A Novel Method for Measuring the Quality of Temporal Integration in Public Transport Systems

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Abstract

Temporal coordination of services, as a crucial aspect of integration in public transport systems, has always been a big concern for transit planners and schedulers. One of the major issues in the way of coordinating transit services is the lack of a robust measure of effectiveness for assessing the quality of temporal coordination in public transport systems. Even though the network-wide summation of transfer waiting times is commonly used as a measure for this purpose, this index is not always calculable particularly when transferring passengers count is unavailable. This paper aims to present a practical method for quantifying the level of temporal coordination in transit systems, even in the absence of transfers count data. In this paper, first the timetable coordination indices proposed in the literature are evaluated and discussed. Then, a quantitative index is mathematically developed based on the actual waiting time incurred by transferring passengers in transit systems. A numerical example is also presented to examine the applicability of the proposed index. The results of this application revealed this index could be reliably used as a measure of effectiveness for assessing the level of coordination between public transport services, as well as for evaluating the impacts of different timetabling scenarios on transit systems integration.

Keywords: Transit, public transport, synchronisation, timetable, schedule

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1. Introduction

Parallel to the growing interest in enhancing urban public transportation, developing integrated transit systems has been receiving more attentions, particularly over the recent years [Poorjafari and Yue, 2013]. In fact, integration is widely known as a key factor enabling public transport systems to compete with private cars through providing seamless services for passengers. Integration in public transportation has various aspects, including physical integration, network integration, fare integration, information integration and institutional integration. Among these aspects, temporal integration of transit services plays an important role in attractiveness of public transport systems.

In public transport systems, passengers may need to transfer between different modes and lines. When transfers are not managed appropriately, they could lead to imposing long waiting times on transferring passengers [Ceder and Perera, 2014]. In contrast, a well-coordinated system provides smooth transfers between different services with minimal delay for public transport users [Wu et al., 2015]. Temporal integration of transit services, which is referred to as *timetable synchronisation,* mainly consists in minimising the delay imposed on the passengers transferring between different transit modes and lines. This task is usually carried out through coordinating arrival and departure times of the transit vehicles from different modes and lines. Because of its complexity, timetable synchronisation is widely believed as the most difficult task for transit planners and schedulers [Ceder, Golany and Tal, 2001]. Temporal coordination of services is one of many planning measures included in network integration strategies for transit systems [Currie and Bromley, 2005]. Nevertheless, a major barrier in the way of improving temporal integration of transit systems is the lack of an appropriate measure for schedule coordination quality. Without a practical and meaningful basis for quantifying the quality of temporal coordination, it is impossible to assess the impacts of different planning strategies and timetabling scenarios on temporal integration of transit systems.

This paper aims to propose a new method for measuring the level of temporal coordination in transit systems. In this study, first the timetable synchronisation approaches are briefly explained and discussed for the purpose of clarifying the difference between their objectives. Then, the synchronisation indices proposed in the previous studies are evaluated in order to reveal the major drawbacks associated with these indices. Afterwards, a new quantitative index (*SQS*) is mathematically formulated, as a measure of effectiveness for timetable synchronisation, based on the actual waiting time incurred by transferring passengers. A numerical example is also presented in this paper to examine the applicability of the proposed method in quantifying the level of temporal integration in transit systems.

2. Schedule Synchronisation Approaches

Several approaches and methods have been proposed in the literature so far for tackling the schedule synchronisation problem. The difference among these methods mainly relies on the difference in their objectives. In terms of problem objective, the synchronisation methods can be classified into two main categories, namely, timed transfers and transfer optimisation [Guihaire and Hao, 2008; Tuzun Aksu and Yılmaz, 2014]. In the timed transfer approach, transit vehicles from different lines are scheduled to meet at certain transfer points at the same time allowing passengers to transfer. The main objective of this approach is to maximise the simultaneous arrivals of transit vehicles at some specific transfer points (i.e. transit centres) in a transit network. In the transfer optimisation approach, however, transit lines are scheduled for the purpose of minimising the total transfer waiting time in transit networks [Guihaire and Hao, 2008; Aksu and Yılmaz, 2014; Castelli, Pesenti and Ukovich, 2004].

In the transfer optimisation approach, all feasible transfers between transit lines at all transfer points are taken into consideration and timetables are set so as to minimise the total transfer waiting time in a transit network. In fact, the main objective of this method is to minimise the aggregated transfer waiting time in transit networks. Apparently, this objective is fundamentally dependent on the number of passengers transferring between all pairs of transit lines intersecting at transfer points, as well as the waiting time incurred by every individual transferring passenger. In other words, the volumes of passengers transferring between any pair of transit lines (i.e. transfer-count data) are essential parts of the data required in this method.

In practice, transfer-count data are not always available due to a range of reasons. In fact, unavailability of such data is one of the biggest issues concerned with the transfer optimisation methods [Currie and Bromley, 2005]. The number of passengers transferring between transit lines is very hard to collect by observation, as recognition of origin and destination lines of every passenger is almost an impractical task, especially at crowded transfer points. This information might be believed to be collectable through interviewing passengers for the purpose of identifying their origin and destination lines. Nonetheless, conducting interviews at transfer points requires lots of surveyors, particularly in the case of dealing with huge transit networks. Such a timely and costly task is not likely to be repeated in short intervals, as usually required for updating public transport schedules.

Transfer-count data can be extracted from electronic ticketing systems where transit systems are equipped with Automated Fare Collection (AFC) systems. However, plenty of public transport systems are not completely equipped with AFC systems, like those operating in most of developing nations. Moreover, AFC data are sometimes hard to obtain due the data confidentiality, particularly when private operators run transit systems. On the top of these, lack of transfer- count data for new transit lines is another issue associated with transfer optimisation methods, even if such information exists for operational lines. Hence, the quality index approach which is independent of transfer-count data has arisen in the literature (in addition to the timed-transfers and the transfer optimisation approaches) in order to cope with the issue of transfer-count data unavailability.

The synchronisation quality approach aims to quantify the quality of synchronisation in a transit system based on the length of waiting time for every feasible in a network rather than the number of passengers transferring in each transfer. In this approach, a global index is usually used as a measure of effectiveness (MOE) for the entire of a transit network and it is intended to maximise the value of this index through appropriately setting transit line timetables.

3. Synchronisation Quality Indices in the Literature

A limited number of studies have addressed the synchronisation quality approach so far and proposed quality indices for this approach. Fleurent, Lessard and Seguin in [Fleurent, Lessard and Seguin, 2004] presented a timetable synchronisation method based on the length of waiting time for each transfer in transit networks.

They used the concept of ‘trip meet’ in order to describe a possible connection between two trips at a transfer point. For each trip meet, they considered three values for waiting time: minimum, ideal and maximum passenger wait times. These values are intended to be specified by schedulers for each transfer based on walking distance and passenger flow at each transfer point.

Based upon these three values of waiting time and the weight factor, they developed a quality index (*QI*) for measuring the quality of synchronisation for each trip meet. The *QI* of trip meet *m* was defined by the following function [Fleurent, Lessard and Seguin, 2004]:

$$QI_m = \begin{cases} w_m\left(I_{min} + \left(\frac{a_m - l_m}{i_m - l_m}\right)(I_{max} - I_{min})\right), & \\ \qquad a_m \in [l_m, i_m] & \\ w_m\left(I_{max} + \left(\frac{i_m - a_m}{u_m - i_m}\right)(I_{max} - I_{min})\right), & \\ \qquad a_m \in (i_m, u_m] & \\ 0 & , a_m \notin [l_m, u_m], m \notin H \\ InfeasCost & , a_m \notin [l_m, u_m], m \in H \end{cases} \tag{1}$$

Where, is the quality index for trip meet *m*, *H* is the set of all historical meets, is the minimum quality index based value for feasible meets, is the maximum quality index based value for feasible meets, is the weight factor associated to meet *m* to reflect its relative importance, is the actual waiting time of meet *m*, is the minimum waiting time for meet *m*, is the maximum waiting time for meet *m*, is the ideal waiting time for meet *m*, and *InfeasCost* is the cost for historical unfeasible meets.

This piecewise linear function shows that *QI* for a trip meet is proportional between and corresponding to the difference between the actual waiting time of the trip meet and its admissible bound values. In fact, the value of *QI* is higher when the actual waiting time of the trip meet is closer to its specified ideal waiting time. is also defined to be equal to a specified negative constant value (*InfeasCost*) when a feasible meet under existing timetables becomes unfeasible, as the consequence of timetable synchronisation. Based on the *QI*, a global synchronisation quality index (*SQI*) is defined in [Fleurent, Lessard and Seguin, 2004] as the summation of the *QI* of all trip meets in a transit network. *SQI* is intended to be used as a measure for assessing the level of synchronisation for the entire of a transit network.

Currie and Bromley in [Currie and Bromley, 2005] argued that the synchronisation quality index (*SQI*) developed in [Fleurent, Lessard and Seguin, 2004] could not be a good indicator for assessing the level of temporal coordination between transit services for two main reasons. Firstly, *SQI* is an accumulative index which is calculated by summing the quality indices of all trip meets in a network. Hence, a transfer point with many poor connections gains a higher value of *SQI* in comparison with a transfer point with fewer but more quality trip meets. Moreover, the number of trip meets at weekends is considerably lower than the number trip meets during weekdays. Therefore, a poor coordination among transit services on weekdays could lead to higher values of *SQI*, compared to a good coordination at weekends. Secondly, *SQI* is a non-scaled, meaningless value which does not clearly represent the quality of synchronisation in a transit network. For instance, it is not clear between two stations with the *SQI* of 19170 and 2310, which one has a better situation in terms of coordination between transit services.

In order to remove the problems associated with *SQI*, another quantitative measure called synchronisation quality ratio (*SQR*) is proposed in [Currie and Bromley, 2005] for quantifying the quality of synchronisation. This index is a function of *SQI* as follows [Currie and Bromley, 2005]:

$$SQR = \frac{SQI}{SQI_{max}} \qquad (2)$$

Where, is the maximum possible value of *SQI* that can be achieved. This parameter is calculated by assuming all meets are feasible and waiting times are ideal for all trip meets. In this approach, in fact, *SQI* is normalised in relation to its maximum possible value to remove the impacts of the number of trip meets.

4. Synchronisation Quality Score (SQS)

Evaluation of the indices presented in the previous section discloses two basic issues associated with both of these indices. Firstly, *SQI* and *SQR* are dependent on minimum, ideal and maximum values of transfer waiting time. These three parameters are to be specified by schedulers for every feasible transfer in a network. In other words, the proposed synchronisation indices are directly influenced by the parameters set by schedulers; that is, the different settings of the parameters, the different values of the synchronisation indices. Secondly, these indices are developed based on transfer time, rather than transfer waiting time. The time spent by passengers on transferring from a transit line to another line (i.e. transfer time) consists of two components: walking time and transfer waiting time. While transfer waiting time depends on temporal coordination of services in transit systems, walking time is the consequence of physical integration in public transport networks. In fact, walking time depends on physical characteristics of public transport networks, such as the distance between stops or platforms, walking speed for different groups of passengers, the ease of access and so on, and is not influenced by temporal coordination of transit services. Hence, it is essential to exclude walking time from synchronisation quality indices in order to make them more useful for timetable synchronisation purposes. In order to resolve these issues, a new synchronisation quality index is proposed in this study as a measure of effectiveness (MOE) for quantifying the quality of timetable coordination in transit systems.

Let us imagine two transit lines *i* and *j* intersecting at transfer point *c* (Figure 1). The waiting time for the passengers transferring from *i* to *j* at *c* () can be expressed as a function of the arrival times of transit vehicles at *c* (*a*), dwell times of transit vehicles at *c* (*d*) and the walking time from *i* to *j* (w_{ij}), as follows:

$$tf_{ij} = a_j + d_j - a_i - w_{ij} \qquad (3)$$

Based on this equation, there are two extreme cases that the transferring passengers may encounter: *no-wait* scenario and *just-miss* scenario.

The no-wait scenario, which is the ideal situation for a passenger transferring from *i* to *j*, occurs when the passenger boards on the next service just slightly prior to its departure time. Under this situation, no waiting time is imposed on the transferring passenger (= 0) and the transfer time is only dependent on the walking time (including boarding and alighting times) between *i* and *j*. Using Equation (3), this situation can be expressed mathematically by the following expression:

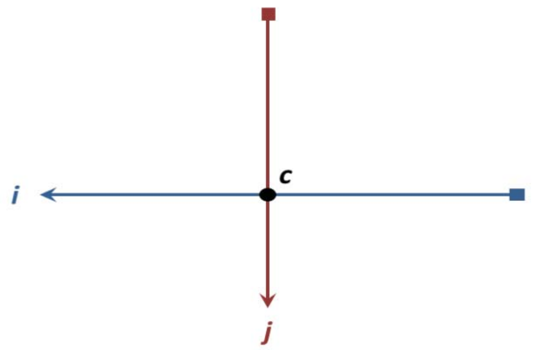

Figure 1. Intersection of two directional transit lines at a transfer point

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$$w_{ij} = a_j + d_j - a_i \tag{4}$$

This equation shows that this situation occurs when the walking time from *i* to *j* is exactly the same as the interval between the departure time of the second service (and the arrival time of the first service. In practice, it is very unlikely to set the timetables by which the no-wait scenario happens to all transfers at all transfer points in a transit network. However, this is the highest level of synchronisation that could be achieved by the process of timetable coordination. Under this situation, the total transfer waiting time in a transit network (*Z*) over an intended scheduling period becomes zero. In fact:

$$Z_{min} = 0 \tag{5}$$

The just-miss scenario, which is the worst case that a passenger transferring from *i* to *j* at *c* may encounter, occurs when the transit vehicle from *j* departs *c* just before the passenger can board on. Using Equation (3) this situation can be expresses as:

$$w_{ij} = a_j + d_j - a_i + \varepsilon \tag{6}$$

Where, is a very little amount of time. This equation shows that the just-miss scenario occurs when the walking time is a little bit longer than the interval between the departure time of the second service and arrival time of the first service. In other words, the transferring passengers do not have sufficient time to alight from the first service, walk to the next service and board it on. This is the worst case that a transferring passenger may face, as they need to wait for the next service from line *j*. Ignoring (very short time), the waiting time imposed on the transferring passengers in this case is equal to the headways of line *j*; that is, . In real-world transit systems, it is very unlikely that just miss scenario happens to all transfers in a transit network over an intended scheduling period. Nevertheless, this is the lowest level of coordination that could exist in a transit system. When the just miss scenario happens to all transfers, the total transfer waiting time (*Z*) reaches to its maximum value. In fact:

$$Z_{max} = \sum_{j=1}^{N} \sum_{c=1}^{M} \sum_{l=1}^{n_{ij}^{c}} h_j \tag{7}$$

Where, *N* is the number of directional lines in a network, *M* is the number of transfer points and is the number of feasible transfers from *i* to *j* at *c* over an intended scheduling period.

In practice, the level of temporal coordination in real-world transit systems is something between the no-wait and the just-miss scenarios. In other words, *Z* in any transit system is a value between Z_{min} and Z_{max} (i.e.). Based on this concept, a new synchronisation quality index, which is called *Synchronisation Quality Score (SQS)*, is proposed in this study as a global index for measuring the level of synchronisation in transit systems. This index is defined by the following equation:

$$SQS = \left(1 - \frac{Z}{Z_{max}}\right) \times 100 \tag{8}$$

Where, *Z* is the total transfer waiting time in the intended transit network. Thus:

$$\lim_{Z \to Z_{max}} SQS = 0 \quad ; \qquad \lim_{Z \to 0} SQS = 100 \tag{9}$$

In simple words, *SQS* is a number between 0, which implies the worst level of synchronisation, and 100 that signifies best level of synchronisation in transit systems. This index is totally dependent on the waiting times incurred by transferring passengers and walking time has no influence on this parameter. The following section presents a numerical example in order to show how *SQS* can be used for measuring temporal coordination in public transport systems.

5. A Numerical Example

Figure (2) schematically illustrates a hypothetical transit network consisting of four transit lines. In this example, a trunk line (Line 1) with the headway (*h*) of 10 min intersects three lines (Lines 2, 3 and 4) with the headways of 15 and 20 min at transfer points A, B and C. The running time from the first stop to the transfer points, as well as over each segment of the network is given in this figure. For the sake of simplicity, the dwell time of transit vehicles and the walking time between the related services are assumed as 1 min and the lines are considered unidirectional.

In this example, two timetabling scenarios (Timetables 1 and 2) are assumed for the intended network. Under Timetable 1, it is assumed that all of the transit vehicles depart the first stops at the same time (8:00 am). Then, this timetable is modified for the purpose of improving the temporal coordination between the services and Timetable 2 was created, as shown in Table 1. Using Equation (3), the waiting time for transferring from Line 1 to the other lines () can be calculated under these timetables (Table 1). It should be noted that the transfer waiting time for the first feasible transfers from Line 1 to the other lines is intended in this example.

Based on Equation (7), the maximum value of transfer waiting time between the first services in this network is calculated as below:

$$Z_{max} = 15 + 20 + 15 = 50\ min \tag{9}$$

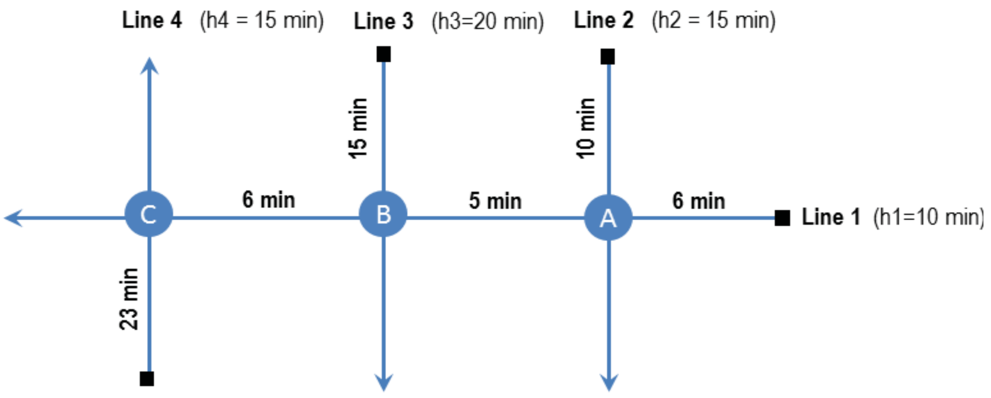

Figure 2. Network Configuration

Table 1. Transfer waiting times under Timetables 1 and 2

Line		1	2	3	4	SQS
Timetable 1	Dispatch time	8:00	8:00	8:00	8:00	78
	(min)	-	4	3	4	
Timetable 2	Dispatch time	8:02	7:59	8:00	7:59	94
	(min)	-	1	1	1	

According to Table (1), the value of *Z* is 11 and 3 minutes for Timetables 1 and 2, respectively. Using Equation (8), the *SQS* value can be computed as 78 and 94 for Timetables 1 and 2, in order (Table 1). This indicates the improvement in the temporal coordination of the services in the intended network, as implied by the reduction in the transfer waiting times.

6. Conclusion

In this paper, a new method has been presented for assessing temporal integration in public transport systems. First, the common approaches for transit timetable synchronisation were briefly described in order to reveal the fundamental differences between their objectives. Then, the synchronisation quality indices proposed in the literature were presented and the deficiencies associated with these indices were discussed. Afterwards, a novel synchronisation quality index (*SQS*) was proposed as a measure of effectiveness for quantifying the quality of temporal coordination in public transport systems. The application of the proposed method to a transit network, as a numerical example, showed the applicability of *SQS* for this purpose.

Compared to the previous synchronisation quality indices, the synchronisation quality score (*SQS*) proposed in this study has several advantages. This index is dependent on transfer waiting time rather than transfer time. Hence, it is not affected by walking time, which is influenced by physical characteristics of transit systems. In addition, this index is not affected by the quantity of transfers; that is, a network with many poorly-coordinated transfers cannot attain higher values of *SQS* compared to a network with fewer but well-coordinated transfers. On top of these, *SQS* quantifies the coordination of transit services only based on the actual waiting time incurred by transferring passengers, and does not depend on the parameters that need to be set by schedulers.

The method presented in this study could be efficiently used by public transport planners and schedulers to assess the level of temporal integration in any transit system. Future work, which is already underway, involves application of this method to functional transit systems for the purpose of testing its applicability under real-world situations. The *SQS* index could also be utilised as a proper objective function for schedule synchronisation models. Hence, further studies could be performed to develop a mathematical programming model for maximising *SQS* value through optimally adjusting transit lines timetable.

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