Time-optimal operation of the hybrid Formula 1 power unit

Dr. Pol Duhr, Marc Neumann, Giona Fieni
27th January 2023

People

Dr. Pol Duhr
PhD from 2018 to 2022

Marc Neumann
PhD student

Giona Fieni
PhD student

First part:
Research of the past 4 years

Second part:
Outlook on future research

Project overview

Since 2012:
Collaboration with the department
"PU Performance and Control Strategies"

3 PhDs completed
2 PhDs ongoing

More than 20 bachelor, semester and master theses

Publications
9 journal papers
5 conference papers

10 optimization tools delivered

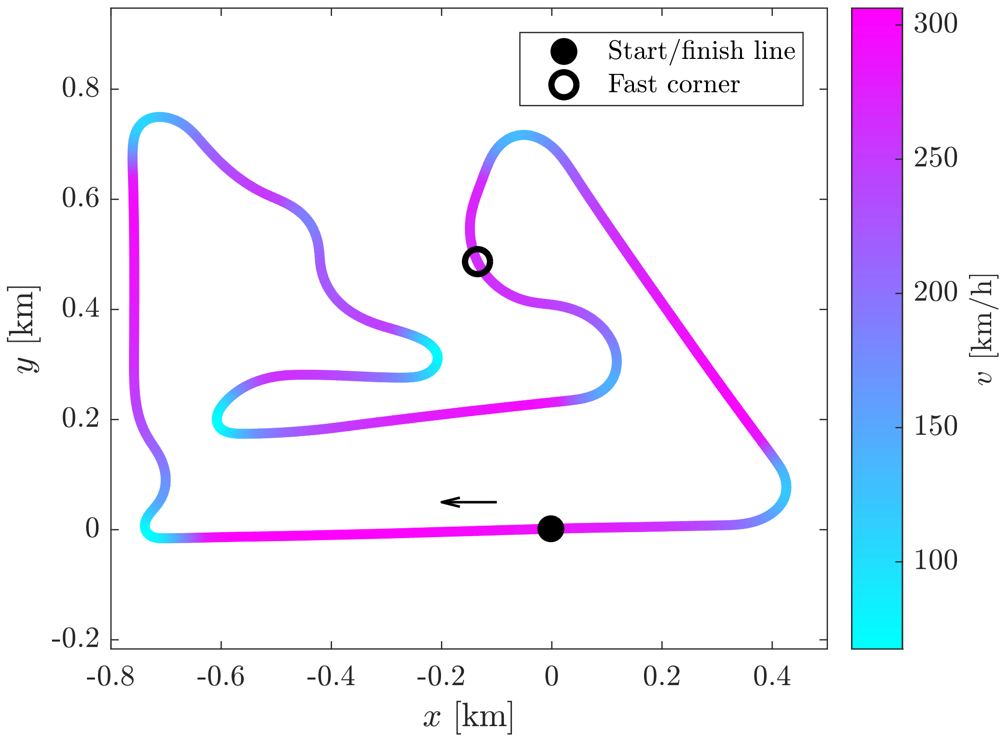
Weekly videocalls for close support of the industrial partner, plus trips to Maranello

Formula 1 racing

Bahrain Circuit

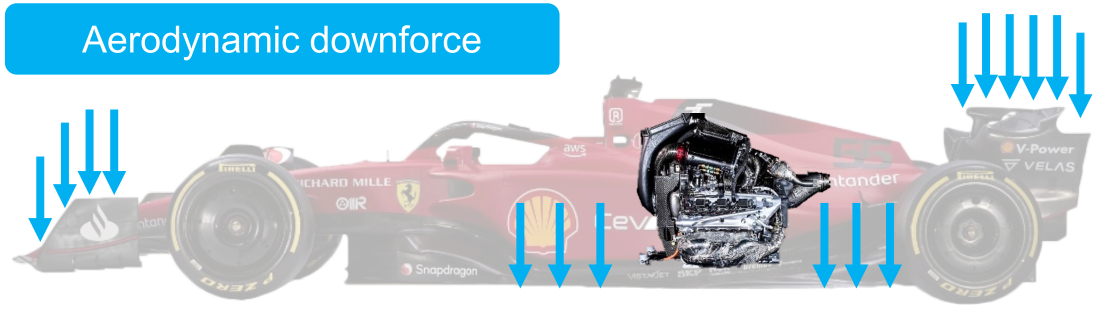
$N_{\text{laps}} = 57 \;\; \Rightarrow \;\; \mathbf{308\ km}$

Race time ≈ 95 min
Lap time ≈ 95 s



High-performance powertrain

Aerodynamic downforce



Examples from 2022:

POS	DRIVER	CAR	Q3
1	Carlos Sainz	FERRARI	1:40.983
2	Max Verstappen	RED BULL RACING RBPT	1:41.055

0.072 s

POS	DRIVER	CAR	TIME/RETIRED
1	Max Verstappen	RED BULL RACING RBPT	1:24:19.293
2	Charles Leclerc	FERRARI	$\boxed{+0.549s}$

Formula 1 racing

Bahrain Circuit
$N_{\text{laps}} = 57 \;\Rightarrow\; 308\ \text{km}$

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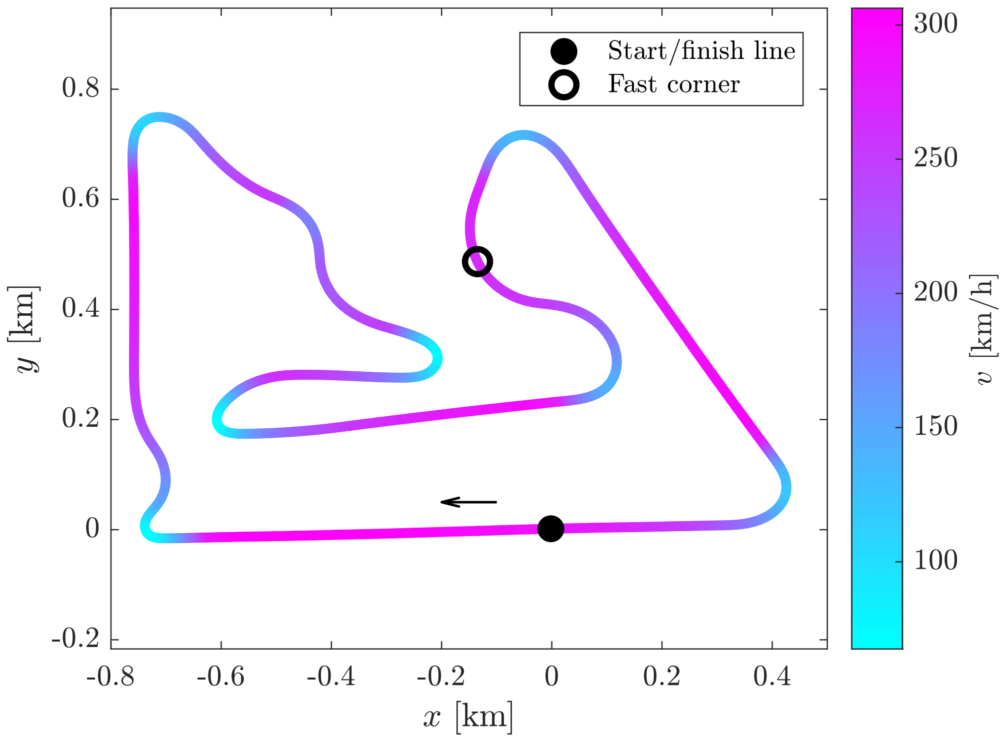
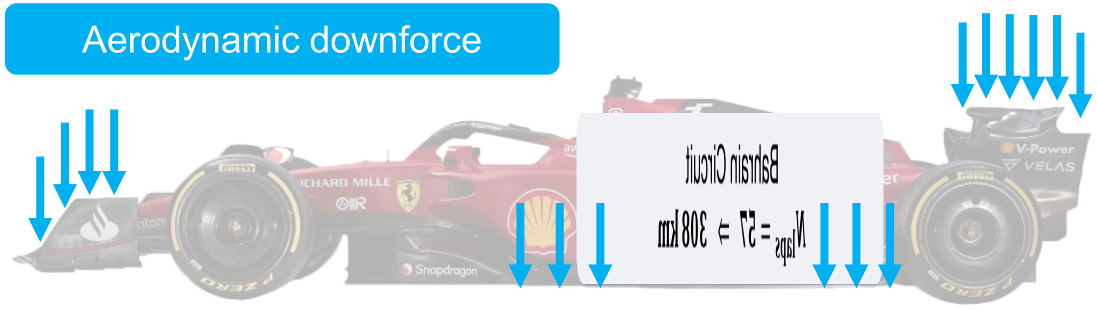
Lap time ≈ 95 s



High-performance powertrain

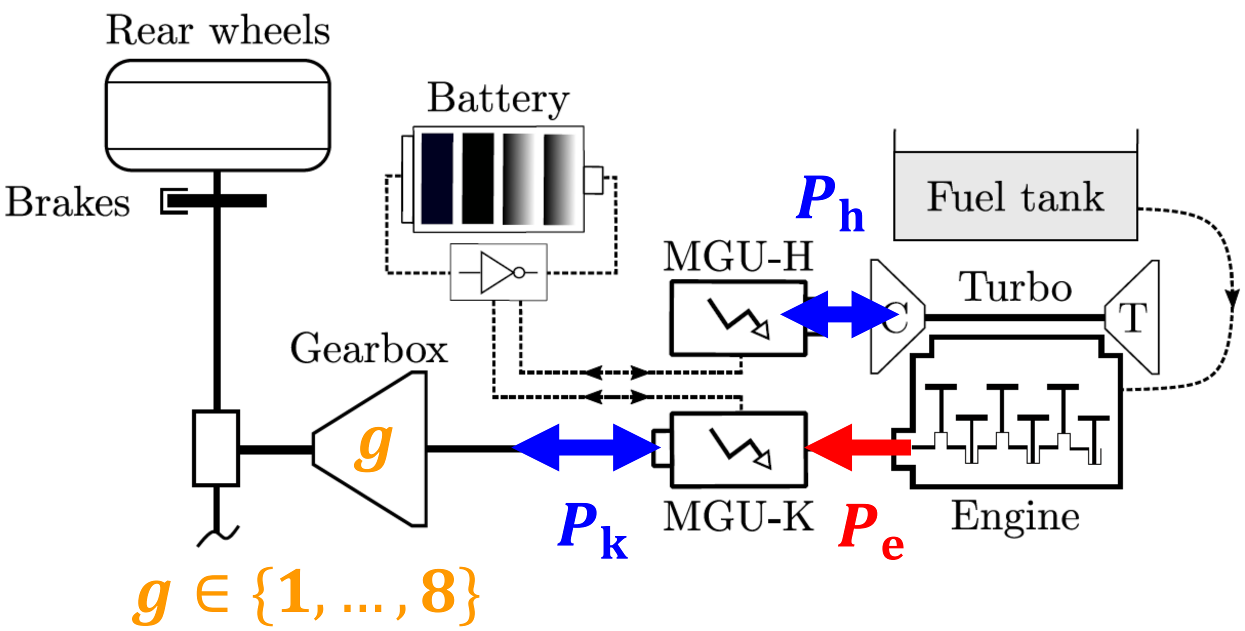
Aerodynamic downforce



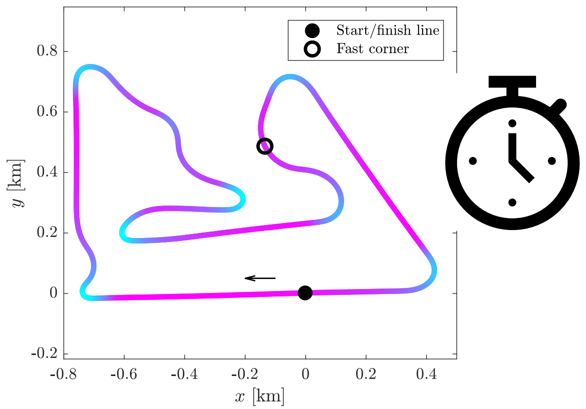
Development progress:
Measured in **milliseconds**!

Maximize powertrain potential → **Win the race**

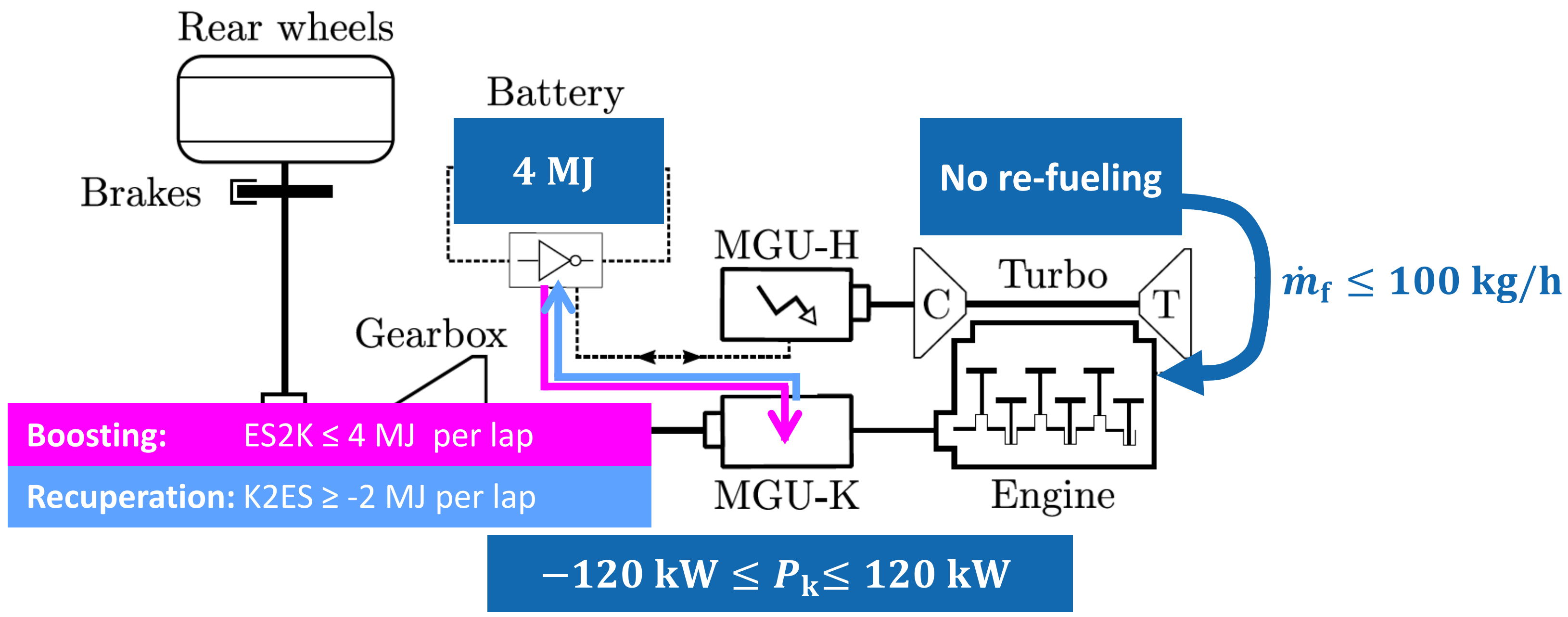
Hybrid Formula 1 power unit



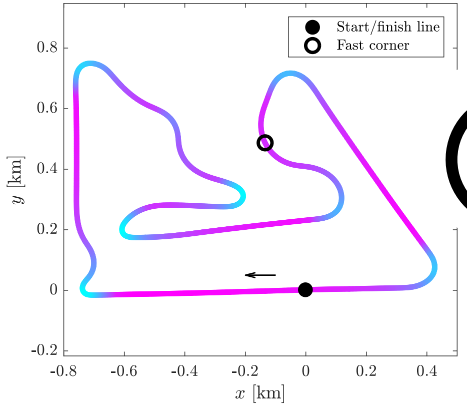
Minimize lap time

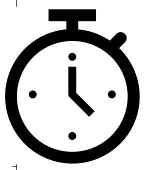


Hybrid Formula 1 power unit



Minimize lap time

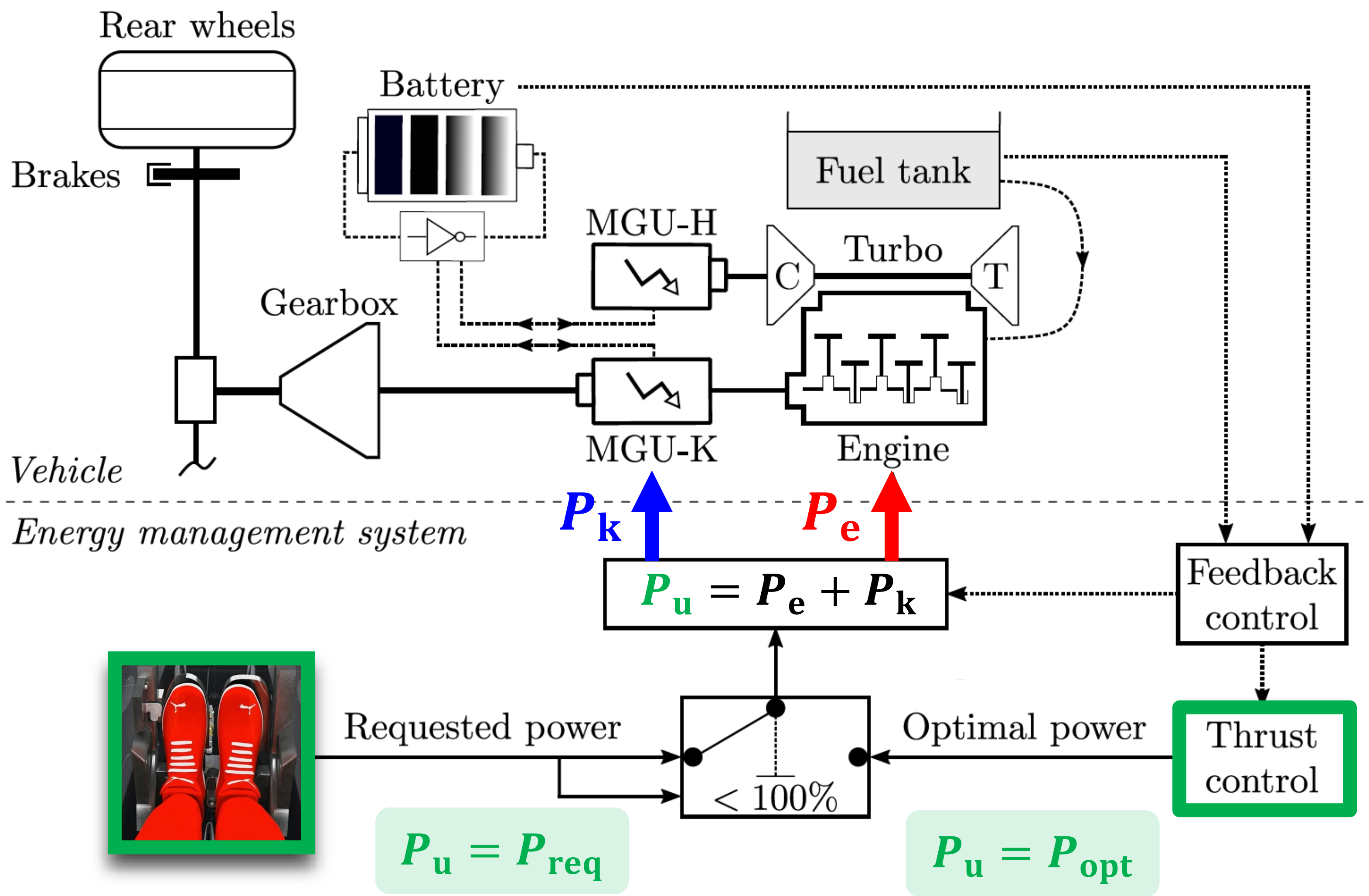




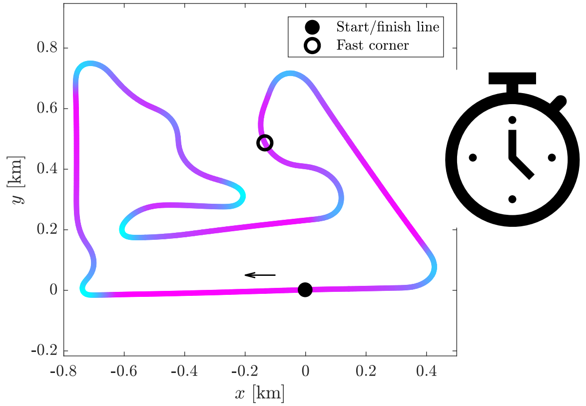
Energy is limited
→ operate PU **efficiently**!

Regulations allow automatic **energy management**

Hybrid Formula 1 power unit



Minimize lap time



Energy is limited
→ operate PU **efficiently**!

Regulations allow automatic **energy management**

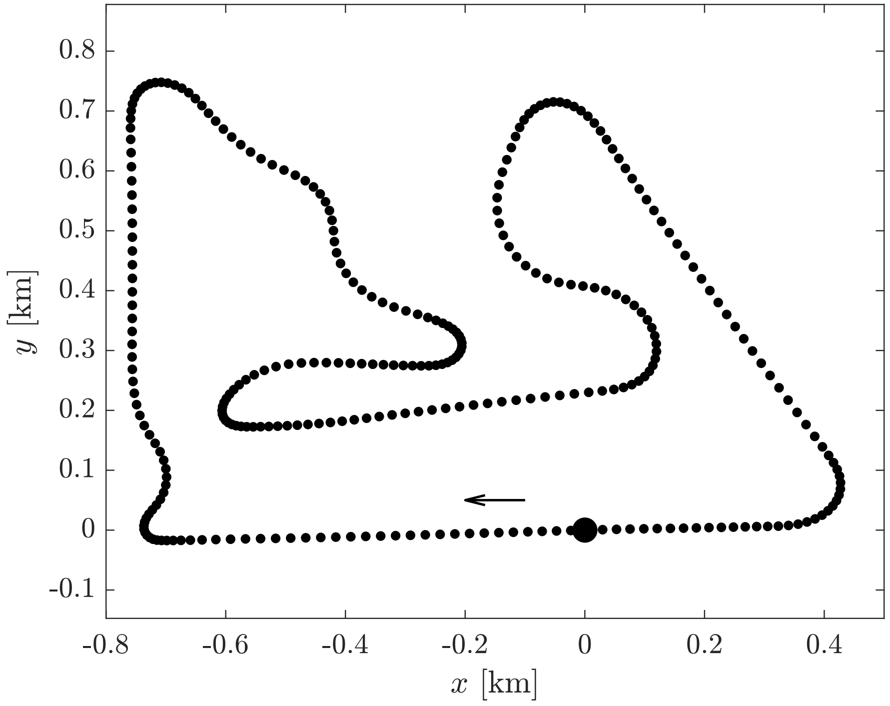
Optimal energy management

Online
Feedback control

Offline optimization
Optimal energy management

Optimal $P_\mathrm{e}, P_\mathrm{k}, P_\mathrm{h}$, ... **at each point** on track?

Not trivial!



Minimum-lap-time optimization

Racing line:
Path variable s
Curvature $\kappa(s)$

Energy allocation:
Fuel ΔE_{f}

Battery ΔE_{b}

$$\min T_{\mathrm{lap}}$$

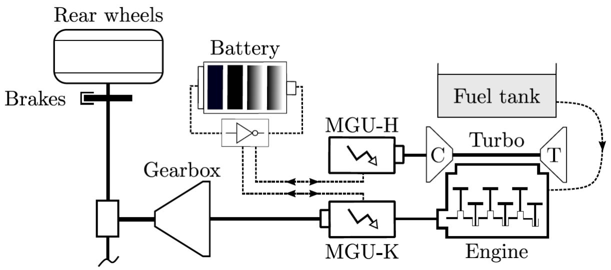
subject to

Longitudinal dynamics model

Grip limit model

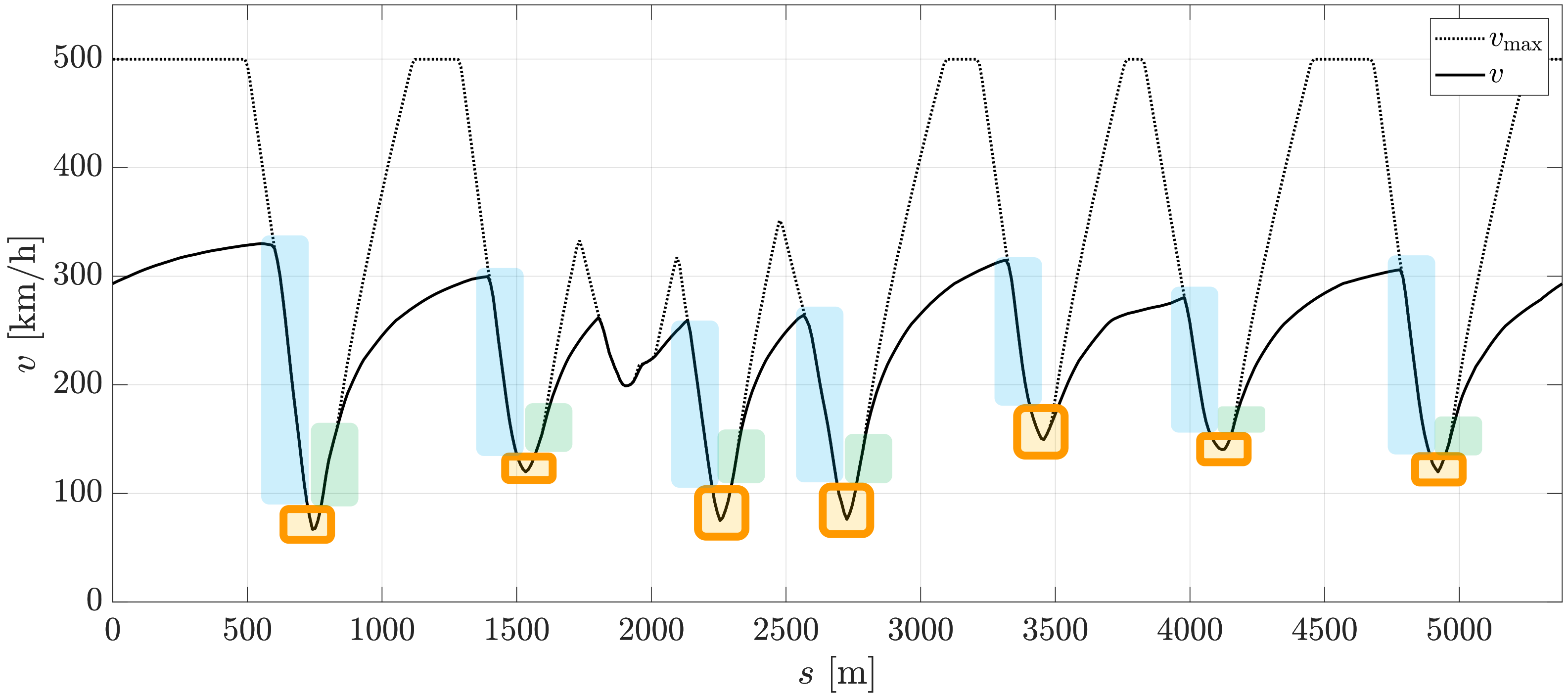
Tire grip

Power unit model



Optimal solution & lap time

Grip limit model



Velocity $v(s)$ not fixed, optimization variable!

Constraint on velocity:

$$v(s) \leq \boldsymbol{v}_{\max}(s) \quad \forall s$$

Corner apex

Braking zone / corner entry

Acceleration / corner exit

Grip-limited regions

Second-order cone program

S. Ebbesen, M. Salazar, P. Elbert, C. Bussi, and C. H. Onder.
Time-optimal control strategies for a hybrid electric race car.
IEEE Transactions on Control Systems Technology, 26(1):233–247, 2018.

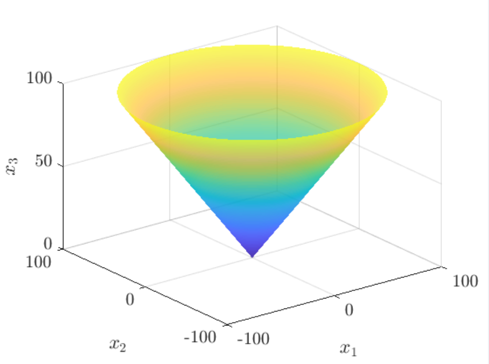
$$\min_{x \in \mathbb{R}^n} \quad f^T \cdot x$$ linear objective

$$\text{subject to} \quad F \cdot x = g$$ linear equality constraints

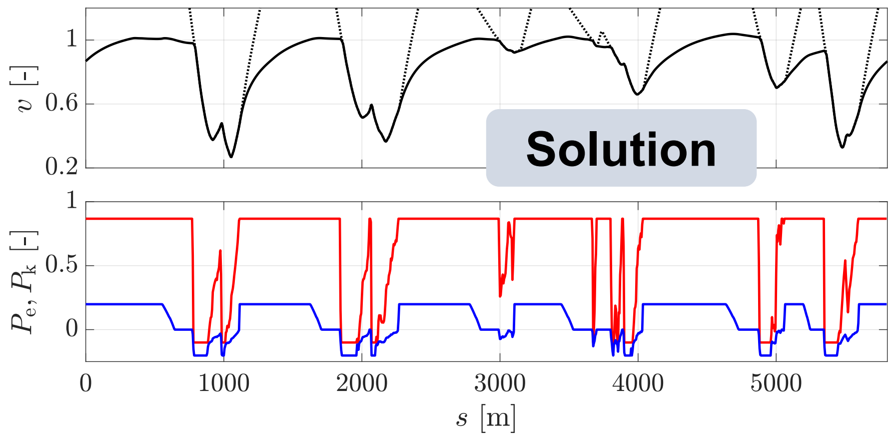
$$H \cdot x \leq k$$ linear inequality constraints

$$\|A_i \cdot x + b_i\|_2 \leq c_i^T \cdot x + d, \quad i = 1, \dots, m$$ **second-order cone constraints**

$$\left\| \begin{matrix} x_1 \\ x_2 \end{matrix} \right\|_2 \leq x_3$$



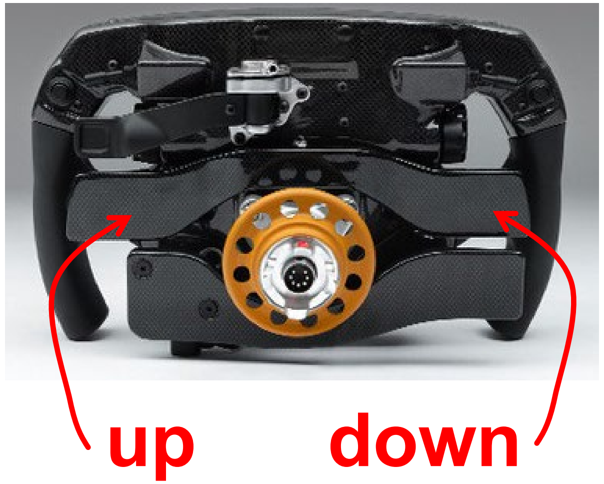
Convex optimization problem:
→ Very efficient numerical algorithms
→ Optimality guarantees

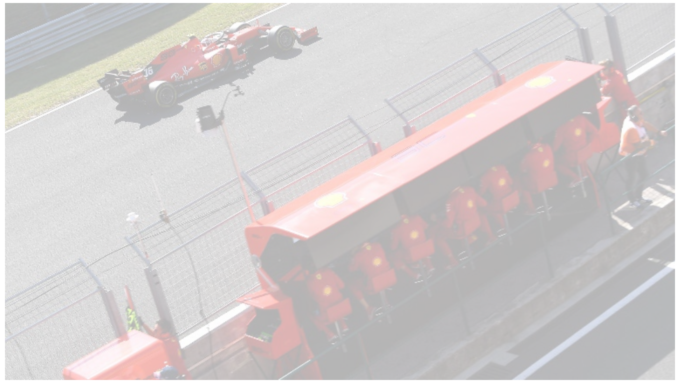


1 Gearshift optimization

2 Convex performance envelope

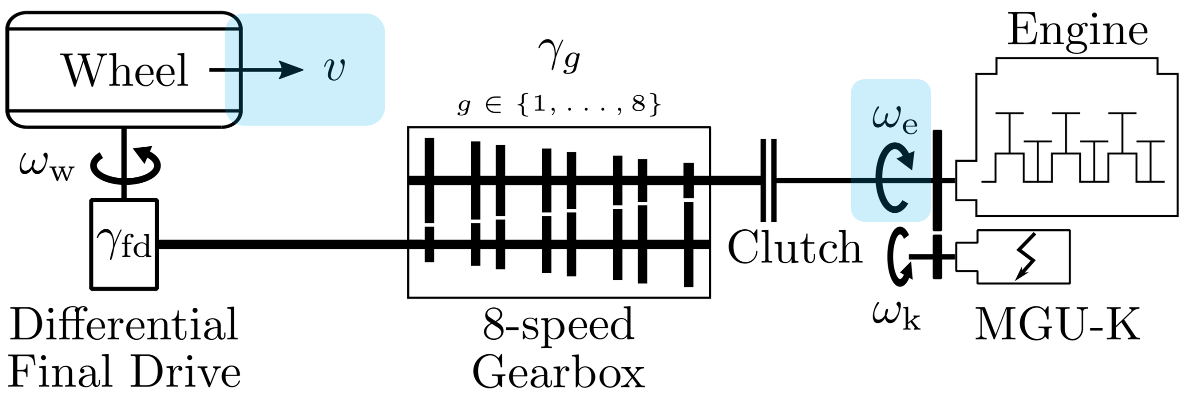
3 Minimum-race-time energy allocation





P. Duhr, G. Christodoulou, C. Balerna, M. Salazar, A. Cerofolini, and C. H. Onder.
Time-optimal gearshift and energy management strategies for a hybrid electric race car.
Applied Energy, 282:115980, 2020.

Drivetrain model



Overall transmission ratio:

$\omega_\mathrm{e} = \boldsymbol{\Gamma_g} \cdot v$

with $g \in \{1, \ldots, 8\}$

Research questions

Selected gear defines engine speed.

Given that the engine speed has an impact on

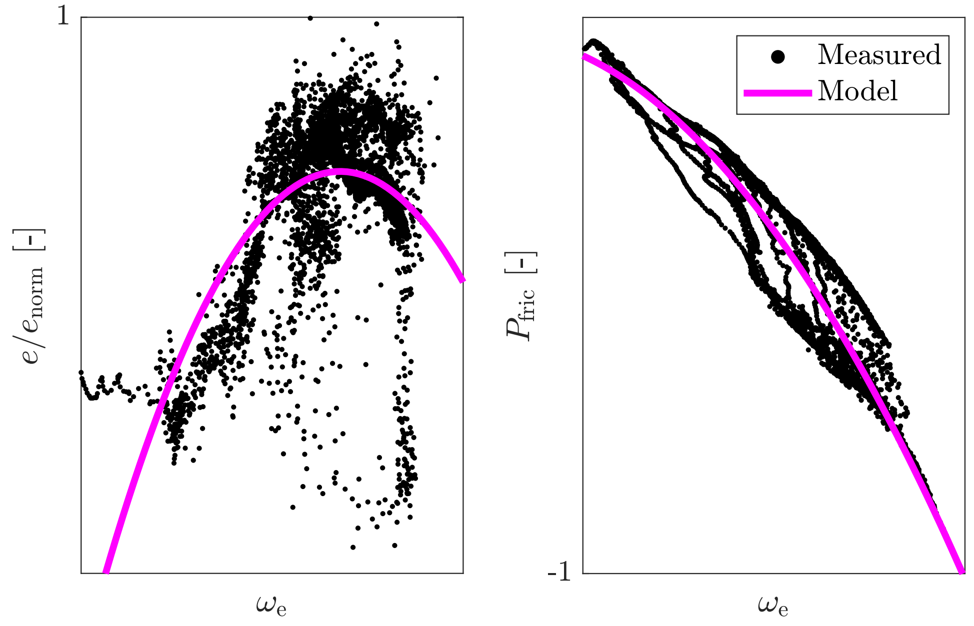
- the achievable propulsive power
- the electric recuperation

→ Interactions between **optimal energy management** and **optimal gear selection**?
→ **Sub-optimality** of a simple heuristic gearshift rule similar to the driver’s behaviour?

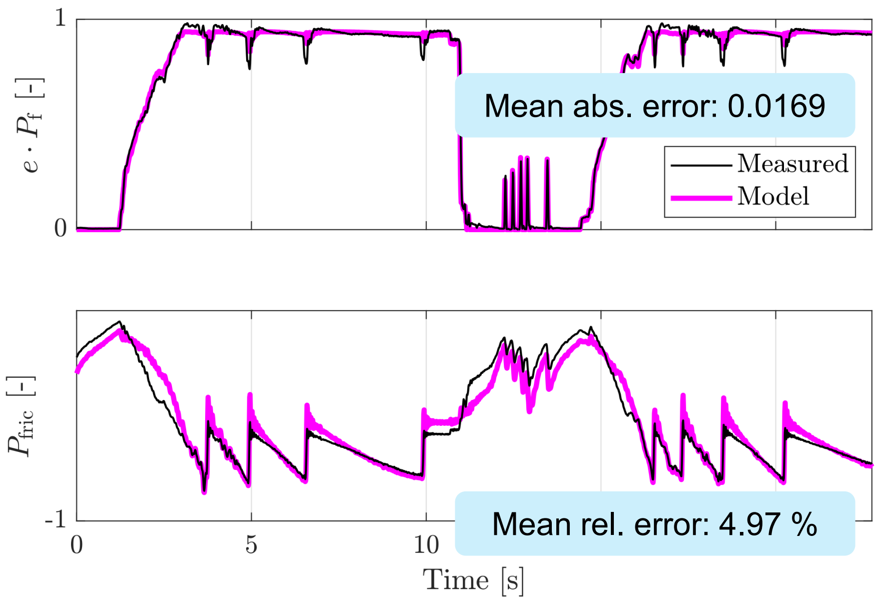
Engine model

Engine power:
$P_{\mathrm{e}} = e(\omega_{\mathrm{e}}) \cdot P_{\mathrm{f}} + P_{\mathrm{fric}}(\omega_{\mathrm{e}}) + P_{\mathrm{pump}}(\omega_{\mathrm{e}}, P_{\mathrm{f}}, r_{\mathrm{wg}})$

Efficiency and friction:
Quadratic fits as a function of ω_{e}



Validation plots:

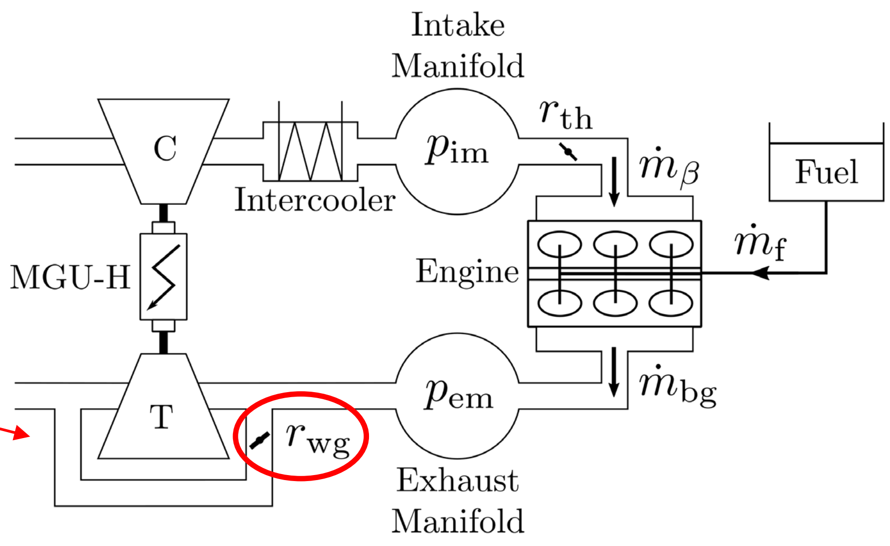


Engine model

Engine power:

$$P_e = e(\omega_e) \cdot P_f + P_{fric}(\omega_e) + P_{pump}(\omega_e, P_f, r_{wg})$$

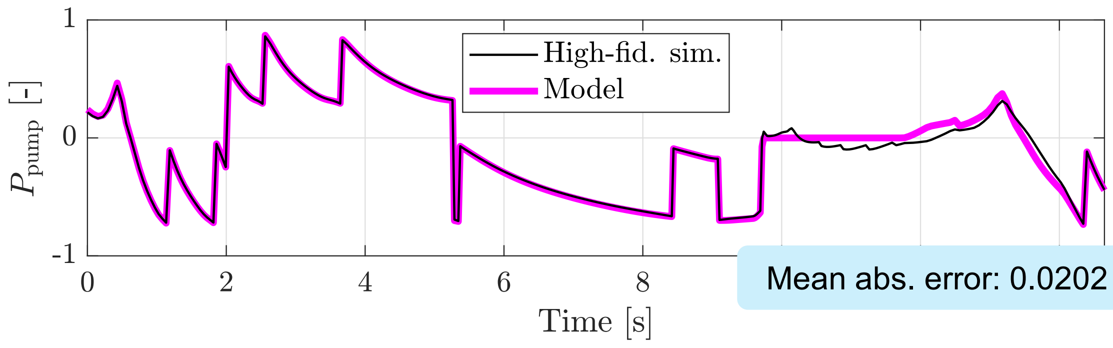
Waste-gate



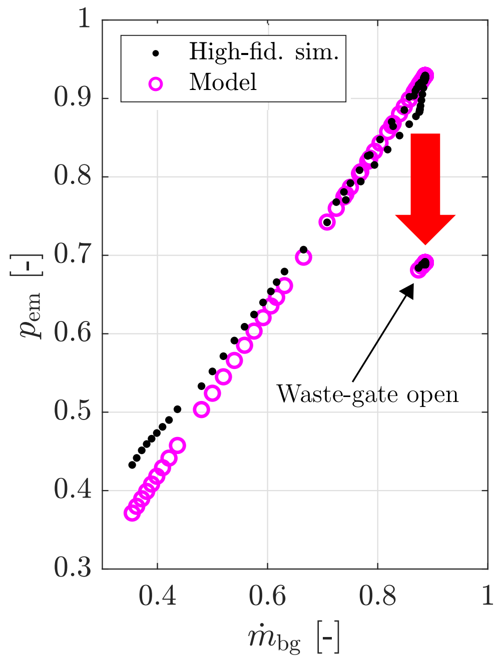
Pumping power:

- Engine can be seen as a **volumetric pump**
- Opening the **waste-gate** reduces exhaust manifold pressure → larger pressure difference → pumping power increases

$$P_{pump}(\omega_e, P_f, r_{wg}) = \left(\frac{C_1}{\eta_{vol}(\omega_e)} - C_2 \cdot \omega_e \cdot (\alpha_{wg,1} \cdot r_{wg} + \alpha_{wg,0}) \right) \cdot P_f$$



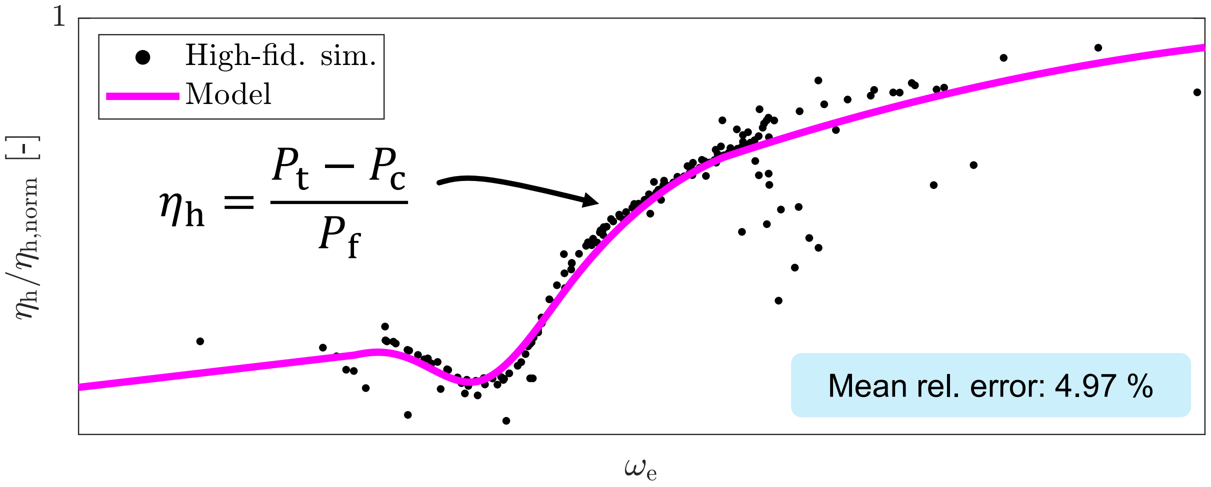
Mean abs. error: 0.0202



MGU-H model

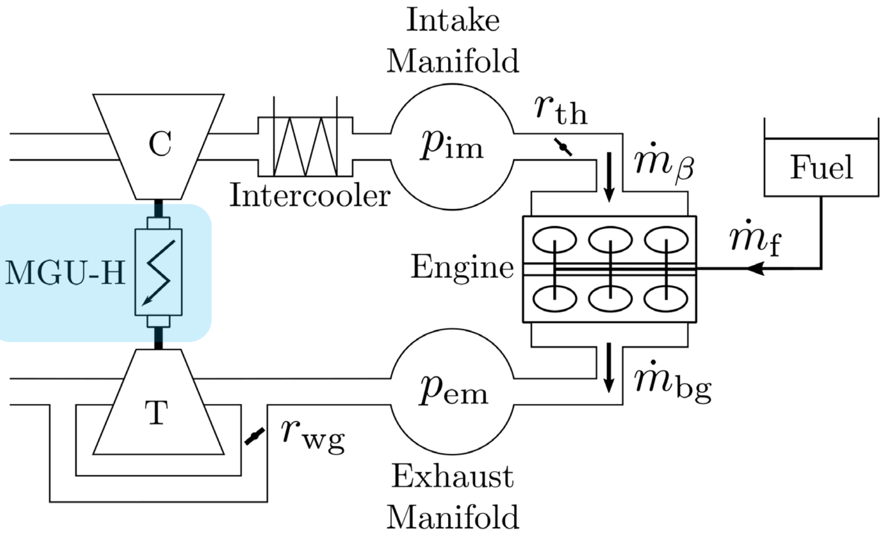
Assumption: MGU-H is only operated in **generator mode.**

$$P_{\mathrm{h}} = \eta_{\mathrm{h}}(\omega_{\mathrm{e}}) \cdot P_{\mathrm{f}} \cdot r_{\mathrm{wg}} \leq \mathbf{0}$$



Waste-gate position:
$r_{\mathrm{wg}} \in [-1, 0]$

-1 → closed
0 → open



Observations – Trade-offs!

- Waste-gate open
  → small increase in engine power
  but
  → MGU-H recuperation becomes zero

- High engine speed
  → engine efficiency decreases
  but
  → more MGU-H recuperation

Optimization problem

Lap time minimization $\min \int_0^T \mathrm{d}t$

Ideally: Optimize everything at once

$\boldsymbol{\omega}_\mathbf{e} = \boldsymbol{\Gamma}_{\boldsymbol{g}} \cdot \boldsymbol{v}$

Terms $\boldsymbol{e}(\boldsymbol{\omega}_\mathbf{e}) \cdot \boldsymbol{P}_\mathbf{f}$

etc.

Not convex

$\boldsymbol{g} \in \{\mathbf{1}, \dots, \mathbf{8}\}$

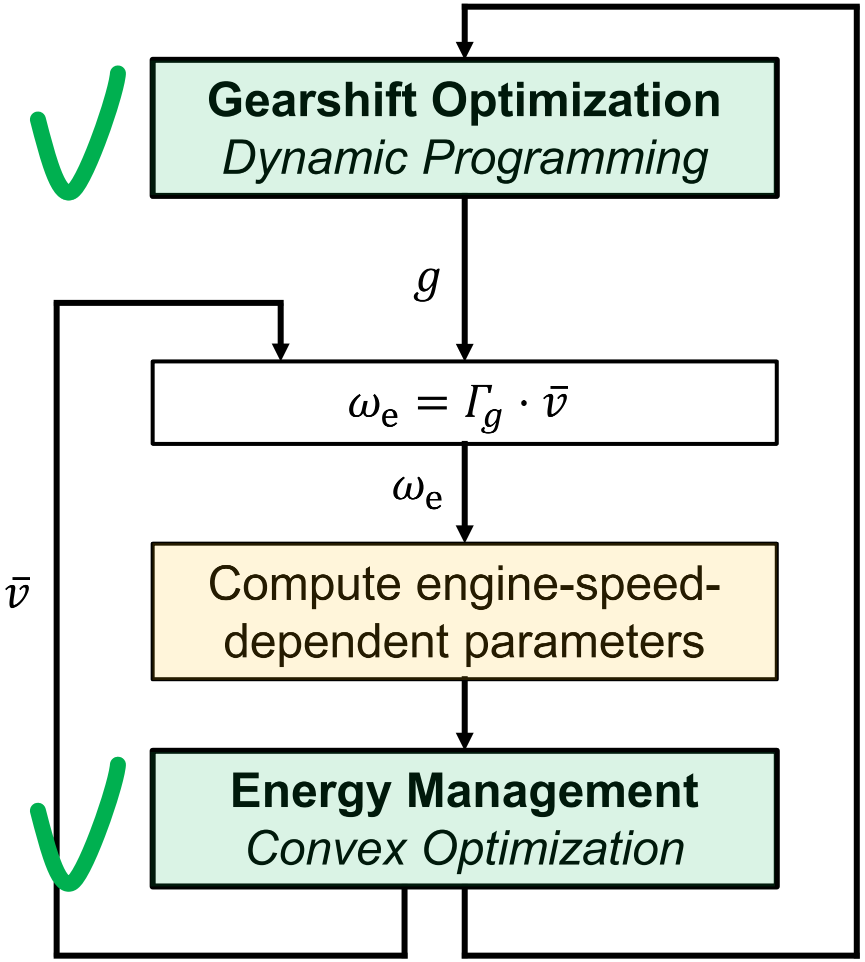
Integer variable

Problem: Would lead to a mixed-integer non-linear program (MINLP)
→ computationally very expensive, convergence and optimality issues

Solution:

- Iterative scheme
- Separate optimization of **integer** and **continuous** variables

Iterative optimization scheme



$\bar{v}$
$\bar{P}_\mathrm{f}, \bar{P}_\mathrm{k}, \bar{r}_\mathrm{wg}, \bar{P}_\mathrm{p}$
Costates λ (damped)

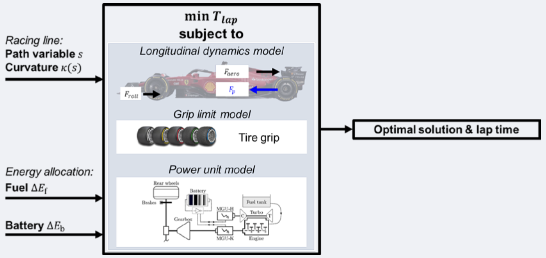
Input: Sequential gearshift command
$\boldsymbol{u_g(k)} \in \{\boldsymbol{-1, 0, 1}\}$

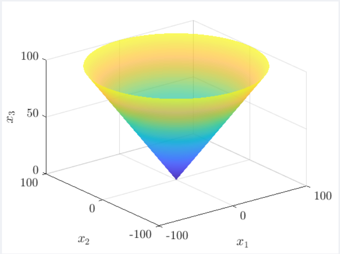
State: Selected gear $\in \{1, \ldots, 8\}$
$\boldsymbol{g(k+1) = g(k) + u_g(k)}$

Stage cost: Hamiltonian
$\tilde{H}\left(\boldsymbol{g(k)}, \bar{v}, \bar{P}_\mathrm{f}, \bar{P}_\mathrm{k}, \bar{r}_\mathrm{wg}, \bar{P}_\mathrm{p}, \lambda\right)$
→ captures optimal trade-offs
→ propulsive power vs. fuel vs. electric consumption

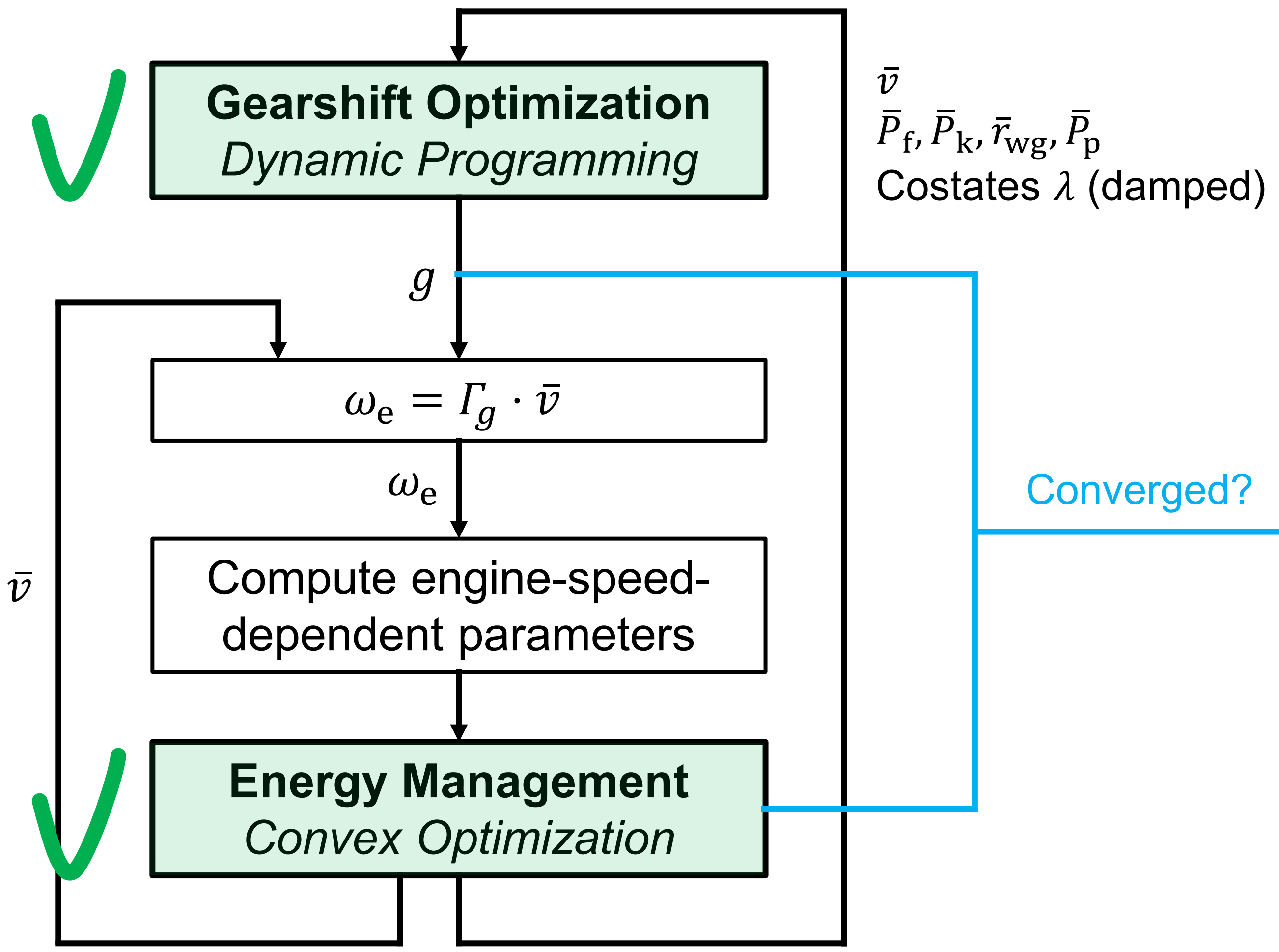
$$P_\mathrm{e} = e(\omega_\mathrm{e}) \cdot P_\mathrm{f} + P_\mathrm{fric}(\omega_\mathrm{e}) + P_\mathrm{pump}(\omega_\mathrm{e}, P_\mathrm{f}, r_\mathrm{wg})$$
$$P_\mathrm{h} = \eta_\mathrm{h}(\omega_\mathrm{e}) \cdot P_\mathrm{f} \cdot r_\mathrm{wg}$$

Second-order cone program





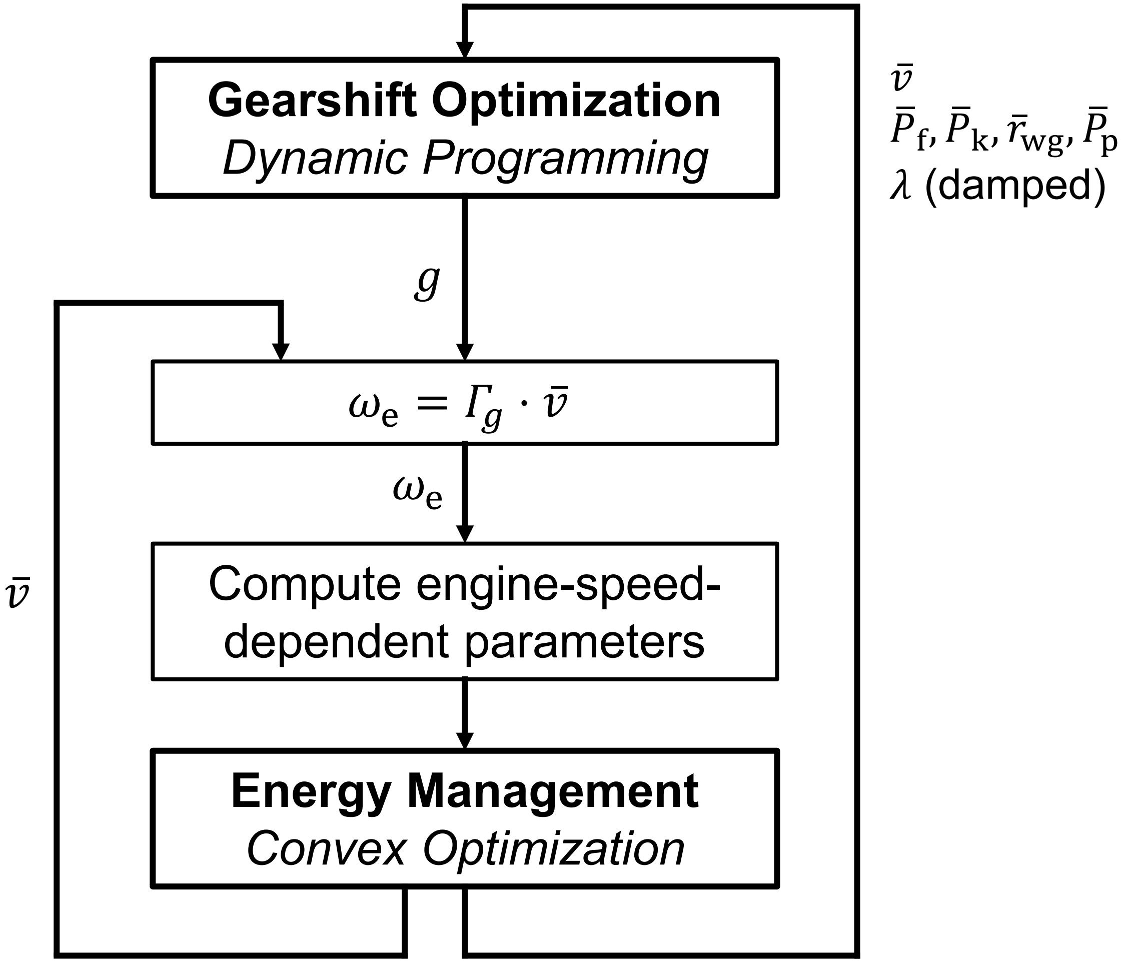
Iterative optimization scheme



Outputs: Optimal

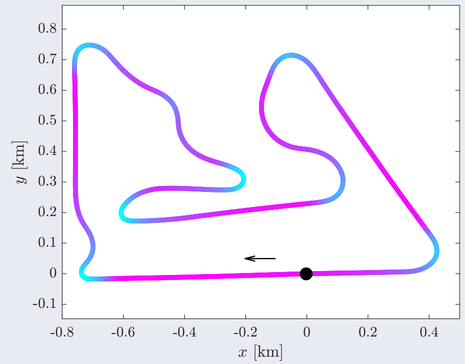
- gearshift strategy g^*
- velocity profile v^*
- energy trajectories $E_\mathrm{f}^*, E_\mathrm{b}^*, E_\mathrm{ES2K}^*, E_\mathrm{K2ES}^*$
- power trajectories $P_\mathrm{f}^*, P_\mathrm{k}^*, P_\mathrm{brk}^*, r_\mathrm{wg}^*$

Iterative optimization scheme



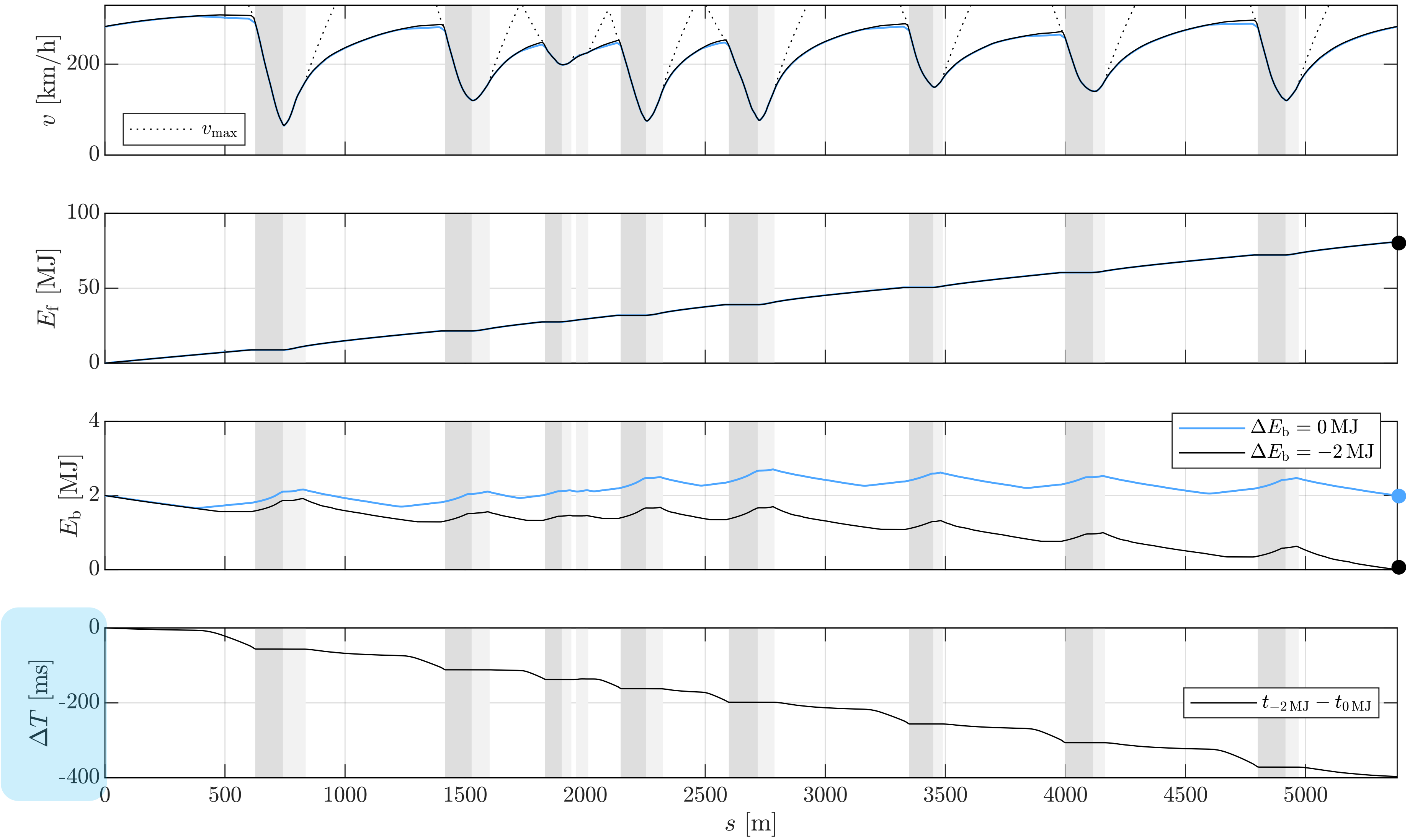
Results – Bahrain Circuit

- Compare optimal gearshift strategy for:
  - $\Delta E_{\mathrm{b}} = 0\ \mathrm{MJ}$ (charge-sustained)
  - $\Delta E_{\mathrm{b}} = -2\ \mathrm{MJ}$ (strong discharge)
- Sub-optimality of a heuristic gearshift rule



Computational time: 10 iterations, 90 seconds

Optimal trajectories



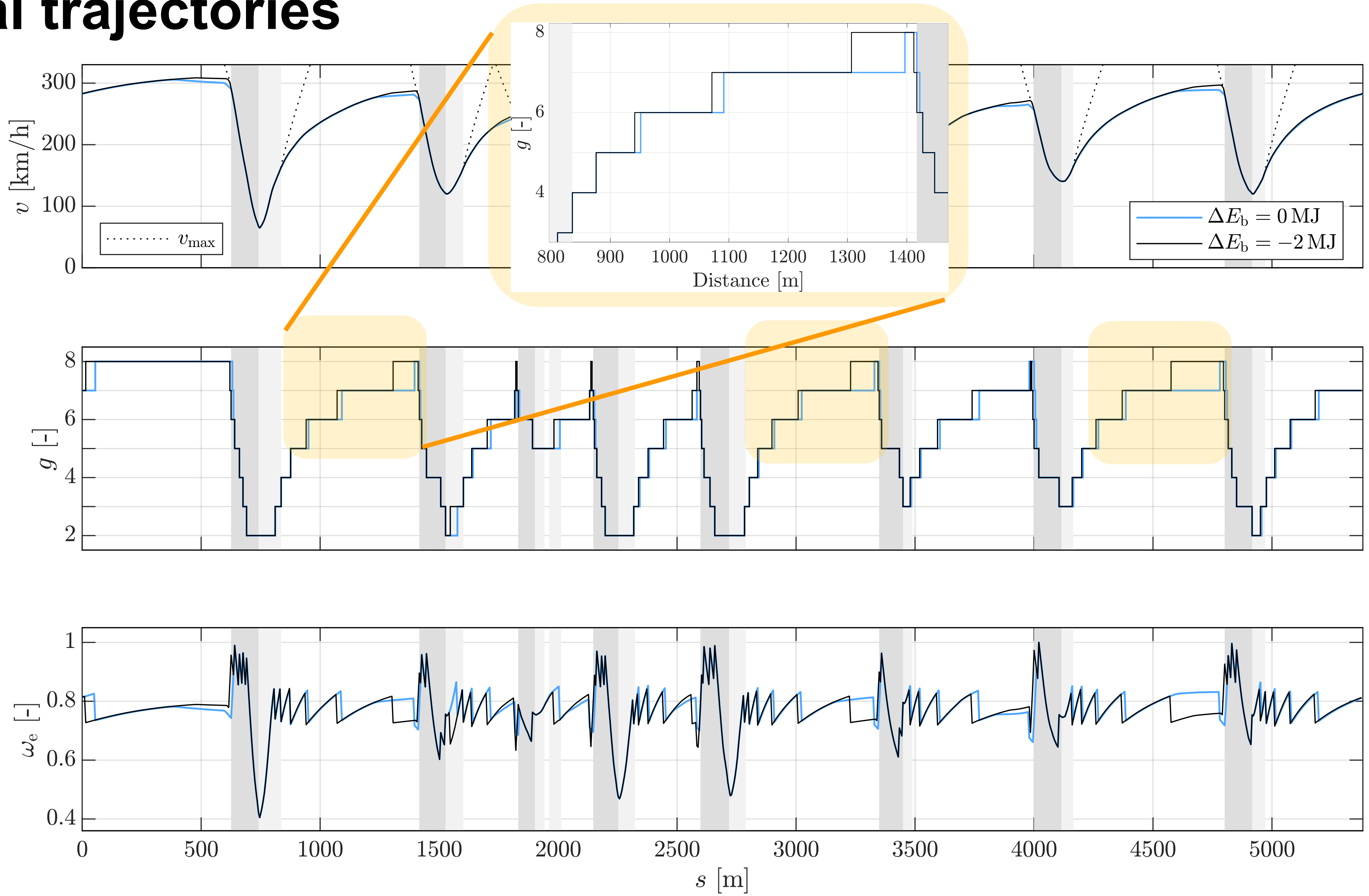
identical fuel allocation ΔE_{f}

charge-sustained

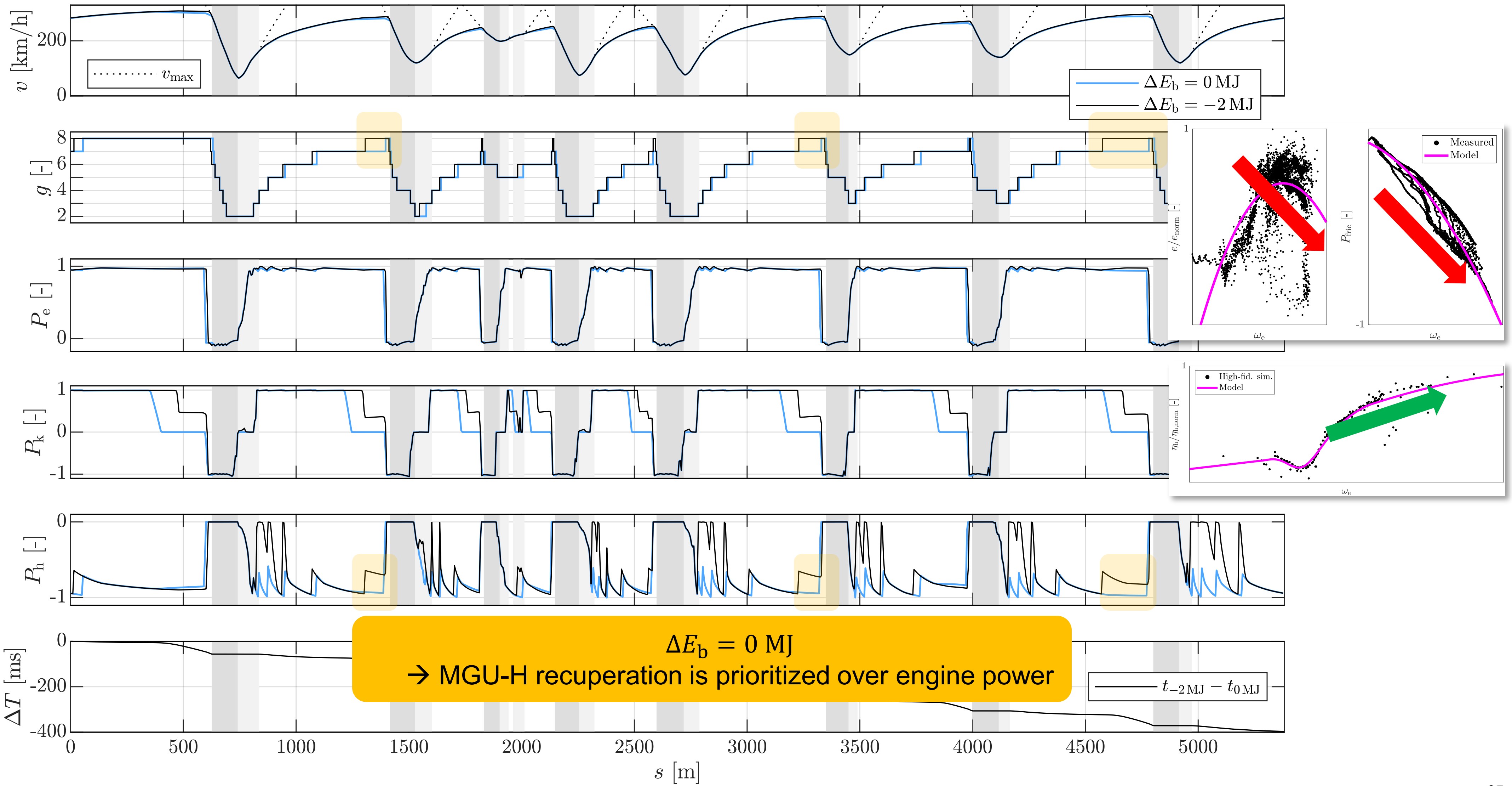
complete discharge

lap time is faster by 0.4 s for discharge case

Optimal trajectories



Optimal trajectories

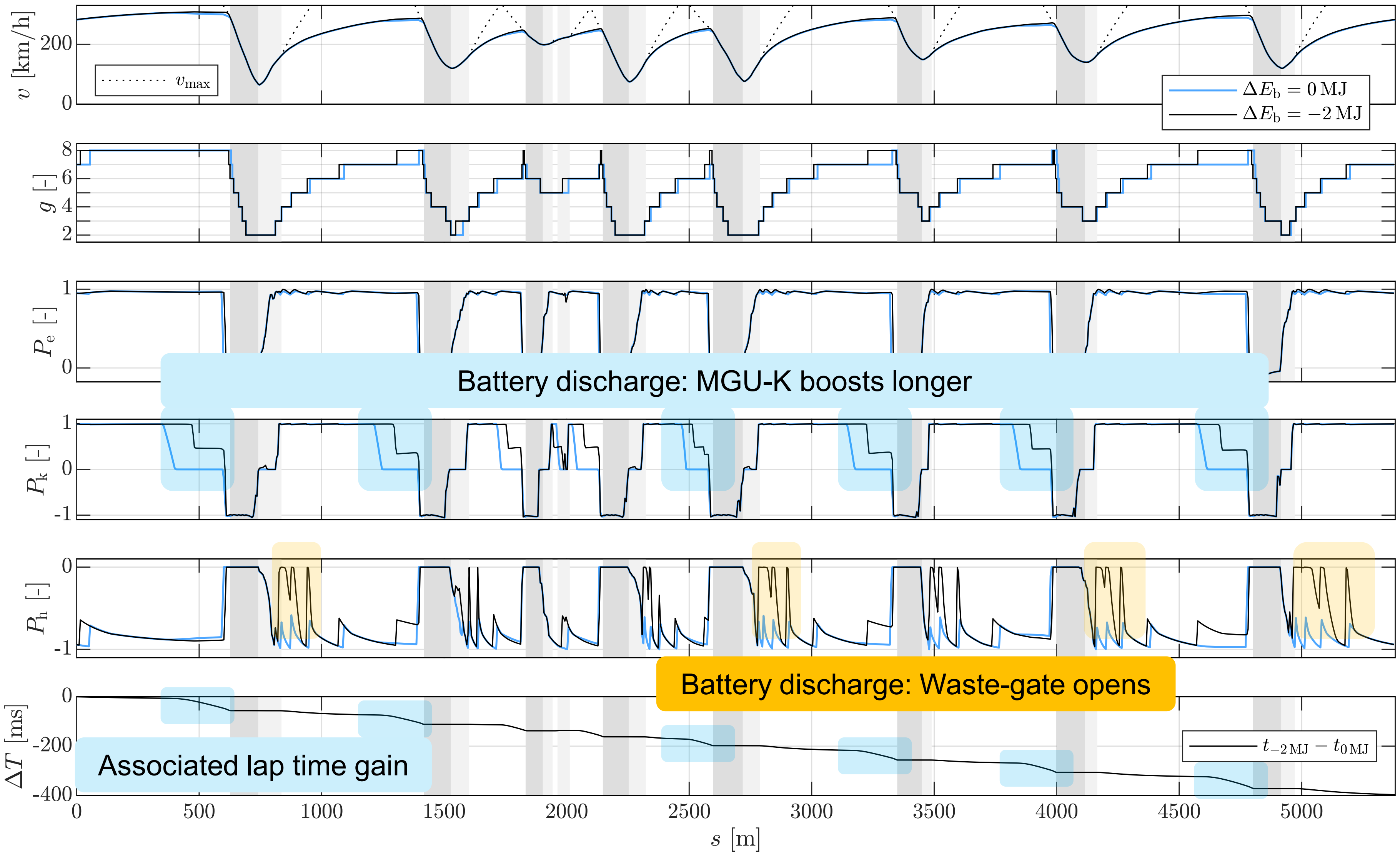


$\Delta E_b = 0$ MJ

→ MGU-H recuperation is prioritized over engine power

ETH zürich

Optimal trajectories

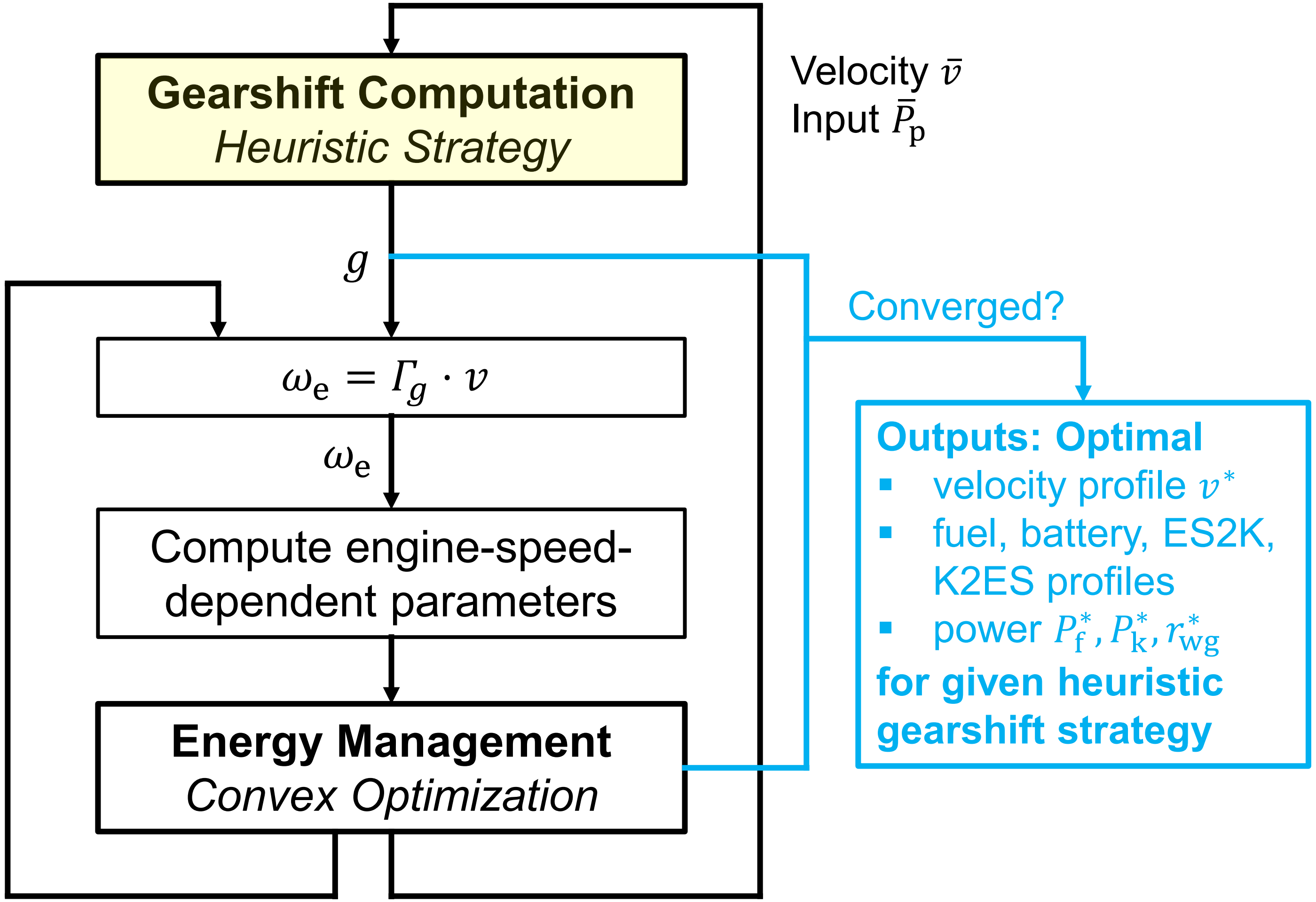


Heuristic gearshift strategy

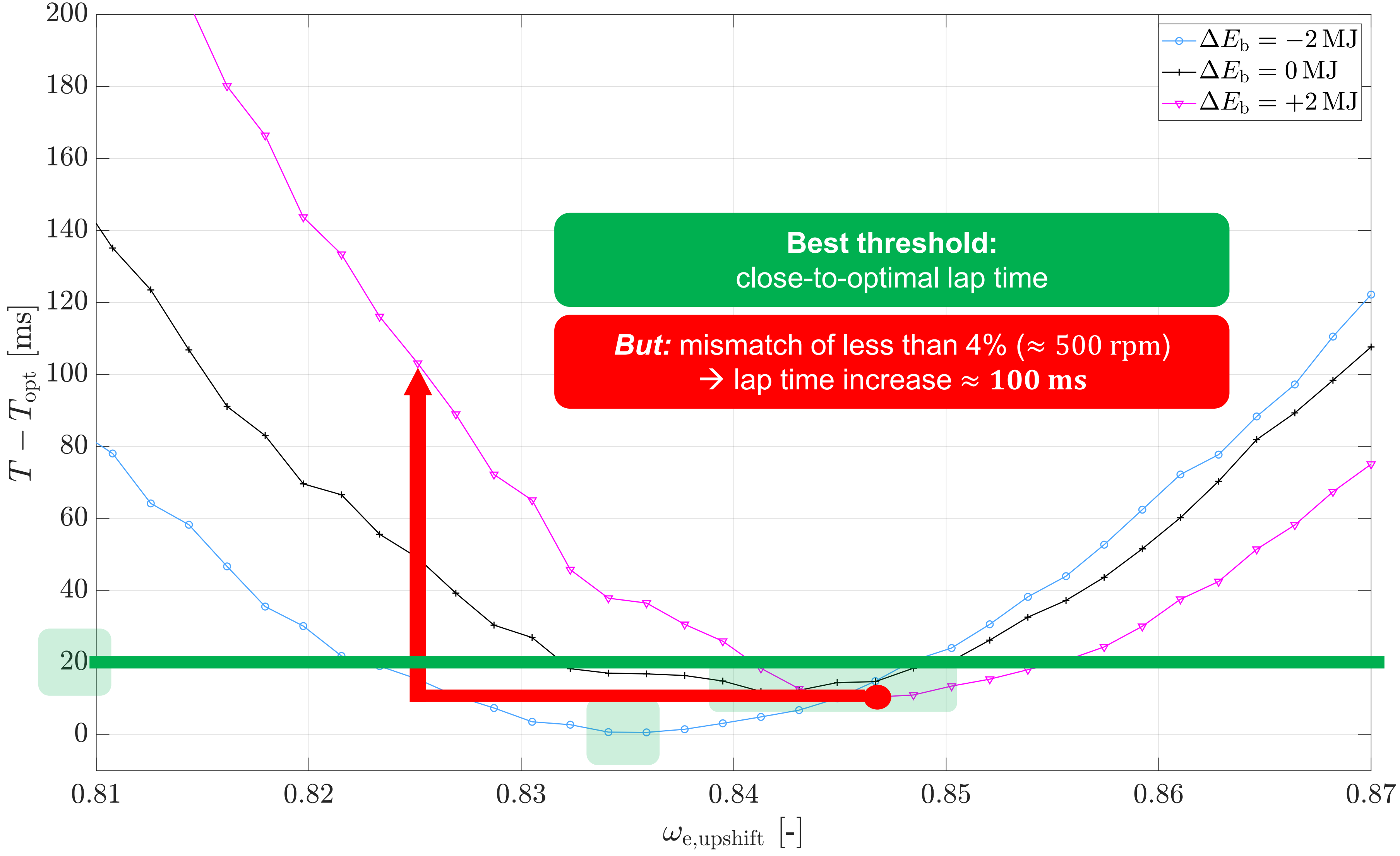
“Real world”: **LEDs** on the steering wheel tell the driver when to upshift

➔ Threshold-based upshift rule

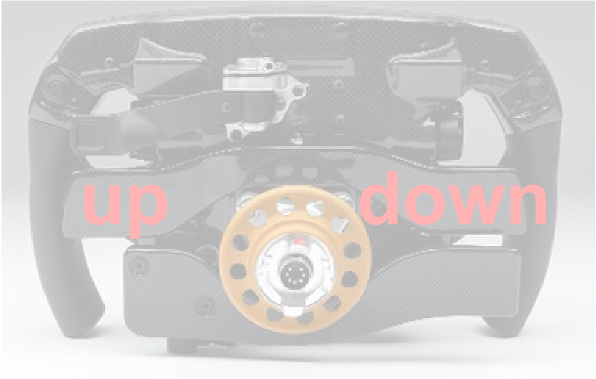
$$\omega_e \geq \omega_{e,\text{upshift}} \rightarrow u_g = +1$$



Sweep in upshift engine speed

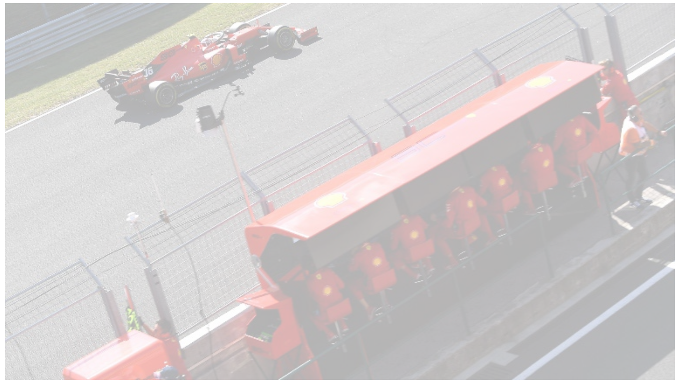


1 Gearshift optimization



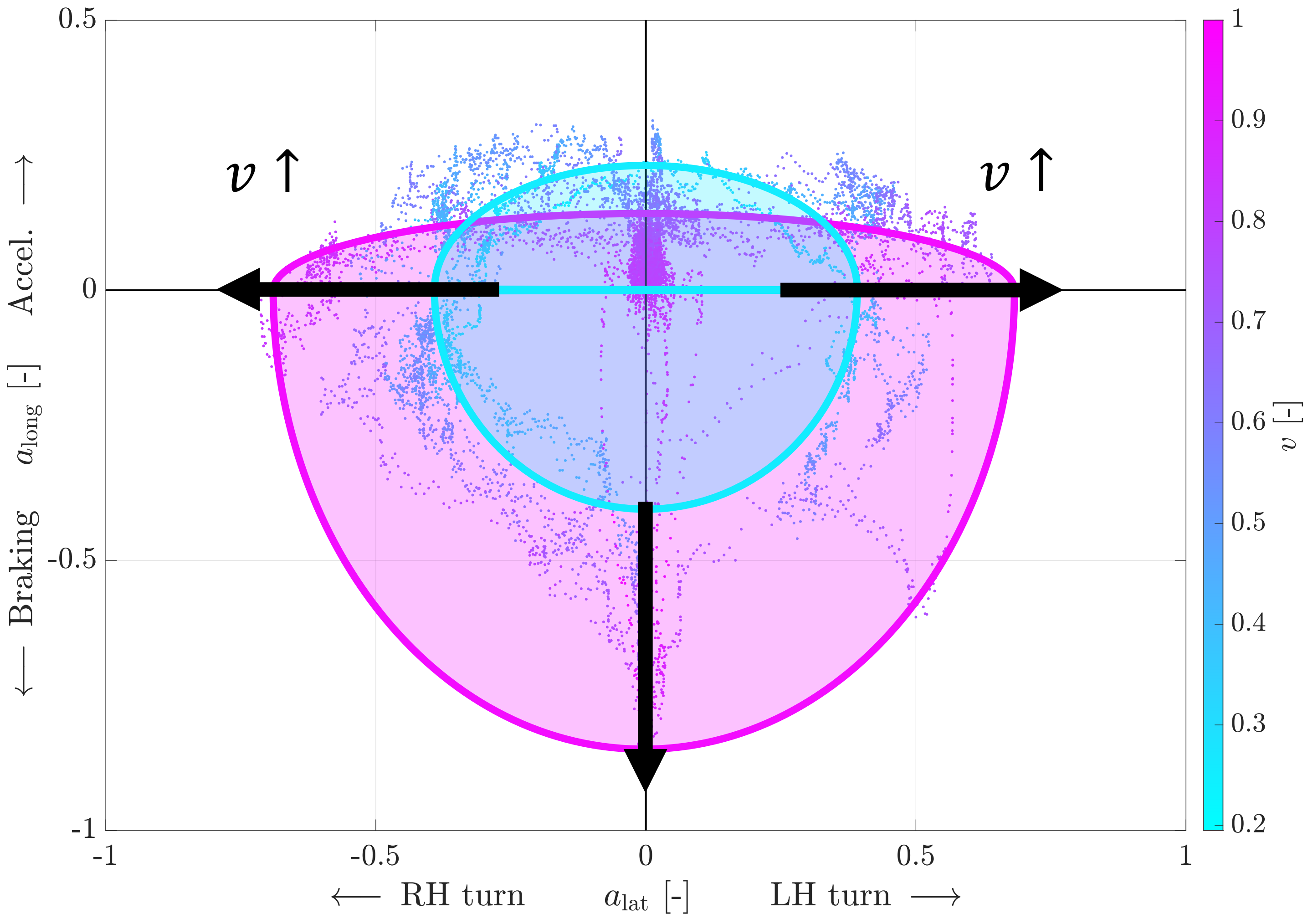
2 **Convex performance envelope**

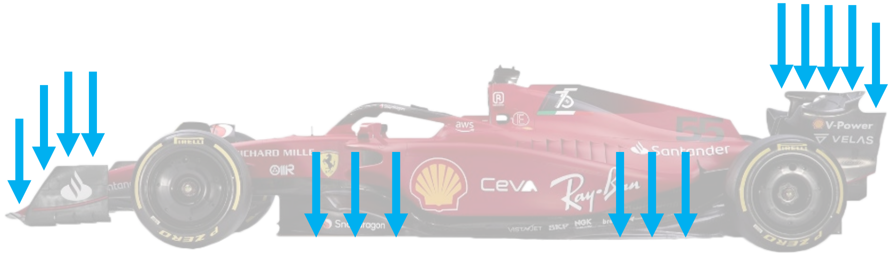
3 Minimum-race-time energy allocation



P. Duhr, A. Sandeep, A. Cerofolini, and C. H. Onder.
Convex performance envelope for minimum lap time energy management of race cars.
IEEE Transactions on Vehicular Technology, 71(8):8280–8295, 2022.

g-g diagram





Aerodynamic downforce
$F_{\text{aero,down}} \propto v^2$

Grip limit = $f(v)$

Boundary of feasible combinations {acceleration, velocity}

=

Performance envelope

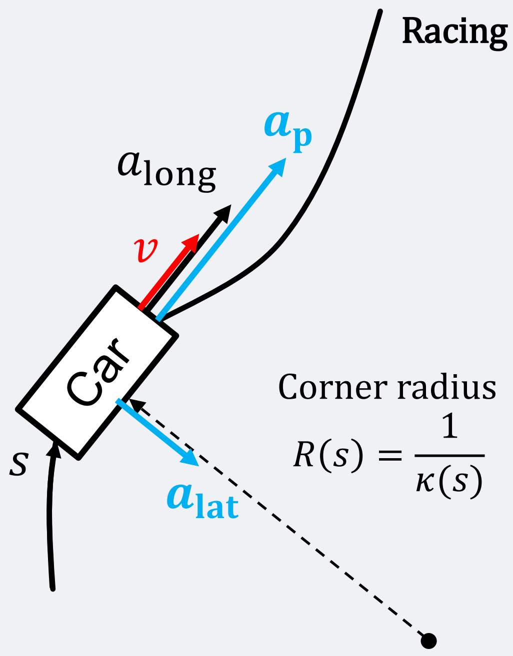
Research question

Given that in minimum-lap-time optimization frameworks

- a model for the car’s grip limit is required
- the simple maximum velocity profile approach has some drawbacks
- convex optimization is computationally very efficient

→ Convex **model for performance envelope**,
using second-order cone constraints?

Vehicle dynamics model



Quasi steady-state approximation

$$v(s) = \frac{\mathrm{d}s}{\mathrm{d}t}(s)$$

$$a_{\mathrm{long}}(s) = \frac{\mathrm{d}v}{\mathrm{d}t}(s)$$

$$\boldsymbol{a}_{\mathrm{lat}}(\boldsymbol{s}) = \frac{\boldsymbol{v}^2}{\boldsymbol{R}(\boldsymbol{s})} = \boldsymbol{v}^2 \cdot \boldsymbol{\kappa}(\boldsymbol{s})$$ $\propto$ total **lateral** tire force

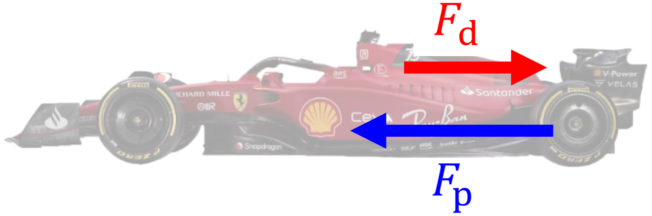
$$\boldsymbol{a}_{\mathrm{p}}(\boldsymbol{s}) = \frac{\mathbf{1}}{\boldsymbol{m}} \cdot \boldsymbol{F}_{\mathrm{p}}$$ $\propto$ total **longitudinal** tire force

Optimization variables

Second-order cone program: **Linear** (in-)equality constraints
Second-order cone constraints

Optimization variable
Normalized kinetic energy

$$\tilde{E}_{\mathrm{kin}}(s) = \frac{1}{2} \cdot v(s)^2$$



Longitudinal dynamics (Newton's law)

$$\frac{\mathrm{d}}{\mathrm{d}s}\tilde{E}_{\mathrm{kin}}(s) = \frac{1}{m} \cdot \left(F_\mathrm{p}(s) - F_\mathrm{d}(s)\right)$$

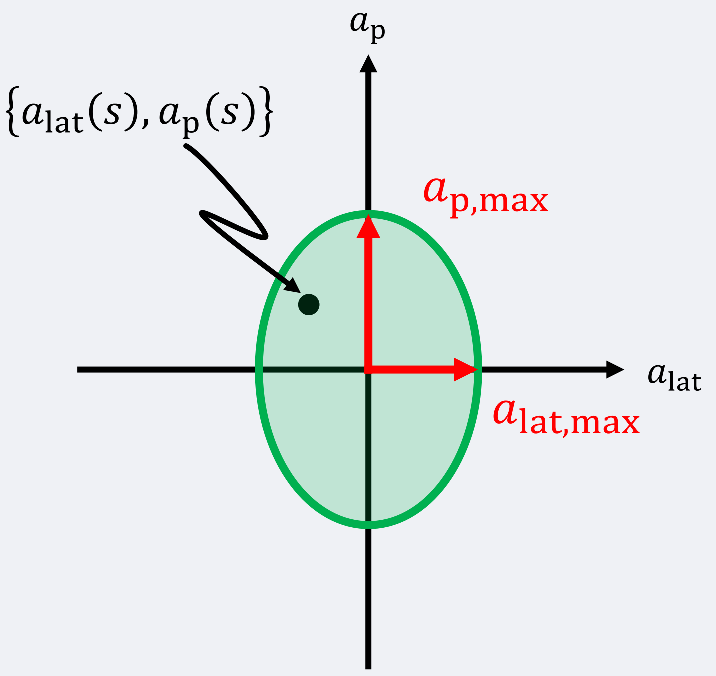
Link between $a_\mathrm{p}, a_\mathrm{lat}$ and longitudinal dynamics:

$$a_\mathrm{p}(s) = \frac{1}{m} \cdot F_\mathrm{p}(s) \longrightarrow \boldsymbol{a_\mathrm{p}(s) = \frac{1}{m} \cdot F_\mathrm{p}(s)}$$

$$a_\mathrm{lat}(s) = v^2 \cdot \kappa(s) \longrightarrow \boldsymbol{a_\mathrm{lat}(s) = 2 \cdot \tilde{E}_{\mathrm{kin}}(s) \cdot \kappa(s)}$$

Linear equality constraints

Performance envelope model



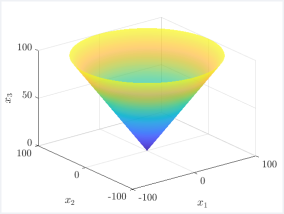
Ellipse equation:

$$\frac{a_{\mathrm{p}}^2(s)}{a_{\mathrm{p,max}}^2} + \frac{a_{\mathrm{lat}}^2(s)}{a_{\mathrm{lat,max}}^2} \leq 1 \qquad | \cdot a_{\mathrm{p,max}}^2$$

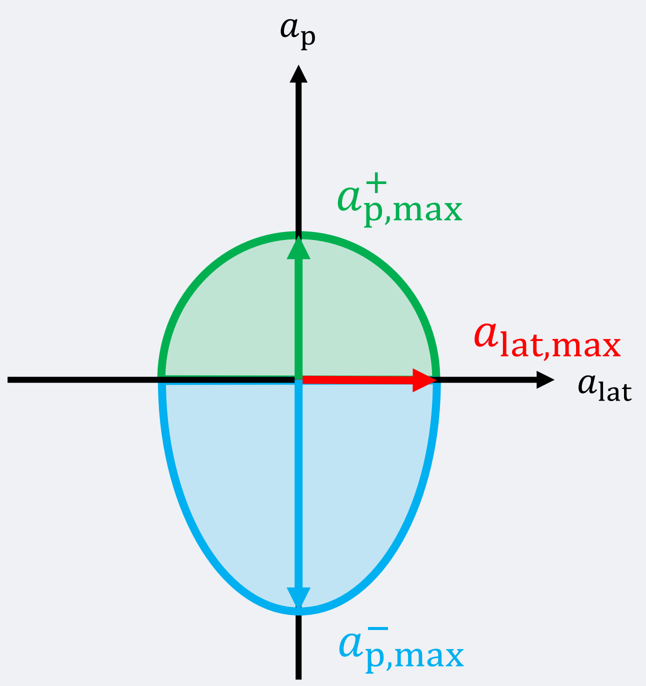
$$\Leftrightarrow \quad a_{\mathrm{p}}^2(s) + \left(\frac{a_{\mathrm{p,max}}}{a_{\mathrm{lat,max}}} \cdot a_{\mathrm{lat}}(s)\right)^2 \leq a_{\mathrm{p,max}}^2$$

$$\Leftrightarrow \quad \left\| \begin{matrix} a_p(s) \\ \frac{a_{\mathrm{p,max}}}{a_{\mathrm{lat,max}}} \cdot a_{\mathrm{lat}}(s) \end{matrix} \right\|_2 \leq a_{\mathrm{p,max}}$$

Second-order cone constraint



Performance envelope model



Vehicles behave differently under acceleration vs. deceleration

→ Two **half ellipses**
→ One for $a_\mathrm{p} \geq 0$, one for $a_\mathrm{p} \leq 0$

$$a_\mathrm{p}(s) = a^+_\mathrm{p}(s) + a^-_\mathrm{p}(s)$$

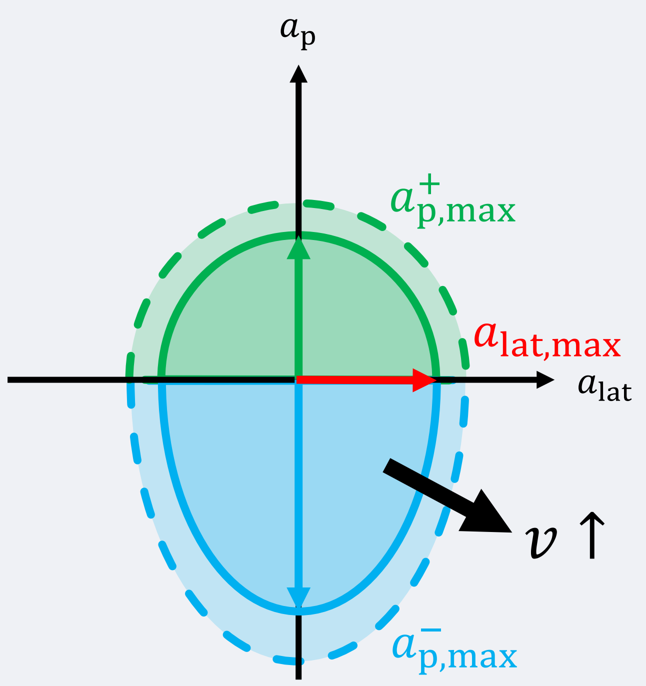
$$\boldsymbol{a^+_\mathrm{p}(s) \geq 0}$$

$$\boldsymbol{a^-_\mathrm{p}(s) \leq 0}$$

$$\left\| \begin{matrix} \boldsymbol{a^+_\mathrm{p}(s)} \\ \frac{a^+_\mathrm{p,max}}{a_\mathrm{lat,max}} \cdot a_\mathrm{lat}(s) \end{matrix} \right\|_2 \leq a^+_\mathrm{p,max}$$

$$\left\| \begin{matrix} \boldsymbol{a^-_\mathrm{p}(s)} \\ \frac{a^-_\mathrm{p,max}}{a_\mathrm{lat,max}} \cdot a_\mathrm{lat}(s) \end{matrix} \right\|_2 \leq a^-_\mathrm{p,max}$$

Performance envelope model



Velocity dependency:

$$a_{\mathrm{lat,max}}(s) = c_1 \cdot v^2(s) + c_2 \cdot v(s) + c_3$$

$$\Rightarrow a_{\mathrm{lat,max}}(s) = 2\, c_1 \cdot \tilde{E}_{\mathrm{kin}}(s) + c_2 \cdot v(s) + c_3$$

For convexity:

$$a^+_{\mathrm{p,max}}(s) = r^+ \cdot a_{\mathrm{lat,max}}(s)$$

$$a^-_{\mathrm{p,max}}(s) = r^- \cdot a_{\mathrm{lat,max}}(s)$$

Linear constraints

$$a_{\mathrm{p}}(s) = a^+_{\mathrm{p}}(s) + a^-_{\mathrm{p}}(s)$$

$$a^+_{\mathrm{p}}(s) \geq 0$$

$$a^-_{\mathrm{p}}(s) \leq 0$$

Second-order cone constraints

$$\left\| \begin{matrix} a^+_{\mathrm{p}}(s) \\ \boldsymbol{r}^+ \cdot a_{\mathrm{lat}}(s) \end{matrix} \right\|_2 \leq \boldsymbol{r}^+ \cdot (\boldsymbol{2}\, \boldsymbol{c}_1 \cdot \tilde{\boldsymbol{E}}_{\mathbf{kin}}(\boldsymbol{s}) + \boldsymbol{c}_2 \cdot \boldsymbol{v}(\boldsymbol{s}) + \boldsymbol{c}_3)$$

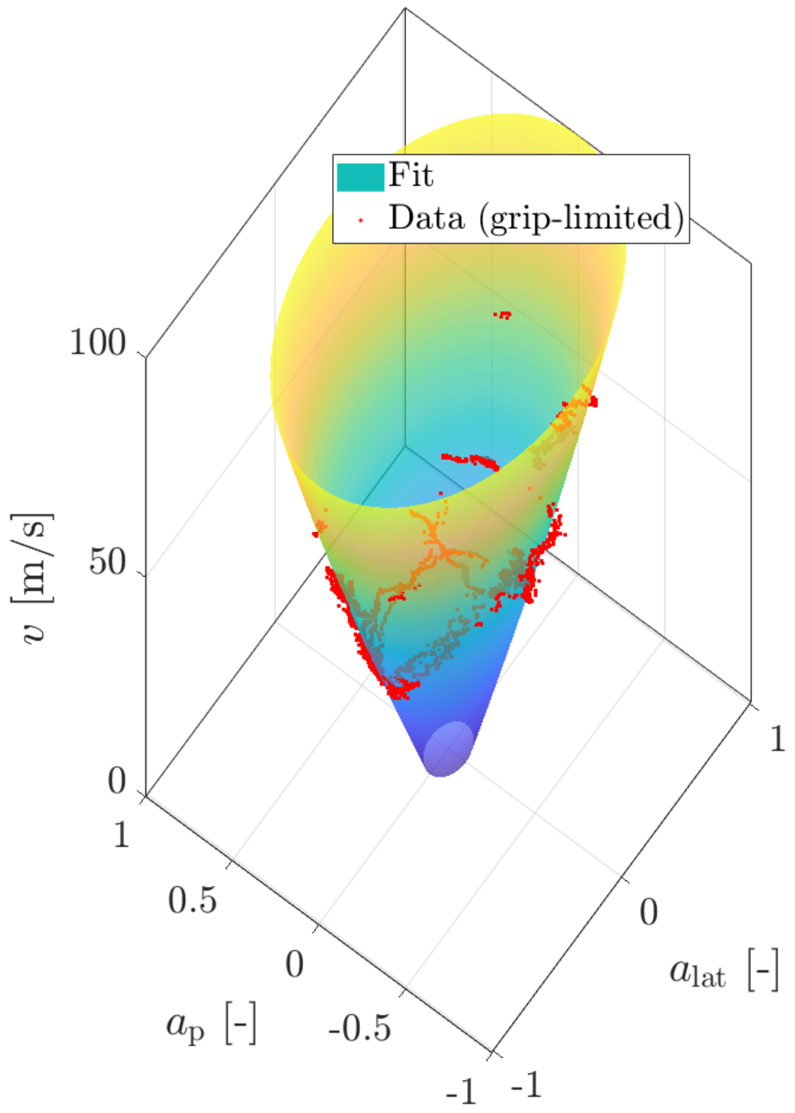
$$\left\| \begin{matrix} a^-_{\mathrm{p}}(s) \\ \boldsymbol{r}^- \cdot a_{\mathrm{lat}}(s) \end{matrix} \right\|_2 \leq \boldsymbol{r}^- \cdot (\boldsymbol{2}\, \boldsymbol{c}_1 \cdot \tilde{\boldsymbol{E}}_{\mathbf{kin}}(\boldsymbol{s}) + \boldsymbol{c}_2 \cdot \boldsymbol{v}(\boldsymbol{s}) + \boldsymbol{c}_3)$$

Performance envelope fit

Model parameters
c_1, c_2, c_3, r^+, r^-

Parameter identification

with grip-limited measurement data



"Curved" conic shape

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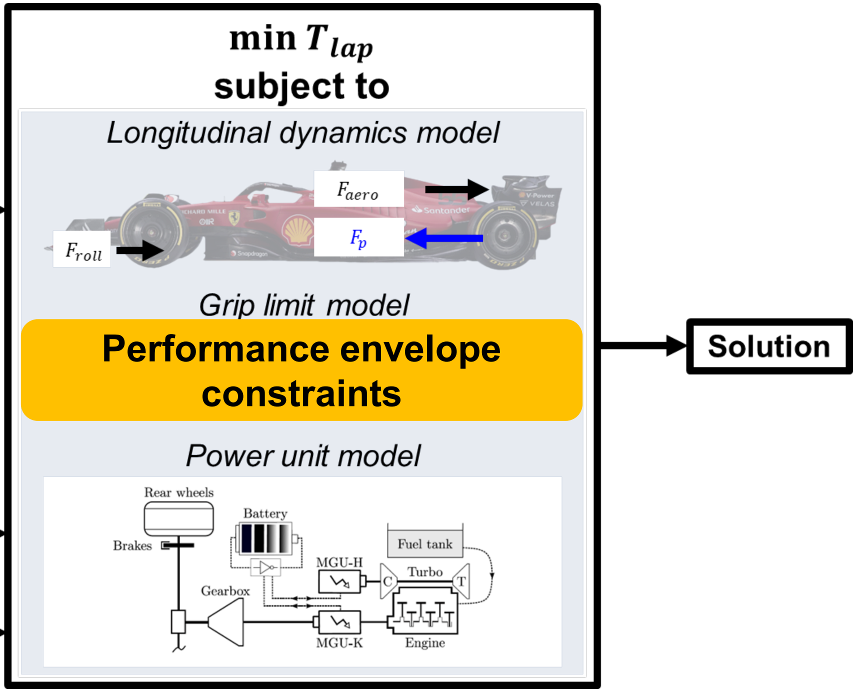
Optimization results

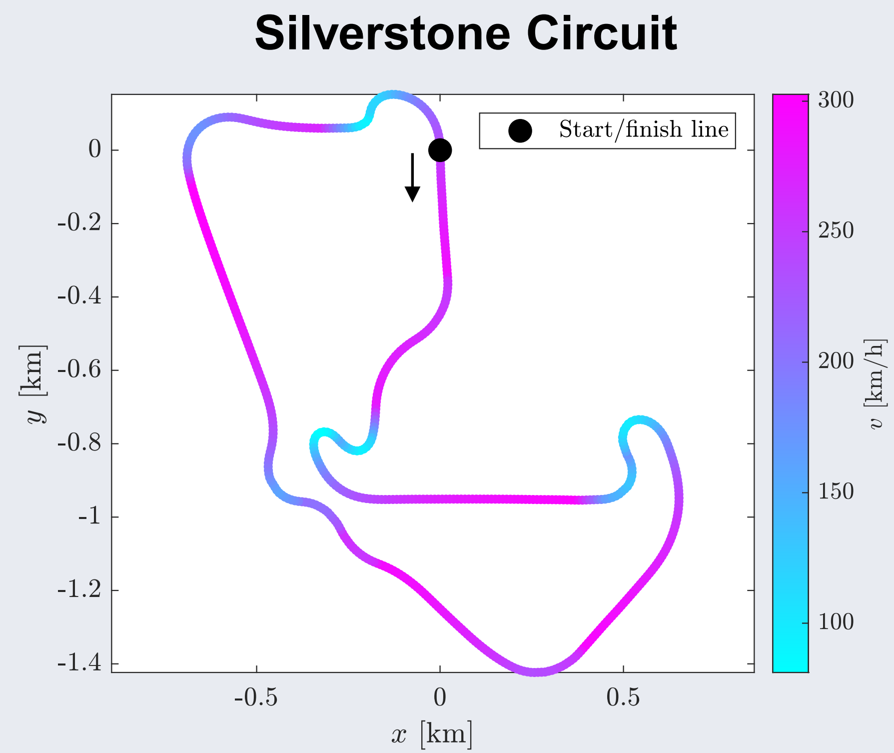
Racing line:
Path variable s
Curvature $\kappa(s)$

Energy allocation:
Fuel ΔE_{f}

Battery ΔE_{b}

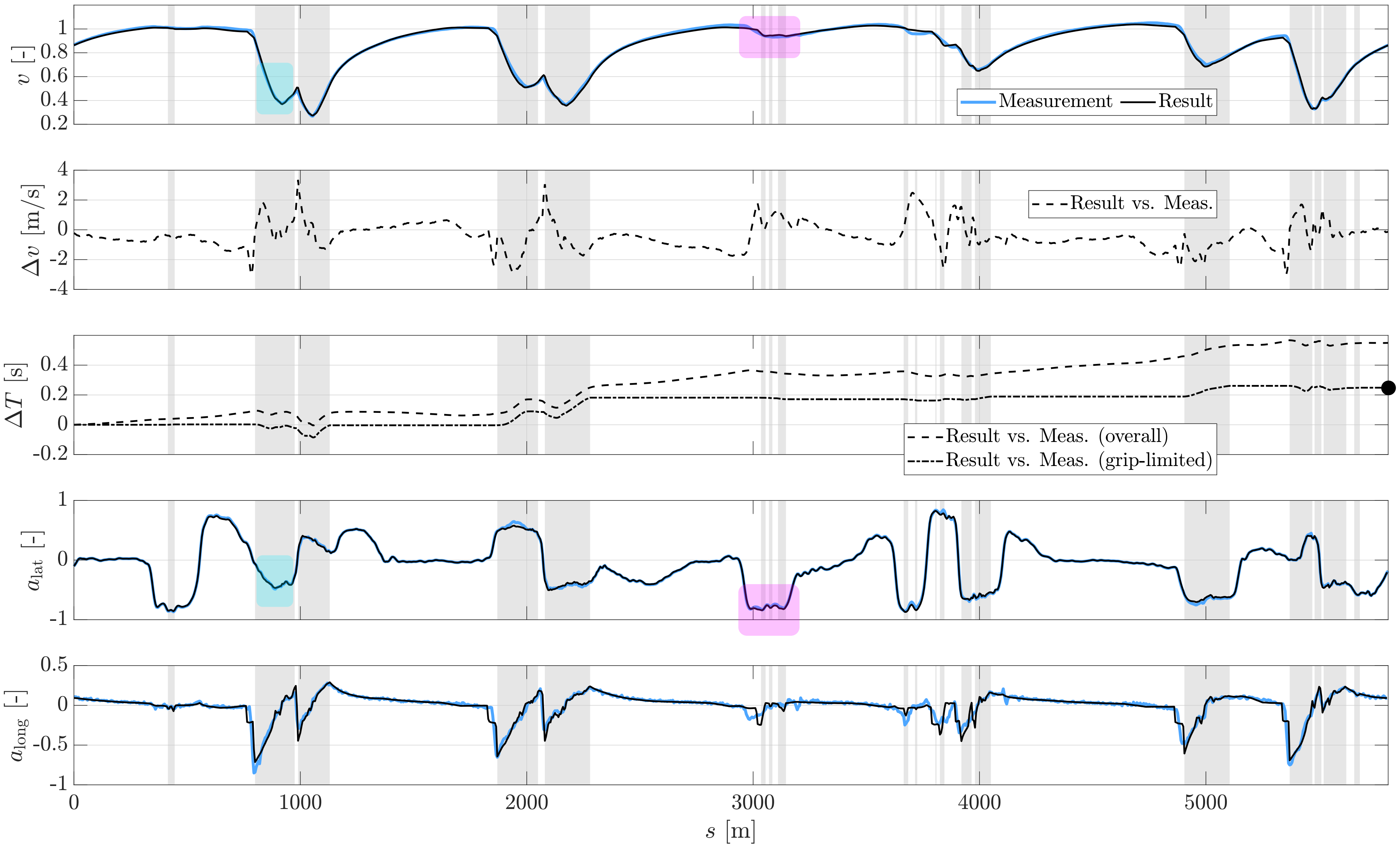


Second-order cone program



Computational time: 1 second

Optimization result vs. measurement



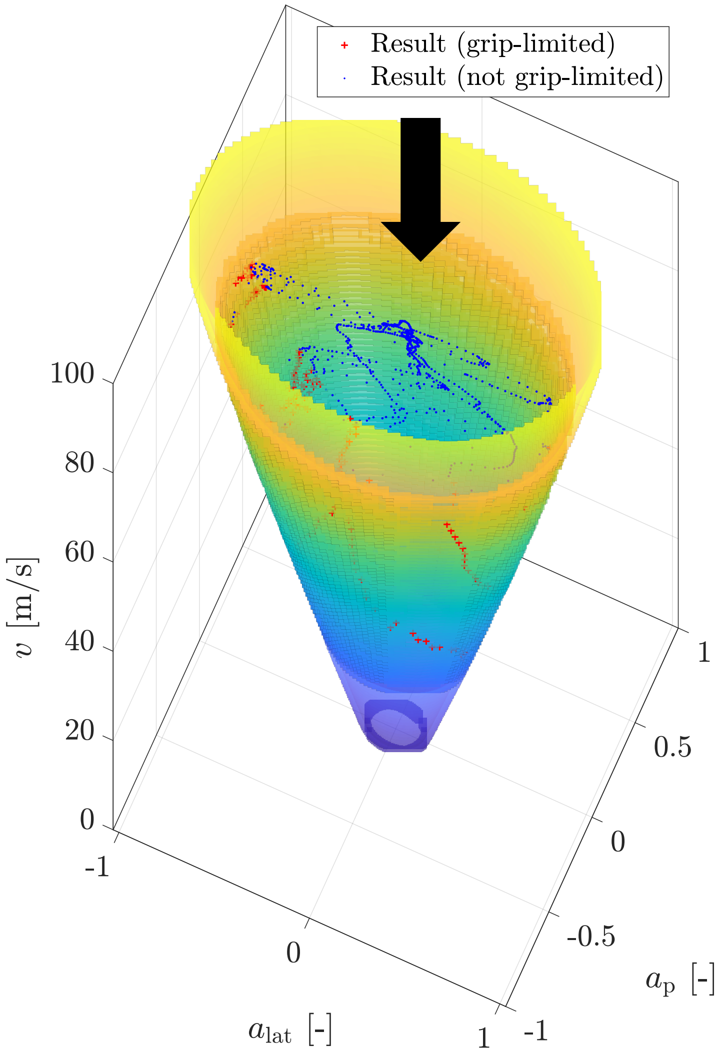
Accurate enough for energy management optimization

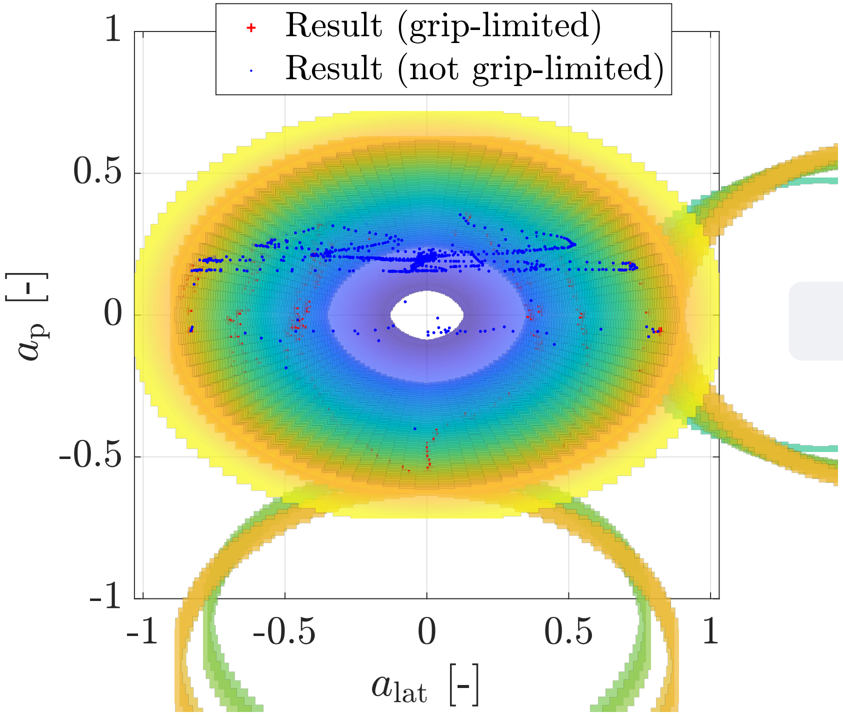
Difference in velocity
max. $\pm 3\ \mathrm{m/s}$

Difference while grip-limited:
$250\ \mathrm{ms} \approx 0.3\ \%$

Acceleration is precise in slow and fast corners
→ accurate velocity dependency

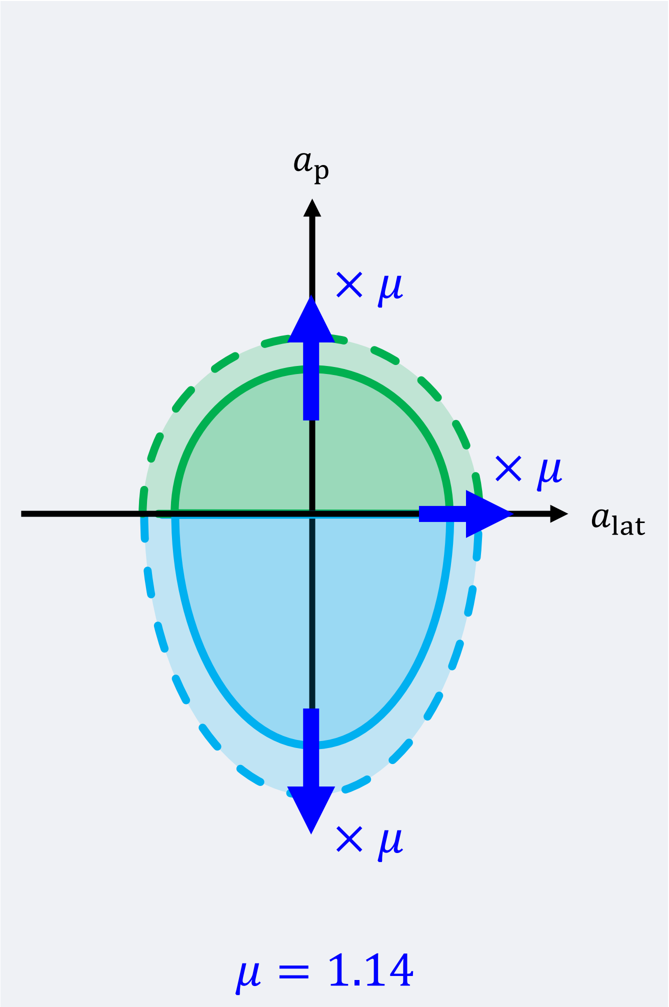
Performance envelope 3D

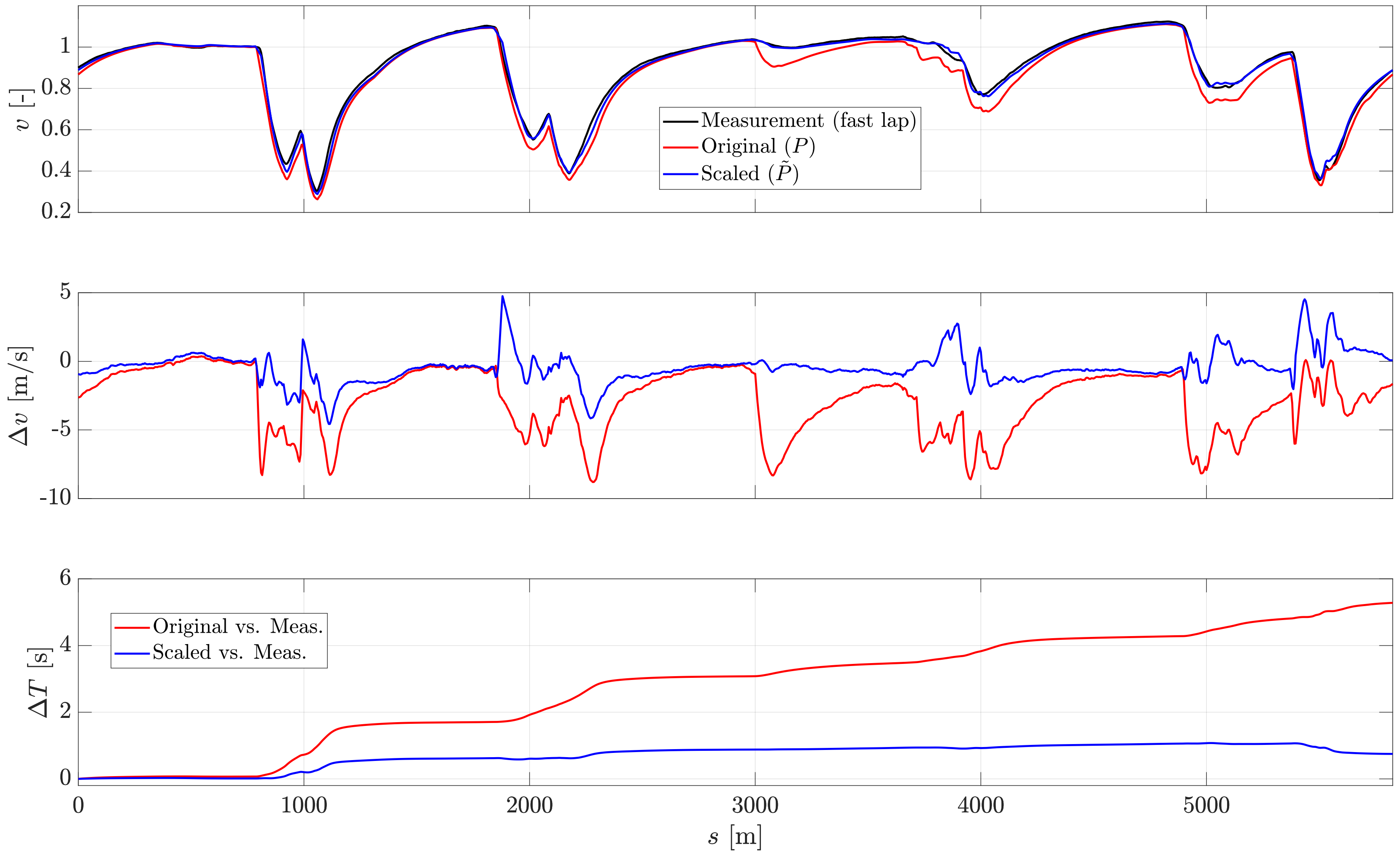




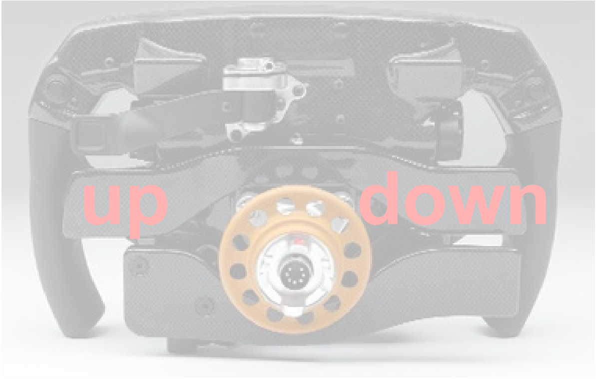
g-g diagram

Scaling the performance envelope



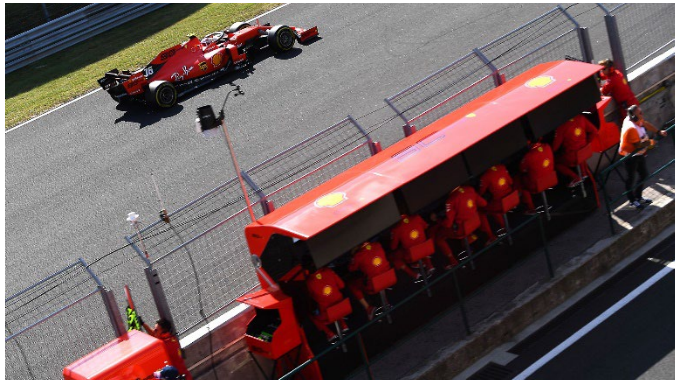


1 Gearshift optimization



2 Convex performance envelope

3 Minimum-race-time energy allocation



P. Duhr, D. Buccheri, C. Balerna, A. Cerofolini, and C. H. Onder.
Minimum-race-time energy allocation strategies for the hybrid-electric Formula 1 power unit.
IEEE Transactions on Vehicular Technology, 2023.

Race energy allocation

Team's objective
Finish race before competitors

Engineering objective
Complete **race** in **minimum time**

During the race

In each lap

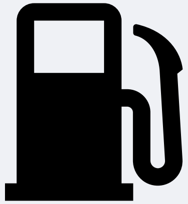
Charge or discharge battery

Set battery target

Use more or less fuel

Power split
Burn fuel while braking
Fuel saving: early lift-off

Before the race



How much fuel to put in the tank?

Trade-off!
More fuel
→ more energy for PU
but
→ heavier car

Research questions

Assuming that

- the objective is to minimize race time
- within each lap, the allocated energy is used optimally

→ Optimal fuel and battery **energy allocation for each lap**?

→ Optimal **fuel load** at the start of the race?

Race optimization framework

Racing line:
Path variable s
Curvature $\kappa(s)$

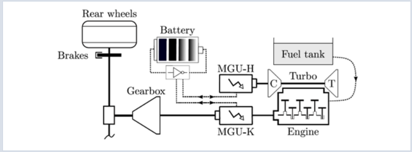
$\min T_{lap}$
subject to

Longitudinal dynamics model

Grip limit model

Performance envelope

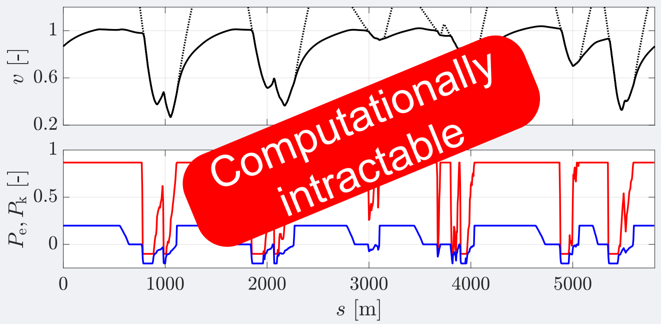
Power unit model



Solution

Energy allocation:
Fuel ΔE_f
Battery ΔE_b

$$\min T_\mathrm{race} = \min \int_0^{T_\mathrm{race}} \mathrm{d}t$$



Race solver

Lap solver

$$\min T_\mathrm{lap}$$

Data

Lap time map

$$T_\mathrm{lap} \approx \mathcal{M}(\Delta E_\mathrm{f}, \Delta E_\mathrm{b})$$

$\mathcal{M}$

Lap-by-lap discretization

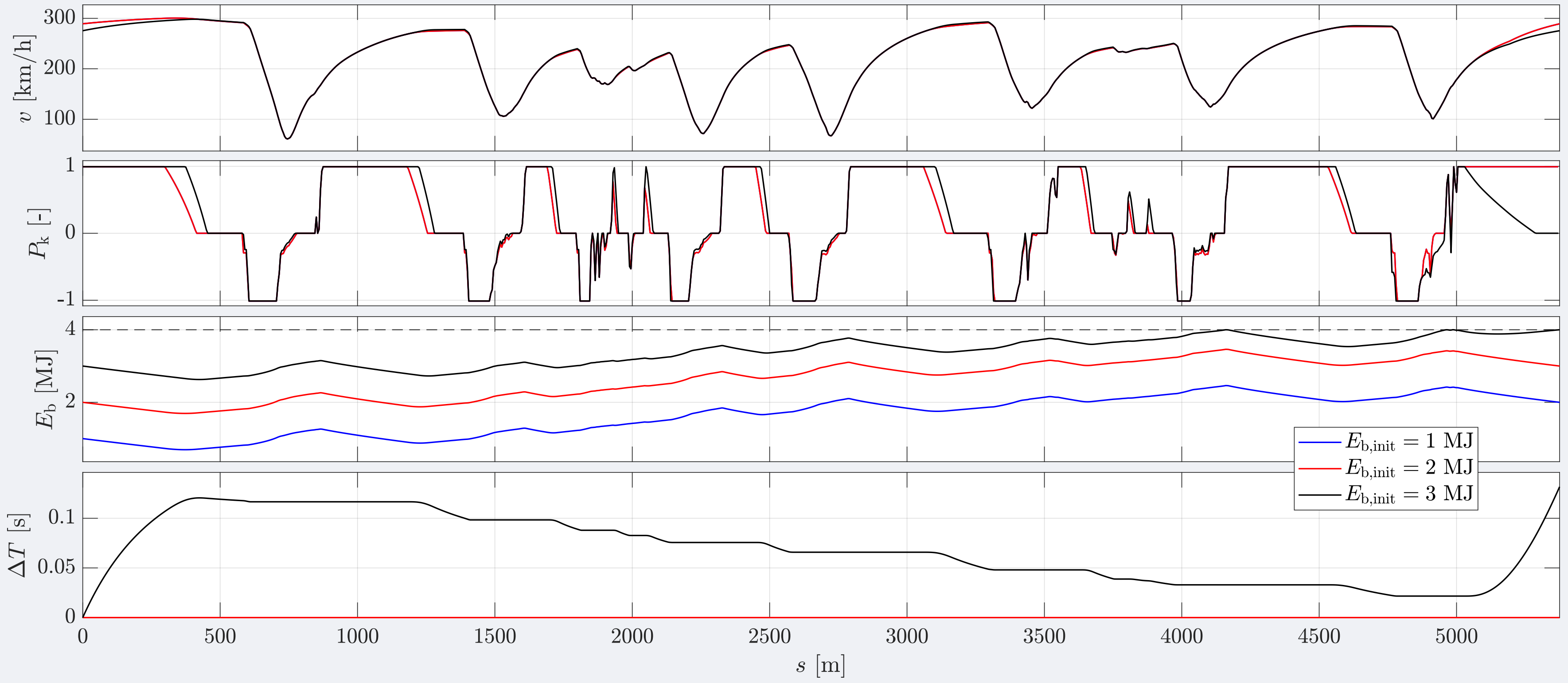
$$\min \sum_{i=1}^{N_\mathrm{laps}} T_\mathrm{lap}[i] \approx \min \sum_{i=1}^{N_\mathrm{laps}} \mathcal{M}(\Delta E_\mathrm{f}[i], \Delta E_\mathrm{b}[i])$$

Optimal $\Delta E_\mathrm{f}[i], \Delta E_\mathrm{b}[i]$
for each lap $i \in \{1, \ldots, N_\mathrm{laps}\}$

Lap time map

$$T_{\text{lap}} \approx \mathcal{M}(\Delta E_{\text{f}}, \Delta E_{\text{b}}, ?)$$

- Fuel consumed during lap ΔE_{f}
- Battery charge/discharge during lap ΔE_{b}
- Mass of the car m ⟶ modeled by scaling the **performance envelope**
- Battery energy at the start of the lap $E_{\text{b,init}}$ ⟶ only influences lap time when close to bounds



blue = red

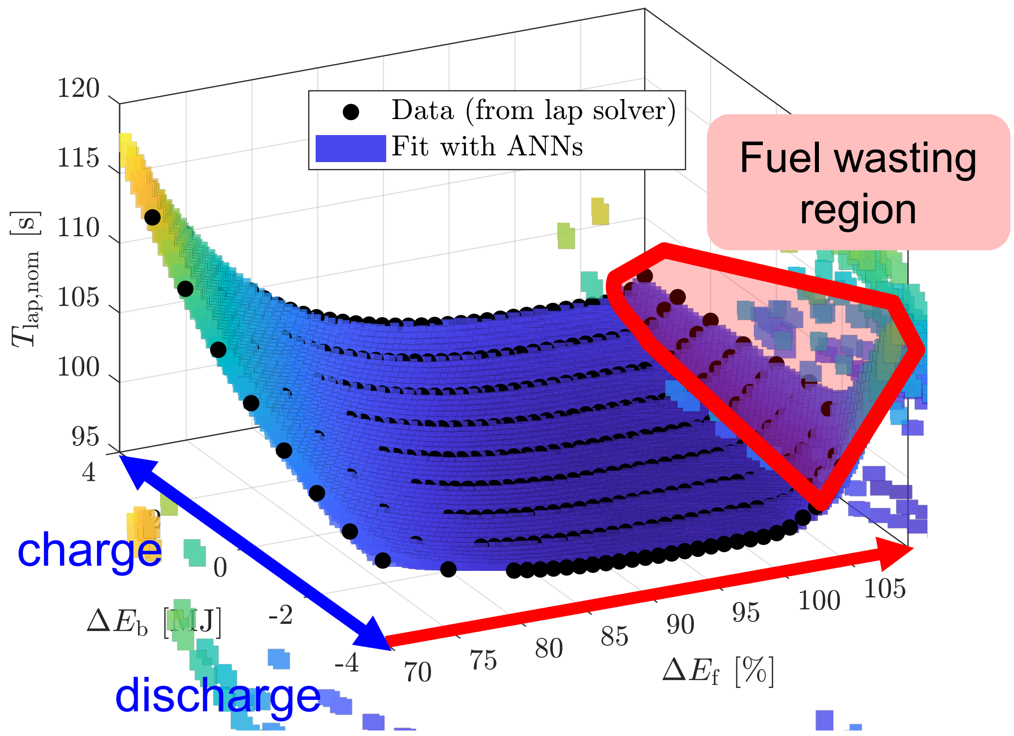
$E_{\text{b,init}} = 3$ MJ **slower** because of battery bounds

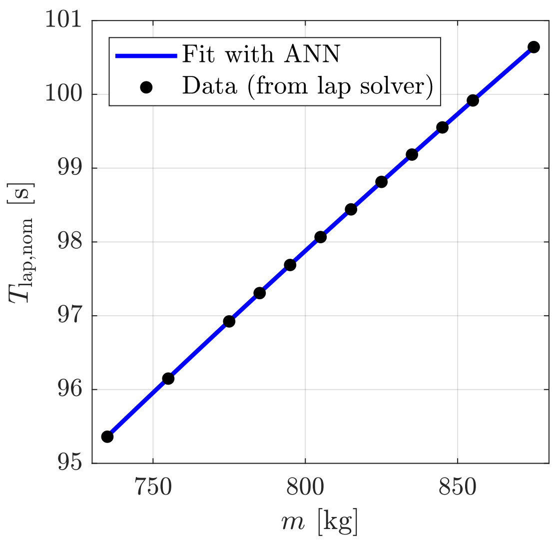
Lap time map

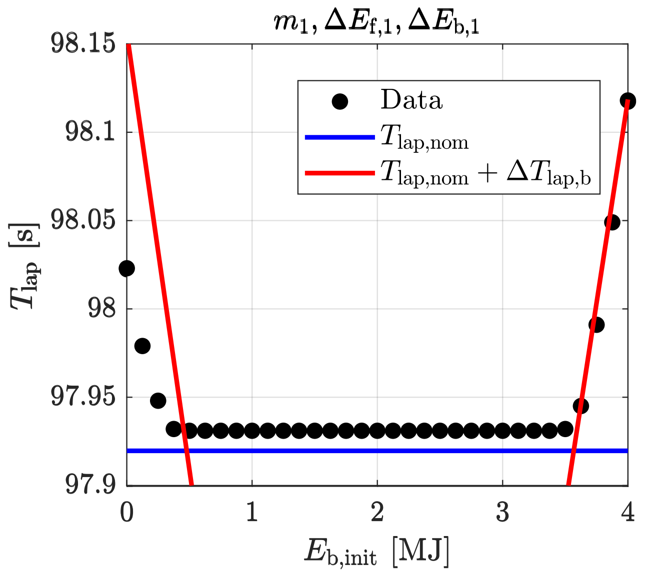
$$T_{\mathrm{lap}} \approx \mathcal{M}(\Delta E_{\mathrm{f}}, \Delta E_{\mathrm{b}}, E_{\mathrm{b,init}}, m) = T_{\mathrm{lap,nom}}(\Delta E_{\mathrm{b}}, \Delta E_{\mathrm{f}}, m) \quad + \quad \Delta T_{\mathrm{lap,b}}(E_{\mathrm{b,init}}, \Delta E_{\mathrm{b}})$$

Nominal lap time
Fitted with
artificial neural networks

Correction term
Obtained from a
support vector machine







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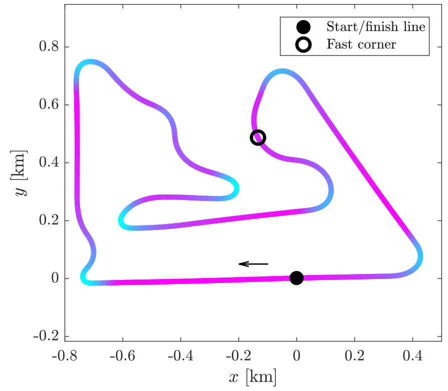
Optimization problem

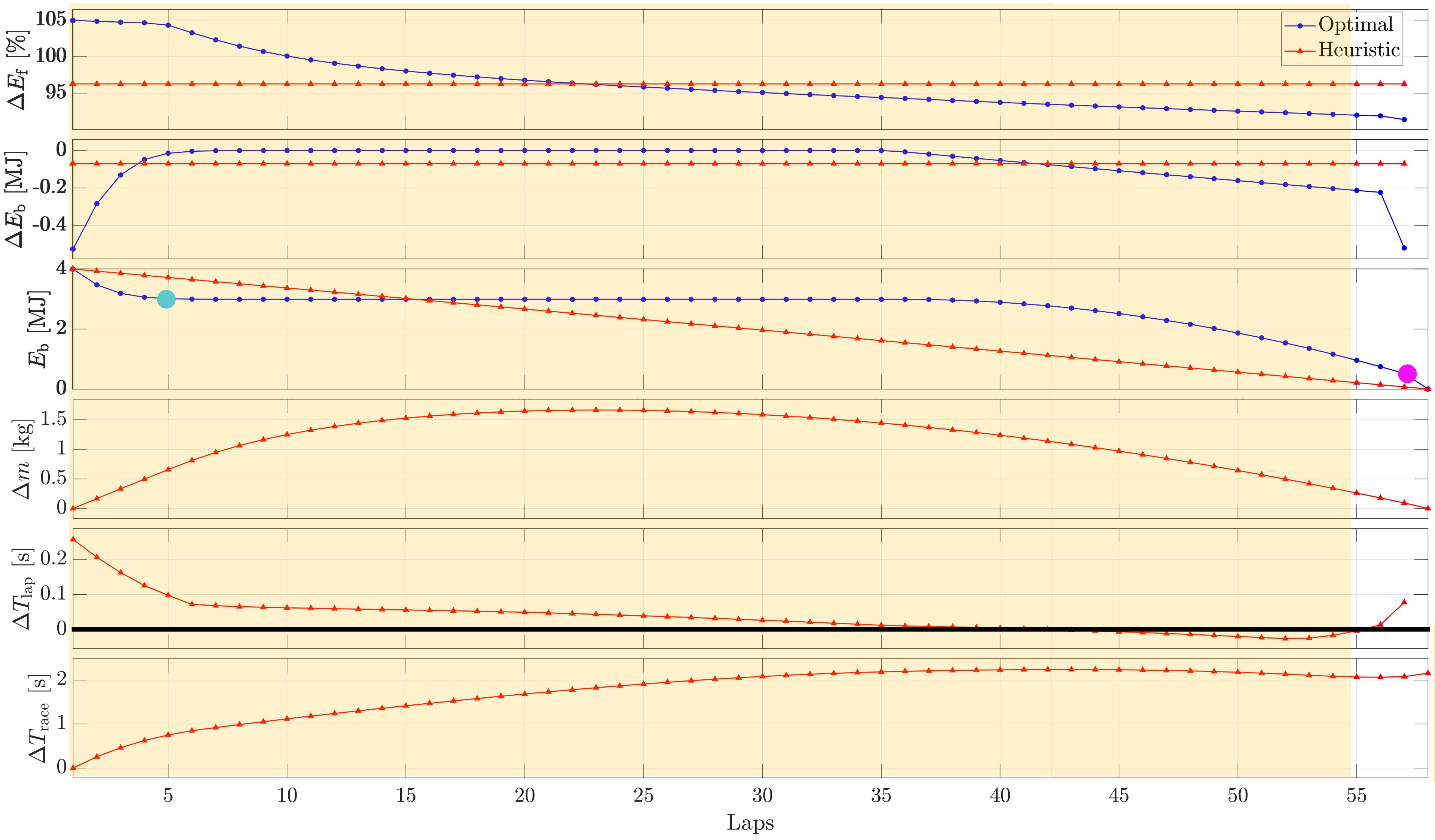
Objective	$\min \sum_{i=1}^{N_{\text{laps}}} T_{\text{lap}}[i]$	**Car mass**	$m[i] = m_{\text{car}} + \boldsymbol{m}_{\mathbf{f}} - \frac{E_{\text{f}}[i]}{H_{\text{lhv}}}$
Inputs	$\Delta E_{\text{f}}[i], \Delta E_{\text{b}}[i], T_{\text{lap}}[i]$ $\Delta E_{\text{f}}[i] \geq 0$ $T_{\text{lap}}[i] \geq \mathcal{M}(\Delta E_{\text{f}}[i], \Delta E_{\text{b}}[i], m[i], E_{\text{b}}[i])$	**Battery constraints**	$E_{\text{b}}[1] = 4\ \text{MJ}$ $E_{\text{b}}\left[N_{\text{laps}} + 1\right] \geq 0\ \text{MJ}$ $E_{\text{b}}[i] \geq 0\ \text{MJ}, E_{\text{b}}[i] \leq 4\ \text{MJ}$
State dynamics	$E_{\text{f}}[i+1] = E_{\text{f}}[i] + \Delta E_{\text{f}}[i]$ $E_{\text{b}}[i+1] = E_{\text{b}}[i] + \Delta E_{\text{b}}[i]$	**Fuel constraints**	$E_{\text{f}}[1] = 0$ $E_{\text{f}}\left[N_{\text{laps}} + 1\right] \leq \boldsymbol{m}_{\mathbf{f}} \cdot H_{\text{lhv}}$

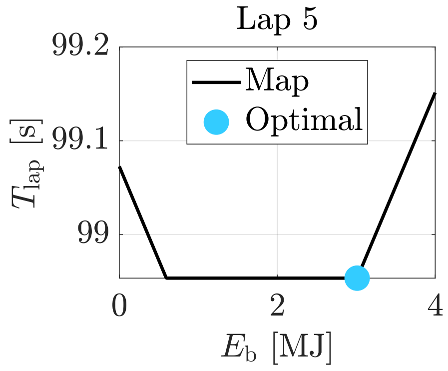
- Parameter: fuel load $\boldsymbol{m}_{\mathbf{f}}$
- Lap time: relaxed to inequality
- Linear equations except for lap time maps (neural networks)

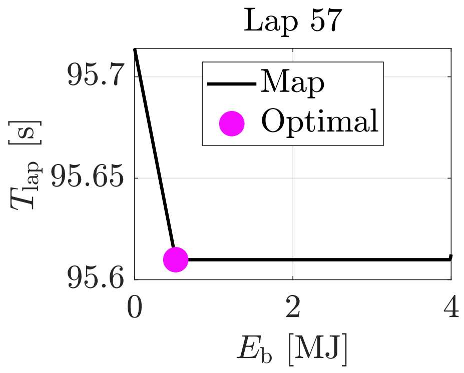
→ **Non-linear program, solved in 1 second**



Optimal solution vs. simple heuristic



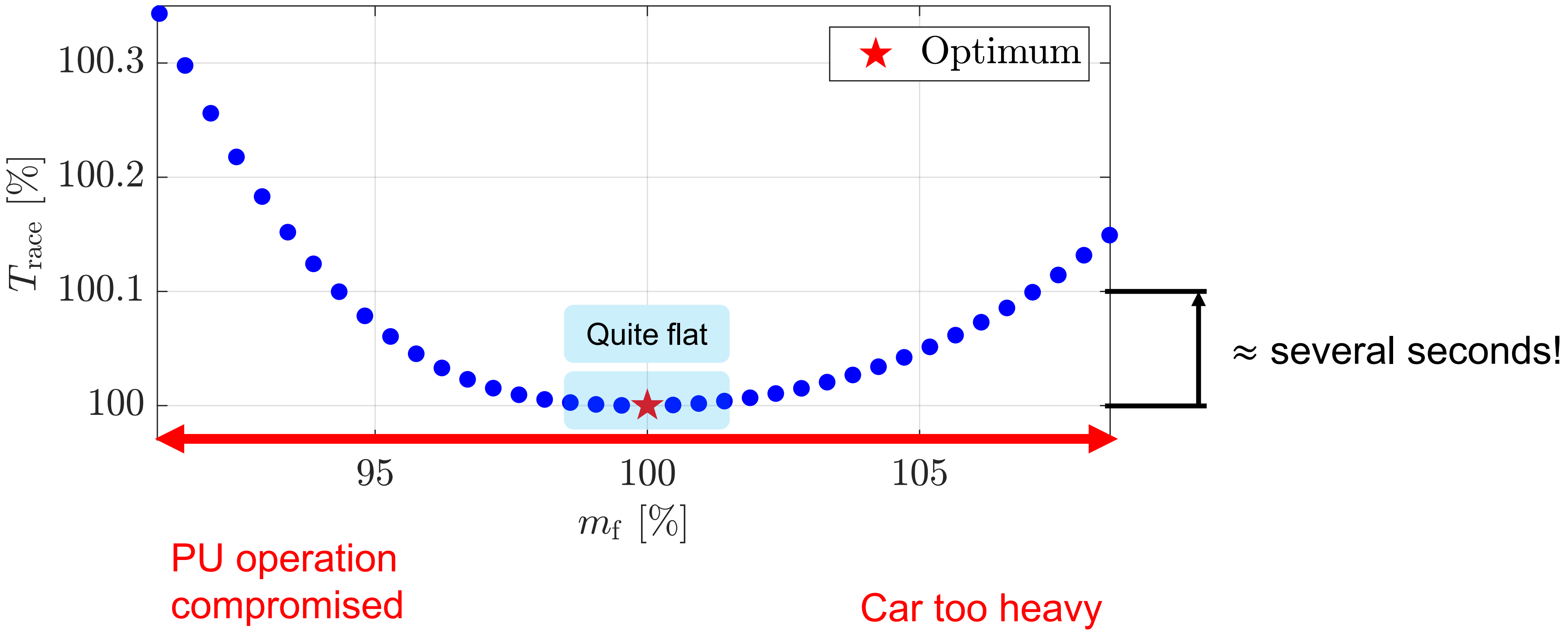




2 seconds difference in race time

Same consumption, only different allocation!

Optimal race fuel load



Summary

1) Energy management has an impact on optimal gearshift strategy

2) Performance envelope is a three-dimensional tube and can be represented by convex constraints

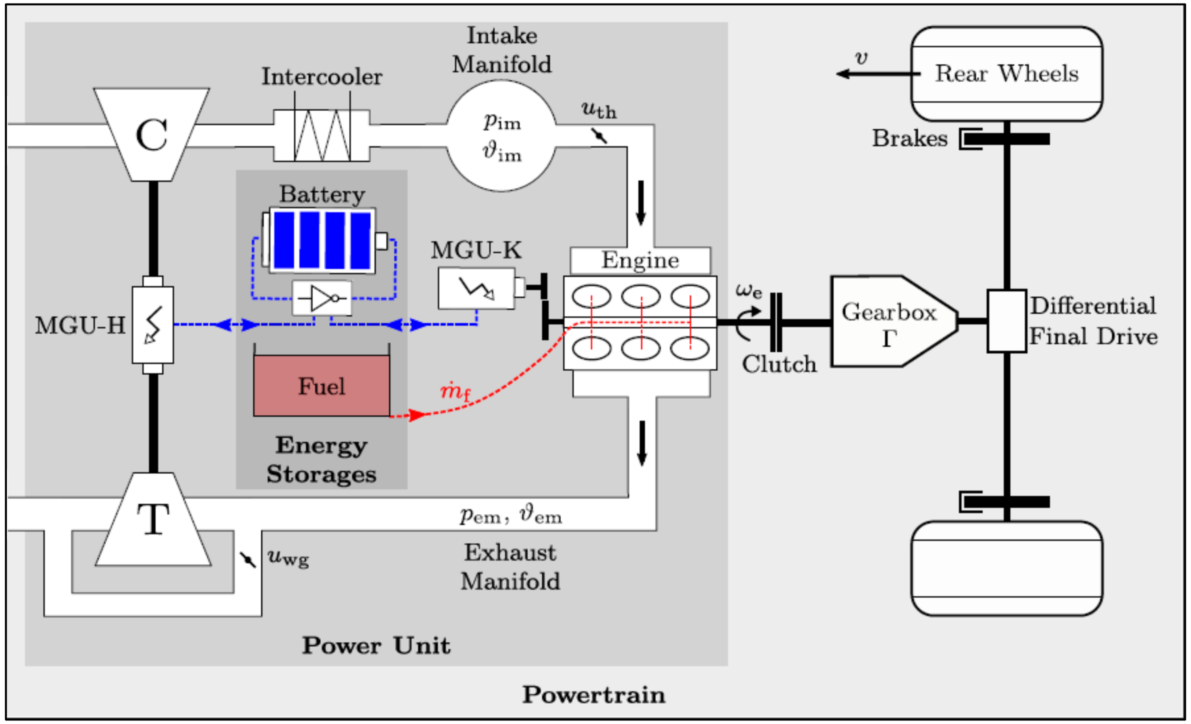
3) Optimal energy allocation can gain several seconds over a race distance

Outlook

Optimal Energy Management of the 2026 F1 Power Unit

Marc Neumann, Giona Fieni, Dr. Pol Duhr
Prof. Dr. Christopher Onder

Formula 1 Power Unit – Models



High-Level Model

- ICE power P_{e}
- MGU-K power P_{k}
- Brake power P_{brk}
- Waste-gate position u_{wg}
  - MGU-H power P_{h}
  - Engine back-pressure

Low-Level Model

- Fuel mass flow $\dot{m}_{\mathrm{f}}$
- MGU-K power P_{k}
- MGU-H power P_{h}
- Waste-gate position u_{wg}
- Throttle position u_{th}
- Spark advance u_{sa}
- Cylinder deactivation Ψ_{e}
- Brake power P_{brk}
- Engaged gear Γ

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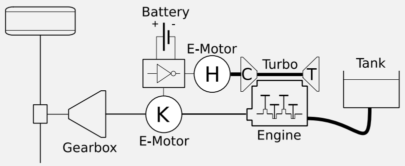
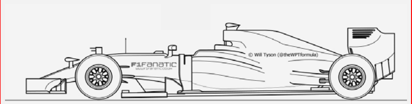
Offline Optimization – Low Level

Racetrack data
- vMax
- DRS
- Curvature
- Slope

Energy Budgets
- Fuel
- Battery





Low Level Optimizer

States:
$v, p_{\mathrm{im}}, E_{\mathrm{tc}}, E_{\mathrm{b}}, E_{\mathrm{f}},$
$E_{\mathrm{K2ES}}, E_{\mathrm{ES2K}}$

$\dot{m}_{\mathrm{f}}$

P_{k}

P_{h}

u_{wg}

u_{th}

u_{sa}

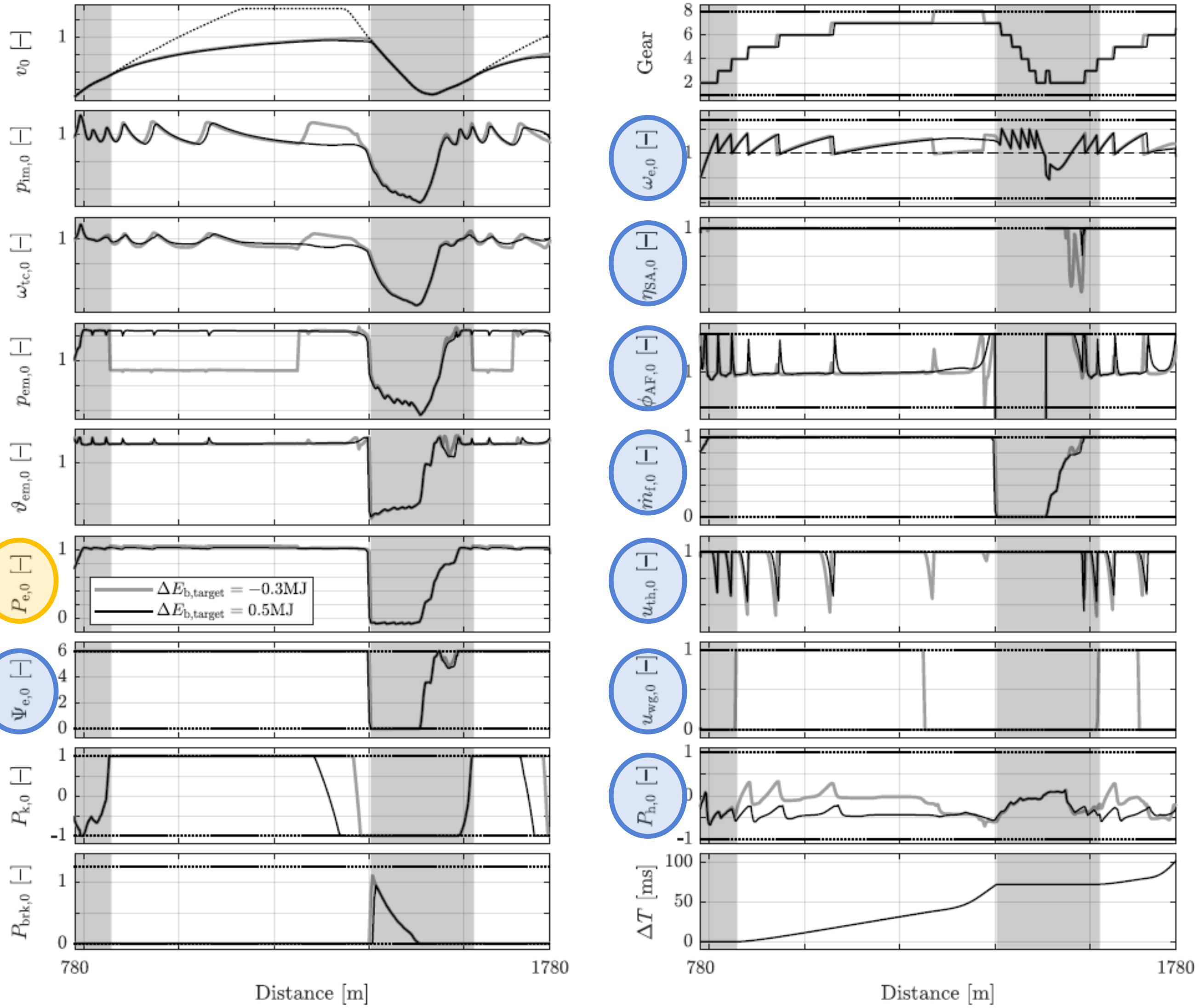
Ψ_{e}

P_{brk}

Γ

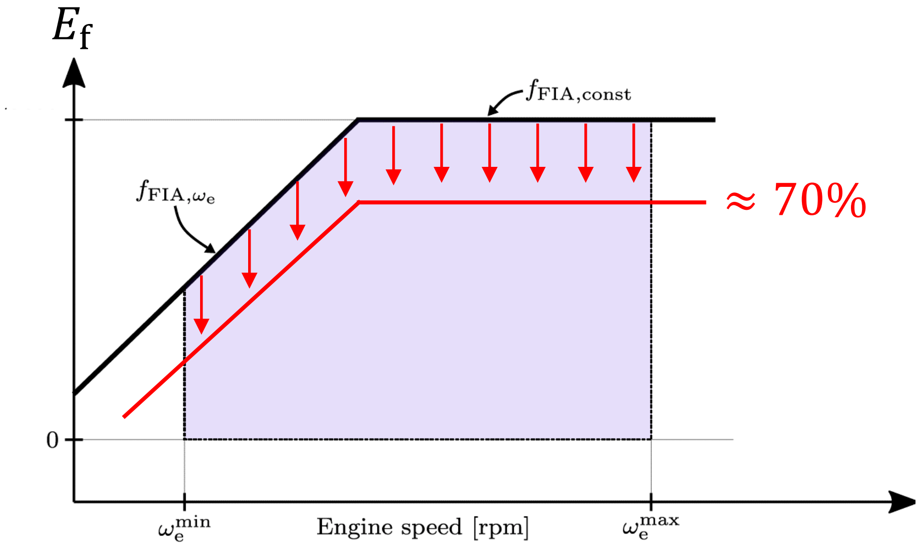
Offline Optimization – Low Level

$$P_\mathrm{e} = f(\quad)$$



C. Balerna, M.-P. Neumann, N. Robuschi, P. Duhr, A. Cerofolini, V. Ravaglioli, and C. Onder, "Time-optimal low-level control and gearshift strategies for the Formula 1 hybrid electric powertrain", *Energies,* vol. 14, p. 171, 2021.

Formula 1 Power Unit – Fuel Regulations



5.4.3 Fuel energy flow must not exceed 3000MJ/h.

5.4.4 Below 10500rpm the fuel energy flow must not exceed EF(MJ/h)=0.27*N(rpm)+ 165

16.3 Fuel properties

The only fuel permitted is petrol having the following characteristics:

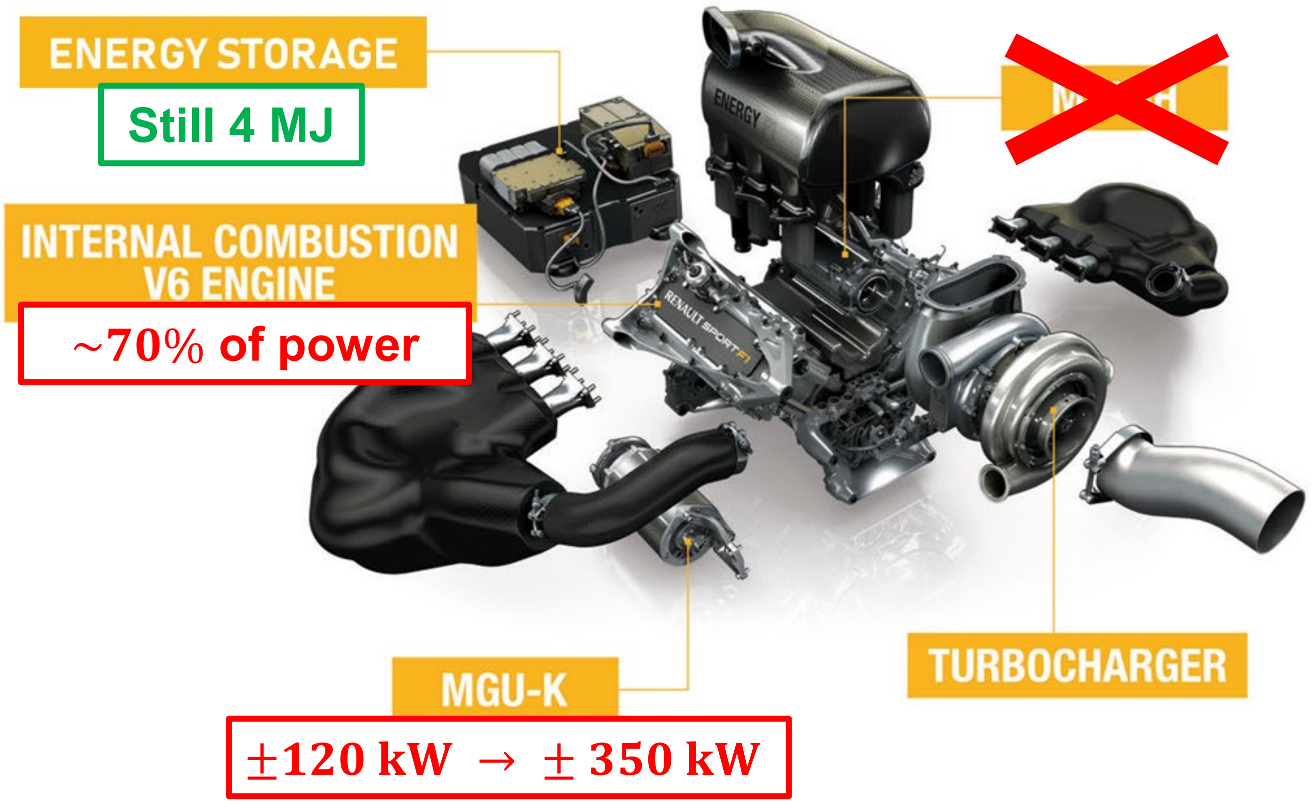
Property	Units	Min	Max	Test Method
RON		95.0 (1)	102.0 (1)	ISO 5164/ ASTM D2699
Sensitivity (RON-MON)			15.0 (1)	ISO 5164/ ASTM D2699 ISO 5163/ ASTM D2700
LHV	MJ/kg	38.0	41.0	GC
Density (at 15°C)	kg/m³	720.0	785.0	ISO 12185/ ASTM D4052
Methanol (2)	% v/v		3.0	EN 1601 or EN 13132 or EN ISO 22854
Oxygen	wt%	6.70	7.10	Elemental Analysis
Nitrogen	mg/kg		500	ASTM D 5762
Benzene	wt%		1	GCMS
DVPE	kPa	45	68	EN130161
Lead	mg/l		5	ASTM D 3237 or ICPOES
Manganese	mg/l		2	ASTM D 3831 or ICPOES
Metals (excluding alkali metals)	mg/l		5	ICPOES

Optimal Energy Management of the 2026 F1 Power Unit

Giona Fieni, Marc Neumann, Dr. Pol Duhr
Prof. Dr. Christopher Onder

Formula 1 power unit 2026 - challenges

From 2026:



No MGUH:

- Less energy recuperation is possible
- Turbo lag becomes relevant

Engine and MGUK balance:

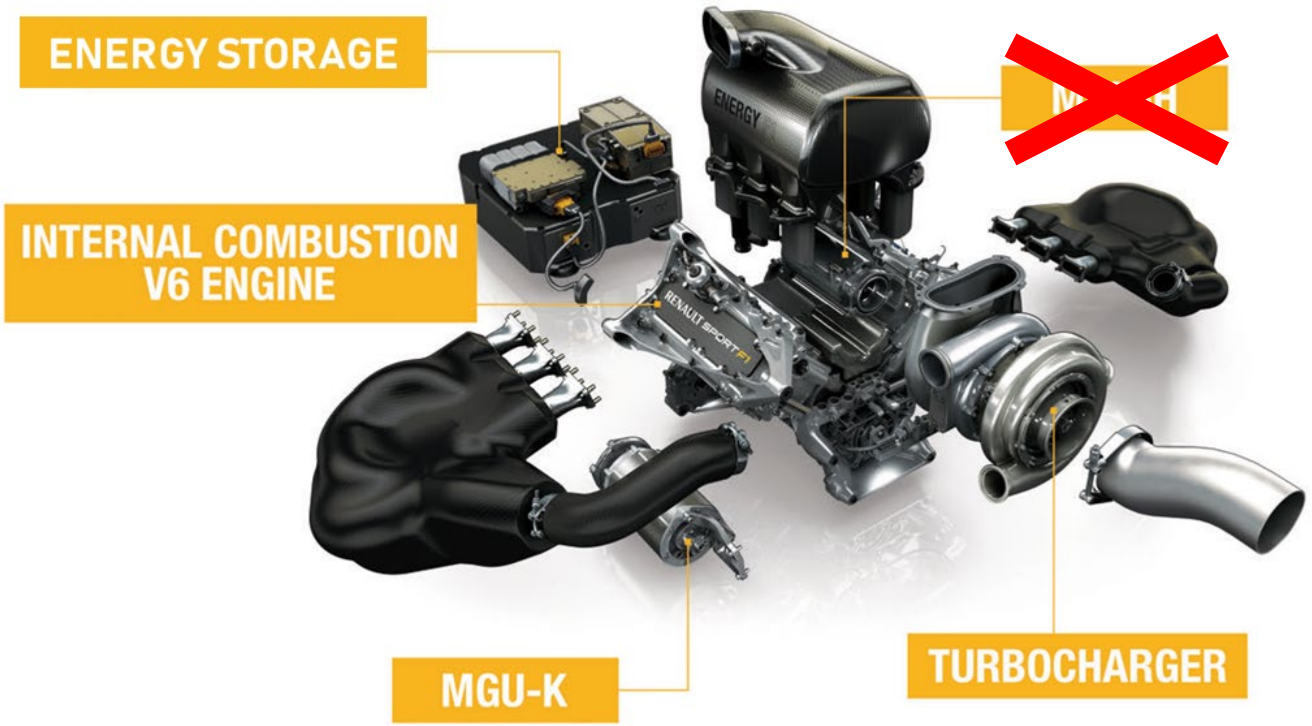
- Power split between engine and MGUK is very different

Battery and MGUK:

- Same battery
- Battery discharge is 3x faster

Power unit operation without MGUH

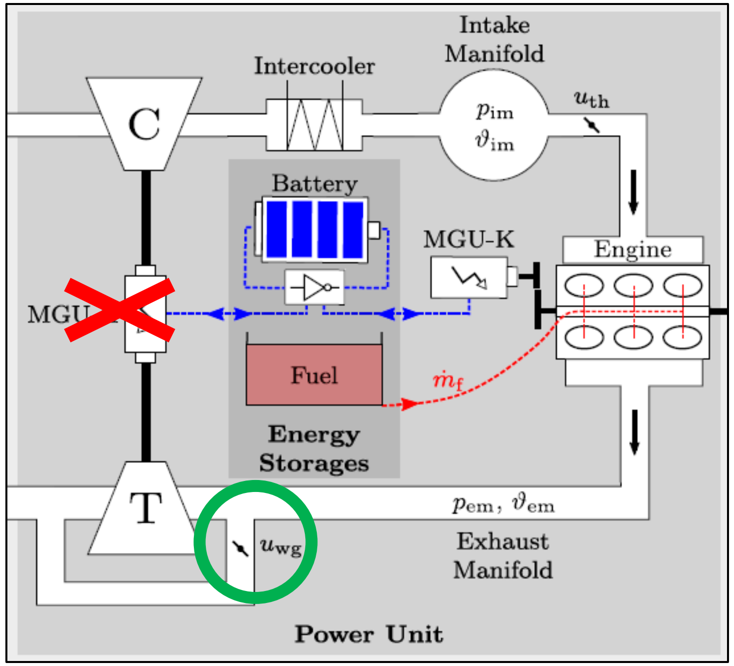
From 2026:



No MGUH:

- Less energy recuperation is possible
- Turbo lag becomes relevant

Power unit operation without MGU-H



Waste-gate:

2023

The waste-gate is used to:

- Increase the engine pumping power
- Control the amount of exhaust gas to allow energy recuperation

The turbocharger speed is controlled using the MGUH, which avoids the turbo lag.

2026

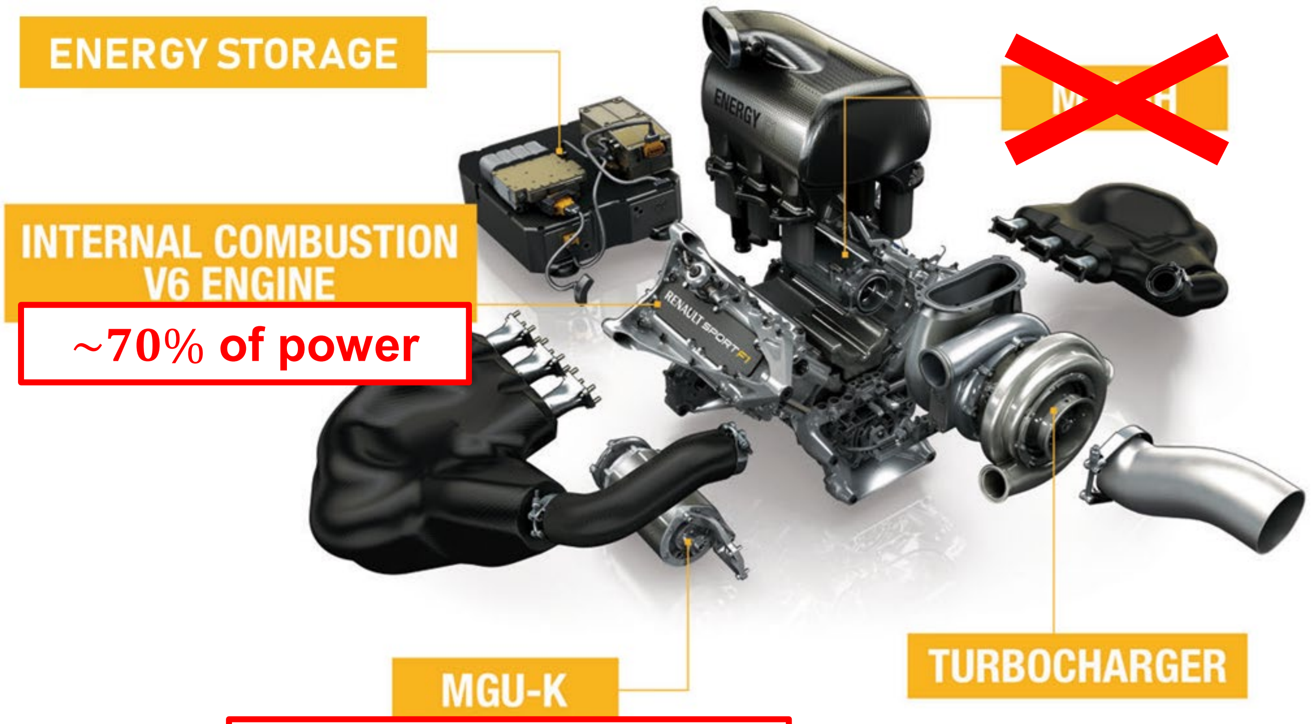
- The waste-gate remains the only component that can influence the turbocharger speed!
- The energy recuperation is possible only through the MGUK
- The turbo lag problem has to be addressed

Consequences for 2026:

- The turbo lag becomes a relevant effect
- The waste-gate will play a different role
- Predictive information can be crucial → MPC?

Engine and MGUK balance

From 2026:



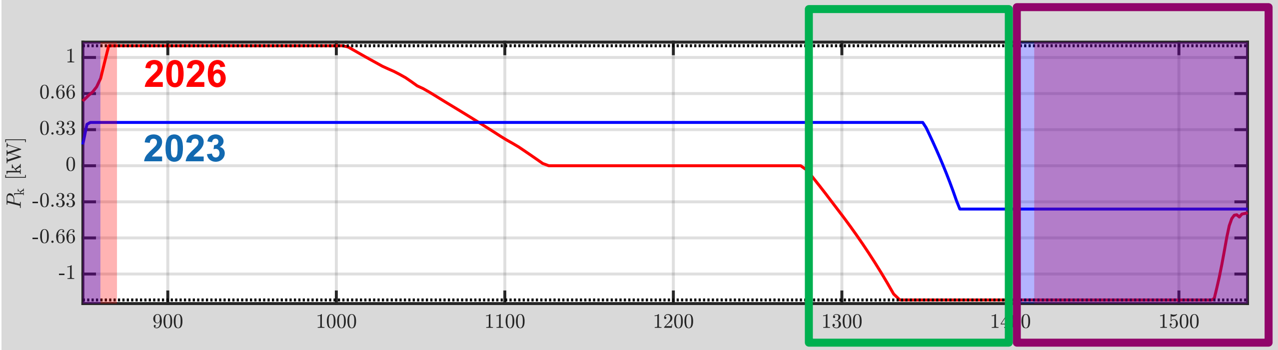
$\sim$70% of power

$\pm 120\ \mathrm{kW} \rightarrow \pm 350\ \mathrm{kW}$

Engine and MGUK balance:

- Power split between engine and MGUK is very different

Engine and MGUK balance



- Recuperation does not take place only during braking phases
- The motor can be operated at 100% power with MGUK in full recuperation to recharge the battery

- Since the battery is depleted quicker than in 2023, the recuperation phase is prolonged
  - ➢ The coasting phase can be quite long!
- Using additional battery energy there, the pilot can count on 700 kW extra for a few seconds to perform an overtake!

2023

$P_{e,max} \sim 500$ kW

$P_{k,min} = -120$ kW

Full recuperation with engine at full power:

$P_{PU} = 380$ kW

Full recuperation and propulsion

2026

$P_{e,max} \sim 350$ kW

$P_{k,min} = -350$ kW

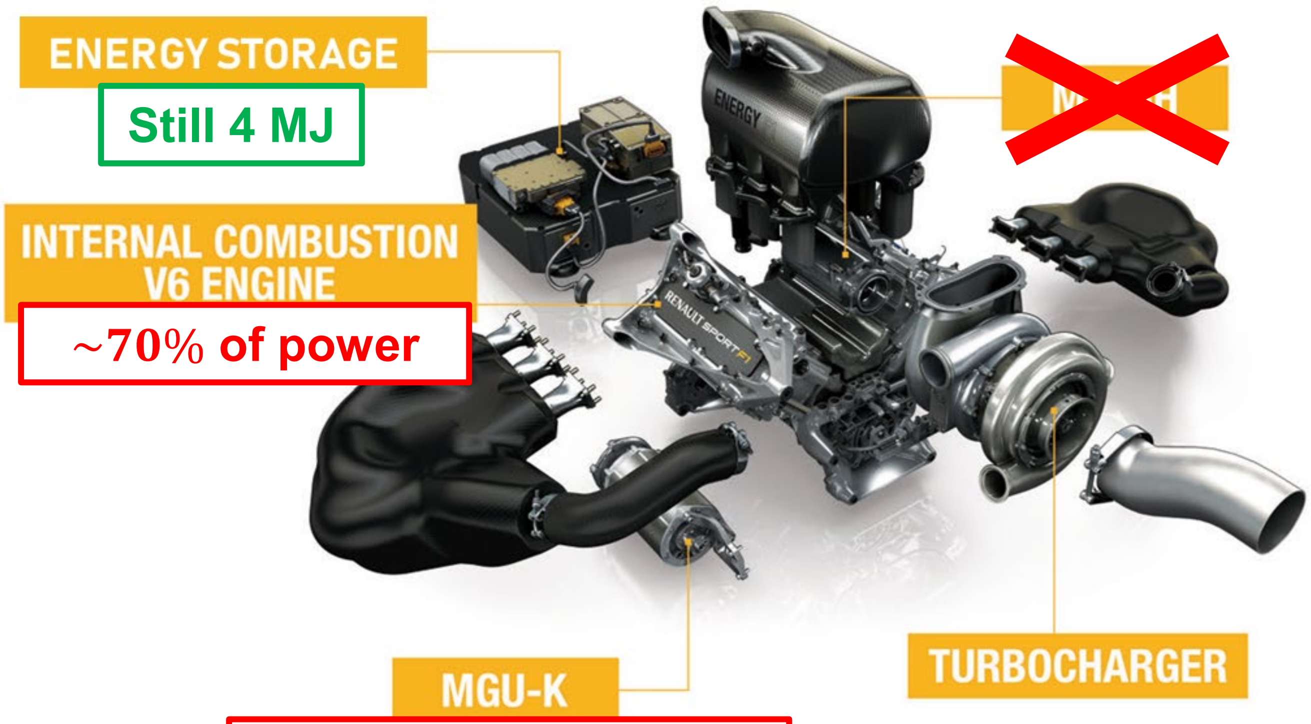
Full recuperation with engine at full power:

$P_{PU} = 0$ kW

Full recuperation but coasting

Battery and MGU-K

From 2026:



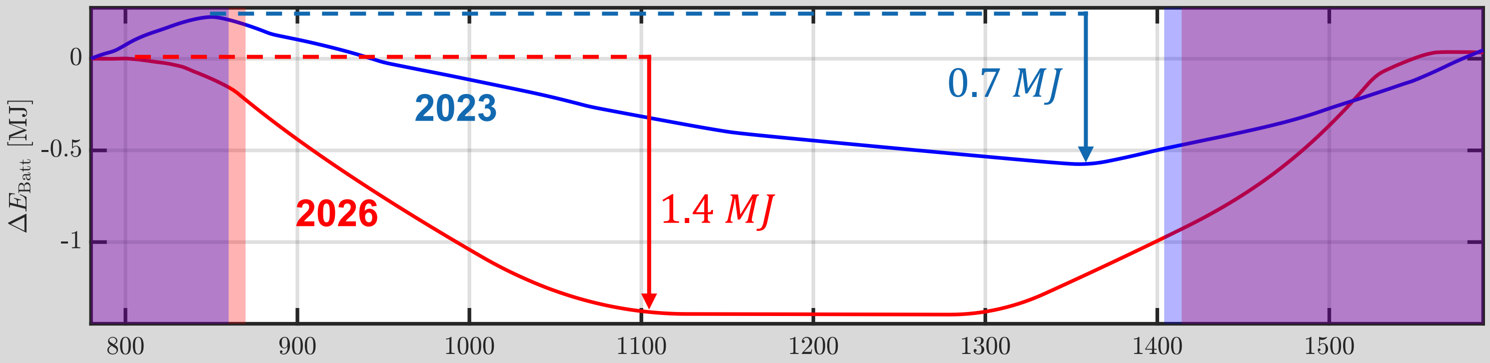
$\pm 120\ \mathrm{kW} \rightarrow \pm 350\ \mathrm{kW}$

Battery and MGUK:

- Same battery
- Battery discharge is $3x$ faster

Battery and MGU-K

Straight without overtake



= 17.5% of the battery energy

= 35% of the battery energy

Example: overtake maneuver

Assume that for an overtake on a longer straight we need $\mathbf{3}s$ extra MGU-K boost time.
This means that the extra energy depleted from the battery is:

2023: $120\ kW = 0.12\frac{MJ}{s} \rightarrow E_{\text{overtake}} = 0.12\frac{MJ}{s} * 3s = 0.48\ MJ$ → 9% of the battery energy

2026: $350\ kW = 0.35\frac{MJ}{s} \rightarrow E_{\text{overtake}} = 0.35\frac{MJ}{s} * 3s = 1.05\ MJ$ → 26.5% of the battery energy

Only for the overtake!

Straight with overtake:

2023:
26.5% of battery energy

2026:
61.5% of battery energy

The battery can be emptied very easily.

Consequences for 2026:

- Sufficient energy must be saved to defend the new position!

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