Rollout-Based Charging Strategy for Electric Trucks with Hours-of-Service Regulations

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Road Freight Electrification

Charging of heavy, electric truck (courtesy of Scania CV AB)

Positive impacts:

1) Reduce air and noise pollution
2) Mitigate climate change
3) Cope with energy shortages
4) Save operational cost
5) Lead to sustainable transport
6) ...

Truck Electrification Lagging Behind...

- Insufficient battery – Range anxiety
- Drivers need to follow HoS regulations

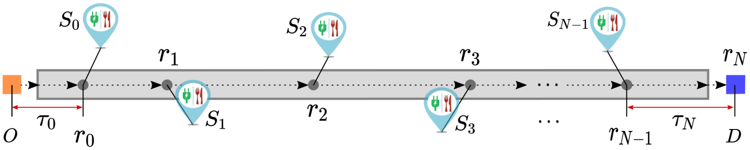
Limited driving range (200-600 km)

	USA	EU	China
Continuous driving time (max.)	8 h	4.5 h	4 h
Mandatory rest time (min.)	30 min	45 min	20 min
Daily driving time (max.)	11 h	9 h	10 h

Hours-of-service (HoS) regulations

Problem: How to design reliable and efficient **charging strategies** for electric trucks to complete delivery missions on time while aligning with the HoS regulations?

Route Model



- Decision variables:

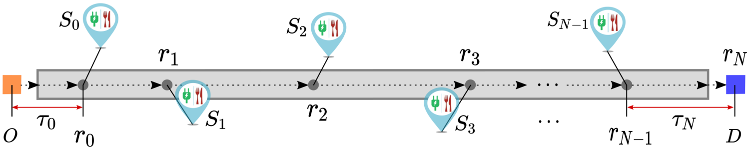
$$b_k, \tilde{b}_k \in \{0,1\}, \quad t_k \in \Re_+$$

b_k: whether to charge at the station S_k

$\tilde{b}_k$: whether to rest at S_k

t_k: how long to charge the truck at S_k if $b_k = 1$

Dynamics



- The **remaining battery** upon arriving at r_{k+1}:

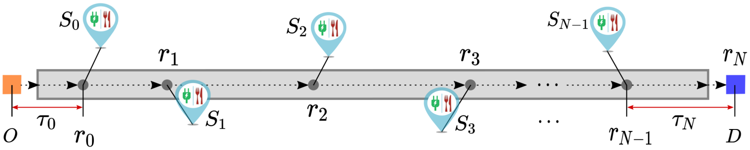
$$e_{k+1} = e_k + b_k \Delta e_k - \bar{P}\Big(2(b_k \vee \tilde{b}_k)d_k + \tau_{k+1}\Big)$$

$$\Delta e_k = t_k \min\{P_k, P_{\max}\} \leq \text{battery capacity}$$

- The **consecutive driving time** at r_{k+1}:

$$c_{k+1} = \tau_{k+1} + (b_k \vee \tilde{b}_k)d_k + (1 - \tilde{b}_k)(c_k + b_k d_k)$$

Constraints



- Sufficient energy to reach S_k: $e_k \geq$ battery for safe operation$+\bar{P}d_k$
- HoS regulations:
  - $c_k + d_k \leq$ the maximum consecutive driving time
  - $\sum_{k=0}^{N} \tau_k + \sum_{k=0}^{N-1} 2(b_k \vee \tilde{b}_k) d_k \leq$ the maximum daily driving time
- Delivery deadline:

$$\sum_{k=0}^{N-1} \max\left\{ b_k\left(2d_k + p_k + t_k\right), \tilde{b}_k\left(2d_k + T_r\right)\right\} \leq \Delta T$$

The Optimal Charging Problem

$$\min_{\{(b_k,\tilde{b}_k,t_k)\}_{k=0}^{N-1}} \quad F\big(b_0, \tilde{b}_0, t_0, \ldots, b_{N-1}, \tilde{b}_{N-1}, t_{N-1}\big)$$

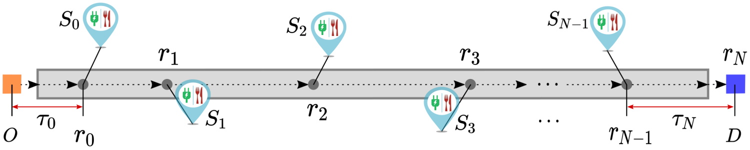
$$= \sum_{k=0}^{N-1} \xi_k b_k t_k + \sum_{k=0}^{N-1} \max\Big\{ b_k(2d_k + p_k + t_k), \tilde{b}_k(2d_k + T_r)\Big\}\epsilon$$

$$\text{s.t.} \quad \text{dynamics and constraints introduced earlier}$$

- **Challenge:** the problem is a **Mixed Integer Program** with *bilinear constraints*
  - It cannot be directly solved by many standard solvers
  - Exact solutions: iterate over all possible combinations of integer variables
    $\rightarrow 4^N$ continuous optimization problems
  - Linear transformation: it may still require an exponential number of iterations [see, p.480][1]

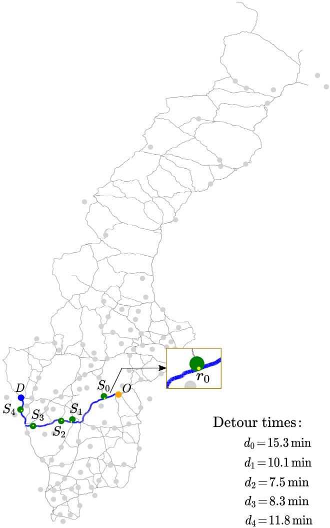
[1] D.Bertsimas and J. N. Tsitsiklis, Introduction to Linear Optimization, vol. 6. Belmont, MA, USA: Athena Sci., 1997.

Rollout-Based Approximate Solution



- Two base solutions:
  - **Greedy solution**: set $(b_k, \tilde{b}_k) = (1, 1)$ if the remaining energy is insufficient to reach S_{k+1}
  - **Relaxed solution**: solve a relaxation of the original problem with $b_k, \tilde{b}_k \in [0, 1]$
- Complexity: it requires solving at most $4N$ continuous optimization problems

Simulation Studies (1)

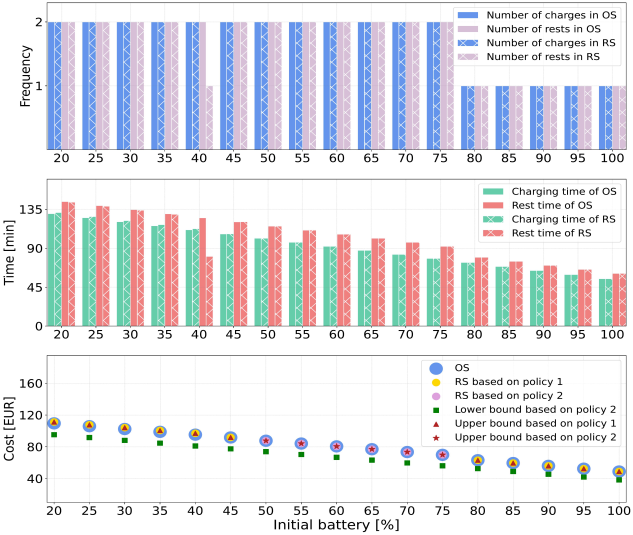


The route of one truck.

- Routes are obtained via *OpenStreetMap*
- Data for electric trucks manufactured by Scania
  - $P_k = 300$ kW
  - $P_{\max} = 375$ kW
  - $e_f = 468$ kWh
  - $\bar{P} = 1.83$ kWh/min
  - $p_k = 6$ min
  - $\xi_k = 0.36$ €/kWh, $\epsilon_k = 0.4$ €/min
- EU's HoS regulations

Simulation Studies (2)

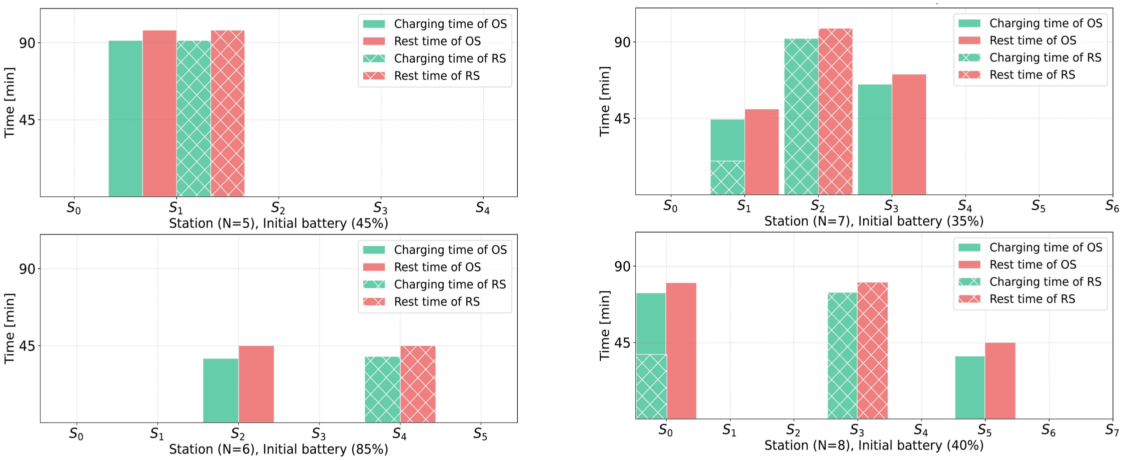
- 6 scenarios (N is between 5 and 10, initial battery is between 20% and 100%)



N=8

Simulation Studies (3)

- Comparison between the optimal solution (OS) and rollout solution (RS).



Simulation Studies (4)

Table: Comparison between the OS and RS

N	5	6	7	8	9	10
Average optimality gap-RS [%]	0	0.55	0.72	0.49	0.03	0.42
Average optimality gap-UB [%]	1.04	5.46	2.23	0.48	4.28	1.72
Average computation time of RS [s]	0.34	0.42	0.57	0.65	0.84	1.43
Average computation time of OS [min]	0.32	1.34	5.45	24.02	98.50	413.68

- The optimality gap between the RS and OS:

$$\frac{(F(RS) - F(OS)) \times 100}{F(OS)}$$

Conclusions

- We formulate the optimal charging problem of electric trucks as a mixed-integer program
- A rollout-based charging strategy is proposed, which provides near-optimal solutions
  - It allows for handling the HoS regulations, subject to delivery deadlines
  - It is of high efficiency and is promising to be applied to real-time strategy planning
- Extensive simulation studies illustrate the effectiveness of the developed approach

Future work:

- Developing optimal charging strategies with limited charging resources at stations