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Robust Adaptation of the Train Speed for Energy Saving under Punctuality and Security Constraints

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Objective of the study

Find deterministic driver's command u^* for a given entry $\mathcal{E}$, minimizing the energy consumed F^E in a specific domain $\mathcal{D}$ (respecting security, punctuality, and comfort constraints), robust to uncertainties $\boldsymbol{X}$. It aims to help drivers and prepare the development of autonomous trains.

$$u^*(\mathcal{E}) = \arg\min_{u \in \mathcal{D}} \mathbb{E}_{\boldsymbol{X}}\left[F^E(u, \boldsymbol{X}, \mathcal{E})\right] \quad (1)$$

Models for High-Speed Trains

- Entry $\mathcal{E}$: Wind and track descriptions.
- Driver's command u: Time-dependent in $[-1, 1]$.
- Longitudinal dynamics for the whole train:

$$M_T k^r \ddot{Y}(t) = \sum_\alpha F^\alpha(u(t), \boldsymbol{X}, \mathcal{E}) \quad (2)$$

with M_T the mass of the train, k^r a factor including the wheels rotation, $\ddot{Y}$ the train acceleration. F^α regroups traction and braking forces, the *Davis* or resistant force, a corrective force in curve, and the weight.

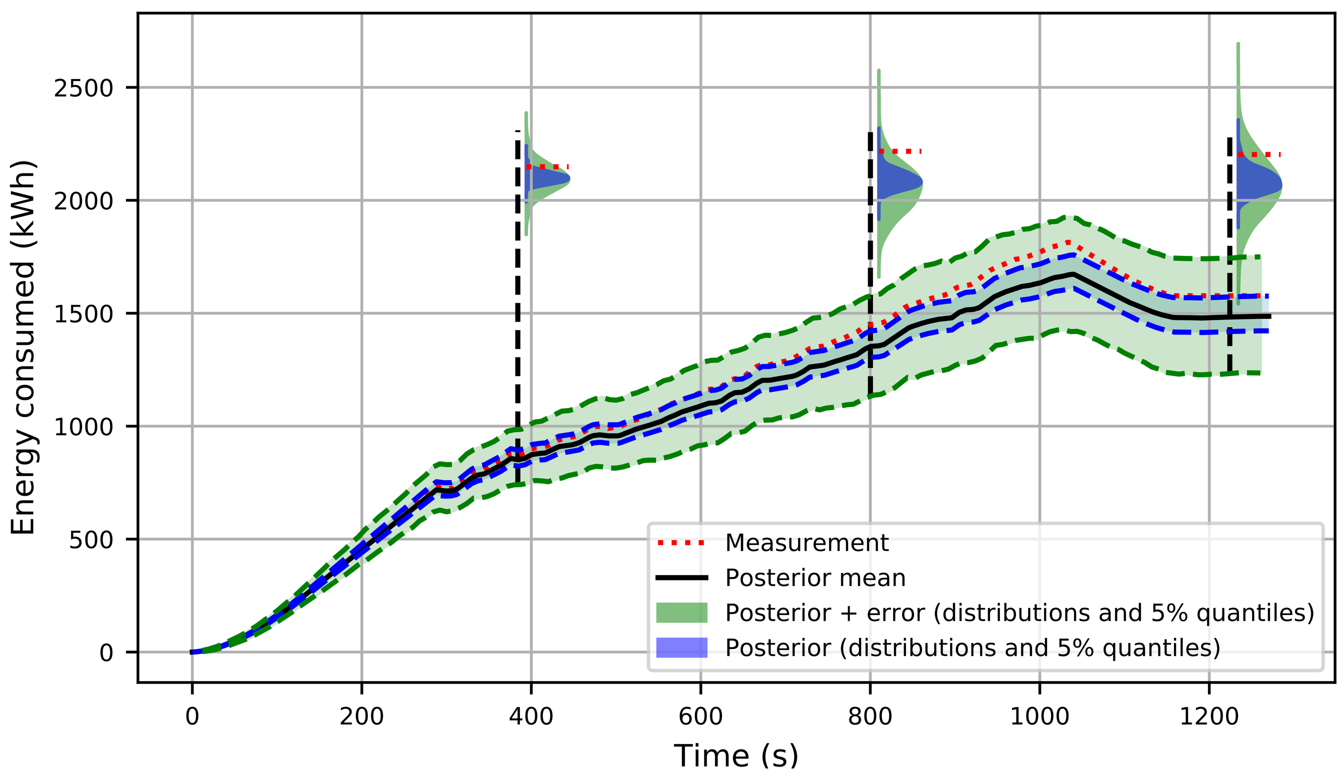
- Energy consumed by the train:

$$F^E(u, \boldsymbol{X}, \mathcal{E}) = \int_{t_s}^{t_f} P^E(u(t), \boldsymbol{X}, \mathcal{E})\, dt\,, \quad (3)$$

where P^E is the electric power and t_s, t_f are the initial and arrival time.

Modeling the Uncertainties

- Sensitivity analysis on the uncertain parameters $\boldsymbol{X}$.
- 4 dynamic and 5 energy consumption parameters.
- Prior distribution: Describe the available information.
- Likelihood function: Quantify the plausibility of a simulation with measurements on commercial trains.
- Markov Chain Monte Carlo (MCMC): Metropolis-within-Gibbs to reach the posterior distribution.



First optimization method

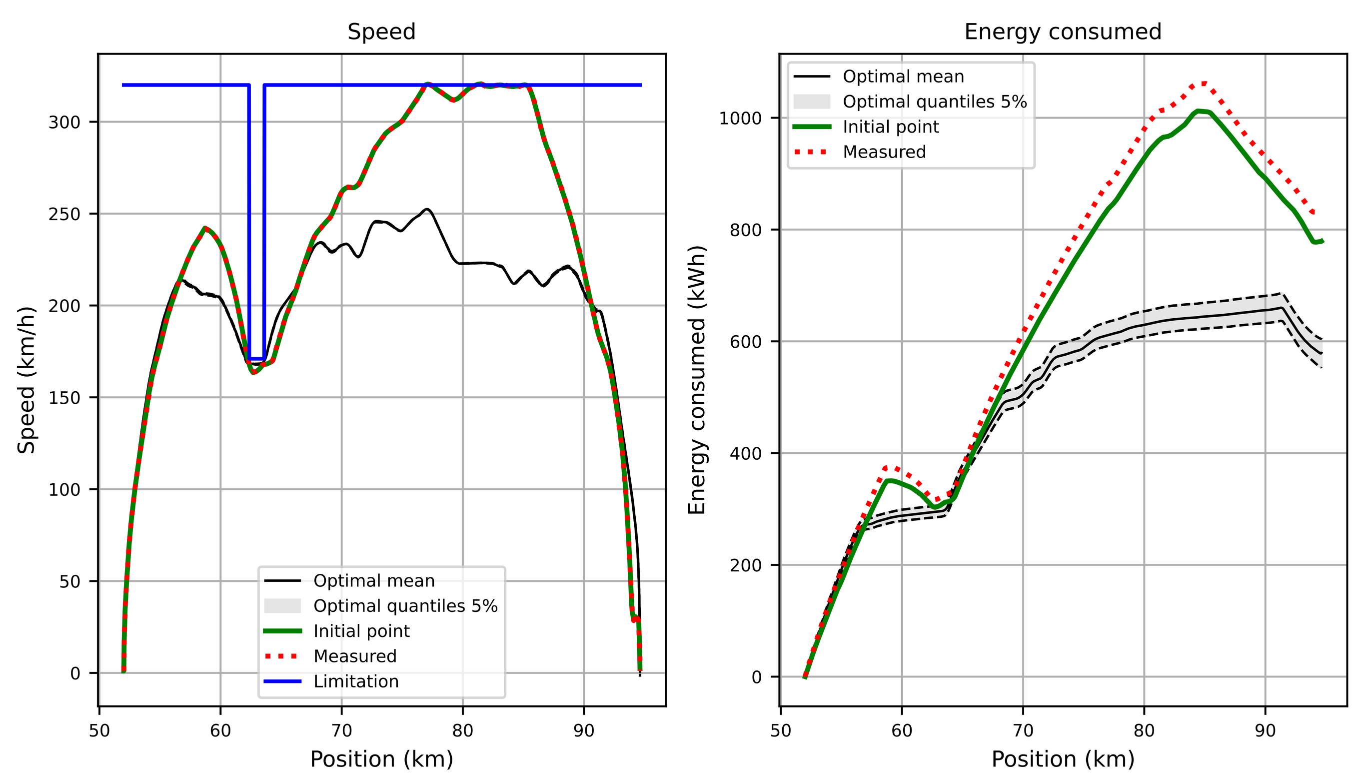
- Idea: Find a family $(u_k^*)_k$ that minimizes the energy consumed in specific configurations $\boldsymbol{x_k}$ drawn in $\boldsymbol{X}$.
- Cost function f^E: Minimize the energy consumed.
- Constraints $\mathcal{C}$: Security, punctuality, and comfort.
- Method: Discretization, penalization with augmented Lagrangian, and CMA-ES iterative algorithm.

$$u_k^*(\mathcal{E}, \boldsymbol{x_k}) = \arg\min_{u \in \mathcal{C}} f^E(u, \boldsymbol{x_k}, \mathcal{E}) \quad (4)$$

Second optimization method

- Idea: Find a deterministic u^* easy to transform to be robust to the fluctuations of $\boldsymbol{X}$.
- Cost function: Minimize the mean of the energy.
- Constraints: Transform u^* as $\tilde{u}^*(\boldsymbol{x_k})$ to be robust to $\boldsymbol{X}$.
- Method: Two discretizations, Principal Component Analysis, and CMA-ES iterative algorithm.

$$u^* = \arg\min_{u \in \mathcal{D}} \frac{1}{K} \sum_{k=1}^{K} F^E(\tilde{u}(\boldsymbol{x_k}), \boldsymbol{x_k}, \mathcal{E})\,. \quad (5)$$



References

[1] Nespoulous J. et al. Optimisation of train speed to limit energy consumption. *Veh. Syst. Dyn.*, 2021.

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