ONLINE STOCHASTIC OPTIMIZATION FOR REAL-TIME TRANSFER SYNCHRONIZATION IN PUBLIC TRANSIT NETWORKS

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1 INTRODUCTION

Public transportation systems are essential to urban mobility, particularly as cities grapple with rising congestion and the demand for sustainable transport solutions. Poor transfer synchronization between transit lines can lead to increased travel times and reduced ridership as passengers miss critical connections. This issue is especially challenging in dynamic transit environments, where operations are affected by unpredictable traffic patterns, delays, and fluctuations in passenger behavior.

Current approaches to transfer synchronization often rely on deterministic models, applied primarily during the planning phase, that lack the flexibility to adapt to real-time uncertainties and dynamic changes in network conditions. Recent studies increasingly address real-time transfer synchronization problems, but most focus on small-scale instances with limited transfer points while considering few sources of uncertainty. Many existing methods lack the adaptability and scalability required for complex, high-demand networks where passenger demand, vehicle delays, and other unpredictable factors introduce significant variability.

This study addresses these limitations by proposing a novel approach for real-time transfer synchronization in public transit networks, leveraging an arc-flow model that comprehensively integrates three key control tactics—the hold, skip-stop, and speedup tactics—to minimize passenger travel times. This formulation enables the application of online stochastic optimization (OSO) algorithms adapting to fluctuations in real time. The proposed models are tested on a large-scale dataset including 27 bus lines from the public transit network of the city of Laval, Canada. This approach illustrates the practical feasibility of applying online stochastic optimization algorithms for the transfer synchronization problem.

2 METHODOLOGY

We develop an arc-flow formulation using a time-expanded graph structure that incorporates three primary control tactics. Tactics can be applied individually or in combination, to optimize transfer synchronization and reduce passenger travel times. The hold tactic involves delaying a bus at a stop to allow transfer passengers to board. The skip-stop tactic reduces travel time and mitigates delays by allowing a bus to bypass certain stops. While this improves efficiency, it may inconvenience alighting passengers, who must walk from the nearest stop, and boarding passengers, who must wait for the next bus. Finally, the speedup tactic increases travel speed between stops, with a speedup factor suggested by the Société de Transport de Laval (STL). The model optimizes the use of these tactics by integrating them into a time-expanded graph, where nodes represent specific times at specific stops, and arcs represent possible travel and waiting times (see Figure 1). Each passenger's journey through the network is represented by flows on the arcs. Our objective is to minimize total passenger travel time, accounting for both in-vehicle time and waiting time at stops and transfer points.

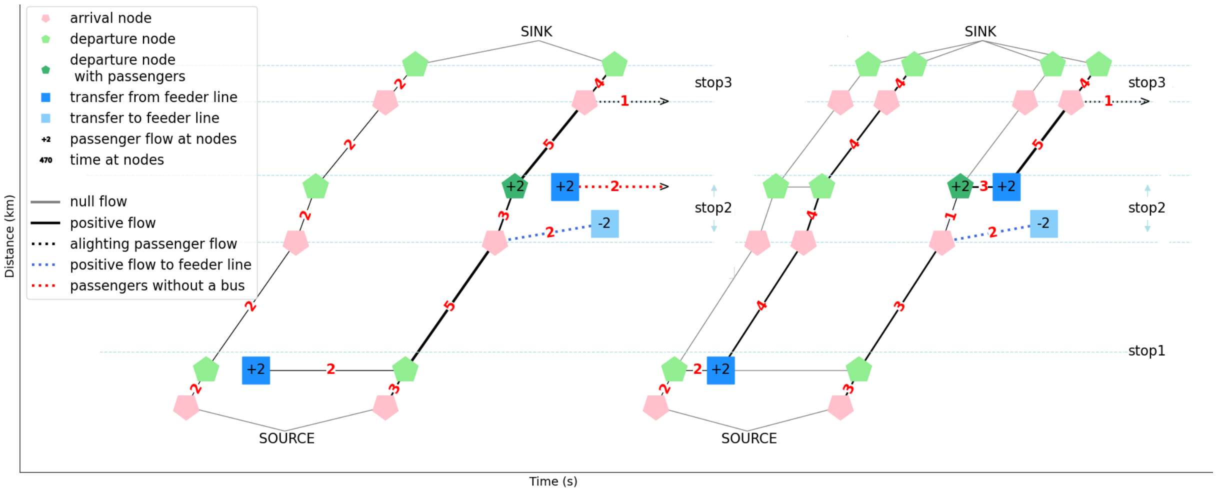

Figure 1 – *Graph for the arc-flow model demonstrating the construction of hold tactics. Left: no tactics, right: with hold tactics.*

We implement two OSO algorithms, Consensus (C) and Regret (R), based on the arc-flow model. Algorithms C and R are adapted from the literature for the transfer synchronization problem. Both algorithms model uncertainty by generating multiple scenarios through sampling, using real-time and historical data. C evaluates multiple scenarios and selects the tactic that is optimal across the greatest number of scenarios. However, C does not account for the performance of other tactics that may be close in effectiveness. In contrast, R evaluates each suboptimal tactic against the optimal tactic for each scenario, quantifying the "regret" as the additional travel and wait time associated with using a suboptimal tactic. It then aggregates these regret values across all scenarios, selecting the tactic with the lowest overall regret. This ensures that the chosen tactic is reliable, as it consistently performs well across scenarios. Operating in a rolling horizon framework, both algorithms re-optimize decisions at each stop as new real-time data becomes available. This dynamic approach enables continuous adaptation to evolving network conditions, making both algorithms well-suited for real-time applications.

To evaluate the performance of the online stochastic optimization algorithms, we also implement two benchmark approaches: the Perfect Information (PI) solution and the Deterministic (D) algorithm. The PI solution applies the offline model in a dynamic setting with complete knowledge of the current state, without uncertainty, for each stop within the control horizon. In contrast, D algorithm operates with a single scenario generated from average historical data, representing an expected system state without modeling variability. This approach uses only mean values for state variables, providing a comparison to evaluate the benefits of scenario sampling in the OSO algorithms. A sensitivity analysis was conducted on key parameters, including the number of scenarios, control horizon length, and the cost of out-of-bus waiting times.

3 RESULTS

The algorithms were tested on a comprehensive dataset from Laval's public transit network, covering 27 bus lines, thousands of passengers, and transfers over a full month. Real-time data from Automatic Fare Collection (AFC), Automatic Passenger Counting (APC), and smart cards were used to simulate real-world operations. The simulation dynamically generates line-specific demand by preprocessing and clustering historical boarding, alighting, and transfer data, capturing variations across lines and times of day. This allows the optimization framework to adapt to diverse passenger flow patterns, transfer dependencies, and stop-level demand distributions. Key performance indicators include the percentage of successful transfers and total passenger travel time. The results of the OSO algorithms are also compared to the Baseline (B), which involves no control tactics and is what happened in real life. The average percentage of passengers with missed transfers for B is 6.09%. A transfer is called missed if it was possible in the planned schedule but impossible in the simulation. In detail, Algorithm R consistently outperforms both C and D algorithms. By adapting to variations in demand and delays, R reduces the percentage of missed transfers by half while lowering passenger travel time by nearly 2.5% over all test instances for 27 bus lines in the STL network (see Table 1 for results). Figure 2 shows results from computations on instances from line 33, involving approximately 1,000 passengers and nearly 250 transfers. On a medium-frequency line like line 33, each successful transfer saves more time for passengers compared to a high-frequency line. The results show that R's performance is closer to the PI solution in this context, suggesting that scenario-based sampling is particularly effective on medium-frequency lines. Algorithm D provides a stable improvement over both B and C, consistently reducing missed transfers without increasing passenger travel

Table 1 – *Mean percentage of missed transfers and mean change in total passenger travel time compared the baseline.*

		Algorithm		PI
Tactics	Average	D	R	Solution
Hold	Passengers with missed transfers	4.21%	3.47%	1.62%
	Reduction in total passenger travel time	1.53%	2.39%	4.21%
Hold & Speedup	Passengers with missed transfers	4.81%	3.41%	1.50%
	Reduction in total passenger travel time	1.27%	2.89%	4.78%
Hold & Skip-stop	Passengers with missed transfers	5.02%	3.35%	1.48%
	Reduction in total passenger travel time	0.50%	2.49%	4.31%

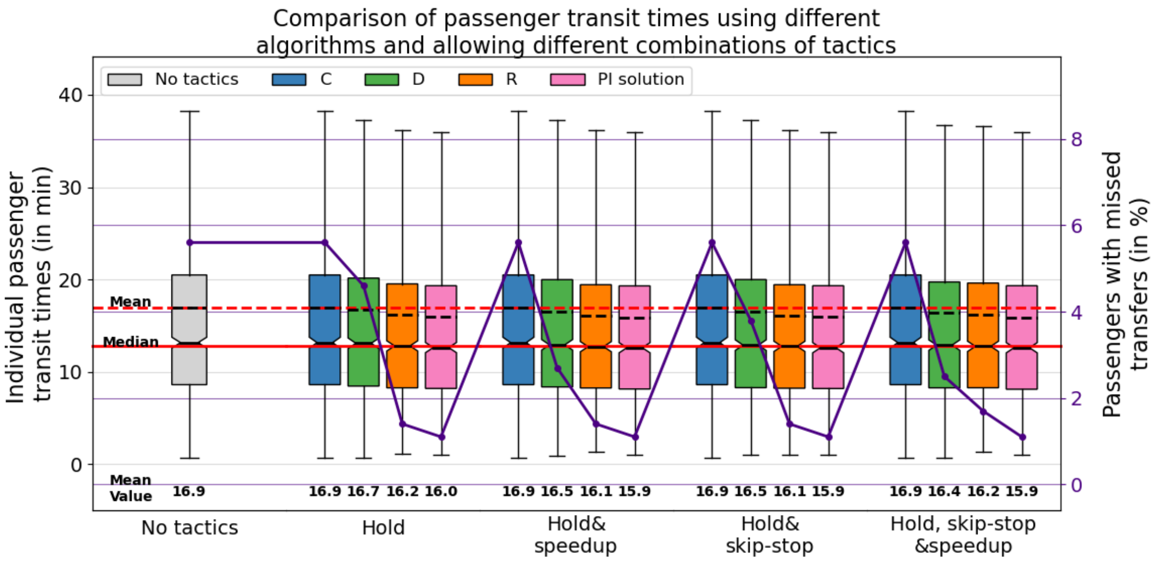

Figure 2 – *Results for line 33.*

times. However, it cannot match the adaptability of R. When the speedup tactic is available, D performs better but still lags behind R. Finally, by focusing on the tactic that is most frequently optimal, C can implement suboptimal choices for the real instance, leading to lower transfer success rates. C's inability to account for the full variability of conditions across scenarios limits its effectiveness. Additionally, these findings indicate that the models are more effective on medium- and low-frequency lines, or on lines with fewer passengers. In such cases, a small set of tactics can significantly impact transfer success while minimizing inconvenience for onboard passengers. Algorithm R achieves the best results when both hold and skip-stop tactics are used. However, when all three tactics are applied, a slight degradation in performance occurs, likely due to the overuse of tactics.

Computation times for both C and R are consistently under ten seconds per re-optimization, allowing for an implementation in real-time. The tests conducted on 27 lines show that R achieves a great reduction in the percentage of missed transfers and in travel time underscoring its robustness in adapting to real-time conditions.

4 DISCUSSION

Transfer synchronization is essential for reliable public transit (PT) service, directly affecting passenger satisfaction. Public transit systems operate in highly uncertain environments, where vehicle delays, passenger demand fluctuations, and unexpected events can disrupt schedules. This study presents a novel approach to real-time transfer synchronization using three control tactics - hold, skip-stop and speedup. We introduce an arc-flow model integrating these tactics into time-expanded graphs. Then we use a discrete-event dynamic environment simulating real-time operations to test two online stochastic optimization algorithms, Consensus and Regret, based on the arc-flow model. By incorporating real-time data into an online stochastic optimization framework, our algorithms provide an adaptable solution for transfer synchronization. Results show a significant improvement in the number of missed transfer as well as in the passenger travel times across 27 bus lines from the public transit system of the city of Laval.

The algorithms are currently being implemented in a network-wide simulation framework to validate their scalability. This implementation required minimal modification of the algorithms. Future work will focus on refining the scenario generation process to improve the accuracy of real-time predictions. Additionally, further research will explore the integration of these methods with other modes of transportation.

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