

Energy-Maximizing Regenerative Braking

for Battery-Electric Regional Rail Under SOC Limits

Amir Torkiharchegani[1], François Cabillon[2], Rickard Persson[3], Thomas Müller[4], Christoffer Ahrling[5], Mats Alaküla[1]

1: Division of Industrial Electrical Engineering and Automation, LTH, Faculty of Engineering, Lund University, Lund, Sweden.
2: Wabtec Corporation, Brakes and safety, R&D department, Piossasco, Italy
3: Department of mechanical engineering, KTH Royal Institute of Technology, Stockholm, Sweden.
4: Institute of Vehicle Concepts, German Aerospace Center, Stuttgart, Germany.
5: Department of Energy Sciences, Lund University, Lund, Sweden.

Core question: How can ED braking remain dominant when the battery becomes the limiting factor?

Amir Torkiharchegani (amir.torkiharchegani@iea.lth.se)

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"This presentation is based on the full paper accepted for the 50th Rolling Stock Conference."

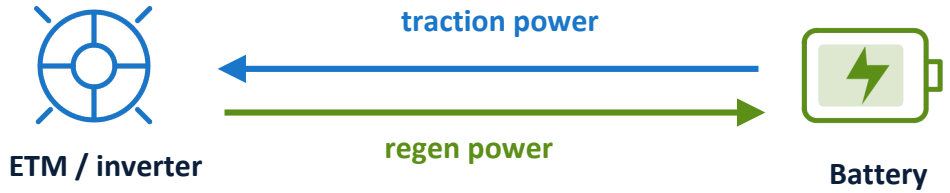
The battery is both the traction source and the braking-energy sink

That makes braking control an energy-management problem.

Can the drive produce it?

Speed-dependent torque / force / power envelope

Motor / inverter limit



Can the battery absorb it?

SOC headroom + charge-power / C-rate limit

Battery acceptance limit

In a battery-electric train, “more regeneration” is not only a motor question — it is a motor + battery + route-timing question.

Main message: maximize energy actually stored — not instantaneous regenerative power.

Why regenerative capture matters for regional battery rail

The benefit is not only lower energy use: regenerative braking changes battery sizing, brake duty and the control problem itself.

1 · ROUTE ENERGY



Low-traffic regional lines

Repeated station stops and descents create recoverable braking energy.

Capturing and reusing more of it lowers net battery discharge over the route.

2 · BATTERY + CONTROL



Battery sizing pressure

Battery sizing is not only a route-kWh question.

SOC headroom, C-rate / charge-power limits and pack capacity determine how much braking energy can actually be accepted.

3 · BRAKE HARDWARE



Brake hardware duty

Every planned-service kWh sent to friction becomes heat instead of stored energy.

Higher ED share reduces avoidable thermal duty and wear — while safety braking remains unchanged.

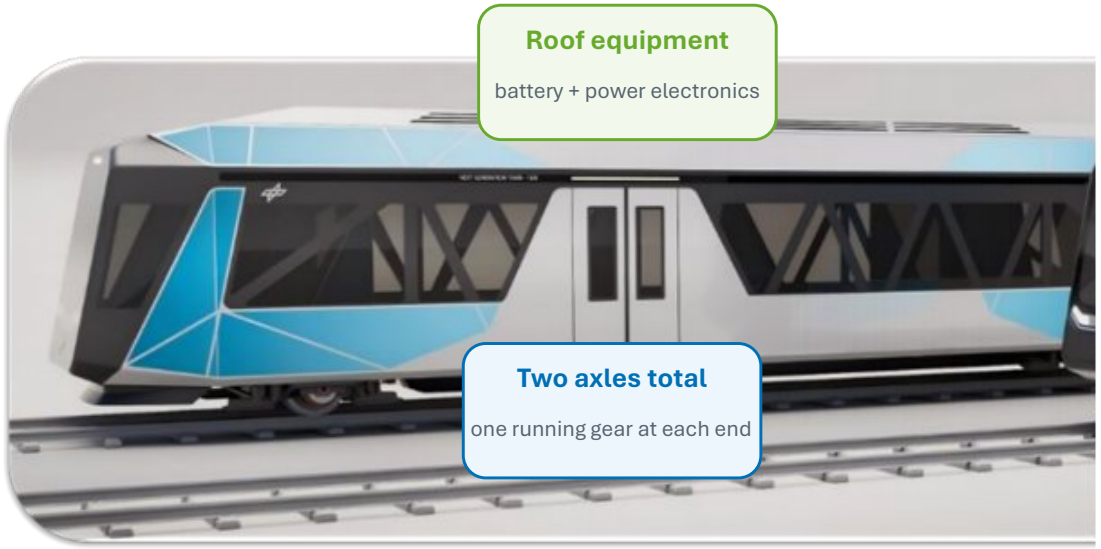
Engineering objective:

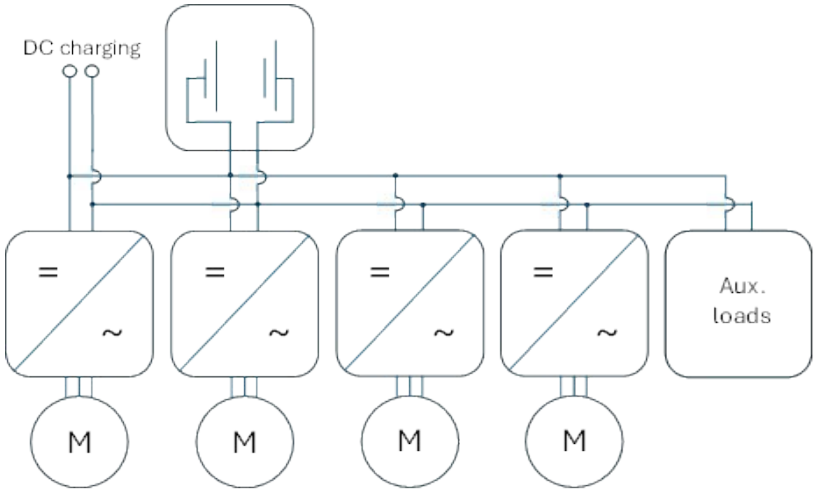
Move as much planned-service braking energy as possible from friction → electrical path → battery, without violating braking demand,

SOC limits, adhesion/WSP or low-speed stopping requirements.

route + timetable — braking timing — ETM / inverter limits — battery headroom — friction residual

Vehicle context: FP6 FutuRe lightweight regional rail vehicle





FutuRe brake-performance context

120 km/h G1 • interoperable vehicle	**0.6 m/s²** service-brake target
390 kW ED brake power	**32 t** G1• full-load mass

30 t simulation model: 0 → 120 km/h ≈ 59.4 s

Why it matters for the talk:

a lightweight two-axle vehicle concentrates traction, braking and battery constraints into one tightly coupled energy-management problem.

Borlänge–Malung route: repeated braking events under changing route conditions

Route-based input: speed reference + elevation/gradient + stop sequence → braking events with different energy and power demands

Route context

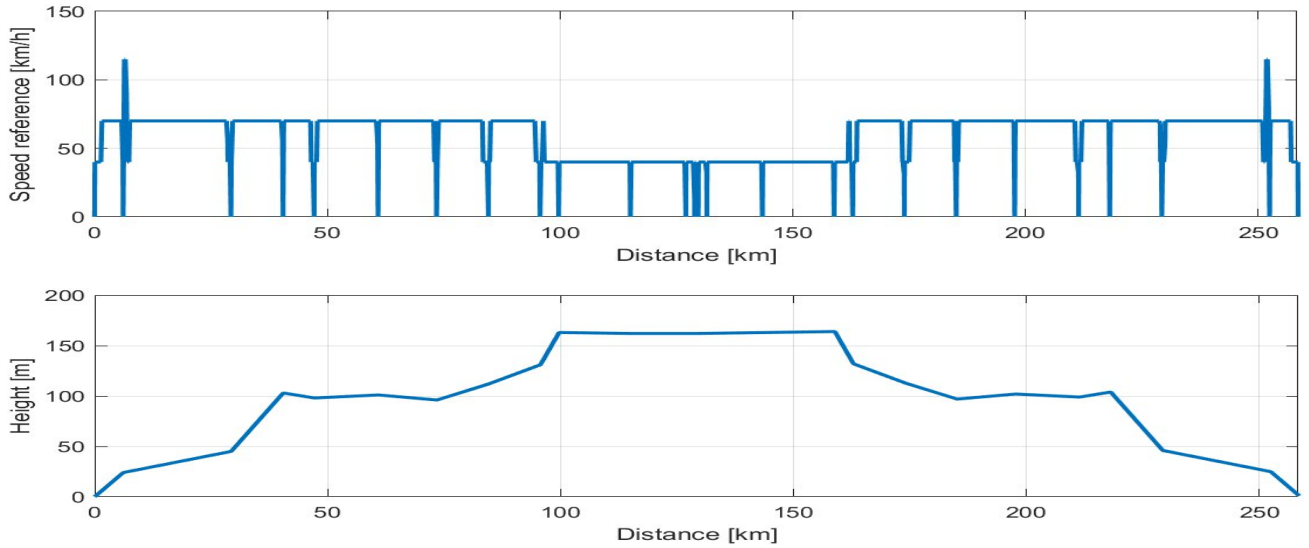


129 km one way

≈258 km round trip

12 intermediate stops
between Borlänge and Malung

Actual speed and altitude profiles used in the route simulation



What enters the braking model from the route?

speed target **gradient** **stops** **position / available distance**

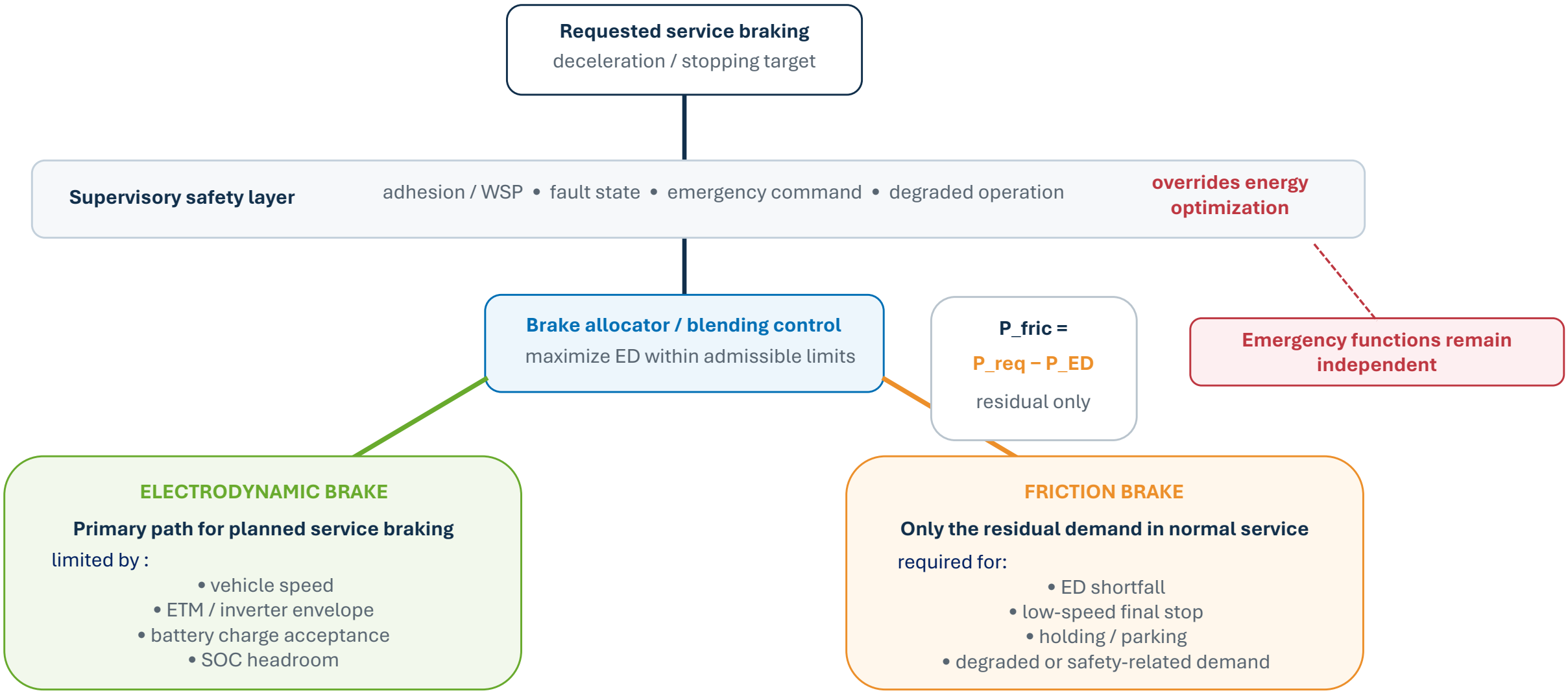
These inputs determine where braking begins and the mechanical braking power that must be absorbed.

Key point

Same route ≠ same braking event

speed drop, gradient, time/distance and recoverable energy change from event to event.

Service braking architecture: electrodynamic braking first, friction fills the gap



Energy optimization acts only inside the safe service-braking envelope — it does not redefine emergency braking.

From route inputs to stored regenerative energy

Every braking event is evaluated through the same calculation chain — route → wheel → electrical drivetrain → battery.

1 Route / timetable

- speed target
- position
- gradient
- station / stop

2 Longitudinal dynamics

$$F_{\text{brake,req}} = ma + F_{\text{res}} + F_{\text{grade}}$$

force balance → required brake force

3 Wheel braking power

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

4 ETM + inverter

- torque–speed envelope
- η(ω,T)
- power limit

5 Admissible ED power

min(brake demand, ETM limit, battery + sink)

6 Battery + SOC

- charge-power limit
- SOC update
- stored energy

Outputs / KPIs

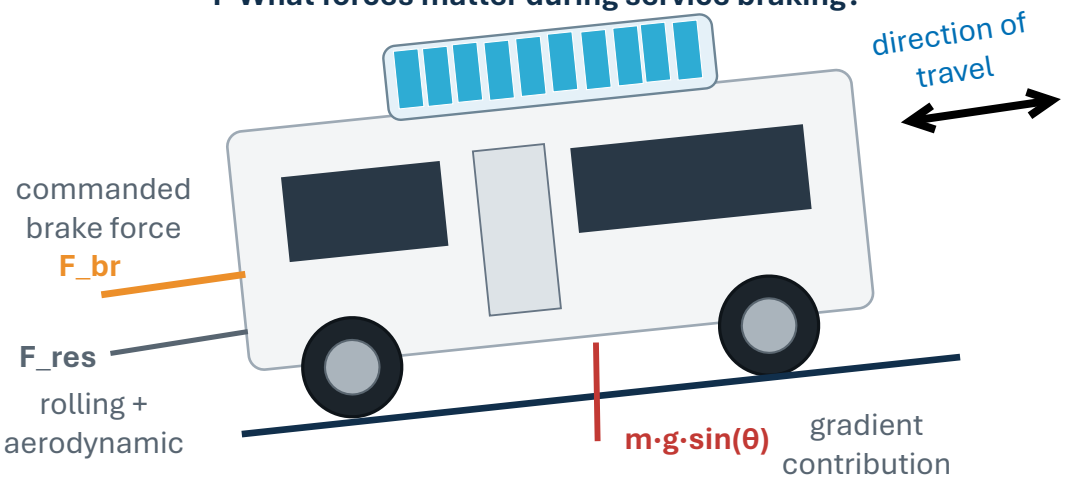
stored regen energy	friction energy	curtailed / non-charge	peak regen power	SOC change	braking time / distance

Key distinction: mechanical braking energy → producible ED energy → battery-stored energy are not the same quantity.

How route conditions become braking-power demand

The route and the requested deceleration define the mechanical braking demand. The brake controller only decides how much of that demand can be electrodynamic.

1 What forces matter during service braking?



θ > 0 uphill

θ < 0 downhill

During pure braking: $F_{tr} \approx 0$

2 Calculate required brake force

Force balance

$$m \cdot a_{ref} = -F_{br} - F_{res} - m \cdot g \cdot \sin(\theta)$$

Therefore

$$F_{br,req} = -m \cdot a_{ref} - F_{res} - m \cdot g \cdot \sin(\theta)$$

Running resistance

$$F_{res}(V) = 400 + 2V + 0.2V^2 \ [N]$$

V in km/h

$$P_{brake,req} = F_{br,req} \cdot v$$

3 What does this mean?

Illustrative service-brake point

$m = 30$ t • $v = 120$ km/h • $a_{ref} = -0.6$ m/s²

At 120 km/h: $F_{res} = 3.52$ kN

+21‰ uphill	level	−21‰ downhill
277 kW	483 kW	689 kW

Installed ED power limit = 390 kW

At high speed, the requested braking power can exceed the available ED power.

Result from this slide:

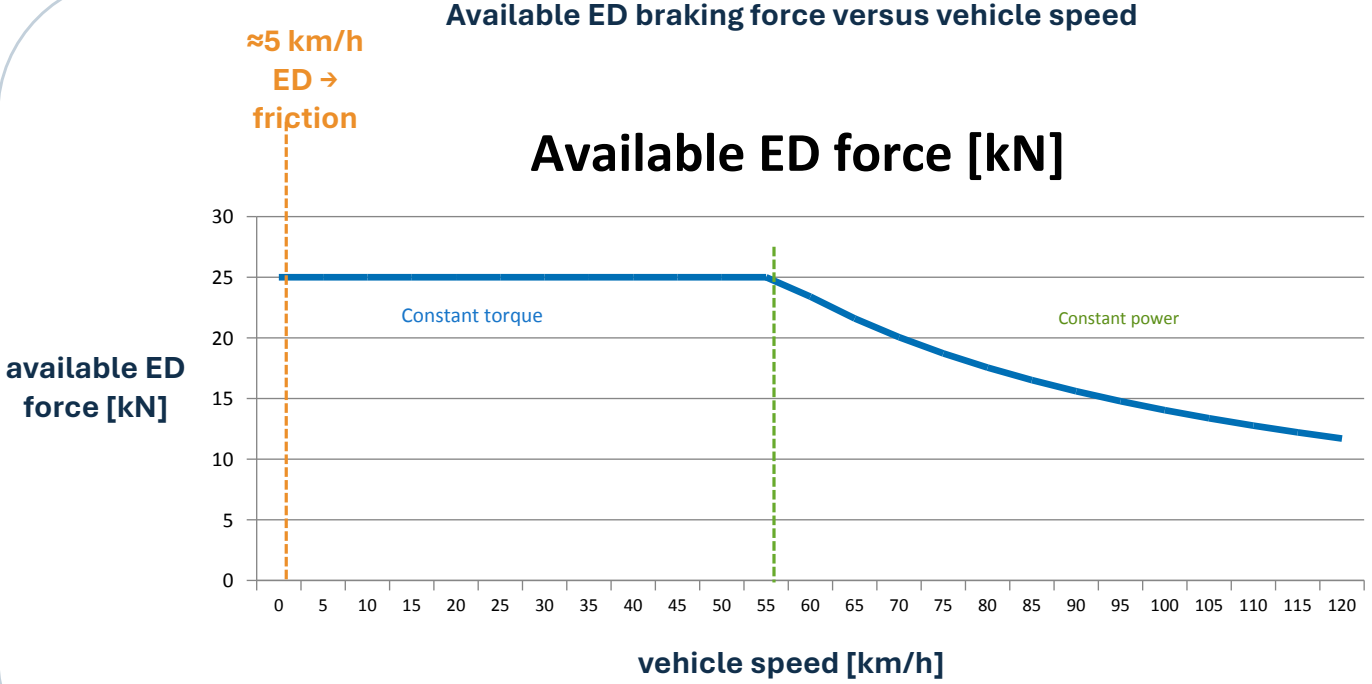
UPHILL	LEVEL	DOWNHILL
less braking demand	reference demand	more energy must be absorbed

If $P_{brake,req} > P_{ED,adm}$ → friction fills the gap, or braking must start earlier / last longer.

Speed-dependent electrodynamic braking envelope

The mechanical braking demand from Slide 8 can be supplied electrically only inside the ETM / inverter envelope.

Available ED braking force versus vehicle speed



$F_{ED,max}(v) = \min(25\ kN, 390\ kW / v)$

Three operating regions

VERY LOW SPEED

$v \to 0 \Rightarrow P = F \cdot v \to 0$

final stopping / holding requires friction

LOW / MID SPEED

force / torque limited

maximum ED effort ≈ 25 kN

HIGH SPEED

electrical power limited

390 kW cap ⇒ available braking force falls as speed rises

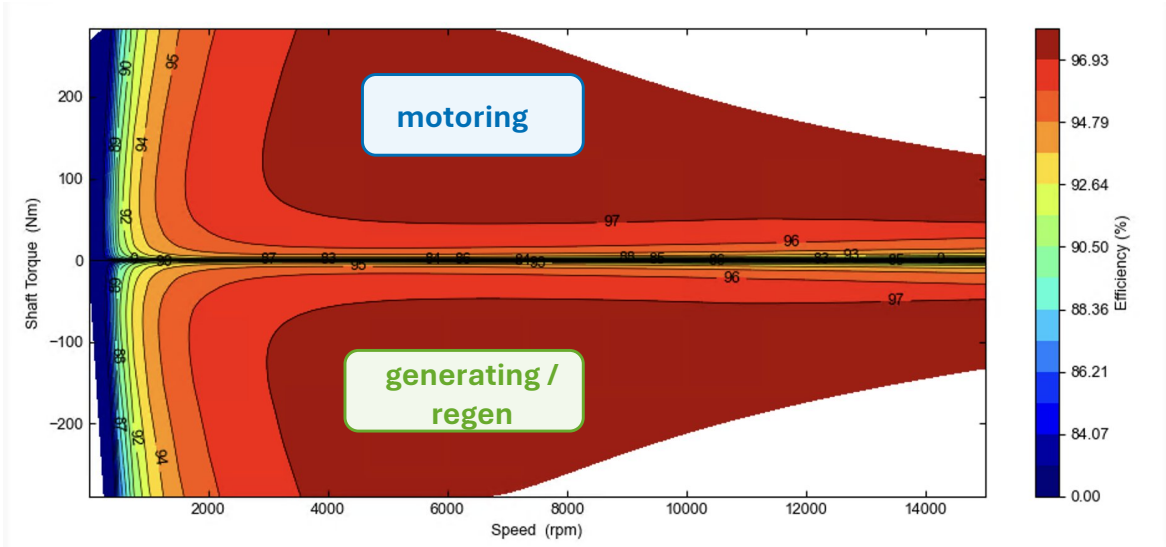
Control implication

If braking demand exceeds this envelope, friction must supply the shortfall — unless the route allows earlier / longer braking to reduce the peak ED demand.

ETM efficiency determines producible regenerative power

The force/power envelope says what the machine can provide; the efficiency map says how much of that mechanical braking power becomes electrical power.

Supporting ETM efficiency map η(ω,T)



Map shown as supporting drivetrain evidence; the conference paper uses an electric-machine efficiency profile at system level.

How the efficiency enters the braking calculation

1 Operating point

vehicle speed + wheel force → motor speed ω and torque T

2 Mechanical power

$P_{mech} = T \cdot \omega$

3 Producible electrical ED power

$P_{ED,prod} = \eta_{gen}(\omega,T) \cdot P_{mech}$

machine losses = $P_{mech} - P_{ED,prod}$

Energy accounting

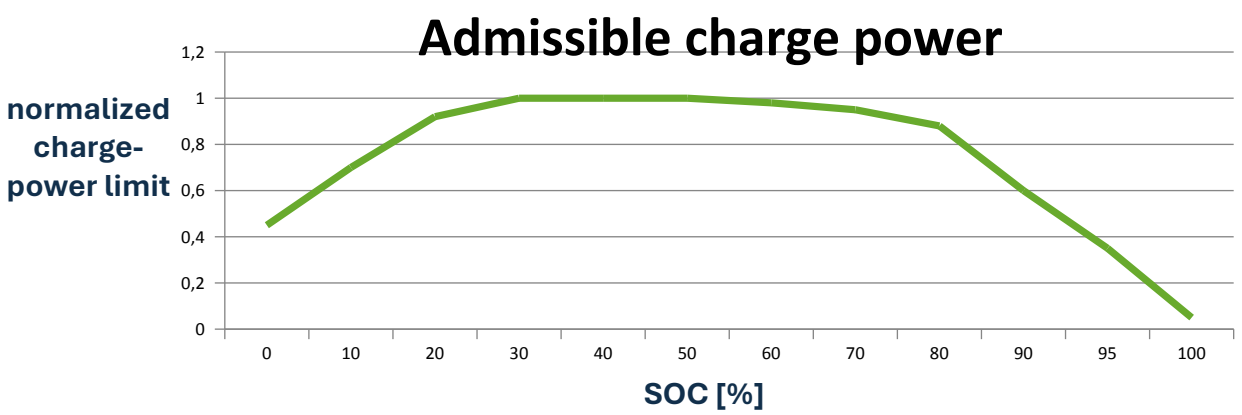
Mechanical braking energy → **producible ED electrical energy** → **battery-accepted energy** depends on SOC + charge limit → **stored regenerative energy** final KPI

Battery charge acceptance is the second regenerative-braking limit

Even when the ETM can regenerate the requested power, the battery may not be able to accept it at the current SOC and charge-rate limit.

Control-oriented SOC-dependent charge-power envelope

low SOC: power-limited | **mid SOC: high acceptance** | **high SOC: headroom drops**



Schematic shape — exact limit is a battery-model input; the controller only needs the admissible power at the current SOC.

What limits regeneration at the battery?

1 Instantaneous charge-power limit

$P_{bat,max} = f(SOC, \text{battery model})$

2 Energy headroom

high initial SOC → less room before SOC_upper

3 Battery size / effective C-rate

Same event energy → larger SOC rise

Same regenerative power → higher C-rate for a smaller battery

$P_{ED,adm} \le P_{bat,max}(SOC) + P_{sink}$

Same braking event

410 kWh	210 kWh	120 kWh
• smaller SOC rise • lower effective C-rate	• larger SOC rise • higher effective C-rate	• largest SOC rise • highest curtailment risk

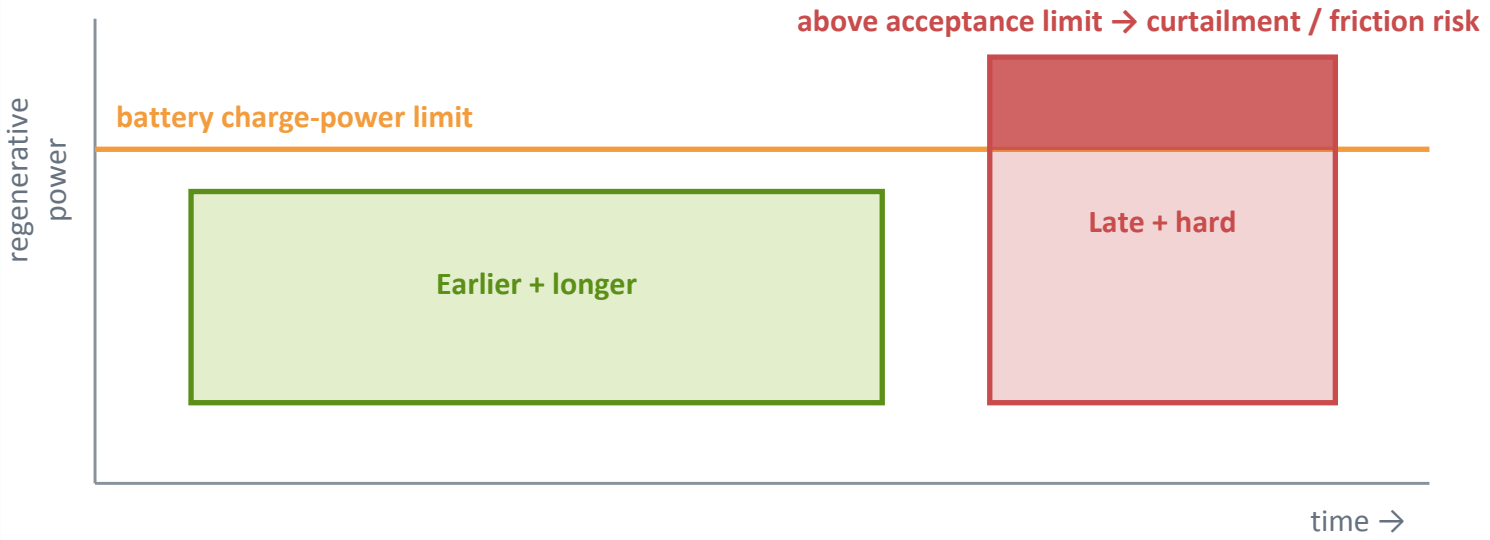
Simple headroom rule

Required headroom [%] ≈ 100 × $E_{reg,pred}$ / $E_{bat,nom}$

Maximum pre-event SOC ≈ SOC_upper − required headroom

Braking timing is a control variable — not just a consequence

Same speed reduction — different regenerative power profile



Conceptual illustration — same Δv, lower peak power when braking is distributed over more time/distance.

If route / timetable margin exists…

1. **initiate braking earlier**
2. **extend braking duration**
3. **select a lower approach speed**
4. **preserve battery SOC headroom**

Goal: keep regenerative power inside both the motor and battery envelopes.

Route-aware brake management: predict the event before braking begins

The controller manages the whole braking event — not only the instantaneous brake command.

1 LOOK AHEAD
- speed limits
- gradient
- station stop
- timetable

2 PREDICT
- event energy
- peak power
- available braking distance

3 PLAN HEADROOM
- maximum pre-event SOC
- battery acceptance margin

4 SHAPE BRAKING
- earlier / longer braking
- or lower approach speed

5 BLEND
- maximize admissible ED
- friction = residual only

Simple pre-event headroom rule

Required headroom [%] ≈ 100 × predicted event energy / battery capacity
Pre-event SOC ≤ SOC_upper − required headroom

Reserve enough empty battery capacity before the predicted braking event.

Diagnose the limiting mechanism

MOTOR / INVERTER LIMITED

$P_{ED,max}(v) < P_{brake,req}$

- remedy: earlier / longer braking
- when timetable and distance allow

BATTERY LIMITED

$P_{bat,max}(SOC)+P_{sink} < P_{ED,prod}$

- remedy: preserve SOC headroom
- or use auxiliary / external sink

Why prediction matters

LATE / HARD BRAKE

short time → high peak power → ED or battery limit reached → more friction

ROUTE-AWARE BRAKE

start earlier → lower peak power → more energy stays inside ED + battery limits

Objective

maximize stored regenerative energy while preserving braking performance and safety constraints

Three tests isolate the limiting mechanisms from a single stop to route-level operation

The cases are ordered from a controlled reference stop → sustained downhill charging → repeated real-route braking.

1 REFERENCE STOP

120 → 0 km/h
level track • 30 t vehicle

Initial speed	**120 km/h**
Vehicle	**30 t**
Track	**level**

What is the basic energy-recovery potential of one high-speed stop?

2 LONG DOWNHILL

80 km/h • 21‰ • 46 km
≈966 m altitude drop

Route condition	**21‰ • 46 km**
Battery cases	**410 / 210 kWh**
Initial SOC	**50%**

Can the battery sustain continuous regenerative charging without rejection?

3 BORLÄNGE–MALUNG

258 km route
repeated station-to-station braking

Route	**≈258 km round trip**
Event pattern	**repeated stops + speed changes**
Battery study	**410 kWh + 120 kWh sensitivity**

How do repeated events and SOC history change route-level capture?

What each case isolates

Case 1: conversion potential — **Case 2: battery acceptance** — **Case 3: route + SOC history** → **results now follow in the same order**

120 → 0 km/h reference stop: ED recovery benchmark on level track

Reference condition: 30 t vehicle • level track • 120 km/h initial speed • ED-first service braking • sufficient battery acceptance

Energy accounting for one high-speed stop

INITIAL KINETIC ENERGY

4.63 kWh

$E_k = \frac{1}{2}mv^2$

electric-machine efficiency profile

PRODUCIBLE ED ENERGY

3.26 kWh

70.4% of E_k

Difference from the kinetic-energy reference **4.63 − 3.26 = 1.37 kWh**

This gap is the difference between initial kinetic energy and the ED electrical reference in this model. It is not the total friction loss or the final battery loss.

Important: 3.26 kWh is an ED reference — not automatically the final battery-stored energy.

What this case tells us

1 Conversion potential

The ED electrical reference is ≈70% of the initial kinetic-energy reference in this model.

2 Battery is not the limiter here

With sufficient SOC headroom, this case isolates the drivetrain / conversion side of regenerative braking.

3 It becomes our reference

Later cases are judged by how closely route and battery constraints allow us to approach this producible-energy benchmark.

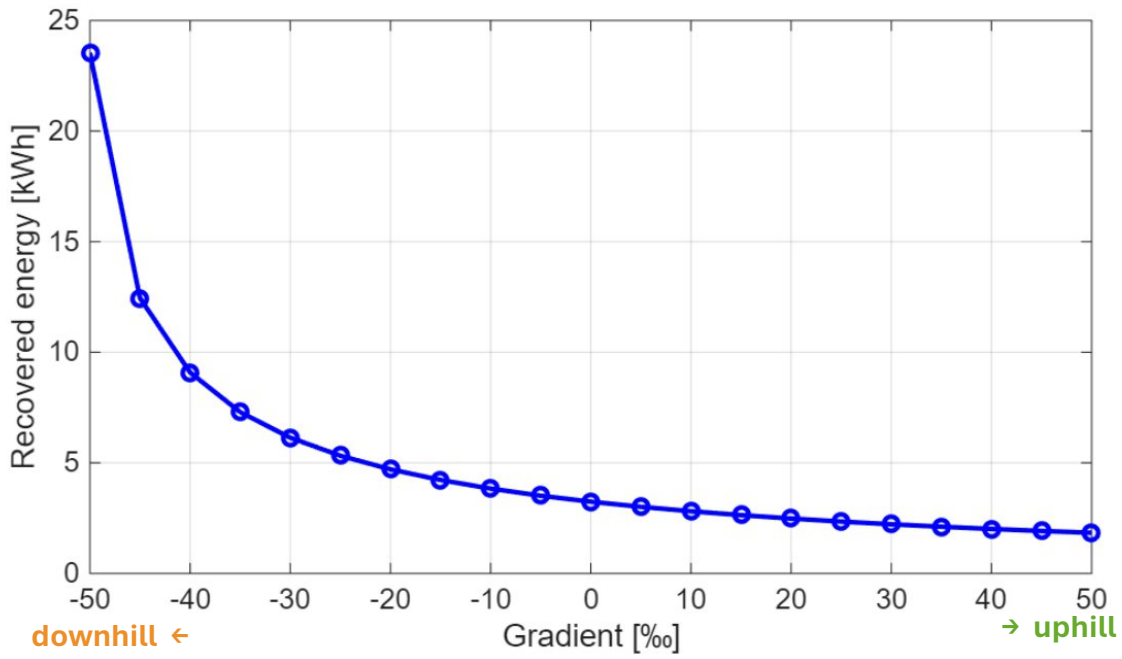
Next question

What happens to the available braking energy when the same 120 → 0 km/h stop occurs on an uphill or downhill gradient?

Gradient changes both regenerative-energy potential and braking feasibility

Same 120 → 0 km/h ED-first braking event, repeated under different constant gradients.

Recovered ED energy versus constant gradient



What changes physically?

DOWNHILL — **Gravity adds energy to the braking task.**

→ more energy must be absorbed by ED / friction / battery

UPHILL — **Gravity helps decelerate the vehicle.**

→ less braking work is required and recoverable energy falls

CONTROL IMPLICATION

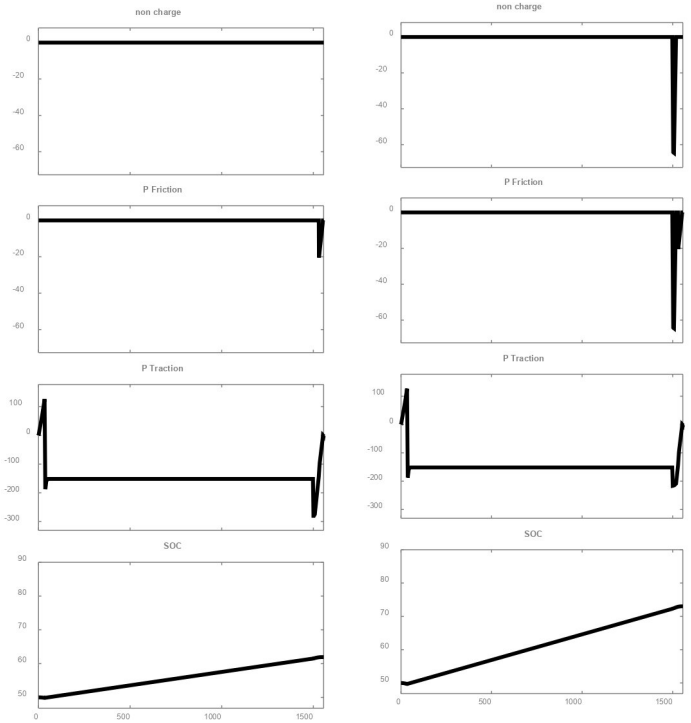
Downhill events may require earlier / longer braking to stay inside ED and battery limits.

This is why the next stress test uses a sustained 21‰ descent over 46 km: short-stop behavior becomes a continuous absorption problem.

With sufficient SOC headroom, both batteries absorb nearly all regenerative power

80 km/h speed regulation • 21‰ descent • 46 km • ≈966 m altitude drop • ≈79 kWh gravitational energy before losses • initial SOC = 50%

Simulation traces from the conference paper



(a) 410 kWh, 50% SOC **(b) 210 kWh, 50% SOC**

How to read the result

Rejected / non-charge power ≈ 0

During the main descent, almost no regenerative power is rejected.

410 kWh

Friction is mainly associated with the low-speed transition.

210 kWh

A larger transient friction contribution appears under the imposed timing profile — not because the battery rejects the steady downhill regen.

Net battery-energy change

410 kWh	Aux 0 kW: **−1.02 kWh/km** Aux 15 kW: **−0.83 kWh/km**	**210 kWh**	Aux 0 kW: **−1.00 kWh/km** Aux 15 kW: **−0.82 kWh/km**	**negative sign = battery gains energy**

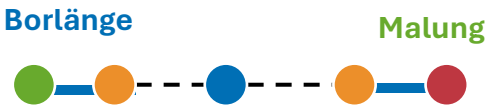
Key result: for this 50% SOC case, battery capacity is not the dominant limit; SOC headroom is sufficient and regenerative absorption remains available.

Borlänge–Malung: same route, very different braking events

Representative events from the ≈258 km round trip show why one fixed braking rule or one fixed pre-event SOC target is not sufficient.



Route context



129 km one way
≈258 km round trip

Repeated speed changes, station stops and changing gradients

Representative braking events extracted from the route

Position	Speed [km/h]	Gradient	Recovered energy	Time	Distance	Peak regen
6.1 km	**70 → 0**	+0.39%	**1.2 kWh**	23 s	217 m	**325 kW**
7.1 km	**115 → 40**	+0.09%	**2.7 kWh**	31 s	695 m	**328 kW**
252.5 km	**115 → 0**	−0.39%	**3.3 kWh**	47.5 s	826 m	**329 kW**
258.6 km	**40 → 0**	−0.39%	**0.4 kWh**	14 s	73 m	**227 kW**

Engineering interpretation

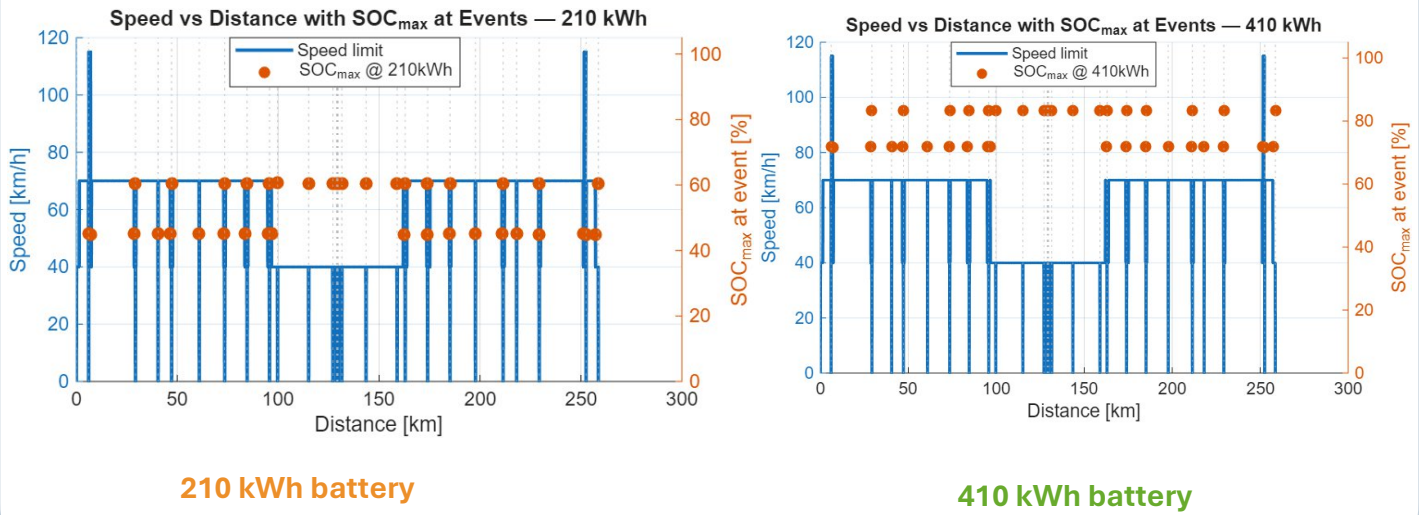
The route does not produce one 'typical' brake event: recovered energy varies from 0.4 to 3.3 kWh, braking distance from 73 to 826 m, while peak regen for the larger events remains around 325–329 kW.

Therefore the allowable SOC before braking must be event-specific — the next slide quantifies that headroom.

Pre-event SOC must be event-specific — and battery-size-specific

Before each predicted braking event, the battery must have enough empty energy capacity to accept the expected regenerative energy.

Predicted maximum allowable SOC before each braking event



210 kWh battery

410 kWh battery

Orange points: allowable SOC before the upcoming event. Blue: route speed profile.

Smaller battery

Same recovered energy consumes a larger fraction of nominal capacity → lower allowable pre-event SOC.

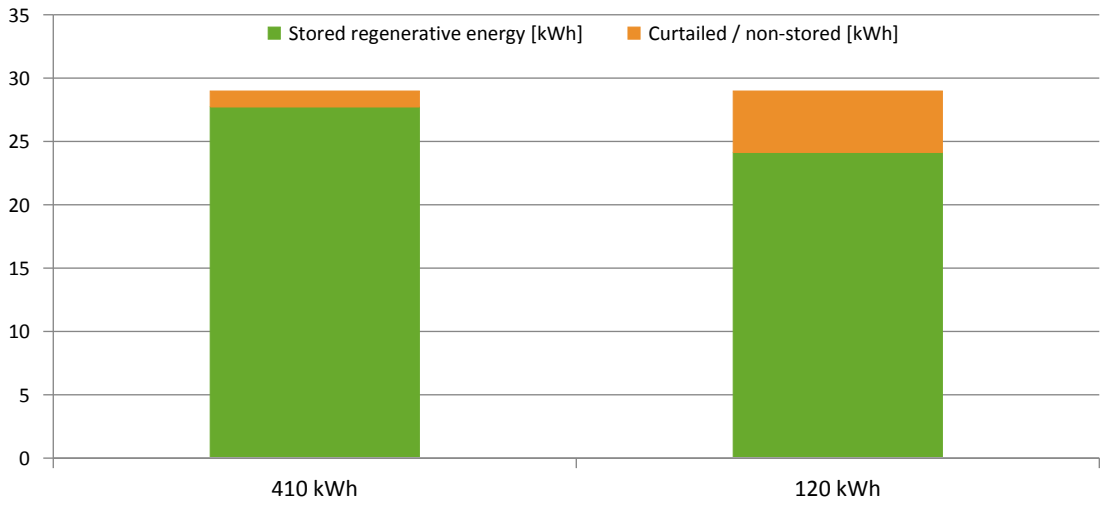
Larger battery

More absolute energy headroom → many events can be accepted at a higher SOC.

Route-level capture: producible regenerative energy is not automatically stored energy

Over the analysed Borlänge–Malung route, the maximum producible regenerative energy is ≈28.98 kWh.

Route-level regenerative-energy accounting



27.72 kWh
• **96%**

24.13 kWh
• **83%**

What changes when the battery is smaller?

Less absolute SOC headroom
the same event consumes a larger fraction of available capacity

Higher effective charge rate
the same regenerative kW corresponds to a higher C-rate

More curtailment risk
battery acceptance is reached earlier during repeated events

Stronger route dependence
charging strategy and event timing become more critical

Key result

410 kWh stores ≈96% of the producible route-level regenerative energy; the 120 kWh sensitivity case stores ≈83%.

120 kWh is a sensitivity case used to expose the limiting mechanism — not a final battery-sizing recommendation.

The limiting mechanism determines the correct engineering response

A braking shortfall is not one problem: motor/inverter limits and battery-acceptance limits need different remedies.

1 MOTOR / INVERTER LIMITED

Symptom Required ED power exceeds the speed-dependent ETM / inverter envelope.

$$P_{ED,max}(v) < P_{brake,req}$$

Best response

- start braking earlier
- extend braking time/distance
- reduce peak braking power
- lower approach speed if timetable permits

Goal: keep the event inside the ED envelope.

2 BATTERY LIMITED

Symptom ETM can generate the power, but the battery / sinks cannot absorb it.

$$P_{bat,max}(SOC)+P_{sink} < P_{ED,prod}$$

Best response

- preserve SOC headroom
- schedule charging strategically
- use auxiliary / external sink when available
- otherwise accept curtailment / friction

Goal: create absorption capacity before the event.

3 FRICTION STILL MATTERS

Normal service role

- residual demand when ED is insufficient
- low-speed final stopping
- holding / parking

Safety role

- degraded operation
- fault / emergency override
- adhesion / WSP supervision

Energy optimization never overrides safe braking.

Design / control takeaway

Route knowledge → SOC headroom → earlier / shaped braking → maximize ED capture → friction only where required

What the results mean for battery-electric regional rail braking

Regenerative braking should be managed as a route-level energy problem — not only as an instantaneous brake-force problem.

1 Produced energy ≠ stored energy
Mechanical braking energy first passes through the ED envelope and ETM efficiency, then through battery charge-acceptance and SOC limits.

2 Two independent bottlenecks
Motor / inverter limitation needs earlier or longer braking; battery limitation needs SOC headroom or an additional energy sink.

3 Route prediction creates usable headroom
Knowing upcoming speed changes, gradient and stops allows the controller to reserve battery capacity and shape braking before the event begins.

4 The three cases support the same control logic
The reference stop defines the drivetrain benchmark. The long downhill shows that, with sufficient SOC headroom, battery capacity alone is not the dominant regenerative limit.

5 Route-level benefit depends on battery headroom
Borlänge–Malung: 28.98 kWh producible regen; 410 kWh pack stores 27.72 kWh (≈96%), while the 120 kWh sensitivity case stores 24.13 kWh (≈83%).

6 Friction braking remains necessary
Friction supplies residual demand, the final low-speed stop, holding / parking, and safety or degraded-operation braking. Energy optimization never replaces safe braking.

Engineering takeaway

Predict the event → reserve SOC headroom → start braking early enough → maximize admissible ED → use friction only where required.

Energy-maximizing brake management must coordinate route information, drivetrain limits, battery acceptance and safe brake blending.

Acknowledgement

- **FP6 FUTURE** → Europe's Rail JU project
- **Goal**: improve regional and capillary rail lines
- **Focus:** reduce total cost, raise reliability, green transport

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Thank you — Questions







Amir Torkiharchegani
Lund University
amir.torkiharchegani@iea.lth.se