxiliary feedback
Pack enclosure	mass, dimensions, thermal properties
Service state	available / isolated / bypassed / faulted
Installation location	vehicle end/roof/underframe/internal/custom tag
Thermal circuit assignment	cold plate/branch/manifold/coolant zone

Appendix C. BMS/CMS calibration output dictionary

Family	Calibration item	Required output
Cell voltage protection	OV warning	Value/map + units + hysteresis/debounce + source/margin metadata
Cell voltage protection	OV derate start	Value/map + units + hysteresis/debounce + source/margin metadata
Cell voltage protection	OV controlled stop	Value/map + units + hysteresis/debounce + source/margin metadata
Cell voltage protection	OV trip	Value/map + units + hysteresis/debounce + source/margin metadata
Cell voltage protection	OV latched trip	Value/map + units + hysteresis/debounce + source/margin metadata
Cell voltage protection	OV release/hysteresis	Value/map + units + hysteresis/debounce + source/margin metadata
Cell voltage protection	UV warning	Value/map + units + hysteresis/debounce + source/margin metadata
Cell voltage protection	UV derate start	Value/map + units + hysteresis/debounce + source/margin metadata
Cell voltage protection	UV controlled stop	Value/map + units + hysteresis/debounce + source/margin metadata
Cell voltage protection	UV trip	Value/map + units + hysteresis/debounce + source/margin metadata
Cell voltage protection	UV latched trip	Value/map + units + hysteresis/debounce + source/margin metadata
Cell voltage protection	UV release/hysteresis	Value/map + units + hysteresis/debounce + source/margin metadata
Cell temperature protection	charge low warning/trip	Value/map + units + hysteresis/debounce + source/margin metadata
Cell temperature protection	charge high warning/derate/trip	Value/map + units + hysteresis/debounce + source/margin metadata
Cell temperature protection	regen low/high limits	Value/map + units + hysteresis/debounce + source/margin metadata
Cell temperature protection	discharge low warning/derate/trip	Value/map + units + hysteresis/debounce + source/margin metadata
Cell temperature protection	discharge high warning/derate/trip	Value/map + units + hysteresis/debounce + source/margin metadata
Cell temperature protection	temperature spread warning/trip	Value/map + units + hysteresis/debounce + source/margin metadata

Family	Calibration item	Required output
Cell temperature protection	dT/dt warning/trip	Value/map + units + hysteresis/debounce + source/margin metadata
Current/power limits	discharge current map	Value/map + units + hysteresis/debounce + source/margin metadata
Current/power limits	discharge power map	Value/map + units + hysteresis/debounce + source/margin metadata
Current/power limits	charge current map	Value/map + units + hysteresis/debounce + source/margin metadata
Current/power limits	charge power map	Value/map + units + hysteresis/debounce + source/margin metadata
Current/power limits	regen current map	Value/map + units + hysteresis/debounce + source/margin metadata
Current/power limits	regen power map	Value/map + units + hysteresis/debounce + source/margin metadata
Current/power limits	continuous and pulse horizons	Value/map + units + hysteresis/debounce + source/margin metadata
Current/power limits	hardware current cap	Value/map + units + hysteresis/debounce + source/margin metadata
SOC/SOE/SOP	SOC min/max	Value/map + units + hysteresis/debounce + source/margin metadata
SOC/SOE/SOP	reserve SOC	Value/map + units + hysteresis/debounce + source/margin metadata
SOC/SOE/SOP	charge target SOC	Value/map + units + hysteresis/debounce + source/margin metadata
SOC/SOE/SOP	SOE calculation parameters	Value/map + units + hysteresis/debounce + source/margin metadata
SOC/SOE/SOP	SOP horizons	Value/map + units + hysteresis/debounce + source/margin metadata
SOC/SOE/SOP	OCV correction settings	Value/map + units + hysteresis/debounce + source/margin metadata
SOC/SOE/SOP	capacity correction vs T/SOH	Value/map + units + hysteresis/debounce + source/margin metadata
Balancing	enable SOC	Value/map + units + hysteresis/debounce + source/margin metadata
Balancing	enable cell-voltage window	Value/map + units + hysteresis/debounce + source/margin metadata
Balancing	start delta-V	Value/map + units + hysteresis/debounce + source/margin metadata
Balancing	stop delta-V	Value/map + units + hysteresis/debounce + source/margin metadata
Balancing	max balance time	Value/map + units + hysteresis/debounce + source/margin metadata
Balancing	max balance duty	Value/map + units + hysteresis/debounce + source/margin metadata
Balancing	temperature inhibit	Value/map + units + hysteresis/debounce + source/margin metadata
Balancing	current inhibit	Value/map + units + hysteresis/debounce + source/margin metadata
Pack protection	pack OV/UV	Value/map + units + hysteresis/debounce + source/margin metadata
Pack protection	overcurrent stages	Value/map + units + hysteresis/debounce + source/margin metadata
Pack protection	short-circuit interface	Value/map + units + hysteresis/debounce + source/margin metadata
Pack protection	isolation/HVIL actions	Value/map + units + hysteresis/debounce + source/margin metadata

Family	Calibration item	Required output
Pack protection	current-sensor plausibility	Value/map + units + hysteresis/debounce + source/margin metadata
Pack protection	pack-voltage plausibility	Value/map + units + hysteresis/debounce + source/margin metadata
Precharge/contactors	max initial delta-V	Value/map + units + hysteresis/debounce + source/margin metadata
Precharge/contactors	precharge timeout	Value/map + units + hysteresis/debounce + source/margin metadata
Precharge/contactors	min/max precharge current	Value/map + units + hysteresis/debounce + source/margin metadata
Precharge/contactors	K+/K-/Kpre sequencing	Value/map + units + hysteresis/debounce + source/margin metadata
Precharge/contactors	weld diagnostics	Value/map + units + hysteresis/debounce + source/margin metadata
Precharge/contactors	open-contact diagnostics	Value/map + units + hysteresis/debounce + source/margin metadata
Precharge/contactors	auxiliary feedback timeout	Value/map + units + hysteresis/debounce + source/margin metadata
Parallel packs	pack-to-bus delta-V	Value/map + units + hysteresis/debounce + source/margin metadata
Parallel packs	SOC mismatch	Value/map + units + hysteresis/debounce + source/margin metadata
Parallel packs	temperature mismatch	Value/map + units + hysteresis/debounce + source/margin metadata
Parallel packs	active-series-count compatibility	Value/map + units + hysteresis/debounce + source/margin metadata
Parallel packs	prospective equalization current	Value/map + units + hysteresis/debounce + source/margin metadata
Parallel packs	connect/reconnect delay	Value/map + units + hysteresis/debounce + source/margin metadata
Parallel packs	leader/failover parameters (generated for systems with a leader/redundant pack configuration)	Value/map + units + hysteresis/debounce + source/margin metadata
Thermal management	cooling request on/off	Value/map + units + hysteresis/debounce + source/margin metadata
Thermal management	heating request on/off	Value/map + units + hysteresis/debounce + source/margin metadata
Thermal management	chiller request on/off	Value/map + units + hysteresis/debounce + source/margin metadata
Thermal management	minimum coolant flow	Value/map + units + hysteresis/debounce + source/margin metadata
Thermal management	minimum/maximum coolant inlet temperature	Value/map + units + hysteresis/debounce + source/margin metadata
Thermal management	pressure/flow plausibility	Value/map + units + hysteresis/debounce + source/margin metadata
Thermal management	derating vs cell temperature	Value/map + units + hysteresis/debounce + source/margin metadata
Thermal management	derating vs coolant fault	Value/map + units + hysteresis/debounce + source/margin metadata
Communications/diagnostics	CMU timeout	Value/map + units + hysteresis/debounce + source/margin metadata
Communications/diagnostics	master timeout	Value/map + units + hysteresis/debounce + source/margin metadata
Communications/diagnostics	CAN/Ethernet timeout	Value/map + units + hysteresis/debounce + source/margin metadata

Family	Calibration item	Required output
Communications/diagnostics	sensor open/short limits	Value/map + units + hysteresis/debounce + source/margin metadata
Communications/diagnostics	open-wire thresholds	Value/map + units + hysteresis/debounce + source/margin metadata
Communications/diagnostics	fault debounce	Value/map + units + hysteresis/debounce + source/margin metadata
Communications/diagnostics	fault release	Value/map + units + hysteresis/debounce + source/margin metadata
Communications/diagnostics	latching/reset authority	Value/map + units + hysteresis/debounce + source/margin metadata
Communications/diagnostics	event logging triggers	Value/map + units + hysteresis/debounce + source/margin metadata

Appendix D. Thermal/hydraulic parameter dictionary

Subsystem	Required parameter capability
Cell thermal	mass, cp(T), kx/ky/kz or effective conductance, surface areas, heat-source allocation
TIM	thickness, k, density/cp, contact resistance (contact resistance may be set to zero)
Cold plate	material, thickness, channel geometry or effective UA, mass/cp
Coolant	type/concentration, $\rho(T)$, cp(T), $\mu(T)$, k(T), freezing point
Channels	length, hydraulic diameter, roughness, area, minor-loss coefficients
Manifold	branch geometry/empirical pressure-drop coefficients
Pump	Q- Δp curve, speed control, efficiency/electrical power map
Heater	power, efficiency, location, control thresholds
Radiator/HX	UA or performance map versus airflow/coolant flow/ambient
Chiller	cooling-capacity and COP map versus temperature/load
Insulation	thickness, k, cp, density, area
Enclosure	mass, cp, surface areas, external h/ ϵ
Ambient	temperature time series, external convection, radiation/solar load (may be set to zero)
Faults	flow reduction, branch blockage, pump/chiller/heater failures, sensor bias

Appendix E. Canonical railway duty-cycle ledger

Field	Definition	Unit
timestamp_s	Chronological simulation time	s
route_chainage_m	Physical route position	m
direction	Outbound/return/custom	text
speed_mps	Vehicle speed	m/s
acceleration_mps2	Longitudinal acceleration	m/s ²
elevation_m	Point elevation	m
gradient_permille	Local grade	‰
curve_radius_m	Local curve radius (may be left empty)	m
speed_limit_mps	Local line/vehicle speed limit	m/s
vehicle_mass_kg	Current gross train mass	kg

Field	Definition	Unit
operating_state	traction/cruise/coast/brake/dwell/charge	text
traction_force_N	Requested/actual wheel force	N
wheel_power_W	Positive traction, negative braking	W
aux_power_W	Vehicle auxiliary load	W
dc_bus_power_W	Net DC-bus power request	W
battery_power_request_W	Requested battery contribution	W
battery_power_actual_W	Delivered/accepted battery power	W
regen_mech_W	Mechanical negative-power opportunity	W
regen_electrical_W	Electrically convertible regen	W
regen_battery_W	Battery-accepted regen	W
regen_rejected_W	Rejected regen	W
friction_brake_W	Mechanical friction-brake power	W
ambient_C	Ambient temperature	°C
charge_available_W	External charge opportunity	W
generator_power_W	Hybrid source output (may be left empty for vehicles without a hybrid source)	W
data_quality_flag	Measured / synthesized / interpolated / invalid	text

Appendix F. Minimum acceptance scenarios

Scenario	Minimum content
High-power acceleration	Low/medium/high initial SOC and multiple ambient temperatures; verify loaded voltage, current, SOP, heat generation and power limitation.
Cruise / charge balance	Sustained traction plus auxiliary load with generator or charger contribution; verify SOC stabilization and energy balance.
Regenerative braking	High SOC and low SOC, warm and cold battery; verify accepted/rejected regeneration and brake blending.
Repeated stop-start cycle	Many acceleration/braking events; verify thermal accumulation and dynamic polarization.
Long gradient climb	Sustained high load; identify thermal or voltage/current limit.
Long gradient descent	Sustained regenerative opportunity; quantify battery acceptance and rejected energy.
Cold soak	Battery and coolant initially cold; determine heater energy and time to defined charge/discharge/regen availability.
Hot ambient	High ambient plus repeated traction; determine cooling duty, cell gradient and chiller/pump energy.
Cooling-loss	Pump or chiller failure during operation; determine derating/trip time and safe-state consequence.
Pack-branch outage	One of multiple pack branches becomes unavailable; recalculate route feasibility and thermal/current loading.
Pack mismatch	Parallel branches with SOC/temperature/resistance mismatch; verify current sharing and connection permissives.
Cell dispersion	Capacity/resistance/SOC spread within series string; identify earliest limiting cell and balancing implications.
Alternative topology	A topology created by Purchaser during acceptance that was not used by contractor during development; verify genericity.
Alternative chemistry	A cell dataset with different voltage/current/thermal behavior; verify that no changes to the model source files are needed.

Scenario	Minimum content
Route telemetry replay	Measured or synthetic CSV/XLSX (or equivalent) data with irregular sampling; verify import, resampling log, energy integral and model response.
Route synthesis	Vehicle + route + mass inputs only; verify calculated speed/power/energy and regenerative opportunity.
Repeated daily schedule	Multiple trips, dwell and charging; verify state carry-over and daily energy/thermal balance.

Appendix G. Detailed parameter-identification and model-calibration requirements

This appendix defines the minimum technical behavior of the parameter-identification workflow. Its purpose is to prevent a situation in which the simulation models accept only hand-entered final parameters without providing a reproducible path from raw cell test data to model coefficients.

G.1 Test segmentation and preprocessing

- The model shall identify or allow the user to mark charge, discharge, rest, pulse and relaxation segments from current sign and threshold logic.
- Raw channels shall retain the original sample timestamps. Filtering, down-sampling, offset correction and outlier rejection shall create derived channels rather than overwrite source data.
- Current-sensor zero offset shall be estimated during verified rest windows. The estimated offset and corrected ampere-hour balance shall be reported.
- Voltage discontinuities immediately after current steps shall be separable from slower polarization response so R_0 is not contaminated by RC relaxation.
- Temperature during each identification window shall be stored as minimum, maximum and mean; a test shall not be represented by a single nominal temperature if the measured cell temperature changes by more than 2 K during the window.
- Identification windows shall be rejectable when voltage, current or temperature data quality falls outside a user-defined criterion.

G.2 Capacity and coulombic-efficiency identification

$$Q_{\text{dis}} = \int I_{\text{dis}} dt / 3600$$

$$Q_{\text{chg}} = |\int I_{\text{chg}} dt| / 3600$$

$$\eta_{\text{coul}} = Q_{\text{dis}} / Q_{\text{chg}} \text{ for a closed reference cycle}$$

Capacity results shall be associated with test temperature, charge protocol, discharge rate, cutoff voltages and rest conditions. The model shall not merge capacities measured under different conditions into one scalar without an explicit normalization rule.

G.3 OCV and hysteresis identification

When relaxation data are supplied, the user shall define the minimum rest time or a dV/dt convergence criterion used to accept a point as quasi-open-circuit. Where separate charge and discharge OCV curves are available, the model shall retain both and either interpolate a hysteresis state or allow the user to select a conservative curve for BMS limit calculations.

$$h_{\text{dot}} = -|I|/(Q \cdot \tau_h) \cdot h + k_h \cdot \text{sign}(I)$$

An equivalent bounded hysteresis state equation may be used if the contractor implements a dynamic hysteresis model. Its parameters shall be user-visible and fitted/validated.

G.4 Pulse-resistance identification at multiple horizons

The cell library shall distinguish the instantaneous/ohmic resistance from resistance inferred at longer pulse durations. The user shall be able to request resistance at several horizons, for example 0.1 s, 1 s, 10 s, 30 s and 60 s, for each horizon covered by the supplied test data. Long-horizon values shall not be substituted for R_0 in the dynamic ECM.

$$R_{\text{app}}(\Delta t) = [V_{\text{before}} - V(t_0 + \Delta t)] / \Delta I$$

The model shall plot R_{app} versus pulse duration and identify whether a selected two-RC model reproduces the measured transient over the required rail-power horizon.

G.5 Two-RC fit objective and constraints

$$J = \sum w_k [V_{\text{meas}}(k) - V_{\text{model}}(k)]^2 + \lambda_{\text{smooth}} \cdot J_{\text{smooth}} + \lambda_{\text{prior}} \cdot J_{\text{prior}}$$

- R0, R1, R2, C1 and C2 shall be constrained to positive values.
- Time constants $\tau_1=R1C1$ and $\tau_2=R2C2$ shall be ordered or otherwise constrained to avoid parameter swapping between neighboring SOC/T points.
- Weights may prioritize high-current rail-relevant transients, but weighting shall be documented.
- Goodness-of-fit shall include RMSE, peak error and residual versus time/current/SOC.
- Fit quality shall be displayed over the same voltage scale used for protection limits so engineering relevance is visible.
- If the identified parameter set is ill-conditioned or not unique, the model shall flag it rather than report false precision.

G.6 Temperature and SOC interpolation of identified parameters

Parameter surfaces shall be created from discrete test points. The model shall use piecewise-linear interpolation as a transparent baseline. It shall preserve the original fitted nodes and prevent negative resistance/capacitance and local extrema not present in the fitted nodes.

G.7 Validation dataset separation

The model shall allow each dataset to be marked as an identification or a validation dataset. Model accuracy shall be reported separately on validation data. A model calibrated and validated on the exact same samples shall be labelled as fit reproduction rather than independent validation.

Appendix H. Detailed BMS/CMS map-generation and protection logic

H.1 Dynamic current map derivation

The purpose of the map generator is to convert the underlying cell capability into implementable BMS limits. For each SOC-temperature breakpoint, the algorithm shall determine the allowed current from all relevant constraints and identify the active constraint.

$$I_{\text{allow,dis}}(\text{SOC}, T, \Delta t) = \min\{I_{\text{supplier}}, I_{\text{voltage}}, I_{\text{thermal}}, I_{\text{hw}}, I_{\text{project}}\}$$
$$|I_{\text{allow,chg}}(\text{SOC}, T, \Delta t)| = \min\{|I_{\text{supplier,chg}}|, |I_{\text{voltage,max}}|, |I_{\text{thermal,chg}}|, |I_{\text{hw}}|, |I_{\text{project}}|\}$$

The voltage-derived current shall be calculated using the dynamic ECM (R0 and RC terms) at the selected time horizon.

$$V_{\text{pred}}(\Delta t) = \text{OCV} - I \cdot R_0 - I \cdot R_1 \cdot (1 - \exp(-\Delta t / \tau_1)) - I \cdot R_2 \cdot (1 - \exp(-\Delta t / \tau_2)) + \text{state_memory_terms}$$

For regenerative charging the same procedure shall be executed independently because the supplier may provide a regenerative/pulse charge envelope different from continuous charging. A single symmetric C-rate limit is not sufficient.

H.2 Cell-voltage protection design

The calibration part of the model shall support at least five functional levels for overvoltage and undervoltage: information/warning, derating start, controlled operating limit, protective trip and latched severe trip. Projects may use fewer levels, but the underlying capability shall exist. Hysteresis and debounce shall be defined for both activation and release. Voltage protection settings shall be checked against charger/inverter control accuracy and measurement tolerance.

H.3 Temperature protection design

Temperature limits shall be direction-specific. Charge, regenerative charge and discharge may have different low-temperature and high-temperature ranges. The model shall additionally

generate temperature-spread criteria and temperature-rate criteria. It shall be possible to derive a derating curve from the current maps rather than applying only a binary thermal trip.

H.4 Measurement tolerance and guard-band calculation

$\text{Limit_BMS} = \text{Limit_cell} - M_{\text{engineering}} - M_{\text{measurement}} - M_{\text{dynamic}}$ [for an upper limit]

$\text{Limit_BMS} = \text{Limit_cell} + M_{\text{engineering}} + M_{\text{measurement}} + M_{\text{dynamic}}$ [for a lower limit]

The margin terms shall be visible individually. Measurement margin shall include cell-voltage accuracy, temperature-sensor accuracy, current-sensor error and synchronization/delay. Dynamic margin shall account for voltage overshoot and thermal lag between sensor and cell core. The model shall not hide all margins inside one unexplained factor.

H.5 Balancing requirement calculation

The model shall estimate passive balancing time from cell capacity/SOC mismatch and balance current. It shall determine whether the selected balancing current corrects the expected manufacturing or ageing spread within the available dwell/charge periods (calculated balancing time $\leq$ available time).

$t_{\text{balance}} \approx \Delta Q / I_{\text{balance}} = Q_{\text{cell}} \cdot \Delta \text{SOC} / I_{\text{balance}}$

Balance resistor thermal dissipation shall be included as a local module heat source when balancing is active.

H.6 Precharge and contactor calibration

- Maximum permitted pack-to-bus voltage difference before precharge starts.
- Maximum permitted voltage difference before main contactor closure.
- Precharge timeout derived from R_{pre} , C_{bus} and minimum expected pack voltage.
- Peak resistor power and energy per event, with recovery/cool-down assumptions.
- Minimum current or voltage-rise criterion used to detect open precharge path.
- Voltage behavior used to diagnose a welded main contactor.
- Auxiliary-contact discrepancy and debounce timing.

H.7 Multi-pack current-limit arbitration

For multiple parallel battery branches, the vehicle-level available charge/discharge power shall be calculated from the individual branch limits and the actual current-sharing solution. The system limit shall not simply multiply one representative pack limit by pack count when pack SOC, temperature, SOH or topology differs.

$P_{\text{sys,allow}} = \sum_k V_{\text{bus}} \cdot I_{k,\text{allow}}$ subject to branch and common-bus constraints

The calibration output shall include branch-isolation behavior and the resulting reduced vehicle power limits for each permitted pack-count state.

Appendix I. Detailed thermal-management sizing calculations

I.1 Cell-to-coolant thermal-resistance chain

$R_{\text{cell} \rightarrow \text{coolant}} = R_{\text{cell,int}} + R_{\text{cell}/\text{TIM}} + t_{\text{TIM}} / (k_{\text{TIM}} \cdot A_{\text{contact}}) + R_{\text{plate,cond}} + 1 / (h_{\text{fluid}} \cdot A_{\text{wet}})$

The model shall permit separate contact areas and resistances for each module/cell group. Effective resistances derived from CFD or testing may replace geometric terms, but the source and applicable flow/temperature range shall be stored.

I.2 Required coolant mass flow from heat load

$m_{\text{dot_required}} \geq Q_{\text{dot_total}} / [c_p \cdot \Delta T_{\text{coolant,allowed}}]$

This is a first sizing bound only. The final flow shall also satisfy local heat-transfer coefficients, branch distribution and pump/system pressure-drop constraints. The model shall report both the heat-capacity flow bound and the hydraulically solved operating point.

I.3 Transient thermal capacity and pulse buffering

$$\Delta T_{\text{adiabatic}} \approx Q_{\text{pulse}} / C_{\text{thermal, effective}}$$

For short rail acceleration/regen pulses, thermal mass may absorb heat with limited immediate coolant removal. The model shall therefore calculate both instantaneous pulse temperature rise and long-term heat rejection. It shall identify whether a cooling system is flow-limited, UA-limited or thermal-mass-limited for each duty segment.

I.4 Heating from cold soak

$$t_{\text{heat}} \geq E_{\text{required}} / (P_{\text{heater}} \cdot \eta_{\text{effective}} - \dot{Q}_{\text{loss, avg}})$$

Because heat loss changes with temperature, the actual time shall be obtained from the transient network. The model shall separately report energy used to heat cells, coolant, plate/enclosure masses and energy lost to ambient.

I.5 Chiller/radiator capacity sizing

The model shall calculate the maximum continuous heat rejection required at selected hot-ambient conditions and the transient peak. It shall determine whether a chiller is required or whether radiator/ambient cooling is sufficient. Where a chiller is used, the model shall report thermal load, electrical load and coefficient of performance over the duty cycle.

$$P_{\text{BTMS, total}} = P_{\text{pump}} + P_{\text{fans}} + P_{\text{chiller}} + P_{\text{heater}} + P_{\text{controls}}$$

$$E_{\text{BTMS, day}} = \int P_{\text{BTMS, total}} dt \text{ over the defined operating schedule}$$

I.6 Pressure-drop and pump-margin reporting

For each operating point the output shall list pump speed, total flow, branch flows, system pressure drop, pump head margin and electrical pump power. The user shall be able to apply a fouling/ageing factor to hydraulic resistance. A branch at unacceptable low flow shall be identified even if total pack flow remains nominal.

I.7 Thermal readiness criteria

The user shall define separate readiness criteria for traction discharge, regenerative braking, normal charging and fast charging. A pack may therefore be considered available for low-power movement while still unavailable for full regen or high-rate charge. The model shall calculate the first time at which each readiness state becomes true and the corresponding electrical/heater energy consumed.

I.8 Daily thermal-energy budget

- Cold-start preheating energy.
- Heating/cooling during operation.
- Cooling during charging.
- Post-run cooling if enabled.
- Pump/fan standby energy.
- Overnight thermal-maintenance energy if configured.
- Total BTMS energy as a percentage of traction battery throughput.
- Sensitivity to insulation level and preconditioning strategy.