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 $u^\ast$ 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 $X$. It aims to help drivers and prepare the development of autonomous trains.

$$u^\ast(\mathcal{E}) = \arg\min_{u \in \mathcal{D}} \mathbb{E}_X[F^E(u, X, \mathcal{E})]$$

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:

  $$M_T k' y(t) = \sum_{i=1}^r F^a(u(t), X, \mathcal{E})$$

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

- Energy consumed by the train:

  $$F^E(u, X, \mathcal{E}) = \int_{t_i}^{t_f} F^E(u(t), X, \mathcal{E}) \, dt,$$

  where $F^E$ is the electric power and $t_i$, $t_f$ are the initial and arrival time.

Modeling the Uncertainties

- Sensitivity analysis on the uncertain parameters $X$.
- 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 $(u_k^\ast)$ that minimizes the energy consumed in specific configurations $x_k$ drawn in $X$.
- Cost function $F^E$: Minimize the energy consumed.
- Constraints $\mathcal{E}$: Security, punctuality, and comfort.
- Method: Discretization, penalization with augmented Lagrangian, and CMA-ES iterative algorithm.

$$u_k^\ast(\mathcal{E}, x_k) = \arg\min_{u \in \mathcal{E}} F^E(u, x_k, \mathcal{E})$$

Second optimization method

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

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

References