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A Simple Adjustment of Runtimes between Stations for Saving Traction Energy by Means of Mathematical Programming

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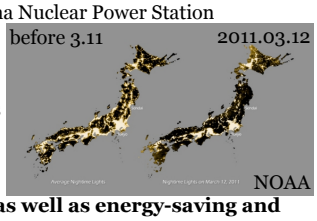
Contents

1. Introduction

Background

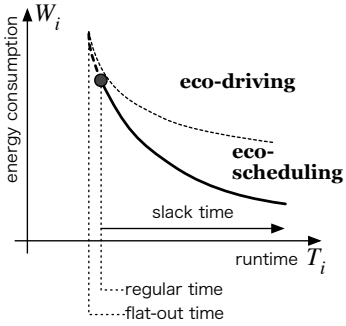
- Lack of robustness against uncertain power supply by
  - East Japan Earthquake Disaster
  - Accident of the Fukushima Nuclear Power Station
- Influence on operation
  - service partially stopped
  - reduced number of trains
- **Being smart rail energy**
  - **Energy management as well as energy-saving and peak power shaving**



Objectives

- **Framework combining energy-saving driving and scheduling by means of optimization for commuter trains with**
  - **few additional cost and disutility of passengers**
  - **easy implementation**
- Eco-driving
  - already presented at COMPRAIL'04, '06 & '08
- Eco-scheduling
  - newly presented at COMPRAIL'12

Energy Savings in Train Operation

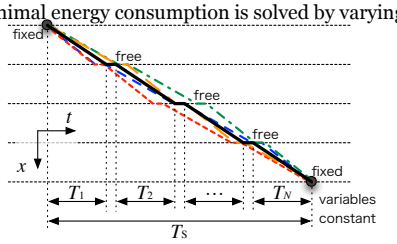


- Eco-driving
  - optimization of train speed profiles for each station
- Eco-scheduling
  - optimization of distribution of slack times for every interstations

2. Optimization Model for Energy-saving Train Scheduling

Energy-saving (Eco) Train Scheduling

- Total trip time T_S is given as a constant.
- Runtime for i-th interstation T_i is a variable.
  - by adjusting slack time
- The minimal energy consumption is solved by varying the T_i.



Formulation with Nonlinear Programming

$$J(T_1, \cdots, T_N) = \sum_{i=1}^{N} W_i(T_i) \rightarrow \min$$

total energy consumption

subject to $\sum_{i=1}^{N} T_i = T_S$ total trip time

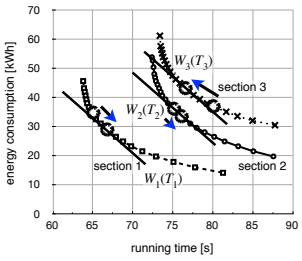
Applying Lagrange multiplier technique

$$L(T_1, \cdots, T_N, \lambda) = \sum_{i=1}^{N} W_i(T_i) + \lambda \left(\sum_{i=1}^{N} T_i - T_S \right)$$

$$\frac{\partial L}{\partial T_i} = \frac{\partial L}{\partial \lambda} = 0 \quad (i = 1, 2, \cdots, N)$$

Derived Law

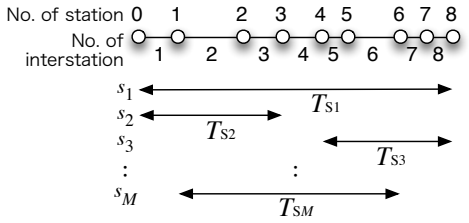
$$\frac{\partial W_1}{\partial T_1} = \frac{\partial W_2}{\partial T_2} = \cdots = \frac{\partial W_N}{\partial T_N} = -\lambda$$



Law of Identical Incremental Energy Consumption

If incremental energy for all interstations are identical, the schedule is optimal.

Generalized Optimization Model



Multiple definition of sets of interstations is assumed.

Generalized Optimization Model

Optimization model with linear objective function and linear and nonlinear constraints

$$J(\boldsymbol{T}, \boldsymbol{W}) = J(\boldsymbol{W}) = \boldsymbol{c}\,\boldsymbol{W} \rightarrow \min$$ objective function: total energy

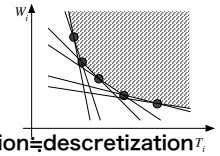
subject to $\boldsymbol{T}_S^{\min} \leq \boldsymbol{A}\boldsymbol{T} \leq \boldsymbol{T}_S^{\max}$ runtime at each set of interstations

$\boldsymbol{T}^{\min} \leq \boldsymbol{T} \leq \boldsymbol{T}^{\max}$ runtime at each interstation

$\boldsymbol{f}(\boldsymbol{T}, \boldsymbol{W}) \leq \boldsymbol{0}$ W-T curve for each interstation

Various numerical solvers can be applied.

If the polygonal approximation is applied to W-T curve, the problem will be a complete linear programming(LP).

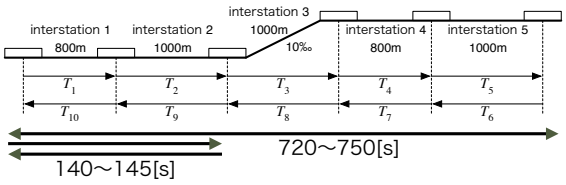


linearization≒descretization

3. Numerical Study for Demonstration

A Numerical Study

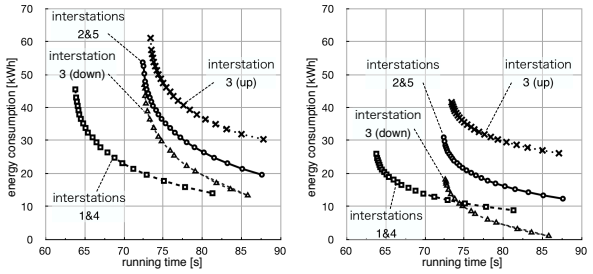
a short round-trip commuting line with short interstations



Simulation results were fitted to the implicit function,

$$f(T_i, W_i) = a_3 W_i^3 + a_2 W_i^2 + a_1 W_i + a_0 - T_i = 0 \quad .$$

Runtimes and Energy



without regenerative energy　　with regenerative energy

Assumed Cases

Cases	T_1 [s]	T_2 [s]	T_3 [s]	T_4 [s]	T_5 [s]	T_6 [s]	T_7 [s]	T_8 [s]	T_9 [s]	T_{10} [s]
regular	65	75	75	65	75	75	65	75	75	65
1	0	5	5	5	5	0	5	5	5	5

without optimization

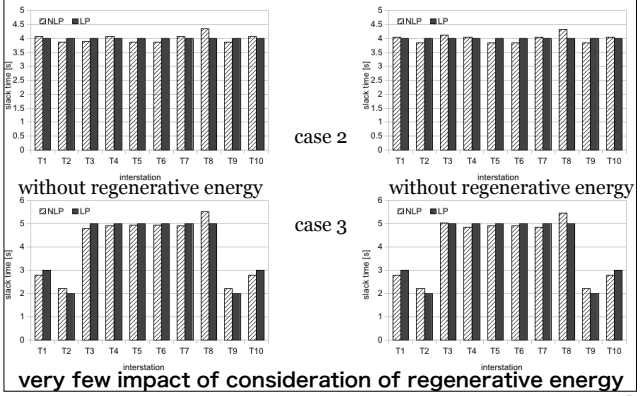
with optimization subject to simple constraints

Cases	$T_{1,4,7,10}$[s]	$T_{2,3,5,6,8,9}$[s]	$\sum_{i=1}^{10} T_i$[s]	$\sum_{i=1}^{2} T_i$[s]	$\sum_{i=9}^{10} T_i$[s]
2	65〜75	75〜85	720〜750	—	—
3	65〜75	75〜85	720〜750	140〜145	140〜145

with optimization subject to complicated constraints

Two types of solving: nonlinear(NLP) and linearized(LP) optimization

Optimized Slack Times



case 2

without regenerative energy　　without regenerative energy

case 3

very few impact of consideration of regenerative energy

Energy Consumption

	total energy [kWh]			
	without regenerative braking		with regenerative braking	
cases	NLP	LP	NLP	LP
1	275.21		165.44	
2	268.29	268.31	161.69	161.70
3	269.72	269.77	162.45	162.48
regular time	355.60		209.86	

very few impact of linearization

4. Conclusion

Conclusion

- Energy-saving train scheduling by adjusting slack times
  - based on a mathematical model
  - very few influence of linearization and regenerative ability on generated slack times
- Future scope
  - optimization considering easiness of recovering from delay and utility of passenger as well as energy consumption