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The Effect of Multiple Shared Bus-Stops on Transfer's Reliability

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Abstract Transfers in Public-Transport (PT) enable an efficient and flexible system on one hand, but contribute to the decrease in service reliability due to missed transfers, on the other hand. The common methods for overcoming the reliability issues are: a) synchronized transfers in which simultaneous arrivals and departures are pre-planned as part of timetables construction, and b) online tactics deployment. These approaches are temporal in nature and neglect the spatial properties of the PT system, meaning that transfers are planned to occur at a single bus-stop. A novel approach to overcome the reliability issues based on the spatial properties was proposed, in which transfers can occur at more than one bus-stop, if the routes share multiple bus-stops. This work proposes a model that based on Automatic Vehicle Location (AVL) data provides: 1) analysis of the effect of multiple shared bus-stops on transfers' reliability, and 2) synchronized transfers' failure detection, and 3) improving transfer's reliability.

Keywords: AVL · Reliability · Synchronized Transfers

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1 Introduction

Public-Transport (PT) systems' Reliability is a major issue for the passengers, operators, and transport agencies. Roads congestion, as well as the climate change are not positive contributors to the problem.

One possible definition of a prudent, well-connected transit path, following Ceder (2007), is this: An advanced, attractive transit system that operates reliably and relatively rapidly, with smooth (ease of) synchronized transfers, part of the door-to-door passenger chain. Designing routes and schedules with a minimum amount of wait time during a transfer may decrease the level of inconvenience. Many articles have been written from 1970s about a variety of ways to design synchronized transit services, such as the work by Ceder, Golany et al. (2001), and more recently by Shafahi and Khani (2010). Bookbinder and Ahlin (1990), and Bookbinder and Desilets (1992) describe transfer optimization and synchronized transfers at the network level. Hadas and Ceder (2008) used simulation for optimization and synchronization problem of transferring passengers at public-transit stops on a network. Improving transit connectivity is one of the most vital tasks in transit-operations planning, and can be modeled as an objective function for the planning process (Guihaire and Hao 2008).

According to the Transit capacity and quality of service manual (Kittelson & Associates., Transit Cooperative Research Program. et al. 2003) four availability factors of public transit systems are identified: (i) spatial – where the service is provided, (ii) temporal – when the service is provided, (iii) information – how to use the service, and (iv) capacity – space available for the passenger. These factors influence, along with the time and transfer attributes, the level of attractiveness of the public-transit system.

Ceder (2007) and Ceder, Net et al. (2009) constructed a set of attributes, both quantitative and qualitative, that represent the spatial, temporal, information, and capacity factors: The common denominator for all transit services are the following quality-of-connectivity attributes: average walk time, variance of walk time, average wait time, variance of wait time, average travel time, variance of travel time, average scheduled headway, variance of scheduled headway, smoothness (ease)-of-transfer , availability of easy-to-observe and easy-to-use information channels, overall intra- and inter-agency connectivity satisfaction.

dell'Olio, Ibeas et al. (2011) studied the quality of service desired by users of PT systems. The desired quality is different from the perceived quality because it does not represent the daily experiences of the users, but rather what they desire, hope for or expect from their public transport system. The study concluded that passengers valued waiting times more than travel time. Those finding strengthen the importance of managing transfers.

To alleviate the uncertainty of simultaneous arrivals, a new passenger-transfer concept was developed by Hadas and Ceder (2008); it extends the commonly used single-point encounter (at single transit stop) to a road-segment encounter in which any point along the road segment constitutes a possible transfer point. In this research, the authors used a simulation tool to show that given multiple shared bus-stops (Fig. 1), the simultaneous arrival of the buses can occur at any shared bus-stop. The reason is that statistically, both travel time and dwell time are not fully correlated, hence the headway between two buses (from two different routes) can change, resulting with increased probability that the buses will dwell at the same time at one of the shared bus-stops. If we analyze each component of the total travel time (ride time and dwell time), it is evident that the dwell time of the two buses is loosely correlated, as demand and passengers arrival rate to a bus-stop are for buses heading to different destinations. Moreover, the travel time between adjacent bus-stop of the two buses can slightly change due to traffic lights, delays at intersections, etc.

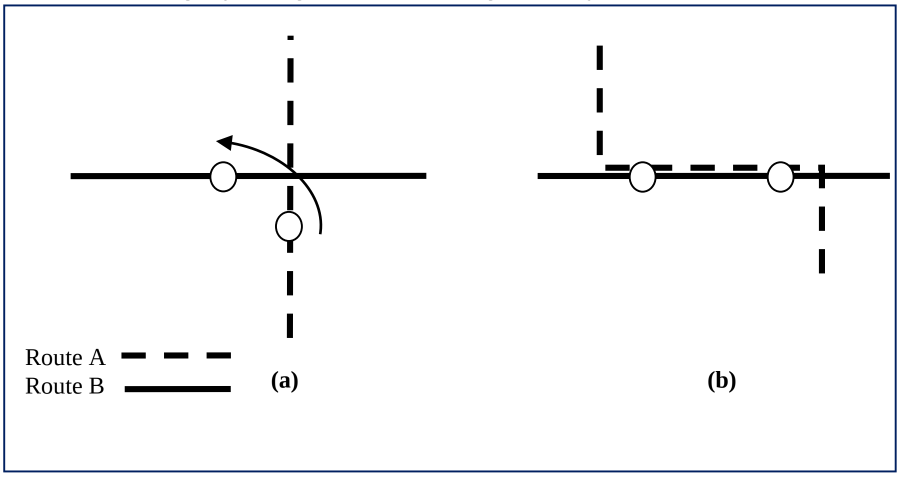

Fig. 1 (a) no shared stops (b) multiple share stops

Automatic Vehicle Location (AVL) is a technology enabling tracking the location of vehicles en route (AVL). The data acquired can be used for analysis, as well as to enhance the performance of public transit systems, and the introduction of advanced models. It was shown that the availability of bus locations, estimated arrival times, number of passengers and their destinations, can open the door to the implementation of bus-dispatching at timed transfer transit stations algorithm (Dessouky, Hall et al. 1999). Such an algorithm can intelligently decide whether to hold a bus in order to achieve a transfer with a late bus or not. Based on AVL technology it is possible to forecast accurately the buses estimated arrival times and to use bus holding strategies to coordinate transfers (Dessouky, Hall et al. 2003). The use of advanced public transit systems in fixed-route and paratransit operations was found important for improvements in departure times and transfers (Levine, Hong et al. 2000). Travel time estimation is also possible (Tétreault and El-Geneidy 2010), as well as the evaluation of transit operations based on AVL data (Strathman, Kimpel et al. 2002), (Furth, Hemily et al. 2006). The availability of AVL data can also be used for the analysis of simultaneous arrival of buses to bus-stops, which is the aim of this work.

1.1 Objectives

The objectives of this research are to: 1) validate the hypothesis that multiple shared bus-stops between two routes will increase the transfer's reliability as opposed to a single shared bus-stop, 2) develop a tool for the identification of transfers' failures and the actions required in order to decrease or eliminate those failures, based on a cost-benefit analysis, and 3) present a case study, based on real data acquired by AVL, of two groups of routes.

2 Analysis Principles

The analysis is comprised of the following steps: a) data preparation, b) simultaneous arrival identification, c) success rate (of a synchronized transfer) calculation for a bus-stop, d) sensitivity analysis of the number of share stops and dwell time offset.

2.1 Data preparation

Given AVL data including date and time, route identification, trip identification, bus-stop, arrival time, and departure time, it is possible to join records from two routes, based on date and bus-stop of two routes sharing at least one bus-stop.

2.2 Identifying simultaneous arrival

Let $a_{i,s,t}$, $d_{i,s,t}$ be the arrival and departure times of vehicle i respectively ($i=1,2$) at a bus-stop s, at time index t, and let $a_{s,t}$ be the latest arrival and $d_{s,t}$ the earliest departure. For clarity purposes we'll omit the i and j indices

$$a_{s,t} = \max\left(a_{1,s,t}, a_{2,s,t}\right) \tag{1}$$

$$d_{s,t} = \min\left(d_{1,s,t}, d_{2,s,t}\right) \tag{2}$$

Based on equations (1) and (2), it is possible to define the dwell time offset:

$$DTO_{s,t} = \max\left(0, a_{s,t} - d_{s,t}\right) \tag{3}$$

A zero DTO reflects that both vehicles dwell at the same time at the stop, while a positive number is the minimal time required to compensate for the missed transfer. Fig. 2 illustrates that, cases (i) and (ii) are with $DTO = 0$ and it is evident that transfers preformed simultaneously, as both vehicles are dwelling at the bus-stop at the same time, while in case (iii) $DTO > 0$, and passengers to be transferred to the early departed bus failed to do so.

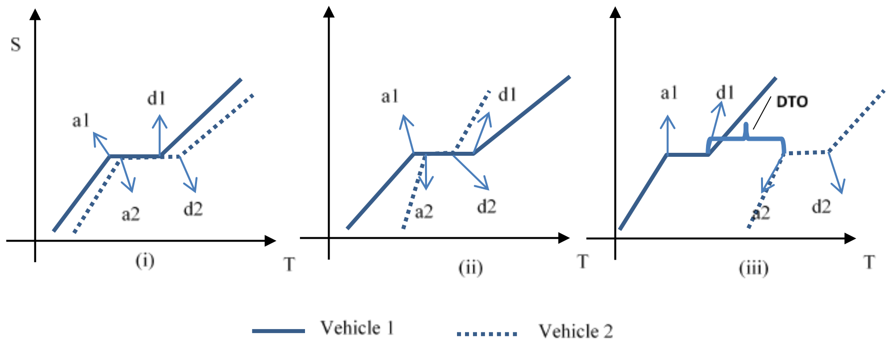

Fig. 2. Time-Space diagrams of vehicles arriving and departing at a bus-stop

2.3 Calculating Success Rate

After marking all simultaneous arrivals, for each two routes trip-pairs, a success rate is to be calculated for each stop. The success rate is the contribution of each shared bus-stop to the successful potential transfer between two routes, along the shared segment. Because it is possible to have more than one simultaneous arrival per trip (the same vehicles dwell together more than once, at different bus-stops), the data must be normalized in order to have an accumulated successful rate equal to 100%.

Let S be a set of shared bus-stops of routes *i* and *j*. Also, let T be a set of all trip pairs of routes *i* and *j*, in which a simultaneous arrival occurred (at one or more bus-stops, for a given period), then based on (3) it is possible to define the encounter matrix X:

$$x_{\substack{s\in S \\ t\in T}} = \begin{cases} 1 & DTO_{s,t} = 0 \\ 0 & otherwise \end{cases} \tag{4}$$

Where “1” represents a successful synchronized transfer, and “0” otherwise.

Thus,

$$C_t = \sum_{s\in S} x_{s,t} \tag{5}$$

$$C_s = \sum_{t\in t} x_{s,t} \tag{6}$$

represent the total number of simultaneous arrivals at all shared bus-stops for a given trip pair, and the total number of simultaneous arrivals at a bus-stop for a given period respectively.

The normalized simultaneous arrivals and success rate are then calculated as indicate in Fig. 3:

1. L=1
2. $p = \left(s \in S \mid \max\left(C_s\right)\right)$
3. $C_p^{'} = \sum_{t \in T} x_{p,t}$
4. $x_{s,t} = 0 \; \forall \left(t \mid x_{p,t} = 0\right)$
5. Remove column *p* from matrix *X*
6. L=L+1
7. If $L \leq |S|$ then return to 2, otherwise stop

Fig. 3. Algorithm for calculating success rate

$$SR_s = 100 \frac{C_s^{'}}{\sum_{b \in S} C_b^{'}} \tag{7}$$

Where SR_s is the success rate of bus-stop *s*.

This algorithm simply captures an encounter only once, and for the bus-stop with the highest number of simultaneous arrivals. Thus, the SR vector will serve as the quantitative measure reflecting the contribution of shared stops on transfer reliability.

2.4 transfer failures identification

Assuming that the routes timetables (or departure times) were planned in order to maximize synchronized transfers, it is possible to: 1) identify the transfer failure, and 2) assess the required measures in order to increase the transfer reliability. It is important to stress that the analysis is of the shared stops, not the common analysis of a single, isolated stop, and is based on the following propositions: 1) decreasing DTO will increase the number synchronized transfers, 2) the larger the DTO, the more difficult to eliminate it, 3) given several shared stops, to achieve maximal transfers, the smallest DTO is to decreases, and 4) the larger the number of shared stops, the higher the chance of a smaller minimal DTO. Based on the above mentioned propositions, it is necessary to 1) identify the minimal DTO stop, and 2) assess the impact of decreasing the DTO.

For each stop *s*, several descriptive statistics can be obtained, namely min. max, average, variance, and percentiles.

Specifically, based on the DTO's α percentile, it is easy to identify the stop with the minimal percentile value.

$$DTO_s^{\alpha} = P_{\alpha}\left(DTO_{s,t}\right) \tag{8}$$

$$DTO_{\min}^{\alpha} = \min_{s \in S}\left(DTO_s^{\alpha}\right) \tag{9}$$

Where equation (8) calculates the α percentile of stop *s* DTO, and equation (9) is the minimal DTO of a multiple shared bus stop segment.

Assessing the impact of deceasing DTO is based on a modified encounter matrix

$$x_{\substack{s \in S \\ t \in T}}^{TH} = \begin{cases} 1 & DTO_{s,t} \le TH \\ 0 & otherwise \end{cases} \tag{10}$$

where TH is a dwell time threshold that represents a maximal DTO to be reduced. For example, TH=10 represents that maximum 10 seconds are to be reduced in order to achieve a transfer.

Thus it is possible to recalculate equations (5), (6), and (7) and assess the projected impact of TH on transfer reliability. DTO reduction can be achieved in the planning phase and in the operations phase. For the planning phase, it is possible to change timetables or departure times in order to maximize the number of transfers. Ceder, Golany et al. (2001) introduced such a model, and it is possible to revise their model for a shared stop network. Furthermore, as the maximal synchronization problem is of high complexity, adding DTO constraints, in the form of TH, can diminish the solution space, and as a consequence, decrease the execution time. For the operations phase, Hadas and Ceder (2007) introduced a model that maximizes the transfers, based on on-line tactics and the known locations of the vehicles. Given TH, it is possible to identify shared stops that can benefit from the reduction of DTO, and as a result a detailed operational tactics deployment program can be developed.

3 Case Study

Auckland buses are equipped with AVL systems which record, among other data, the arrival and departure times of each bus at each bus-stop along a route. For the analysis two groups of routes were analyzed: a) inter-city, timetable based routes and, b) frequency based routes. The former group represents transfers made between a local route collecting passengers from a suburb to an inter-city route (or distributing passengers). Those low frequencies routes (morning and evening peaks) are timetable based and transfers are pre-planned. The latter group represents transfers to a high frequency local route which serves major points within the city. Transfers are usually not pre-planned, but waiting time is not desirable.

It is important to understand that the current PT system policy has not implemented multiple shared bus-stops to increase system reliability. The routes that do share more than one bus-stop do so for other reasons. The analyzed routes were selected based on that fact, thus the results are meant for validation purposes and not for optimal bus-stop selection. AVL data from 9/2009, 10/2009, 11/2009, 3/2010, 4/2010, and 5/2010 were used for the analysis. As the aim of the research is to analyze simultaneous arrival of buses at a bus-stop, the analysis neglects any early arrival, which can be acceptable when a unidirectional transfer is carried, as well as late arrivals. In other words, the research is a "what-if" analysis of the impact of the number of shared bus-stops on direct transfers (transfers performed without any wait), hence the results are within that context.

3.1 Timetable based routes

Passengers heading from Army Bay (north of Auckland city) can use route 898 (to Silverdale) where they transfer to route 895 (Waiwera to Auckland city) to complete the trip (MAXX 2011). Fig. 4 presents the routes (dark line - 898, green line – 985), and Fig. 5 zooms at the shared bus-stops (5 in total) where transfers can be performed.

From the results summarized in Table 1 it can be seen that bus-stop # 3692 has the highest frequency of simultaneous arrivals. Also, it is uncommon for two buses to simultaneously arrive at more than one bus-stop (only twice the same buses arrived at the same time to bus-stops # 3677 and # 3692). Such phenomena can be explained by the high correlation of travel time, as the roads are usually uncongested. It is evident that if only one bus-stop is shared, or at least used for transfers, and we further assume that the most promising bus-stop is used (#3692) then 28% of the direct transfers are missed. The sensitivity analysis of DTO is summarized in Table 2. Based on the analysis, the planner has quantitative measures on the effect of reducing DTO, and relate it to the required actions. For example, a 10 seconds reduction of the DTO will increase the number of synchronized transfers by 34%.

Fig. 4. Routes 898 and 895 overview

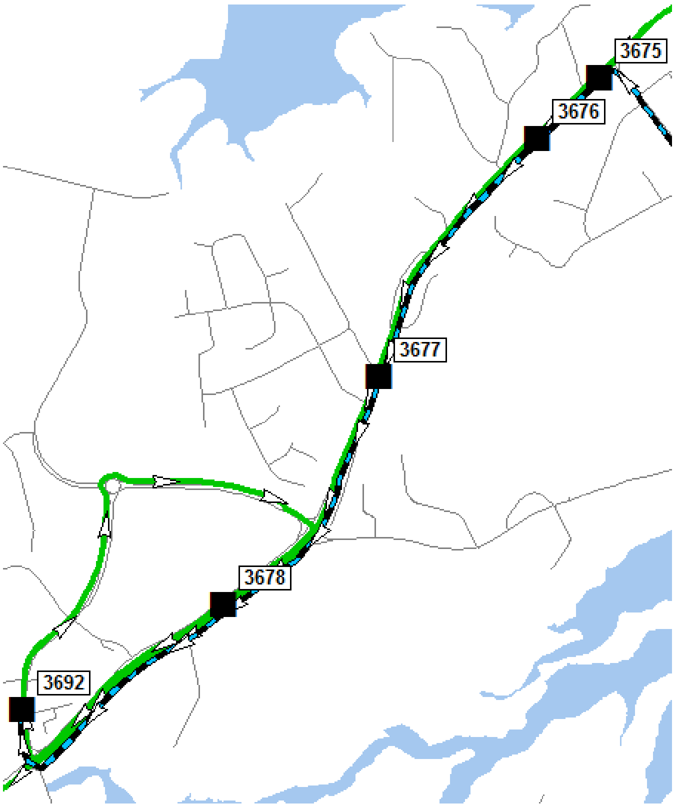

Fig. 5. Routes 898 and 895 shared bus-stops

Table 1. results of route 898 and route 895 analysis

	Stop		
	3676	**3677**	**3692**
Total number of simultaneous arrivals	4	21	51
One simultaneous arrival per trip	2	17	48
Two simultaneous arrivals per trip	1	3	2
Three simultaneous arrivals per trip	1	1	1
Success Rate (SR)	3%	25%	72%

Table 2. sensitivity analysis of DTO of route 898 and route 895

DTO (seconds)	Simultaneous Arrivals	Difference (%)
0	71	
10	95	34%
30	122	28%
60	160	31%

3.2 Frequency based routes

Route 680 is heading from Cockle Bay (to the south of Auckland city) to Auckland city center. This route share 7 bus-stops with the LINK route, a circular route with 10-15 minutes headways, which is serving major locations such as the hospital, university, shopping centers, etc., thus smooth transfers are desirable in order to increase patronage and provide high quality PT service. Fig. 6 provides an overview of the routes, and Fig. 7 presents the LINK route and the shared bus-stops with route 680 (MAXX 2011).

Fig. 6. Routes 680 and the LINK overview

The results of the analysis are summarized in Table 3, Table 4, Table 5, and Table 6. These results are quite different from the inter-city analysis, presented earlier, mainly due to the fact that the analysis area is urban and traffic lights, congestion and travel demand increase the variance of travel time and dwell time.

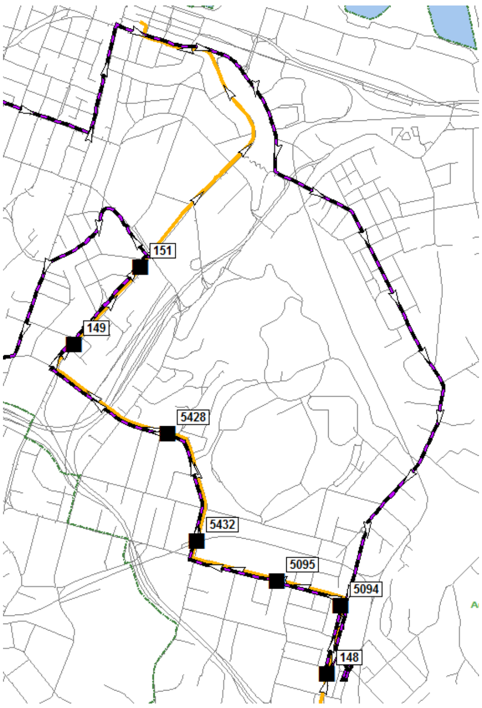

Fig. 7. Route 680 and the LINK shared bus-stops

Table 3 presents the distribution of Simultaneous arrivals per trip, meaning that 46% of the trips had one simultaneous arrival at a bus-stop, 31% of the trips had two simultaneous arrival at a bus-stop (the same buses had the potential to perform two transfers), etc. Table 4 provides a more detailed presentation of the number of simultaneous arrivals by bus-stop. Bus-stop # 5094 has the highest number of simultaneous arrivals, with high number of arrivals shared with other bus-stops (with two – 159, with three – 88, etc.). Table 5 summarized the normalized simultaneous arrivals and success rate based on the algorithm presented in Fig. 3. Again, as was evident in the previous analysis of the inter-city routes, the contribution of multiple shared bus-stops on successful transfers is huge. Performing a transfer at one bus-stop has a success rate of 46%, while enabling transfers at 5 bus-stops can double the success rate, and as a result can increase transfer reliability as well as ease of transfer. Finally, Table 6 summarizes the DTO sensitivity analysis.

Table 3. distribution of simultaneous arrivals per trip for route 680 and the link

Simultaneous arrivals per trip	Frequency	Percentage
1	397	46%
2	266	31%
3	122	14%
4	44	5%
5	30	3%
6	8	1%
7	1	0%

Table 4. break down of simultaneous arrivals by bus-stop

	Stop						
number of simultaneous arrivals	**148**	**5094**	**5095**	**5432**	**5428**	**149**	**151**
Total	364	402	224	87	181	202	216
1	129	90	43	11	29	36	59
2	120	159	67	12	39	71	64
3	69	88	61	16	42	45	45
4	21	29	24	23	36	22	21
5	17	27	21	20	27	19	19
6	7	8	7	4	7	8	7
7	1	1	1	1	1	1	1

Table 5. normalized simultaneous arrivals and success rate - route 680 and the link

Bus-stop	**Normalized Simultaneous arrivals**	**Success Rate (%)**
5094	402	46
148	159	18
151	147	17
5428	65	7
149	61	7
5428	34	4
5432	11	1
Total	879	

Table 6. sensitivity analysis of DTO of route 680 and the link

DTO (seconds)	Simultaneous Arrivals	Difference (%)
0	868	
10	1024	18%
30	1201	17%
60	1498	25%

4 Conclusions

From the analysis it is evident that multiple shared bus-stops has the advantage of increasing the chances that a direct (synchronized) transfer will occur. Furthermore, a simple tool was developed, that based on public the transport network and AVL data, can assist the planner to: a) identify transfer reliability issues, b) assess the impact of timetable change and operational tactics deployment on transfer reliability.

Based on the proposed tool, additional paths can be explored:

1. Multiple shared bus-stops design has the potential of increasing service reliability, hence reducing waiting time and providing smooth and easy ride from origin to destination. Even though such an approach will increase routes overlap, which is undesirable. The trade-off in the form of increased transfer reliability has numerous advantages.
2. It is possible to develop a simulation tool, which can assist with the planning process of locating bus-stops serving as transfers’ points, pinpointing those bus-stops which can optimize the transfer chances.

3. Advanced PT Information system can easily incorporate a model that will notify each passenger on the exact location of transfer, based on real-time data. Such a tool will enable the implementation of a multiple shared bus-stops design into the public transport planning phase.

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