Real-Time Integrated Re-scheduling for Tramway Operations

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1 Introduction

Our work aims to develop practical solution approaches for real-time dispatch of crews and vehicles for disruption management. The practical motivation for our research arose from the operations of a public tramway system in Hong Kong. The tram system shares the road with other vehicular traffic in an urban area of the city, and thus is subject to congestion and other disruptions (unexpected traffic conditions, accidents, etc.), making it a challenge to run to schedule. Delays accumulating and propagating over the course of a day can lead to poor service and high operational cost. In this research, we investigate how the availability of historical and real-time auto-sensed location and traffic information can be utilized to improve the real-time scheduling decisions. The historical information is used to estimate the travel times for each route during different periods of the day, while the real-time information about the tram locations is utilized to update the expected completion times of the current assignments for each motorman. Updated estimated travel times and completion times of tasks are fed to a mixed-integer programming model for re-optimization of the schedule.

The dynamic and integrated vehicle and crew scheduling problem for real-time control studied in our research has the following characteristics: 1) the actual travel times may deviate from the planned times and are dependent on the time of day and 2) while the on-going route/activity assigned to a motorman cannot be revised, the future assignments can be re-optmized when unexpected events occur. We adopt a rolling horizon approach to re-optimizing the future activities of the motormen from time to time. Upon an arrival of a motorman at a tram terminus or depot, he will be given a sequence of future task assignments, consisting of the routes to run and the scheduled departure times. The motormen will follow his revised sequence of future task assignments until the next re-optimization is performed. The objective is to achieve the target route frequencies in order to provide good quality of services to passengers, and minimize the violation of staff regulations (meal-break delays and overtime). While our application is motivated by tram services, our model can also be extended for other logistics services that suffer from daily transportation disruptions and require prompt recovery of schedules, particularly for those in an urban city setting.

The literature on the relevant techniques and applications is immense. We refer the reader to Cacchiani et al. (2014) for a comprehensive review of dynamic vehicle routing problems and Pillac et al. (2013) for an overview of real-time recovery models and algorithms for railway disruption management.

2 Notation and Problem Formulation

Our model makes use of the following **notation**:

T : set of all tram termini and depots
D : set of tram depots
L_d : set of termini walkable from/to depot d
M_t^1 : set of motormen who are not having any duty and will be available for task (re-)assignments at terminus/depot t within the coming period
M_t^2 : set of motormen who are having a duty heading to terminus/depot t within the coming period
M_t : $M_t^1 \cup M_t^2$
S_t^m : set of sequences of task assignments originating from terminus/depot t that are feasible for motorman m
R : set of tram service routes
P : set of time periods
d_{rp} : target number of trams departures for route r in period p
T_t : current number of trams available at terminus/depot t
a_{rp}^{ms} : 1, if assignment of motorman m to sequence of task assignments s covers route r in period $p; 0$, otherwise
c_t^{ms} : 1, if the first duty of assignment of motorman m to sequence of task assignments s originates from terminus/depot t within the coming period; 0, otherwise
q_t^{ms} : 1, if assignment of motorman m to sequence of task assignments s ends with a meal-break/sign-off at terminus/depot t within the coming period; 0, otherwise

Our model requires the following **decision variables**:

x_{ms} : 1, if motorman m is assigned sequence of task assignments s; 0, otherwise

u_{gp} : shortage in tram deployments for route g in period p

s_{gp} : over-deployments of trams for route g in period p.

Our **model formulation** is as follows:

$$\min \quad \sum_{t\in T}\sum_{m\in M_t}\sum_{s\in S_t^m}\omega_{ms}^{x}x_{ms}+\sum_{p\in P}\sum_{g\in R}\omega_{gp}^{u}u_{gp}+\sum_{p\in P}\sum_{g\in R'}\omega_{gp}^{s}s_{gp} \tag{1}$$

$$\text{subject to} \quad \sum_{t\in T}\sum_{m\in M_t}\sum_{s\in S_t^m}a_{gp}^{ms}x_{ms}+u_{gp}-s_{gp} = d_{gp} \qquad \forall g\in R, p\in P \tag{2}$$

$$\sum_{s\in S_t^m}x_{ms} = 1 \qquad \forall t\in T, m\in M_t \tag{3}$$

$$\sum_{t\in L_d}\sum_{m\in M_t^1}\sum_{s\in S_t^m}c_d^{ms}x_{ms}+\sum_{m\in M_d^1}\sum_{s\in S_d^m}c_d^{ms}x_{ms} \leq T_d+\sum_{m\in M_d^2}\sum_{s\in S_d^m}q_d^{ms}x_{ms} \qquad \forall d\in D \tag{4}$$

$$\sum_{m\in M_t^1}\sum_{s\in S_t^m}c_t^{ms}x_{ms}+\sum_{m\in M_d^1}\sum_{s\in S_d^m}c_t^{ms}x_{ms} \leq T_t+\sum_{m\in M_t^2}\sum_{s\in S_t^m}q_t^{ms}x_{ms} \qquad \forall d\in D, t\in L_d \tag{5}$$

$$u_{gp}, s_{gp} \geq 0 \qquad \forall g\in R, p\in P \tag{6}$$

$$x_{ms} \in \{0,1\} \qquad \forall m\in M, t\in T, s\in S_t^m \tag{7}$$

Objective (1) aims to minimize a weighted sum of the penalty for assignments (regarding expected deviations of staff meal-break and sign-off times from the planned schedule, idle time, violation in maximum working hours, and reduced mileage) and shortages and over-deployments of trams. Constraints (2) calculate the shortages or over-deployments of trams for all routes in all periods. Constraints (3) ensure that each motorman required for a (re-)assignment is assigned to a sequence of duties for the rest of the operational day. Constraints (4) and (5) ensure that there are sufficient trams available for assignments of motormen to sequences of duties. Constraints (6) and (7) respectively impose non-negativity and binary conditions on the relevant decision variables.

We adopt an enumeration approach to generating the set of feasible sequences of task assignments for each motorman, with the provision of the real-time information about their locations, the updated expected arrival time to the destination, and the historical travel times. These sources of information will be used to construct the sets M_t^1, M_t^2, S_t^m, and a_{rp}^{ms}. Since each sequence of tasks has scheduled departure times, they will be used for determining a_{rp}^{ms}. In addition, T_t are also updated through the real-time tram-locating system.

3 Computational Study

We evaluated the performance of our approach using a simulation model of the tram network with actual data provided by the company. The travel times of trams were stochastic in the simulation model and modelled with historical data. In our experiments, we revised the assignments of motormen every 30 minutes under a rolling horizon framework. We adopted IBM ILOG CPLEX 12.6.2 as our mixed-integer programming solver.

In consultation with the tramway company that motivated our work, we came up with a set of weights for the objective function. We evaluated the effectiveness of our approach by comparing it with the baseline scenario, where no re-scheduling was performed and motormen followed their original planned schedules for the whole operational day. The computational results show that our re-scheduling approach can increase the overall mileage by 548 miles and the service coverage by 5%, and reduce the average staff idle time by 9 minutes and early sign-off time by 11 minutes, with a slight increase in staff overtime of 4 minutes. Our model can also be used to explore the trade-off between different objectives terms (e.g., overtime, mileage and service coverage) with adjustments made in the weights in the objective function. Our computational experiments also suggest that our mathematical model can be solved efficiently. The average and worst computational times to perform an re-optimization were 21.39s and 48.46s. The solution times demonstrate the practicality of our approach for near-real time implementation.

References

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