Improving synchronized transfers in public transit networks using real-time tactics

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Abstract

This work presents an optimization procedure with real-time operational tactics to decrease or eliminate bus operational deviation from schedules, and to increase the actual occurrence of synchronized transfers at planned network transfer points. An arrival time deviation-based dynamic speed adjustment model is proposed for updating vehicle operating speed in real time. Three operational tactics, including changing speed, holding and skip stopping strategies are tested in the optimization using real-time information. A case study tests how close the vehicle's running status keeps up with the planned schedule and how much delays change after deploying the tactics tested. Results show that by applying the proposed methodology, the length of deviation interval for direct transfer can be significantly increased on two routes tested by between 798% and 353%. Buses can arrive at transfer points as planned while departure time deviation ranges from -600s/+417s and from -600s/+839s for the two routes tested. Areas for future research are identified.

Key word: public transport, transfer optimization, operational tactics, synchronized transfers

1 Introduction

Public transit (PT) systems are playing important roles in improving urban mobility, reducing road traffic accidents, decreasing air pollution and fostering more livable cities. It is apparent that advanced, reliable, convenient, and comfortable PT systems can attract more private car users.

A major feature of successful PT systems is convenient and well coordinated (or synchronised) transfers between public transport modes at stations and interchange points. Bus systems operating in mixed traffic on roads dominate most public transport systems provided in cities. One of the most challenging problems of providing PT in cities is how to operate buses reliably in mixed traffic (Ceder, 2007). The dynamic, stochastic, and uncertain characters of traffic often make bus schedules erratic and the planned synchronized PT transfers do not always materialize in practice. More than 50 years ago Newell and Potts (1964) had already pointed out that if no control strategies are used, even a very small disturbance can cause serious off-schedule running. To cope with this situation, they proposed a real time operational phase aimed at improving the transfer reliability using operational tactics with real-time data. With the recent development of information and communication technology obtaining real-time data and deploying online tactics is now feasible, however approaches to make these tactics work in practice are needed to enable deployment of these methods.

This research paper presents an optimization procedure with real-time operational tactics to decrease or eliminate bus operational deviation from schedules, and to increase the actual occurrence of synchronized transfers at planned network transfer points. The paper is structured as follows; firstly, previous research in the field is outlined, then some concepts of PT route performance relevant to the modelling are introduced. This is followed by an a description of the operational time deviation predictive model the a dynamic speed adjustment model. A case study using routes on the Beijing PT network is then outlined and is used to assess the benefits of methodology. The paper ends with a summary and conclusions including identification of areas for future research.

2 Research Context

Two major phases have been identified where planning of public transport might be improved; the planning phase and the operations phase (Ceder et al.,1986; Ceder,2007). The planning phase consists of network design and timetable creating two activities based on a priori data. Network design aims to reduce transfer walking time (Ceder, 2015; Chowdhury et al., 2013, Zhao, 2004) by measuring of network integration, integrating the physical connection of transfers and optimizing the layout of transfer centers. Timetable development is a critical part of the planning phase with a focus on improving schedule reliability of PT routes by developing a maximum synchronized fixed timetable (Domschke, 1989; Voss, 1992; Ceder et al.,2001) or timed transfer (Vuchic, 2005; Abkowitz et al.,1987, Maxwell, 1999), and optimizing slack time (Lee,1991; Zhao,2006) within the schedule.

Because of the dynamic, stochastic, and uncertain characteristics of traffic, planned synchronized PT transfers do not always materialize in practice. Indeed, more than 50 years ago, Newell and Potts (1964) had already pointed out that if no control strategies are used, even a very small disturbance can cause serious off-schedule running. To cope with this situation, an operations phase was proposed by researchers aiming at improving transfer reliability using operational tactics with real-time data. The more recent development of information and communication technology makes obtaining real-time data and deploying online tactics more feasible in contemporary operations planning. However a major challenge remains in how to best go about this.

In the operations phase, recent studies focus on using real-time control strategies with available information. Dessouky (1999) showed the potential benefits of real-time control of timed transfers by using intelligent transportation systems[0], and examined simulated systems using holding and dispatching (2003). Research by Hadas et al. (2010), Ceder et al. (2013), Liu et al.(2014;2015), and Nesheli et al.(2014) also showed that by using selected operational tactics, the total passenger travel time can be considerably reduced and the frequency of direct transfers can be significantly improved.

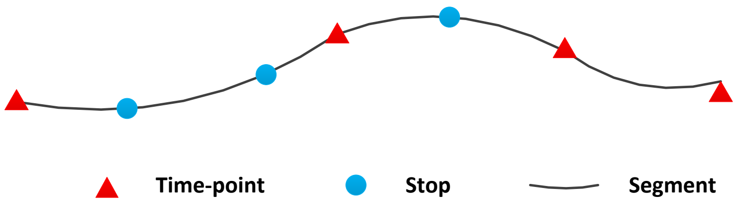
Though the operations phase can contribute greatly to the improved occurrence of synchronized transfers at transfer points, their remain two major gaps in research in this field: firstly, existing studies forecast only vehicle arrival times at transfer points as a reference. In practice reliability needs to be focussed on a wider set of locations and for departures as well as arrivals. Secondly, existing research only considers the effects of improved operations on the number of direct transfers or total passenger travel time. The actual schedule adherence performance of the vehicle is not considered. Yet this affects all passengers on the bus route who are not transferring (in many cases in the real world this can represent a majority of users). This is clearly a major omission in existing research. In this study, the above issues are addressed in an approach to optimise synchronised transfers using real time operational tactics.

3 Conceptual explanations

This analysis adopted timing points as the locations most suitable to adjust bus operations in real time. Other researchers e.g. Liu et al (2014) have used transfer points as the nodes to improve operational performance. However, this method may reduce the prediction accuracy, in the case of a long distance between the actual location of vehicle and transfer point. In addition there are typically many more timing points on bus routes than transfer points hence more chances to improve operational reliability in real time.

Timing points chosen on bus routes to be control points in order to prevent bunching and to hold buses if they are running early to schedule. With the use of the time-point, it is possible to obtain more accurate prediction of operational deviation. Time-points may be terminal, transfer points, a key stop/station with larger passenger alighting and/or boarding, or other key places on abus route. A public transit route can be divided into several sections by time-points, and each section is regarded as a control unit in this research. Besides, in order to describe with convenience, the no-time-point is called stop and the part between two consecutive stops or between stop and time-point is called a segment. Therefore, the typical structure of a public transit route is shown in Figure 1.

Figure 1 Structure of a typical public transit route



4 Model

In this section, two different models are proposed, including: 1) the operational time deviation predictive model, and 2) the time deviation-based dynamic speed adjustment model. The first one is built to forecast operational time deviation of vehicle arrival at each time-point with some real-time information, such as passenger demand and traffic condition. The second one is designed for deciding which kind of speed change (speed up or down) will be chosen and recommending what target speed to adopt for bus operations.

4.1 Notation

Some notations, which will be used later in this paper, are shown as following:

k = The code of time-point;

$T_a(k)$ = Planned arrival time at time-point k, which is given in timetable;

$\overline{T}_a(k)$ = Predictive arrival time at time-point k;

$T'_a(k)$ = Actual arrival time at time-point k;

$d_a(k)$ = The arrival deviation at time-point k;

$t(x)$ = Dwell time at place x , which could be a stop or time-point;

b = Dead time required for vehicle deceleration and acceleration;

Δ_B = Marginal dwell time per boarding passenger;

Δ_A = Marginal dwell time per alighting passenger;

$B(x)$ = Estimated number of boarding passenger at place x ;

$A(x)$ = Estimated number of alighting passenger at place x ;

$\alpha_a(k)$ =The range of travel time when vehicle running-late between time-point k and k+1;

$\alpha_b(k)$ = The range of travel time when vehicle running-early between time-point k and k+1;

Δt_i = The change of travel time in segment i;

L_i = The distance of segment i;

V_{Pi} = The planned average travelling speed in segment i;

V_{Ri} = The recommended average travelling speed in segment i;

$V_{i\max}$ = The maximum average travelling speed in segment i;

$V_{i\min}$ = The minimum average travelling speed in segment i;

$d_{agb}(x)$ = The actual arrival time deviation at transfer point x without tactics;

$d_{aga}(x)$ = The actual arrival time deviation at transfer point x with tactics

4.2 Assumptions

Without loss of generality, the following assumptions are made:

A1：A maximum synchronized timetable is created for a PT network, which means all the arrival time of each trip at every time-point is known.

A2：It is assumed that the real-time estimation of passenger origin-destination matrix, vehicle real-time location and traffic condition along PT route are available.

A3：Some operational factors, such as the maximum/minimum average travelling speed, and average planned travelling speed, are available.

A4：PT operators can deliver timely suggested operational tactics information to drivers without a very long delay.

A5: Driver will comply with the recommended operational tactics provided by PT operators, and the reaction time can be ignored.

A6: Passengers who arrive after the departure time will wait for the next vehicle of this route.

4.3 The operational time deviation predictive model

Understanding the operational status of a vehicle is one of basic tasks for operators to conduct when running vehicles in real time. Unfortunately, it is still a problem for researches and operators to figure out how to obtain a more accurate prediction of travel time. In order to increase the actual occurrence of synchronized transfers, some researches chose connectional vehicle running status as a comparison. It can make two or more vehicles meet successfully at transfer point, without considering the problem whether vehicles run on time or not.

From the perspective of public transit system, obtaining a synchronized time-table is the major goal. Hence, the synchronized time-table will be chosen as preference in this paper. The operational time deviation, which is defined as the difference between predictive and planned arrival time at time-point, is regarded as a predictive indicator. Consequently, the time deviation of vehicle at time-point k+1 can be determined as formula (1):

$$d_a(k+1) = \overline{T}_a(k+1) - T_a(k+1) \tag{1}$$

The predictive arrival time at time-point k+1 can be got as formula (2).

$$\overline{T}_a(k+1) = T'_a(k) + \sum t(x) + \sum L_i / V_{Pi} \tag{2}$$

The dwell time at time-point or stop x can be obtained as formula (3).

$$\mathrm{t}(x) = \begin{cases} b + \Delta_B \cdot B(x) + \Delta_A \cdot A(x), & \text{single-door, if } B(x) > 0 \text{ or } A(x) > 0 \\ 0, & \text{single-door, if } B(x) = A(x) = 0 \\ b + \max(\Delta_B \cdot B(x), \Delta_A \cdot A(x)), & \text{double-door, if } B(x) > 0 \text{ or } A(x) > 0 \\ 0, & \text{double-door, if } B(x) = A(x) = 0 \end{cases} \tag{3}$$

Hence, according to the formula (1)~(3), the operational time deviation of vehicle arrival at time-point k+1 can be predicted with some real-time public transit information .

4.4 Deployments of operational tactics

With the use of the predictive model, it is extremely effortless to gain the operational time deviation arrival at every time-point. The real-time speed operational tactics, including speed change, skipping stop and vehicle holding at transfer point, will be recommended to driver based on the outcome of predictive model.

4.4.1 The dynamic speed adjustment model

The update rules for average running speed adjustment are given as follows:

Situation 1: running late, namely, $d_a(k+1) > 0$

If $\alpha_a(k) \geq d_a(k+1)$

$V_{Ri} = L_i / (L_i / V_{Pi} - \Delta t_i)$

else $\alpha_a(k) < d_a(k+1)$

$V_{Ri} = V_{i\max}$

Situation 2: running early, namely, $d_a(k+1) < 0$

If $\alpha_b(k) \geq |d_a(k+1)|$

$V_{Ri} = L_i / (L_i / V_{Pi} + \Delta t_i)$

else $\alpha_b(k) < |d_a(k+1)|$

$V_{Ri} = V_{i\min}$

Situation 3: running on time

$V_{Ri} = V_{Pi}$

End

Where, a) Δt_i is the change of travel time, which is obtained by decomposing time deviation in proportion, it cannot exceed to the range of traveling time, b) $\alpha_a(k)$ and $\alpha_b(k)$ are the range of travelling time in each section if vehicle travel with maximal and minimal speed respectively, which can be determined as following:

$$\alpha_a(k) = \sum (L_i / V_{Pi} - L_i / V_{i\max}) \tag{4}$$

$$\alpha_b(k) = \sum (L_i / V_{i\min} - L_i / V_{Pi}) \tag{5}$$

4.4.2 Skip stopping tactics

In situation 1, if the vehicle is still running late with the application of speed change tactics, the skip stop tactic should be deployed at some stops. The rules of choosing a stop to be skipped are: a) compare the number of alighting passenger at every stop, and choose the stop having the least number to implement a skipping tactic, b) otherwise, in order to decrease the additional walking time of passengers who want to alight at a skipped stop, two consecutive stops cannot implement a skip stop tactic at the same time.

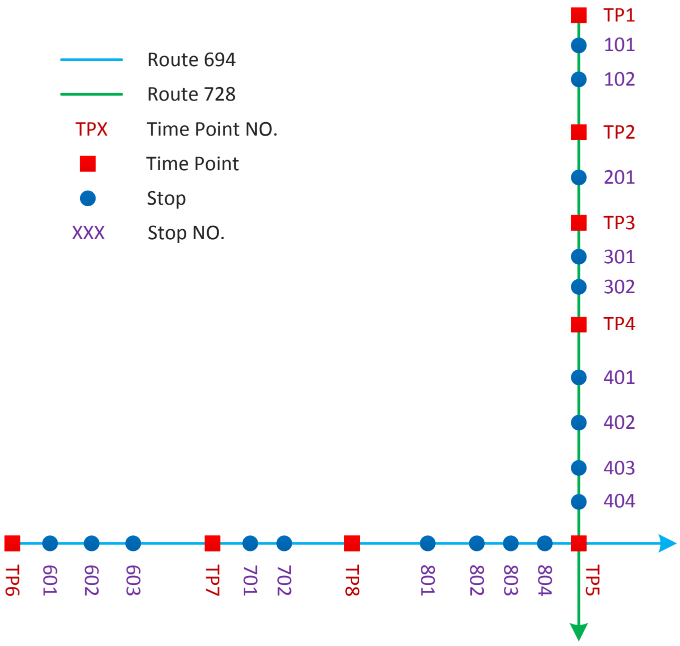
4.4.3 Holding vehicle at transfer point

In situation 1, if the vehicle is still running late with the deployment of speed change and stop skipping, the connecting vehicle should be held, and in situation 2, if speed change cannot meet the deviation, the current vehicle should use a holding tactic at the transfer point. The holding tactic can be implemented at the transfer point until it’s time to leave according to plan or be kept longer if the transfer vehicle is required, but the holding time can’t exceed the maximum allowable value.

5 Case study

A case study is adopted to assess the effectiveness of the adjustment model and its potential deployment. This case study relates to a real-time PT network in Beijing, China, which has been used in previous studies (Tao Liu, 2014). The PT network of the case study is illustrated in Figure 2. It consists of 2 bus routes with a transfer point. Route 694 runs from north to south and Route 728 runs from west to east. Time-point 5 is a transfer point, which provides transferring service for the passengers of the two Routes.

Figure 2 Schematic diagram of case study bus routes



5.1 Data collection

The data include information on routes, vehicles, and passengers. It is worth to note that in this study some data are collected from the research by Liu et al (2014).

5.1.1 Route information

Route information comprises route ID, route direction, the number of stops, stop ID, the distance between two consecutive stops, and planned synchronized timetable.

5.1.2 Vehicle information

All vehicles of the two routes are equipped with GPS devices, so they can share their real-time location and speed information with the control center. The information is updated in intervals of 30s. The collected information of vehicle includes vehicle ID, driver ID, planned headway, vehicle location, and average running speed in each segment. Maximal and minimal average traveling speed ought to be predicted with traffic condition and vehicle character.

5.1.3 Passenger information

Passenger information comprises the number of passengers alighting and boarding at each stop and the number of passengers transferring at each transfer stop. In practice, the passenger information should be forecast with the history passenger demand data, for simplicity, the data collected from IC or smartcards was regard as predictive. The collected data are shown in Table 1.

Table 1 Route, vehicle and passenger Information of PT Routes

Stop	Planned timetable		Passengers		Distance between stops(km)
	Arr. Time	Dep. Time	Boarding	Alighting	
Route694, Headway=10 min, Vehicle ID: 13984					
TP1	8:01:00	8:04:00	27	0	0
101	8:07:15	8:08:00	16	0	0.696
102	8:10:33	8:11:07	7	15	0.792
TP2	8:15:24	8:16:35	13	9	1.114
201	8:19:50	8:20:25	0	3	1.247
TP3	8:23:26	8:25:00	19	7	1.151
301	8:29:10	8:29:55	5	2	0.857
302	8:33:58	8:34:20	19	20	1.55
TP4	8:38:19	8:40:15	13	8	1.493
401	8:47:39	8:48:34	10	24	2.553
402	8:52:18	8:52:39	0	3	1.845
403	8:54:40	8:55:08	8	16	1.033
404	8:57:53	8:58:09	4	15	1.419
TP5	9:06:28	9:07:36	6	8	2.655
Route728, Headway=9 min, Vehicle ID: 64431					
TP6	7:59:20	8:00:20	5	0	0
601	8:05:26	8:06:20	21	2	1.186
602	8:09:10	8:09:40	3	2	1.2
603	8:14:50	8:15:12	0	2	1.756
TP7	8:27:10	8:28:20	10	3	2.52
701	8:32:10	8:32:58	2	1	0.782
702	8:35:10	8:35:30	1	2	1.031
TP8	8:40:41	8:42:12	1	2	2.46
801	8:47:36	8:48:22	0	7	2.308
802	8:53:35	8:54:20	1	4	2.022
803	8:57:03	8:57:24	1	5	1.198
804	9:02:03	9:02:20	1	6	1.219
TP5	9:06:35	9:07:43	2	4	1.81

5.2 Principles

Taking the actual operational situation into consideration, the following principles will be used:

Vehicle’s actual departure time cannot be earlier than planned at any time-point. However, at any stop, if vehicle’s dwell time meets the demand for passenger alighting and boarding, vehicle is permitted to depart stop earlier than planned. For simplicity, 120% and 50% of planned average traveling speed are regarded as maximal and minimal average traveling speed, respectively. Besides, the maximal holding time of the two case study routes are same with 60s. All vehicles have a single door for passenger alighting or boarding, and the capacity of vehicles are 60, including 40 seats and 20 standing.

5.3 Evaluation of performance

As mentioned above, in the predictive model, it adopts the planned synchronized timetable as a reference to forecast the operational time deviation of the vehicle. Therefore, it is necessary to develop an evaluation indicator, which can describe how the operational status of vehicle changes in relation to the planned schedule after deploying the real-time tactics.

With the concept of operational time deviation, the operational deviation ratio is defined to access the deployment effect of tactics. The operational deviation ratio can be determined as following:

$$R_{AT} = \frac{d_{agb}(x) - d_{a \cdot a}(x)}{d_{agb}(x)} \times 100\% \tag{6}$$

It is apparent that the bigger the operational deviation ratio is, the better the optimization is. If the operational deviation ratio is equal to 100%, the running status of vehicle is coincident with the planned schedule.

5.4 Implementation and results

In the case study, real-time tactics are recommended to the current vehicle using the dynamic speed adjustment model in various scenarios with different departure time deviation at the first stop of the route, meanwhile, it is assumed that the transferring vehicle is able to arrive at transfer point as planned.

Taking the vehicle departure on time as a reference, add or reduce the deviation of departure time with an interval of 30s every time. For early departure, take the actual situation into consideration, the maximal deviation is controlled as 10 min. For late departure, the interval is added to the deviation gradually, until the direct transfer can’t be achieved at transferred point with any of the real-time tactics.

The outputs of each scenario are segments deployed with the speed change, skipped stop, or holding time tactics at the transfer point, whether direct transfer or not, and time deviation of vehicle arriving at the transfer point. Here, the text includes two situations;

- route 694 has departure deviation and 728 on time; and
- route 728 has departure deviation and 694 on time.

All the outputs are shown in table 2 and 3, respectively. It is worthy to note that some deviations, which have common tactics, are not listed in the tables considering the space limits for this paper.

Table 2 outputs of case study (transfer from route 694 to 728)

R694			**R728**	**Performance**				
Dep. time dev. at 1th stop (sec)	**Real Time Tactics**			**Direct transfer?**		**Time Dev. at transfer point**		**Dev. Ratio (%)**
	Speed change segment	**Skipped stop**	**Holding time**	with	without	with	without	
-600				YES	NO	0	-522	100
-570	TP1-TP3(d)/TP4-TP5(u)			YES	NO	0	-492	100
-420	TP1-TP2(d)/TP3-TP5(u)			YES	NO	0	-342	100
-270	TP1-TP2(d)/TP3-TP5(u)			YES	NO	0	-192	100
-150	TP1-TP2(d)/TP3-TP5(u)			YES	NO	0	-72	100
-120	TP1-TP2(d)/TP3-TP5(u)			YES	YES	0	-42	100
-60	TP1-TP2(d)/TP3-TP5(u)			YES	YES	0	18	100
0	TP1-TP2(u)/TP3-TP5(u)			YES	NO	0	78	100
60	TP1-TP2(u)/TP3-TP5(u)	101		YES	NO	0	138	100
120	TP1-TP5(u)	101		YES	NO	0	198	100
180	TP1-TP5(u)	101		YES	NO	0	258	100
210	TP1-TP5(u)	101\201		YES	NO	0	288	100
240	TP1-TP5(u)	101\201\301		YES	NO	0	318	100
300	TP1-TP5(u)）	101\201\301		YES	NO	0	378	100
360	TP1-TP5(u)	101\201\301		YES	NO	0	438	100
390	TP1-TP5(u)	101\201\301\402\404		YES	NO	0	468	100
420	TP1-TP5(u)	101\201\301\402\404	3	YES	NO	3	498	99.40
480	TP1-TP5(u)	101\201\301\402\404	60	NO	NO	66	558	88.17

NOTE: 1) the sign “(u)” means speed up; and 2) the “(d)” means speed down, the same in Table 3.

Table 3 outputs of case study (transfer from route 728 to 694)

R728			**R694**	**Performance**				
Dep. time dev. at 1th stop (sec)	**Real Time Tactics**			**Direct transfer?**		**Time Dev. at transfer point**		**Dev. Ratio (%)**
	Speed change segment	**Skipped stop**	**Holding time**	with	without	with	without	
-600				YES	NO	0	-588	100
-300	TP6-TP7（d）			YES	NO	0	-288	100
-150	TP6-TP7（d）			YES	NO	0	-148	100
-60	TP6-TP7（d）			YES	YES	0	-58	100
-30	TP6-TP7（d）			YES	YES	0	-28	100
0					YES		0	na
90	TP6-TP7（u）			YES	YES	0	0	na
180	TP6-TP7（u）			YES	YES	0	0	na
240	TP6-TP7（u）			YES	YES	0	27	100
270	TP6-TP7（u）	603		YES	YES	0	57	100
420	TP6- TP8（u）	603		YES	NO	0	207	100
450	TP6- TP8（u）	603\701		YES	NO	0	237	100
570	TP6- TP8（u）	603\701		YES	NO	0	357	100
660	TP6- TP9（u）	603\701		YES	NO	0	447	100
810	TP6- TP9（u）	603\701		YES	NO	0	597	100
840	TP6- TP9（u）	603\701\802	1	YES	NO	1	627	99.84
870	TP6- TP9（u）	603\701\802\804	13	YES	NO	13	657	98.02
930	TP6- TP9（u）	603\701\802\804	60	NO	NO	73	717	89.82

The analysis of results can be divided into the two situations:

1) Route 694 has departure deviation and 728 on time

The departure time deviation of route 694’s vehicle ranges from -600s to 480s. the arrival time deviation at the transfer point is 78s without using tactics while the vehicle departs on time at first stop, direct transfer fails because the vehicle needs more dwell time than planned for to permit passenger alighting or boarding. The direct transfer only can be obtained when the departure time deviation ranges from -138s to -18s without tactics. However, using real-time tactics, the direct transfer can be successfully made while deviations range from -600s to 477. The length of interval increase is almost 797.5%. Besides, the vehicle can arrive at the transfer point as planned with deployment of real-time tactics while the departure time deviation ranges from -600s to +417s, clearly this is an important strategy to improving the reliability of vehicle.

2) Route 728 has departure deviation and 694 on time

As table 3 shows, the departure time deviation of route 728’s vehicle ranges from -600s to 930s. If the vehicle departs from first stop on time, it can arrive at the transfer point as planned without using any tactics. The direct transfer can be obtained when the depart time deviation range from -62s to 273s without tactics. After using real-time tactics, the range is from -600s to 917. The length of interval expands by almost 352.8%.

What’s more, the vehicle can arrive at the transfer point as planned with deployment of real-time tactics while departure time deviation ranges from -600s to 839s.

6 Conclusions

Planned synchronized transfers do not always materialize due to the stochastic character of traffic flow, driver behavior and fluctuation of passenger demand on feeder bus routes. Missed transfers frustrate passengers as well as reducing the potential for encouraging new users onto the public transport system.

This work presents an optimization procedure with real-time operational tactics to decrease or eliminate vehicle operational deviation, and thus to increase the actual occurrence of synchronized transfers in planned PT networks. An arrival time deviation-based dynamic speed adjustment model is proposed for updating vehicle speed. Three operational tactics, changing speed, holding and skip stopping, are used in the optimization with real-time vehicle speed and location information. The case study tests how close the vehicle keeps with planned schedules and how much delays change after deploying tactics. Results show that by applying the proposed methodology, for the two routes explored, the length of deviation interval for direct transfer can be significantly increased 797.5% and 352.8%, respectively. Vehicles also can arrive at transfer point as planned with application of proposed methodology while departure time deviation range from -600s to 417s for route 694, and from -600s to 839s for route 728.

The methodology described in this paper is a first step in a wider project which aims to develop new approaches to optimising the adoption of real time strategies in bus services to improve reliability and transfer synchronisation. There are a number of ways that methods of this kind can be improved. Clearly wider application of the approach to a large set of data would improve our understanding of the performance of the approach developed. There are also a wider range of potential operational tactics which might be employed including express operation and in terms of fleet deployment approaches such as ‘dead heading’. In addition the analysis might consider real time provision of data to drivers wherever they are on a route, rather than at timing points as has been used in this paper. In theory, adopting GPS and real time in cab communications with bus drivers, it may be possible to update bus drivers on how they may adjust operations to better drive to transfer points to achieve better synchronisation. Indeed if one considered a possible future involving autonomous vehicles including driverless buses, procedures as described in this paper might be deployed to inform vehicle driving instructions using direct communications with the driving control system.

Overall the methods described in this paper provide the basis to improve bus operations by making the most of new technologies to provide and react to real time information. Advanced approaches of this kind have the potential to significantly improve reliability and network performance of transit systems into the future.

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