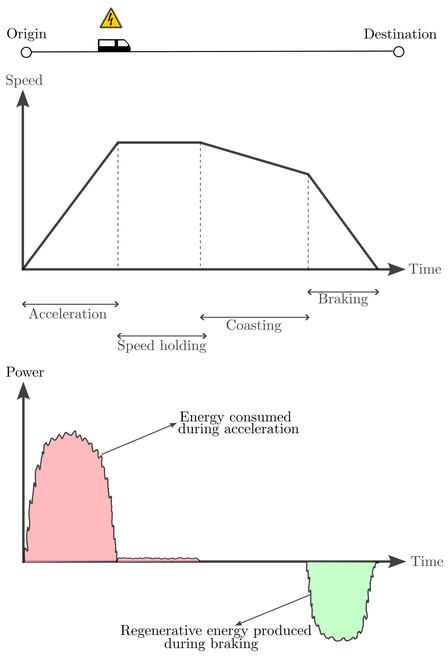
Energy-optimal Timetable Design for Sustainable Metro Railway Networks

Shuvomoy Das Gupta
MIT Operations Research Center
`shuvomoy.github.io`
joint work with Bart Van Parys & J. Kevin Tobin

What is the problem?

- Collaboration with `Thales Canada Inc`, the largest provider of communication-based train control systems worldwide
- Railway timetable is a data-structure that
  - contains the arrival and departure time of every train
  - to and from all the platforms that train visits
  - over the entire service period (e.g., 18 hours)
- **Goal:** Want to design the energy-optimal railway timetable that will
  - minimize the energy consumption of the trains
  - maximize the transfer of regenerative energy
  - subject to the functional constraints in the railway network

Energy consumption and regeneration of a train



Why should we care?

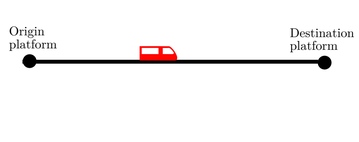
- Most modern railway networks are equipped with regenerative energy transfer mechanism
- Example. New York City Transit (NYCT) consumes more than 1,600 GWh of electricity annually
- All the new trains installed since 2018 are capable of producing regenerative braking energy, can regenerate up to 50% of the consumed energy
- If scheduled properly, a braking train can successfully transfer its regenerative energy to a nearby accelerating one
- So the energy-optimal timetable can lead to significant energy saving *without any infrastructure update*

Our real-time optimization model

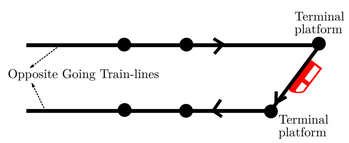
- Constraints
  - constraints are associated with trip, dwell, connection, headway (safety), and travel time
  - the constraints are linear and has a *network-flow problem* like structure
  - our formulation is robust with respect to box uncertainty
- Cost function to minimize
  - total effective energy consumption = total energy consumed during acceleration - total transferred regenerative energy from braking trains to accelerating trains
  - models the interplay between consumed and regenerated energy

Constraints

(a) Trip time constraint
(for a track)

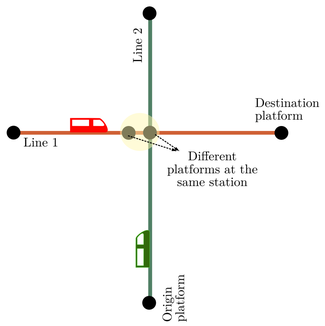


(b) Trip time constraint
(for a crossing-over)

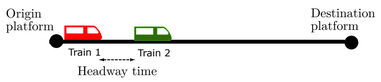


(c) Dwell time constraint

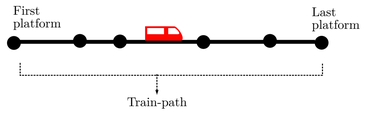
(d) Connection constraint



(e) Headway constraint



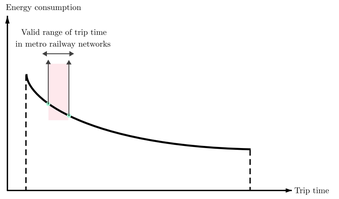
(f) Total travel time constraint



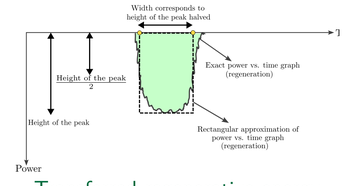
Cost function

- Energy consumed during acceleration can be modeled as a linear function in trip time for metro railway networks
- Total transferred regenerative energy can be modeled as piecewise minimum of linear functions ⇒ can be transformed into linear constraints

Modeling effective energy consumption

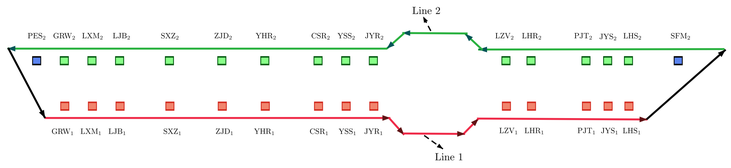


Energy consumption



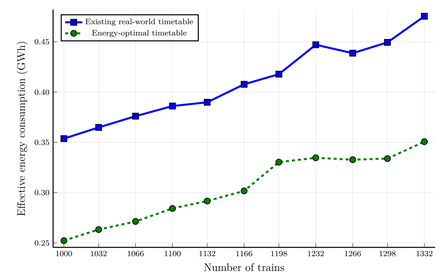
Transferred regenerative energy

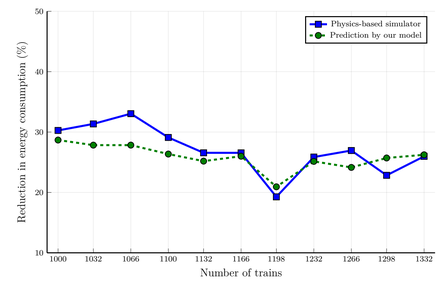
Application to Shanghai Metro Network



- We apply our model to Line 8 of Shanghai Metro Network – one of the largest and busiest railway services in the world
- Compare the energy saving with existing real-world timetables
- Optimization model solved using a custom parallel interior-point algorithm
- Solution time less than 1 sec on a standard desktop computer

Reduction in effective energy consumption





Summary

- Real-time linear optimization model for designing energy-optimal timetables
- Set to be implemented globally by `Thales Canada Inc`