Queueing analysis of a battery-backed electric vehicle fast charging system

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Outline

Introduction

Single-server model

Single-server in steady-state

Optimal battery regime

Numerical results

The many-server case

Conclusions

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Motivation

- DC fast chargers deliver 150 kW or more per port, but stations are idle a large portion of the time.
- Sizing the grid connection for the peak is wasteful: infrastructure costs, and demand charges may dominate operating costs [National Renewable Energy Laboratory, 2023].

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Place a battery between the grid and the charger: charge it slowly from the grid, discharge it fast into the car.

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- Battery storage at EV stations: mostly studied for renewable integration [Bayram et al., 2011; Kabir et al., 2020; Tran et al., 2019; Tang et al., 2026].
- Queueing models of EV charging: mostly fixed service rates [Bayram et al., 2013; Dupont and Hayel, 2023; Tan et al., 2014].

The question

A queueing question

How often does a vehicle find the battery depleted, and is forced to charge at the slower grid rate?

- The coupling between the continuous battery state and the discrete occupancy distinguishes this system from a standard queue.
- Natural framework: piecewise-deterministic Markov processes (PDMP) [Davis, 1984, 1993].

Key points of this talk

- A PDMP model of a battery-buffered station, with state (occupancy, battery level).
- Closed-form stationary distribution for the single-server loss system, with a decoupling property.
- Explicit blocking probability, mean charging time and slowdown factor.
- An optimal battery regime: average slowdown depends only on hardware parameters $\Rightarrow$ explicit battery sizing.
- The many-server case: an eigenvalue problem for a matrix pencil.

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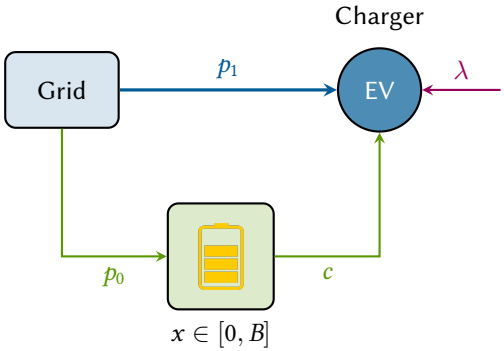
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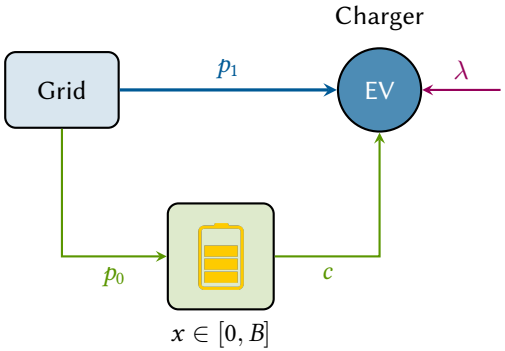
Setting

- Poisson arrivals λ, demands $Y \sim \text{Exp}(\mu)$.
- Loss system: one charger, cars finding it busy are lost.
- Battery level $x(t) \in [0, B]$.
- p_1: grid power; $p_2 > p_1$: fast charging; $c := p_2 - p_1$; $0 < p_0 \leq p_1$: idle recharge.



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- p_1: grid power; $p_2 > p_1$: fast charging; $c := p_2 - p_1$; $0 < p_0 \leq p_1$: idle recharge.
- Two-phase service: fast at p_2 while $x > 0$ (battery drains at c), slow at p_1 once $x = 0$.

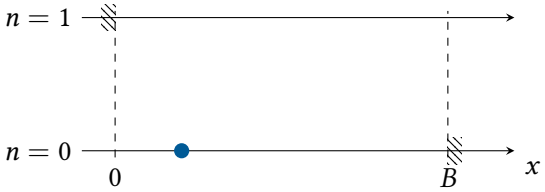


Departure rate $\mu p(x)$, with

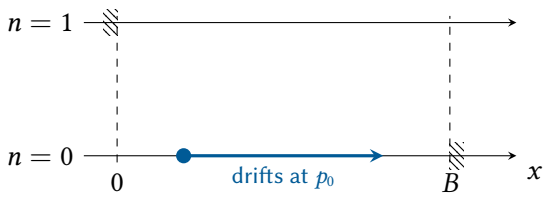
$$p(x) = p_2 \, \mathbf{1}_{\{x>0\}} + p_1 \, \mathbf{1}_{\{x=0\}}.$$

State space and dynamics

- State: $Z(t) = (n(t), x(t)) \in E = \{0, 1\} \times [0, B]$.



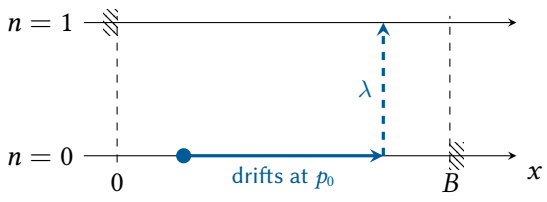
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- Between jumps $\dot{x} = r(n, x)$:

$$r(n,x) = \begin{cases} p_0 & n = 0,\ x < B, \\ 0 & n = 0,\ x = B, \\ -c & n = 1,\ x > 0, \\ 0 & n = 1,\ x = 0. \end{cases}$$

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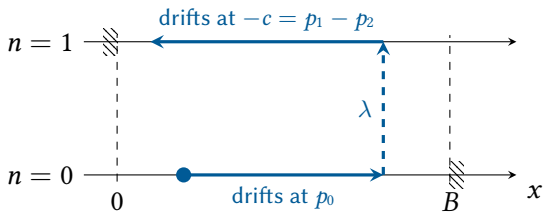


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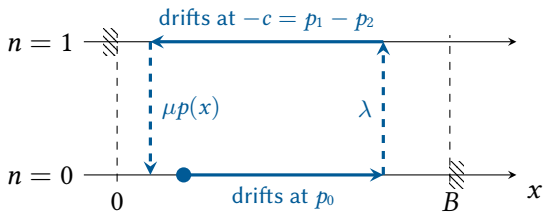


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- Jumps: $(0, x) \mapsto (1, x)$ at rate λ, $(1, x) \mapsto (0, x)$ at rate $\mu p(x)$.
- The battery level is unchanged at jumps.

A PDMP outside the standard framework

The standard theory [Davis, 1984, 1993] requires an open state space and forces a jump before reaching the boundary. Here E is compact, and the flow reaches $x = 0$, $x = B$ in finite time.

- The vector field is bounded and monotone on each mode $\Rightarrow$ well-defined flow.
- Bounded jump rates, jumps leave x unchanged $\Rightarrow$ strong Markov via the martingale problem (cf. Davis [1984, Thm. 4.8]).

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Extended generator, for $\psi(n, \cdot)$ absolutely continuous on $[0, B]$:

$$\mathcal{A}\psi(0,x) = r(0,x)\,\psi_0'(x) + \lambda\,[\psi(1,x) - \psi(0,x)],$$
$$\mathcal{A}\psi(1,x) = r(1,x)\,\psi_1'(x) + \mu p(x)\,[\psi(0,x) - \psi(1,x)].$$

A stationary distribution satisfies $\int \mathcal{A}\psi\, d\pi = 0$ for all $\psi \in \mathcal{D}(\mathcal{A})$: the weak form of $\mathcal{A}^*\pi = 0$.

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Balance equations

E compact, $Z(t)$ irreducible $\Rightarrow$ unique π [Meyn and Tweedie, 1993]. We seek a mixed measure:

$$\pi = f_0(x)\,dx + f_1(x)\,dx + \pi_{0,B}\,\delta_{(0,B)} + \pi_{1,0}\,\delta_{(1,0)},$$

with atoms at the corners where the drift points towards the boundary.

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Interior $x \in (0, B)$:

$$\begin{aligned} p_0 f_0'(x) &= -\lambda f_0(x) + \mu p_2 f_1(x), \\ -c f_1'(x) &= \lambda f_0(x) - \mu p_2 f_1(x). \end{aligned}$$

Boundary fluxes:

$$\begin{aligned} c f_1(0^+) &= \mu p_1 \pi_{1,0} = p_0 f_0(0^+), \\ p_0 f_0(B^-) &= \lambda \pi_{0,B} = c f_1(B^-). \end{aligned}$$

Stationary distribution

Theorem

Let $\theta := \dfrac{\mu p_2}{c} - \dfrac{\lambda}{p_0}$. *The unique stationary distribution of* $Z(t)$ *is:*

$$f_0(x) = \frac{e^{\theta x}}{K}, \qquad f_1(x) = \frac{p_0}{c} \cdot \frac{e^{\theta x}}{K}, \qquad x \in (0, B),$$

$$\pi_{1,0} = \frac{p_0}{\mu p_1 K}, \qquad \pi_{0,B} = \frac{p_0\, e^{\theta B}}{\lambda K},$$

with

$$K = \frac{p_0 + c}{c} \cdot \frac{e^{\theta B} - 1}{\theta} + \frac{p_0}{\mu p_1} + \frac{p_0\, e^{\theta B}}{\lambda}.$$

Proof sketch: decoupling

- Adding both interior equations: $\frac{d}{dx}\left[p_0 f_0 - c f_1\right] = 0$.
- The flux conditions at $x = 0$ give $p_0 f_0(0^+) = c f_1(0^+)$: the constant is zero.

Decoupling property

$$f_1(x) = \frac{p_0}{c} f_0(x) \quad \forall x \in (0, B) :$$

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- Substituting: $f_0' = \theta f_0$, so the densities are exponential.
- Atoms follow from the boundary equations.

Interpretation of θ

In an idle-busy cycle ignoring the boundaries, the expected net battery change is

$$\Delta := \frac{p_0}{\lambda} - \frac{c}{\mu p_2} \qquad \text{(same sign as } \theta\text{)}.$$

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With offered load $\rho := \lambda/\mu$ (average external power request):

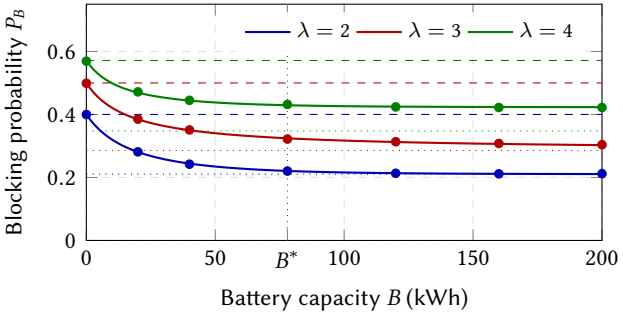
- $\theta > 0 \Leftrightarrow \rho < \dfrac{p_0 p_2}{c}$: lightly loaded, the battery tends to fill.
- $\theta < 0$: highly loaded, the battery tends to drain, much service at the slow rate p_1.
- $\theta = 0$: the battery neither fills nor drains on average, uniform density on $(0, B)$.

Blocking probability

By PASTA, P_B is the probability that the charger is working:

$$P_B = \int_0^B f_1(x)\,dx + \pi_{1,0} = \frac{p_0}{K}\left(\frac{e^{\theta B}-1}{c\,\theta} + \frac{1}{\mu p_1}\right).$$

- $B \to 0$: M/M/1/1 at rate p_1, $P_B \to \frac{\rho}{\rho+p_1}$.
- $B \to \infty$, $\theta > 0$: M/M/1/1 at rate p_2, $P_B \to \frac{\rho}{\rho+p_2}$.
- $B \to \infty$, $\theta < 0$: strictly in between, the battery regularly depletes.



Dashed/dotted: M/M/1/1 at p_1/p_2. Dots: simulation.

Charging time and average slowdown

At most one car in service, so $E[N] = P_B$. By Little's law:

$$E[T] = \frac{P_B}{\lambda(1-P_B)} = \frac{p_0\left(\dfrac{e^{\theta B}-1}{c\,\theta} + \dfrac{1}{\mu p_1}\right)}{\lambda\,\dfrac{e^{\theta B}-1}{\theta} + p_0\,e^{\theta B}}.$$

- Average slowdown w.r.t. always serving at p_2: $\bar{S} := \dfrac{\mu p_2\,E[T]}{E[Y]}$.
- In the balanced case $\theta = 0$: $E[T] = \dfrac{1}{1+\lambda B/p_0}\left(\dfrac{B}{c} + \dfrac{1}{\mu p_1}\right)$.

Slowdown factor

Service degradation as a function of the requested energy:

$$S(y) := \frac{E[T \mid Y = y]}{y/p_2} \geq 1.$$

- Key quantity: $x_y := cy/p_2$, the battery level exactly depleted by demand y.
- A car with demand y admitted at level x takes

$$T(x, y) = \frac{y}{p_2} + \frac{(x_y - x)^+}{p_1}.$$

- For $y \geq x^* = p_2 B/c$, slow charging is unavoidable regardless of the battery level.

Slowdown factor

Closed form

Proposition

Let $\mathcal{J}(a) = \dfrac{e^{\theta a} - 1 - \theta a}{\theta^2}$ *and* $K(1 - P_B) = \dfrac{e^{\theta B} - 1}{\theta} + \dfrac{p_0 e^{\theta B}}{\lambda}$. *Then:*

$$S(y) = 1 + \frac{p_2}{p_1\, y} \cdot \frac{\mathcal{J}(x_y)}{K(1 - P_B)}, \qquad y < \frac{p_2 B}{c},$$

$$S(y) = 1 + \frac{p_2}{p_1\, y} \left[\frac{\mathcal{J}(B)}{K(1 - P_B)} + (x_y - B) \right], \qquad y \geq \frac{p_2 B}{c}.$$

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- $S(y) \to 1$ as $y \to 0$; $S(y) \to p_2/p_1$ as $y \to \infty$ or $B \to 0$.
- As $B \to \infty$: $S(y) \to 1$ only if $\theta \geq 0$. If $\theta < 0$, $S(y) \to 1 + \frac{p_2}{p_1 y} |\theta| \mathcal{J}(x_y) > 1$: even an infinite battery does not remove the slowdown.

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For battery health: charge it slowly, and keep it cycling rather than fully charged or depleted for long periods.

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Choose the idle recharge rate p_0 to reach the balanced regime $\theta = 0$.

- Setting $\theta = 0$ uniquely determines

$$p_0^* = \frac{\lambda c}{\mu p_2} = \tilde{\rho}\, c, \qquad \tilde{\rho} := \frac{\rho}{p_2} = \frac{\lambda}{\mu p_2}.$$

- Feasible ($p_0^* \le p_1$) iff $\rho \le \rho_{\max} = p_1 p_2 / c$. Above it, $\theta < 0$ regardless of p_0.

Average slowdown in the optimal regime

- $\alpha = p_2/p_1 > 1$: speed-up ratio.
- $\beta = \mu B p_2/c$: normalized battery capacity, number of fast-charge sessions the battery sustains.

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With $\theta = 0$ and $p_0 = p_0^*$:

$$\bar{S} = \frac{\alpha + \beta}{\beta + 1}.$$

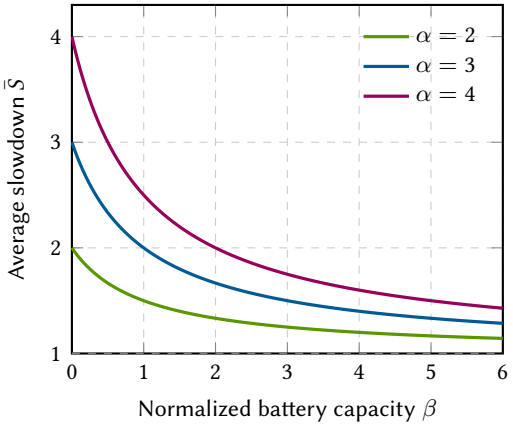
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$$\bar{S} = \frac{\alpha + \beta}{\beta + 1}.$$

Remarkably, it does not depend on the load: the same design works for all $\rho < \rho_{\max}$!



Battery sizing

Setting a target slowdown $\bar{S}_0 \in (1, \alpha)$:

$$\beta^* = \frac{\alpha - \bar{S}_0}{\bar{S}_0 - 1} \quad \Longleftrightarrow \quad B^* = \frac{c}{\mu p_2} \cdot \frac{\alpha - \bar{S}_0}{\bar{S}_0 - 1}.$$

- β^* grows with α: a large speed-up drains the battery fast relative to its recharge.

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Blocking probability in this regime:

$$P_B = \frac{\tilde{\rho}\bar{S}_0}{1 + \tilde{\rho}\bar{S}_0},$$

an M/M/1/1 blocking formula with effective load $\tilde{\rho}\bar{S}_0$.

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A design example

Hardware:

- $p_2 = 150$ kW: typical DC fast charger.
- $p_1 = 60$ kW: medium-sized grid connection.
- $c = 90$ kW, $\alpha = 2.5$.

Demand:

- $1/\mu = 20$ kWh (22 kWh average per DC fast session [National Renewable Energy Laboratory, 2023]).
- Mean fast session: $1/(\mu p_2) \approx 8$ min.
- Target $\lambda = 3$ cars/h.

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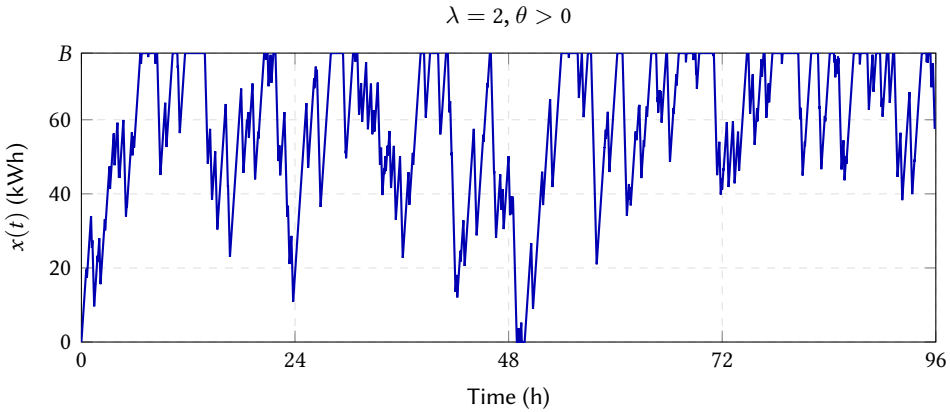
- $\theta = 0$: $p_0^* = \tilde{\rho} c = 0.4 \times 90 = 36$ kW.
- Feasible: $\tilde{\rho} = 0.4 < 1/(\alpha - 1) = 2/3$.
- Target $\bar{S}_0 = 1.2$: $\beta^* = 6.5$, so

$$B^* = 78 \text{ kWh}.$$

Mean service time: $8 \times 1.2 = 9.6$ min, vs. 20 min at the slow rate p_1.

Sample paths

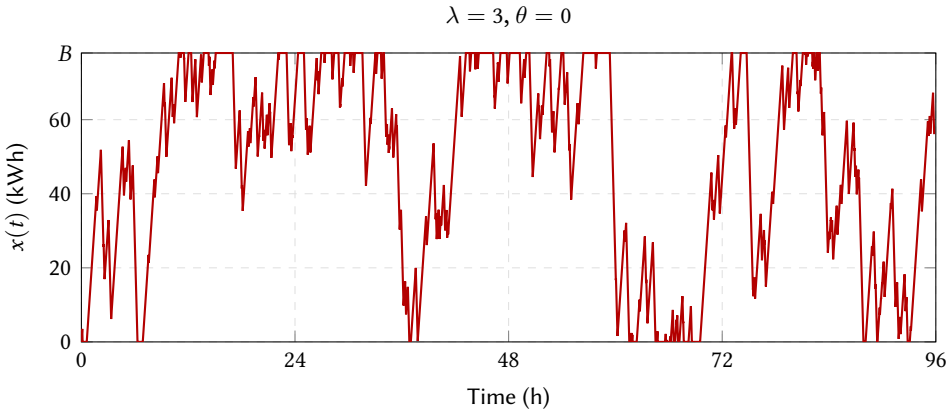
Three load regimes, same design



Lightly loaded: the battery drifts towards B and spends long periods near full.

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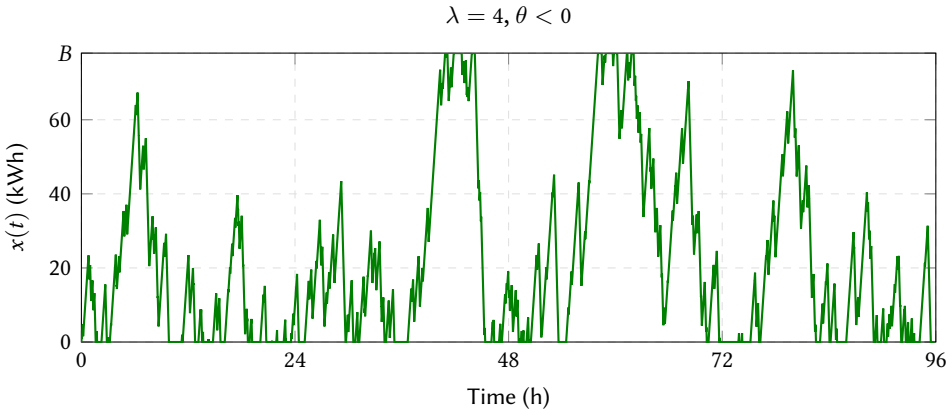
Three load regimes, same design



Critical: the battery oscillates freely across $(0, B)$ without dwelling at either boundary.

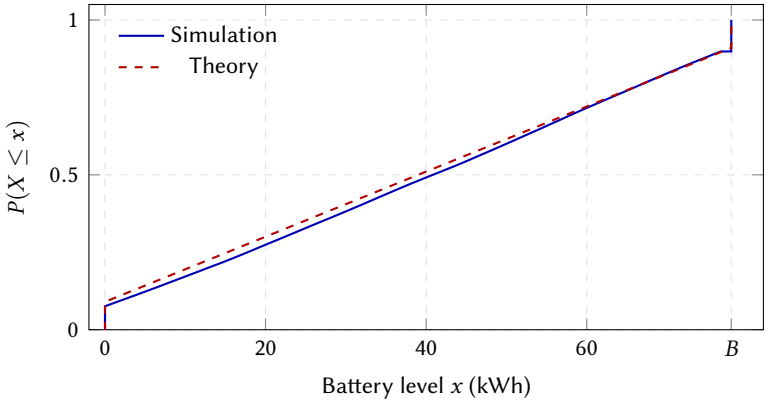
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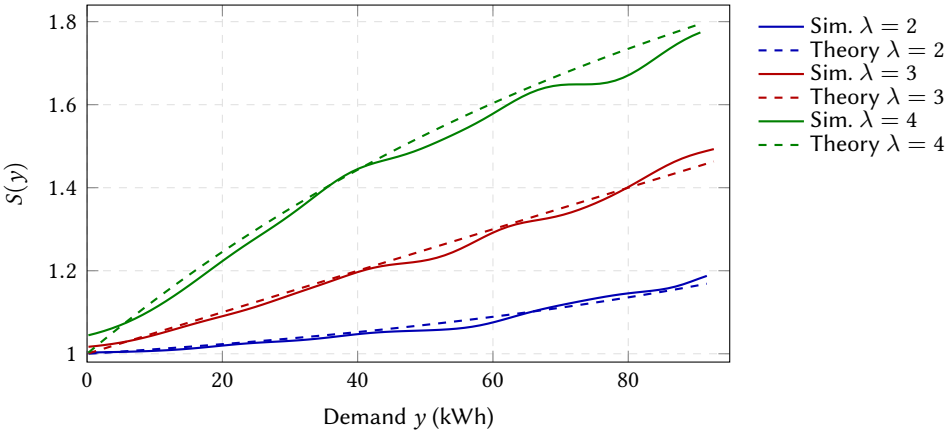
Heavily loaded: the battery drains, and service frequently degrades to the slow rate.

Stationary distribution of the battery level



$\lambda = 3$ ($\theta = 0$): uniform density on $(0, B)$ plus atoms at $x = 0$ and $x = B$ ($\pi_{1,0} = \pi_{0,B} = 0.0901$).

Slowdown factor



Solid: kernel regression from simulation. Dashed: analytical formula.

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Several chargers: a matrix pencil

s chargers share the battery and the grid ($p_0 = p_1$). Drift $r_n = p_1 - np_2$: charges for $n \le n^* := \lfloor p_1/p_2 \rfloor$, drains above.

- Interior balance: $R\,\mathbf{f}'(x) = Q^T\,\mathbf{f}(x)$, $R = \mathrm{diag}(r_0, \dots, r_s)$, Q the occupancy chain generator.
- R invertible when $p_1/p_2 \notin \mathbb{N}$: solutions $\mathbf{a}\, e^{\theta x}$ with $(\theta, \mathbf{a})$ an eigenpair of $R^{-1}Q^T$.
- $\theta = 0$ is always an eigenvalue, with Erlang-B weights $a_n = \tilde{\rho}^{\,n}/n!$.

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- $\theta = 0$ is always an eigenvalue, with Erlang-B weights $a_n = \tilde{\rho}^{\,n}/n!$.

- The interior solution superposes all $s+1$ modes; the boundary conditions give exactly $s+1$ equations.
- Unlike $s = 1$, the full spectrum of the pencil (Q, R) is generically needed.

Ongoing work: the eigenvalues are always real (reversibility of Q), and a solution with positive densities and corner atoms exists and is unique.

Outline

Introduction

Single-server model

Single-server in steady-state

Optimal battery regime

Numerical results

The many-server case

Conclusions

Messages from the talk

- A battery-buffered EV fast charging station is naturally a PDMP.
- Single-server: closed-form stationary distribution, with a decoupling property.
- Explicit blocking probability, mean charging time and slowdown factor.
- Optimal regime ($\theta = 0$): average slowdown depends only on hardware, not on load $\Rightarrow$ explicit battery sizing.
- Many servers: all the eigenmodes of the pencil (Q, R) are needed.

Thank you!

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