Schedule-Free High-Frequency Transit Operations

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Outline

1. Framework
2. Methodology
3. Application
4. Concluding Remarks

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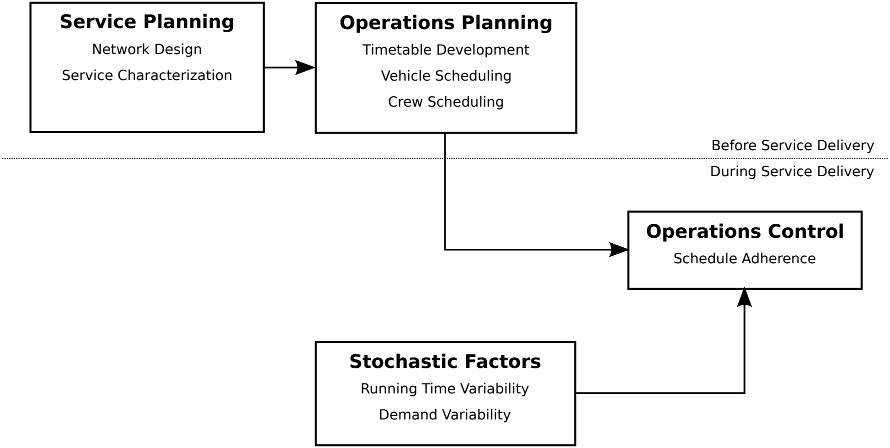
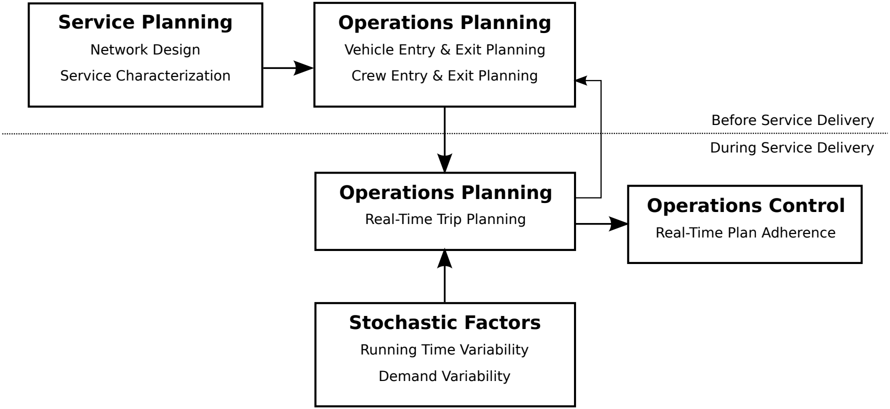
Schedule-Based Paradigm



Schedule-Free Paradigm



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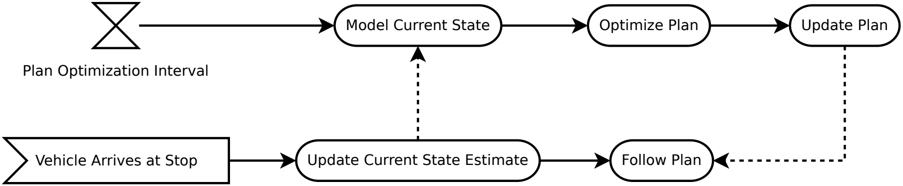
General Methodology



Optimization Problem

$$\underset{x \in X}{\text{minimize}} \quad C(x;p)$$

- $C(x;p)$ is a general non-convex cost function covering the horizon
  - passenger cost: waiting and in-vehicle time
  - driver exit lateness cost
  - plan complexity cost
- x is a candidate plan; X is the set of all feasible plans
- p is a set of exogenous parameters and initial conditions
- Constraints
  - vehicles may not exit later than latest allowed exit time
  - vehicle must exit at required exit locations
  - lower and upper bounds on holding times

Spatiotemporal Decomposition

Trip sequences are discrete, spatial variables

$$\underset{s \in S}{\text{minimize}} \quad C(s; d_s^*, p)$$

- s is a candidate combination of trip sequences for all vehicles
- S is the set of all feasible trip sequence combinations
- d_s^* are optimal departure times for each given s

Departure times are continuous, temporal variables

$$\underset{d \in D}{\text{minimize}} \quad C(d; s, p)$$

- d is a set of departure times for all vehicles
- D denotes the feasible space of departure times

Problem Complexity

$$\mathcal{O}\left(\sum_{i=1}^{\prod_{v \in V} |S_v|} k_i\right)$$

- S_v is the set of candidate trip sequences for vehicle v
- k_i is the complexity of optimizing departure times for a set of trip sequences i

Example: 20 vehicles, 5 sequences per vehicle, constant complexity k

$$\mathcal{O}\left(k \cdot 5^{20}\right)$$

Simplified Methodology

Decomposition into sequentially solved subproblems for each vehicle

$$\underset{s_v \in S_v}{\text{minimize}} \quad C(s_v; s_{\bar{v}}, d_s^*, p)$$

- s_v is a candidate trip sequence; S_v is the set of feasible trip sequences
- $s_{\bar{v}}$ are the trip sequences assumed for all other vehicles
- d_s^* are the optimal departure times for each trip sequence combination

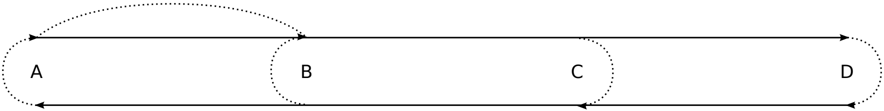
Example: 20 vehicles, 5 sequences per vehicle, constant complexity k, g passes

$$\mathcal{O}\left(gk \cdot 5 \cdot 20\right)$$

Optimization Algorithm

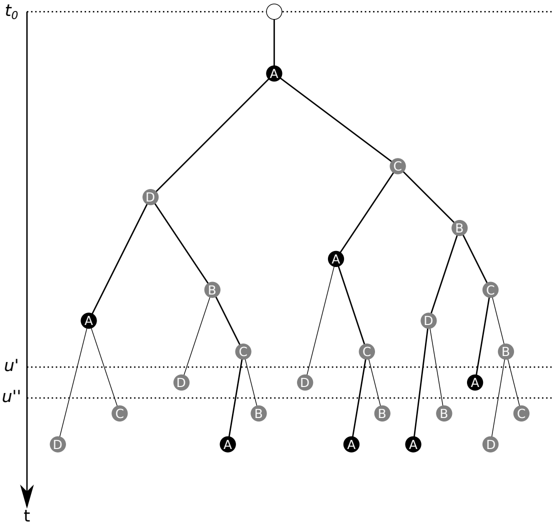
1. Generate *basic trip sequences* for each vehicle
2. Rank vehicles
3. Optimize trip sequence and departure times for each vehicle
    1. Enumerate feasible trip sequences
    2. Discard likely suboptimal trip sequences
    3. Optimize departure times for each trip sequence
        - constrained even headway algorithm
        - constrained rolling horizon optimization
    4. Evaluate performance for each trip sequence
    5. Select best plan
4. Update operations plan

Modeling Variations



- trips between terminals
- short-turning (benign or aggressive)
- deadheading
- expressing (benign or aggressive, including skip-stop)

Generating Feasible Trip Sequences



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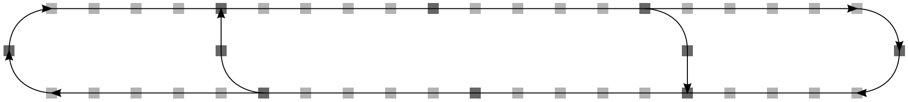
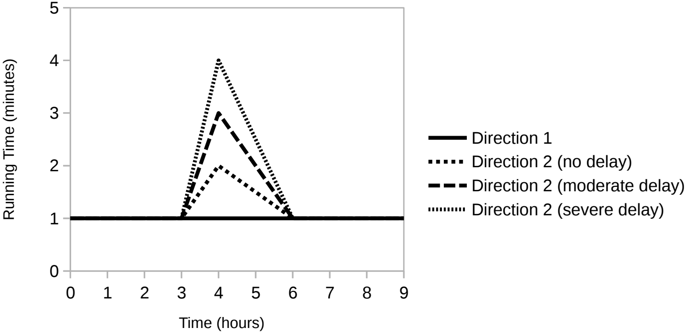
Application



- 25 vehicles (not all operating simultaneously)
- each with capacity for 60 passengers
- trips dispatched over a period of 8 hours
- deterministic running times: no delay, moderate delay, severe delay
- Poisson demand, but with common random numbers
- vehicles should not exit more than 15 minutes after the last scheduled stop

Application: Running Time Delays



- The schedule assumes no delays
- The real-time operations planning algorithm assumes no further delays

Results: No Delay

Delay	Performance Measure	Short-Turning SB	Short-Turning SF	No Short-Turning SB	No Short-Turning SF
None	Waiting Time (min)	2.6	2.6	2.6	2.6
	Excess Waiting Time (min)	0.0	0.0	0.0	0.0
	In-Vehicle Time (min)	9.6	9.5	9.5	9.5
	Late Exits	0	0	0	0
	Max Exit Lateness (min)	0.0	0.0	0.0	0.0
	Trips	190	192	190	190
	Short Turns	0	3	—	—

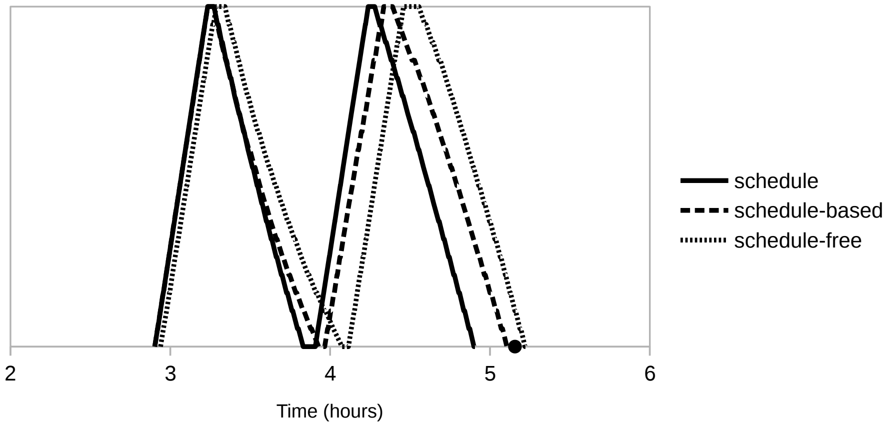
- schedule-based and schedule-free paradigms perform similarly

Results: Moderate Delay

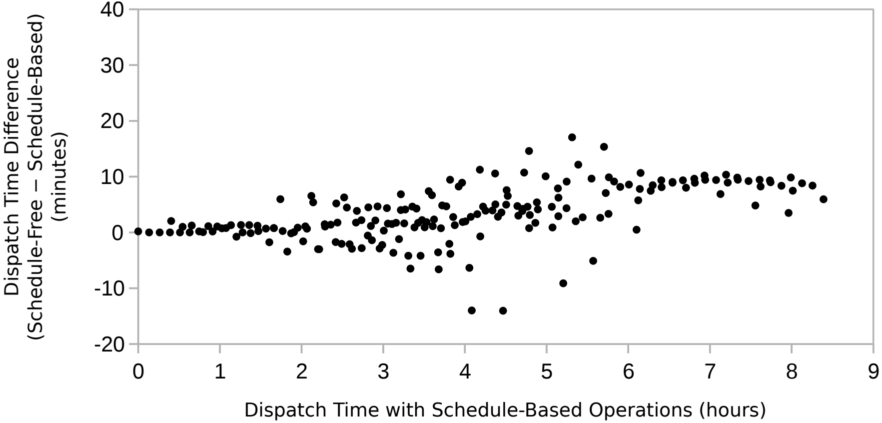
Delay	Performance Measure	Short-Turning SB	Short-Turning SF	No Short-Turning SB	No Short-Turning SF
Moderate	Waiting Time (min)	3.3	2.7	3.4	2.7
	Excess Waiting Time (min)	0.7	0.1	0.8	0.2
	In-Vehicle Time (min)	10.8	10.7	10.7	10.7
	Late Exits	0	6	1	5
	Max Exit Lateness (min)	0.0	4.1	0.6	1.0
	Trips	190	190	190	186
	Short Turns	2	2	—	—

- schedule-free paradigm improves passenger experience
- schedule-free paradigm can lead to greater driver exit lateness
- allowance of short-turning can be counter-productive

Trajectory of Vehicle with Latest Exit: Moderate Delay



Schedule-free dispatch lateness



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Concluding Remarks

1. Under the SFP, vehicle trips are planned in real-time, utilizing real-time information.
2. The real-time planning problem is formulated as a cost minimization problem, but decomposed into related subproblems for each vehicle for tractability.
3. The SFP is feasible and potentially beneficial. However, it can lead to greater exit lateness when delays are unexpected.

Future Work

1. Stochasticity
2. Information modeling
3. Control strategies
4. Entry and exit plan optimization
5. Real-time planning optimization methods
6. Driver constraints
7. Autonomous fleets
8. Organizing informal systems
9. Policy implications
10. Tests on real transit lines

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