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Optimal Public-Transport Transfer Synchronization Using Operational Tactics

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Abstract

Transfers in public-transport are used to create a more efficient network, by reducing operational costs and allowing more flexible route planning. However because of the stochastic nature of traffic, scheduled transfers do not always occur, thus increasing the total passenger travel time and reducing the attractiveness of the public-transport service. This work analyzes how to use selected operational tactics in public-transport networks for increasing the actual occurrence of scheduled transfers. A model is developed to determine the impact of instructing vehicles to either hold at or skip certain stops, on the total passenger travel time and the number of simultaneous transfers. The model is comprised of two components. First, a simulation of public-transport network examines the two tactics for maximizing the number of transfers. Second, an ILOG optimization model is used for optimal determination of the combination of the two tactics to achieve the maximum number of simultaneous transfers. An Auckland bus network was created, as a case study, to verify the impact of the model's application. The results show that applying online operational tactics dramatically improved the frequency of simultaneous transfers. The concept has large potential for increasing the efficiency and attractiveness of public-transport networks which involve scheduled transfers.

Keywords: Operational tactics, real time tactics, public transport networks, transfer, transfer synchronization, transfer optimization.

1 Introduction

In any public-transport (PT) network, it is impractical to have routes between every conceivable trip origin and every conceivable trip destination. There are too many possible routes and the service cannot be economically provided. Transfers in the network allow routes to complement each other meaning fewer routes are able to provide the same level of coverage. This in turn enables higher frequency services and an easier network to understand and remember, increasing the attractiveness as a whole (Mees, 2000).

Transfers in general allow more flexibility in route planning and more effective use of services which results in a more efficient PT network, associated environment

(Waterson et al., 2003), economic (Jakob et al., 2006), health and social benefits (Barton and Tsourou, 2000) (Frank et al., 2006).

Conversely transfers are cited as a key reason for PT being less attractive than cars (Knoppers and Muller, 1995). Due to the stochastic nature of travel times, dwell times and passenger demands in PT networks, two vehicles which are scheduled to arrive simultaneously at the same stop (a scheduled transfer) have a small encounter probability of (a direct transfer). This can cause frustration, longer passenger waiting times and a less efficient system as a whole.

Transfer synchronization aims to increase the number and probability of bus encounters. Some researchers e.g. Ceder, Golany et al. (Ceder et al., 2001), Domschke (1989) and Fleurent, Lessard and Séguin (2007) have used mathematical relationships to generate timetables with the maximum opportunity for direct transfers.

Another way of improving the occurrence of transfers is by using "operational tactics" in real time, first outlined by Ceder (2007). Hadas and Ceder (2008) evaluated the specific tactics of holding vehicles at stops in anticipation of connections and instructing skip-stops and shortcuts of routes to meet subsequent connections. Use of these tactics was assessed with simulation on synchronized transfers, in a complex although contrived, discrete model. The stochastic nature of transfers was taken into account with estimates of probabilities of encounters, based upon the difference in arrival times. It was shown that large increases in the number of direct transfers and small reductions in the total user travel time could be achieved. They suggested that this would dramatically increase the comfort of passengers and the attractiveness of the network (Hadas and Ceder, 2008).

This research analyses how instructing vehicles to either hold at or skip certain stops can increase the occurrence of direct transfers and improve the efficiency as measured by total passenger travel time in the PT network as a whole. It develops a model and methodology to determine the effect of various tactics at various stops and how these tactics should be best applied.

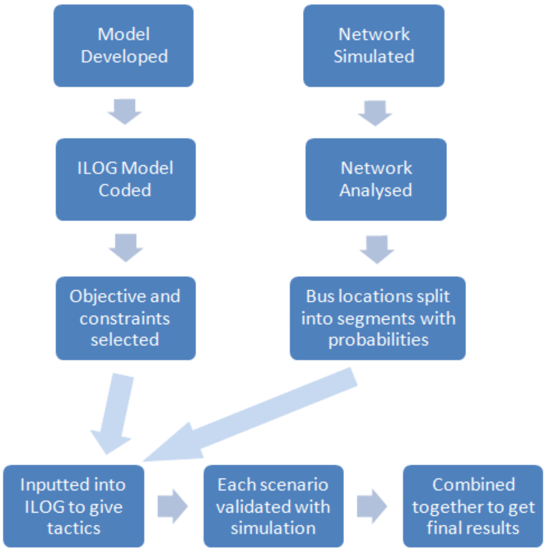
A simulation of an appropriate PT network in Auckland was developed in order to determine the effect of the network's stochastic nature on direct scheduled transfers, with and without operational tactics.

These were integrated in order to assess the impact of operational tactics for the simulated Auckland network.

2 Methodology

2.1 Model Derivation

A model was derived from first principles in order to assess what the impact of operational tactics was on the network. This impact was measured by two criteria, the number of direct transfers, and the change in total passenger travel time (ΔTPTT). It is intended for use with deterministic data.



Parameters:

R	is the set of all bus routes
N	is the set of all bus stops
$Y_{X\mu}^{n}$	= 1 if bus X is late causing a missed direct transfer with bus µ at stop n, before any tactics and n is a transfer point between X and µ = 0 otherwise
f	the ratio of average bus to average pedestrian travel speed through urban areas
e_X^n	number of passengers entering the network onto bus X at stop n (i.e. excl. transferring passengers)
l_X^n	number of passengers leaving the bus network from bus X at stop n (i.e. excl. transferring passengers)
$t_{X\mu}^{n}$	number of passengers wishing to transfer from bus X to bus µ at stop n
d_X^n	dwell time of bus X at stop n
p_X^n	number of passengers riding bus X as it arrives at stop n.
c_X^n	the estimated time between bus X arriving at stop n and arriving at the previous stop (without tactics)
Q_X^i	vector listing all stops of route X in order defined by a natural number position, *i*
V_X^n	vector listing the positional index, *i*, of stop n on route X (0 if not on route)
h_X	headway between buses route X
T_X	initial time difference that bus X is behind schedule
m_X	total number of stops on route X
k_X	positional index, *i*, of the next stop on route X that the bus will arrive at
g_X	elapsed time since bus X arrived at the previous stop on the route to its current position

Figure 1: Methodology flow chart

Decision Variables

W_X^n	time to hold bus X at stop n
S_X^n	= 1 if bus X skips stop n = 0 otherwise
$Z_{X\mu}^{n}$	= 1 if bus X is late causing a missed direct transfer with bus µ at stop n, after any tactics and n is a transfer point between X and µ = 0 otherwise
$DT_{X\mu}^{n}$	= 1 if a direct transfer occurs for bus X with µ at stop n after any tactics = 0 otherwise

Objectives:

(1) Minimise $\Delta\text{TPTT} = \sum_{X\in R} \sum_{n\in N}$

$$\text{(a)}\, W_X^n \ \{ \ p_X^n - l_X^n + e_X^n \ + (\textstyle\sum_{\mu\in R,\mu\neq X} \ (1 - Y_{\mu X}^n)\, t_{\mu X}^n - t_{X\mu}^n) + \sum_{i=V_X^n+1}^{m_X} [\, e_X^{Q_X^i} + \sum_{\mu\in R,\mu\neq X} \ t_{X\mu}^{Q_X^i}\,(1 - Z_{\mu X}^{Q_X^i})] \ \}$$

$$\text{(b)} + S_X^n \ \{ l_X^n \, f c_X^{Q_X^{V_X^n+1}} + e_X^n(h_X - \ T_X + \textstyle\sum_{i=k_X}^{V_X^n-1} [S_X^{Q_X^i}\, d_X^{Q_X^i} - W_X^{Q_X^i}]) - d_X^n \ (p_X^n + \sum_{i=V_X^n+1}^{m_X} [\, e_X^{Q_X^i} + \ \sum_{\mu\in R,\mu\neq X} \ t_{X\mu}^{Q_X^i}\,(1 - Z_{\mu X}^{Q_X^i})])\}$$

$$\text{(c)} + \textstyle\sum_{\mu\in R,\mu\neq X} \ [t_{X\mu}^n\{ \ Z_{X\mu}^n\,(h_\mu - T_X \ + \sum_{i=k_X}^{V_X^n-1} [S_X^{Q_X^i}\, d_X^{Q_X^i} - W_X^{Q_X^i}]) \ - Y_{X\mu}^n\,(h_\mu - T_X)\}]$$

(2) Maximise $= \sum_{X\in R} \sum_{\mu\in R,\mu\neq X} \sum_{n\in N} \ DT_{\mu X}^{n}$

Subject to:

(3) $\boldsymbol{\sum_{i=k_A}^{V_A^n} c_A^{Q_A^i} - g_A - \sum_{i=k_A}^{V_A^n-1} \left[S_A^{Q_A^i} d_A^{Q_A^i} - W_A^{Q_A^i}\right] - \sum_{i=k_B}^{V_B^n} c_B^{Q_B^i} + g_B - d_B^n - W_B^n + \sum_{i=k_B}^{V_B^n-1} [S_B^{Q_B^i} d_B^{Q_B^i} - W_B^{Q_B^i}] \leq 9999 Z_{AB}^n}$

(4) Y_{AB}^n = 1 if true: $\sum_{i=k_B}^{V_B^n} c_B^{Q_B^i} - g_B + d_B^n \leq \sum_{i=k_A}^{V_A^n} c_A^{Q_A^i} - g_A$
= 0 otherwise, or any variables are undefined

(5) $DT_{\mu X}^n$ =1 if true: $Z_{\mu X}^n + Z_{\mu X}^n = 0$, $t_{\mu X}^n + t_{\mu X}^n > 0$
=0 otherwise

(6) $S_X^n \left(\sum_{\mu \in R, \mu \neq X} [t_{X\mu}^n + t_{\mu X}^n]\right) = 0$

(7) S_X^n , $W_X^n = 0$ when $V_X^n < k_X$

(8) $S_X^n + S_X^{Q_X^{V_X^n+1}} \leq 1$

(9) $S_X^n W_X^n = 0$

Assumptions:

- Foreknowledge of the route information, including travel times, passenger demands, transferring passengers and dwell times. In this way the model was designed to work with deterministic data.
- Passenger demands do not change with a varying bus arrival time.
- Transfers are scheduled and the next buses are on time.
- Any waiting passengers skipped, or those that miss their transfer connections will wait for the next bus which is also on time.
- Transfers can only occur at a single physical bus stop, this means that the time for passengers to transfer is ignored.
- Stops where people want to transfer cannot be skipped, nor can more than one stop in a row be skipped.

Equation 1 represents the change in total passenger travel time (ΔTPTT). This consists of three parts, the holding, skip stop and a late to transfer effect, 1a, 1b and 1c respectively.

Holding a vehicle in (1a) increases the travel time for the passengers on the bus and those waiting for the bus further along the route. Determining the number of passengers on the bus is complicated by whether or not passengers transferring onto the bus have boarded and made the transfer. By assuming that the bus would not be holding if these passengers had already boarded, and will only hold until they board, these passengers can be ignored. This is improved by assuming they would have made the transfer without the application of any tactics at all and increasing the passengers held on board by $(1-Y_{X\mu}^n)\, t_{X\mu}^n$.

Those advantaged by the skip stop (2a) with the time saving d_X^n are those who are currently on the bus $p_X^n$and those that will get on the bus in the future.

Those that wanted to alight and those that wanted to board are now disadvantaged.

The approximation of the extra travel time for these passengers is$fc_X^{Q_X^{V_X^n+1}}$. It is assumed that the extra dwell time at the subsequent bus stop from extra passengers alighting is negligible; it is unlikely a stop would be skipped if large numbers were alighting.

The wait for those that wanted to board skipped is $h_X - T_X$ if no tactics were applied, but if tactics had been applied at previous stops the wait is $h_X - T_X + \sum_{i=k_X}^{V_X^n-1} [S_X^{Q_X^i} d_X^{Q_X^i} - W_X^{Q_X^i}]$.

For (1c) if a bus is late to a scheduled transfer, the passengers on board that wanted to transfer are disadvantaged. Transferring passengers on the earlier bus will only have to wait for the other bus to arrive, and any tactics to this bus affecting these passengers are taken into account in 1a and 1c.

For transferring passengers on bus X missing the connection to bus µ at stop n, the wait is h_μ -T_X pre-tactics and $h_\mu - T_X + \sum_{i=k_X}^{V_X^n-1} [S_X^{Q_X^i} d_X^{Q_X^i} - W_X^{Q_X^i}]$ post-tactics. If a direct transfer is made then there is no transfer waiting delays at all. The difference between the two delays before and after tactics is the ΔTPTT relating to making/missing direct transfers that occurs from applying tactics. All Xµ combinations are summed.

Equation 2 represents the total number of buses that make a direct transfer. (3) and (4) determine Y and Z respectively. If either route does not travel to stop n, c_B^n, c_A^n is undefined and Y, Z is taken as 0. Z was taken as a decision variable to enable use with IBM ILOG. (5) determines if a bus makes a direct transfer while (6) states stops cannot be skipped where passengers want to transfer. (7) ensures there is no tactics on stops that a bus is not going to or is already passed. Finally (8) allows only one skipped stop in a row and (9) provides for no skipping and holding at the same stop.

2.2 IBM ILOG Optimization

This model was then inputted into the optimization software IBM ILOG to enable the best operational tactics for any situational input or objective to be computed.

The CP programming tool was used, which required the decision variables to be discrete. Hold time was calculated to the second, with 0 indicating no holding. A maximum hold time constraint was added of no more than half the headway of the route, $W_X^n \leq \frac{1}{2} h_X$

The ILOG model was integrated with excel spreadsheets so data initialization was easier for a wide range of network types and situations.

3 Application to Auckland

3.1 Auckland PT routes

To assess the effectiveness of the model and potential for implementation, it was applied to an Auckland PT network. Three routes with two transfer points from the Northern bus network were chosen as an Auckland PT network to evaluate. These routes and the Northern Busway in general have been designed around the concept of transfers. There are no current synchronized or scheduled transfers, but there is future potential for their implementation here.

The routes were the 155 route on the Northern Busway, the 880 route which runs north-south (east of the busway) and the 913 feeder loop which transfers with both (see Figure 2 below).

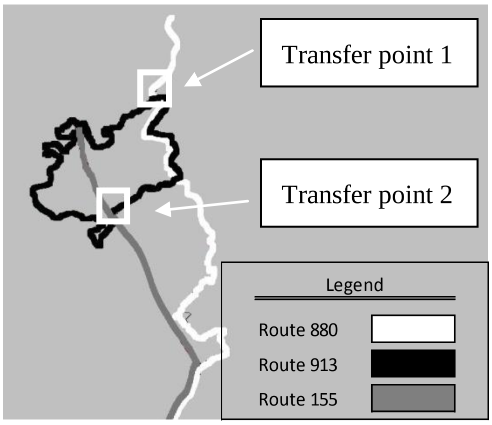


Figure 2: North Shore City with three bus routes. Transfer point 1 and 2 located in white squares. Source: Google Maps.

ARTA provided the information for these three routes. Route 880 starts from Long Bay Regional Park, Route 913 starts from Massey University, Albany and Route 155 starts from Albany Station Platform 2a.

Route 880 and 913 intersect at transfer at point 1 on Bute Road, Browns Bay. Route 913 and 155 connect at transfer point 2 at the Constellation Bus Station, Albany.

3.1 Microscopic simulation model

The versatile microscopic traffic simulation software used was TransModeler 2.6 created by the Caliper Corporation in order to simulate transit vehicles in a stochastic network.

The simulation consisted of carriageways that are used by the bus route only. Due to the complexity of the model and time limitations, the model did not include external traffic, intersection control and side streets. A function within TransModeler however allowed the ‘road class’ to be selected to suit the speed-density function of a particular segment of road. Route 155 (Northern Busway) was classified as an Expressway. Routes 880 and 913 are a mixture of minor and major arterial roads.

This software allowed the stochastic transit routes to be simulated as the derived model used deterministic data.

3.2 Data collection

Bus route data for the different routes were collected from the Auckland Transport Authority (ARTA). Important information such as the road layout and physical stops were used for the construction of the simulation. Other data had to be assumed.

Each road segment was given a road class. Route 155 in particular was classified as an expressway as there was no traffic variability on the busway.

The travel time of buses from one stop to another could be obtained from the outputs produced by TransModeler. Parameters which affected the speed of buses such as the acceleration function were left to their recommended default values.

The dwell times of buses depended on the parameters in TransModeler. The fleet size of the buses were set to having a capacity of 40 sitting and 20 standing in order to take into bus ‘crowding’. The dead time, passenger boarding time and passenger alighting time was set to the default values of 4, 3.5 and 2.2 seconds respectively. These times were consistent with a study by (Dueker et al., 2004).

Passenger demand was assumed by using the known numbers of stops for each route. The passenger demand was set to be higher at transfer stops in order to simulate the event of passengers transferring.

3.3 Analysis

The tools developed were then used together in the application to the selected North Shore bus network to assess the potential impact of operational tactics. This was done by first simulating the network with no operational tactics used. The departure times of each bus was adjusted so that the mean arrival time at each transfer point was the same. The percentage of direct transfers at each transfer point was evaluated.

Also from this simulation the different bus locations before the transfer point was evaluated. When the 913 bus arrived at a stop four stops before the transfer point, the other bus could be in many different locations. By dividing the other bus's route up into small segments the probability of it being present was found.

The 'situation' of the buses in each of these segments was plugged into the ILOG optimization model, assuming that any bus in a particular segment was in the middle of that segment, and using deterministic data estimated from the average quantities already witnessed in the network. The selected objective criterion was the number of direct transfers. This was coupled with the constraint that no tactics could be implemented unless both the total passenger travel time of the network was decreased and a direct transfer was predicted.

Finally each of these 'situations' was simulated in TransModeler with the tactics employed. This enabled the deterministic model to integrate and be evaluated with a stochastic environment. This enabled a validation percentage to be obtained outlining the percentage of times applying those tactics to a particular segment actually resulted in a direct transfer.

The probabilities for each segment were then multiplied by the percentage of the time that the operational tactics actually enabled the direct transfer and summed. This resulted in a final percentage for the amount of scheduled direct transfers that actually resulted in a direct transfer to be ascertained, for each headway spacing and transfer point.

4 Results

It was shown that because of the stochastic nature of the network that direct transfers occurred infrequently without tactics (see Figure 3 right).

The occurrence of direct transfers without tactics was rare. This was expected due to the stochastic nature of the network. The different headway saw no statistically significant difference between the percentages of direct transfers at each transfer points. Transfer point two had significantly lower percentages of direct transfers than transfer point one. This was because it was further from the start of the routes, so there was greater variability in the travel time, the arrival time and

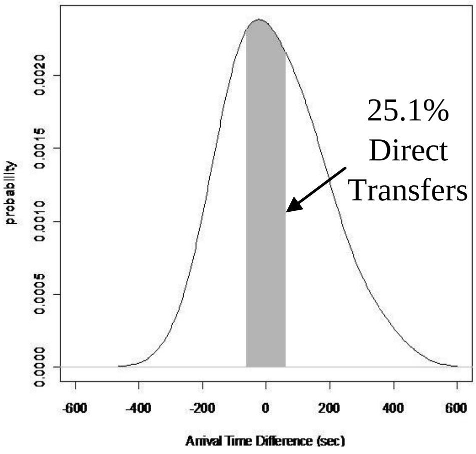


Figure 3: Percentage of successful transfers and arrival time difference at transfer point 1 with 5 minute headways.

therefore the arrival time differences.

The tactics implemented by the model made a substantial improvement to the percentage of direct transfers for all headways and transfer points (see Table 1 below). The tactics implemented also improved the efficiency of the network, reducing the total passenger travel time substantially.

Table 1: The percentage of direct transfers achieved for each scenario

Percentage of direct transfers		**Without tactics**	**After Tactics**	**After Validation**	**Ratio of increase**
Transfer1	5 min hw	25.1%	55.2%	51.9%	2.1
	20min hw	23.1%	77.6%	48.7%	2.1
Transfer2	5min hw	9.7%	20.3%	20.3%	2.1
	20min hw	13.7%	53.4%	50.4%	3.7

The 20 minute headways, especially at transfer point two, had greater potential for implementation of tactics. This was because of two reasons. Firstly there was less variability in the travel times for 20 minute headways, as bus bunching did not occur as often or to the same magnitude. Secondly the time delay for passengers that miss transfers with larger headways was higher, so more often are tactics implemented to make the transfer and improve the total passenger travel time.

Overall the validation showed that when the optimization model indicated certain operational tactics to be employed to make a direct transfer, this actually occurred 95.2% of the time. Most of the times that the tactics did not result in the direct transfer occurring, the buses only just missed each other. A second application of tactics in this case should increase the validation percentage to close to 100%.

5 Discussion

There are several limitations to the model developed, and these relate to the assumptions used in its derivation. The assumptions of the next bus being on time and the passenger demands not changing for small variations in bus arrival times are not always valid. This was a reasonable assumption for small deviations of the bus from schedule. As the deviation from schedule increases the model will be less accurate. Significant deviations could be due to heavy traffic conditions or other delays upstream which will affect subsequent buses.

As headways increase so does the likelihood that passengers have consulted a timetable prior to travelling and the effect of arrival time variations on passenger demand was reduced.

Therefore it was suggested that the deviation from the schedule be compared to the headways to analyze the validity of this assumption.

Another limitation of the model was its reliance on deterministic data. Although in a real time application some of the parameters will be known, such as the passengers on the bus, other parameters such as the downstream passenger demands and travel times may not. The model was best used with the expected values for these quantities and will be less accurate with greater variability in them.

The simulation package used was not able to process transferring passengers. The boarding and alighting rates were increased to compensate, but it was not possible to actually model the interchange of passengers between buses. If this had been included it would have affected the dwell times of buses at transfer points, however this difference would be small and was deemed inconsequential compared to other variability's in the executing of the simulation. Also affected would have been the passenger demands for on buses after missed transfers, but again this was ignored.

In practice, different routes will have different types of buses which have different passenger capacities. However, TransModeler did not allow different passenger capacities of different routes. This means that routes with buses that generally carry more passengers will have to carry less resulting in slightly biased results.

Calculating travel time was based on the simulated time for the bus to get from one point to another. The route and speed at which the buses travel at are limited to the class of the road and the geographic GIS layer. The assumption made was that it was accurate given that traffic signals and traffic of the real world are ignored

The derived model defined routes as a specified sequence of stops from the set of all stops and calculated the tactic effects of all routes on all stops, constrained if the stop was not part of the route. Changing of the notation of the problem to have each route and its stops individually defined and the tactics effects calculated thus could improve the processing efficiency of the model, for application to larger networks. It is also suggested that heuristics could be used for this type of problem in real time.

For the application to the North Shore example network the model and ILOG tool worked well. The lack of integration between the optimization and simulation programs limited the evaluation of the tactic effectiveness. However the method of evaluation used could be implemented to assess the impact of operational tactics on different types of networks.

6 Conclusion

Without the use of tactics successful transfers based on a synchronized timetable do not occur often. The further from the start of the route the transfer was, the lower the probability of the vehicles achieving a successful transfer.

Implementing tactics using deterministic optimization software and stochastic simulation software improves the synchronization of bus transfers thus increasing the number of successful transfers. With higher headways, there was larger potential to use tactics to make transfers successful to reduce the total travel time of passengers. This gives rise to the potential to apply online real-time tactics in the real world make PT more reliable and attractive.

The derived model and associated ILOG-based processor are powerful tools for implementing these operational tactics with deterministic figures and this could be used in real time with continuous and expected data.

7 Further Studies

Application to continuous data – The logical next step would be applying the model in "real time" in a simulated environment; allowing the model to instruct the network whether to apply operational tactics to correct the variability's that arise using known data for what would actually be available in practice and expectancies for other quantities such as passenger demands and travel times.

Multi-objective optimization – Other factors which could be evaluated are operator cost and bus arrival time reliability. Further exploration of the relationship between these and the total passenger travel time and the number of direct transfers achieved could be interesting.

Application to different networks – Other bus networks can be analyzed using the same optimization model. While this model involved three routes and two transfer points, more complex with more routes and transfers can be easily implemented to compare the effectiveness of the model.

Assessment of the effect on long term ridership – Holding buses and skipping stops negatively affects some passengers, while making direct transfers advantages others. A study on how these factors relate to the overall attractiveness of the PT network would be crucial before any implementation could take place.

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