Developing Measures of Public Transport Schedule Coordination Quality

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1 Introduction

> "Despite the rhetoric and "big bucks", the government is yet to provide an exemplary interchange "opportunity" anywhere in Brisbane. For example, if you wish to travel from the city to St Lucia, there is no evidence of coordination of bus and rail or ferry in terms of timetables or routes"
>
> Yeates (2002)

Coordinating the timetables of fixed route public transport has long been an aim of public transport planners and the community. A well coordinated timetable enables easy transfer between public transport services. This involves a balance between allowing enough time to transfer between alighting to boarding services whilst also minimizing waiting time during the transfer. Effective transfers can substantially increase the catchments of bus and rail service and enable network wide travel on public transport. Wong and Leung (2004) demonstrated that adjustments to schedules for the optimization of transfer times on the Hong Kong Mass Transit railway could reduce passenger wait times by between 43% and 73% for little immediate cost.

Timetable coordination is one of many planning measures included in network integration strategies for public transport systems. Despite regular reference to policies which seek to improve coordination there is little demonstrated evidence of improvements resulting from such policies. A major problem is that it is difficult to measure coordination and hence it is difficult to demonstrate the benefits of improved coordination. 'Lack of bus rail coordination' remains a common complaint of users of public transport throughout the world.

This paper explores the issues surrounding the problem of schedule coordination on public transport networks. It takes the view that a major problem in planning for schedule coordination is the lack of a robust and objective measure of schedule coordination quality. Without a practical means of quantifying coordination quality, there is no systematic and defendable basis for demonstrating the benefits of improved coordination or a means of planning for optimal approaches to improve schedule coordination.

This paper starts with a review of issues associated with schedule coordination to provide context. It then reviews approaches to measurement. A relatively new approach to measuring schedule coordination termed the 'Synchronization Quality Index' is then outlined and the results of an application of this method described. A new development of the methodology termed the 'Synchronization Quality Ratio' is then presented and results from a small scale application of this approach outlined. Some conclusions on the next steps required to realize the potential benefits of the new approach are presented.

2 Issues in Schedule Coordination

This section explores issues affecting the planning of public transport schedule coordination to provide context for the paper.

2.1 Mixed and Conflicting Objectives

Adjusting schedules to optimise transfer times is only one of many factors which authorities aim to achieve with schedule development. Ceder et al (2001) point out that transport operators have numerous objectives when setting timetables e.g.

- Minimising operator costs
- Minimising user wait times
- Minimising vehicle and crew allocations
- Determining appropriate frequencies based on demand
- Matching the schedule to crew working conditions.

The minimisation of passenger wait times can often conflict with a requirement to minimise vehicle and crew requirements since the former requires that vehicles spend time waiting whilst the latter requires faster speeds and shorter waiting. In many cases poor vehicle and crew utilisation can be more a direct concern of operators than passenger waiting time because it is a more direct and tangible factor which affects financial performance.

2.2 A Complex Time Space Issue

While it can often appear desirable at a localised level to shift a particular scheduled arrival time of bus A to better meet with train B, it can often be undesirable and impractical on a network wide basis to do this. Shifting times of a particular arrival means that all other timings on that particular bus vehicle trip are also adjusted. This can cause two problems:

a. Other coordinated arrival times along the route can be affected (both positively and negatively)
b. The even headway interval between bus trips can be made uneven. This can cause an uneven service performance for those waiting at stops along the route and in extreme cases cause uneven loadings and bunching of services.

Schedule coordination is thus a complex numerical problem. It lends itself to computational and mathematical research methods. Indeed most large public transport agencies employ sophisticated scheduling software such as the HASTUS system (Rousseau and Hamer, 1993) to identify optimal solutions which balance their needs for minimal vehicle and crew inputs to the passenger requirements of schedules.

Complexity also acts to make schedule coordination a very abstract and difficult to describe issue. User groups in particular can see tangible localised problems with schedules at a given station but do not perceive the network wide constraints on scheduling. Complexity also makes transit planners focus schedule planning on a few high profile locations. Rarely are the wider impacts of adjusting schedules to achieve better coordination at a particular location traded off against impacts on a larger number of medium and lower order interchanges.

2.3 The Constraints of Multi-Operator Planning

Computerised schedule planning systems such as HASTUS can trade off network coordination of schedules against vehicle and crew resource minimisation goals. However this is almost never a practical solution to schedule coordination for most cities:

- Certainly in Australasia, no cities have bus and rail (and tram) schedules being planned by a single central multi-modal scheduling system
- Rather each city has a separate scheduling system for rail, for bus (and for tram)
- More often there are many alternative scheduling systems being used by different bus companies ranging from manual to high quality computer systems. In Melbourne there are 37 bus operators and at least 10 alternative methods to scheduling.

The general approach to this issue has been to mandate that all operators must plan schedules with coordination in mind. These requirements are usually included in operating contracts. In Victoria for example, the Department of Infrastructure has established guidelines for modal coordination whereby bus operators must make their 'best endeavours' to accomplish timetable coordination. Little detail on what this means is specified or detailed monitoring of outcomes apparent. Operators may for example be faced with a very real trade off between additional costs in vehicle and crew requirements as a result of schedule changes which improve network coordination. No formal approach to this issue appears to have been developed. In the absence of clear direction from regulators and also because of the complexity of the issue, schedule coordination is somewhat 'glossed over'. Planning is undertaken but outcomes are not clear.

2.4 Schedule Coordination in Practice

The research literature terms schedule coordination schedule or network 'synchronization'. The difficulty of the task and the approach most commonly taken is typified by the following quote from the literature:

> "Synchronization is the most difficult task of transit schedulers and is currently addressed intuitively"
>
> Ceder et al (2001)

Public transport schedulers typically identify critical coordination nodes on the network and plan schedules around achieving reasonable coordination at these points. In many cases timetables involve 'timed transfers' i.e. with connections to specific pairs of rail and bus services identified within the schedule. This approach is a practical and effective means of targeting the coordination problem at major interchanges; however it tends to ignore the issue of coordination at second and third tier interchanges. The intuitive approach avoids the complex task of balancing coordination on a network wide basis in favour of a pragmatic attention to a few key points.

Regulators of public transport are therefore faced with a difficult and complex problem. Because multiple approaches to scheduling are used no systematic system wide approach to optimising schedule coordination is feasible. This is exacerbated by the lack of an easy approach to measuring schedule coordination quality.

3 Measuring Schedule Coordination

There are 2 main approaches to measuring schedule coordination quality; passenger wait time and the Synchronisation Quality Index (SQI).

3.1 Passenger Wait Time

The most common approach to measuring the quality of schedule coordination is to sum 'passenger waiting time'. Voss (1992), Daduna and Voss (1995) and Ceder et all (2001) used an approach involving:

- Measuring passenger wait times (including transfer walk time) for transfers
- Weighting transfer times by passenger volumes
- Developing mathematical optimisation techniques which aim to minimise passenger wait times and balance this against other schedule development objectives.

There are a number of problems with this approach:

- Data Availability - Information on passenger travel volume is not always readily available particularly on a network wide basis and certainly not for individual transfers. While information on schedule timings is generally readily available, passenger demand data on individual transfers requires considerable data collection resources.
- Minimising Wait Time Can Be The Wrong Objective – Although minimising transfer time is an attractive objective, if times are too short there is a danger that some passengers, notably those with mobility challenges, may not be able to make a given transfer. In practice it may be appropriate to differentiate between:
  a. a minimum transfer time, where some passengers can make the transfers
  b. a maximum transfer time, where all passengers can make the transfer; and
  c. an ideal transfer time, which is a balance between a and b.

  In this case providing good coordination is an optimisation process which seeks a balance between times a. b. and c. Minimising transfer wait time is a simplistic approach when the timing of transfers and the implications for different passenger groups is considered.

3.2 The Synchronisation Quality Index (SQI)

Fluerent et al (2004) developed the Synchronisation Quality Index as a means of more elaborately measuring the concerns of users in relation to schedule coordination. Two main concerns were built into their approach:

- The need to differentiate between *minimum*, *maximum* and *ideal* transfer times; and
- The need to differentiate the importance of some transfers over others. For example transfers onto CBD bound commuter services can have a higher priority than counter-peak connections. Also some interchange locations might have more network wide strategic significance compared to others.

Figure 1 shows the basic components related to a transfer.

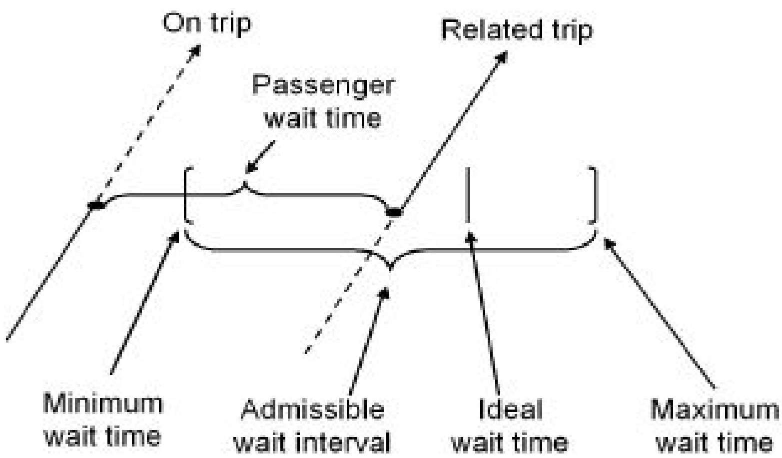

Figure 1 : Key Elements of a Transfer Trip (Fleurent et al, 2004)

Passengers make a bus rail transfer from the *on trip* (bus) to the *related trip* (rail). The *admissible wait interval* is the time where a transfer is possible or *feasible*. A transfer is *feasible* if a *minimum wait time* is allowed such that passengers can walk between the *on trip* to the *related trip*. The *admissible time interval* also has a *maximum wait time*. This can be set as the time which the slowest person might require to make the transfer. It may also be set to ensure transfers are possible allowing some element of leeway for unreliable services. Some time cushion may also be required to avoid the next related trip based on the rail service headway. An *ideal wait time* might lie somewhere between the *minimum* and *maximum*. This could be set near the *minimum* to make for 'tight' transfers or be close to the *maximum* to ensure more people can achieve a transfer in unreliable conditions.

Each interaction between an *on trip* and a *related trip* is termed a *trip meet*. In this case it is a *feasible meet*. If the transfer takes less than the *minimum wait time* or more than the *maximum wait time* it is not an *admissible wait interval*. It is also termed an *unfeasible meet*.

Fluerent et al (2004) present a formula to measure the quality of coordination termed the 'Synchronization Quality Index' or SQI. The SQI is calculated for each trip meet *m* using Formula 1:

$$SQI_m = \begin{cases} QI_m = w_m\left(I_{\min} + \left((a_m - l_m)/(i_m - l_m)\right)(I_{\max} - I_{\min})\right), a_m \in [l_m, i_m] \\ QI_m = w_m\left(I_{\max} + \left((i_m - a_m)/(u_m - i_m)\right)(I_{\max} - I_{\min})\right), a_m \in [i_m, u_m] \\ QI_m = 0, a_m \notin [l_m, u_m], m \notin H \\ QI_m = w_m UnfeasCost, a_m \notin [l_m, u_m], m \in H, \end{cases}$$

Formula 1[1]

where:

- w_m = weight to apply to trip meet *m*
- $I_{\min}$ = minimum quality index base value for feasible meets
- $I_{\max}$ = maximum quality index base value for feasible meets
- a_m = actual wait time of meet *m*
- l_m = minimum wait time for meet *m*
- i_m = ideal wait time for meet *m*
- u_m = maximum wait time for meet *m*
- $UnfeasCost$ = cost for historical feasible meets
- H = set of all historical meets.

This formula follows the process identified in Figure 2.

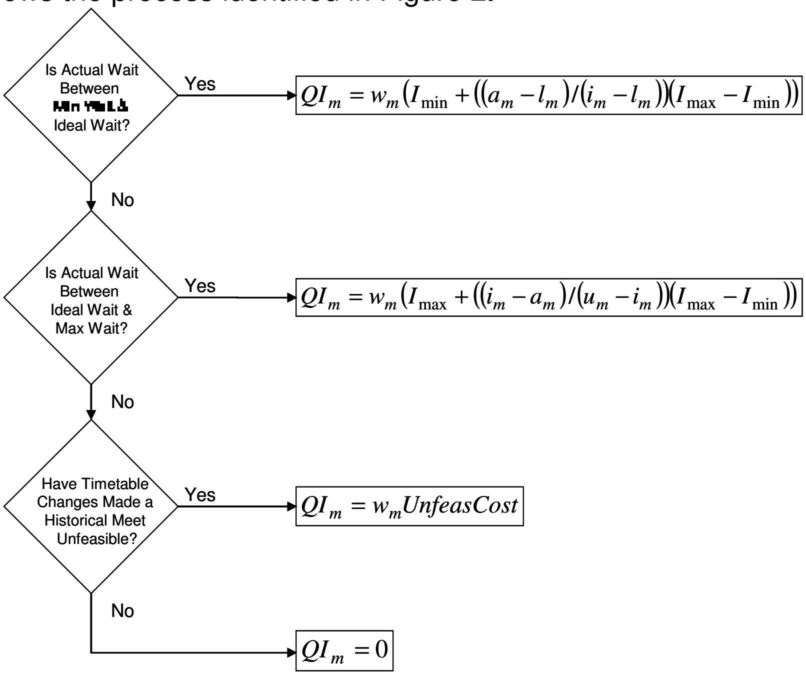

Figure 2 : Process of SQI Measurement

[1] Note: The second line in this equation has been altered from the original form in Fleurent et al (2004). We have consulted with the authors who agree with this adjustment. In addition the form of the equation with respect to *historical meets* has been adjusted to add weighting for trip meets.

The SQI value is large and positive for *trip meets* where *actual wait time* is equivalent to *ideal wait time* i.e. where coordination is good. The formula for calculating SQI is different if actual wait time is between the *minimum* and *ideal wait* than it is if it is between the *ideal* and *maximum waits*. In addition a separate process is used if a *feasible* meet becomes *unfeasible* as a result of changes in the schedule. This is termed a *historical meet* i.e. one that used to exist before the timetable change. A penalty is applied if a *historical meet* is no longer *feasible*. Termed $UnfeasCost$ it is applied to create a negative value for SQI. Finally if a trip meet is *unfeasible* i.e. the *actual wait time* is less than the *minimum* or more than the *maximum* but has not changed as a result of changes in the timetable, then the SQI value is zero.

In addition to the above, values for SQI_m are weighted (w_m) to represent the level of importance of the *trip meet*.

Figure 3 shows how values for SQI_m vary under various scenarios of transfer time.

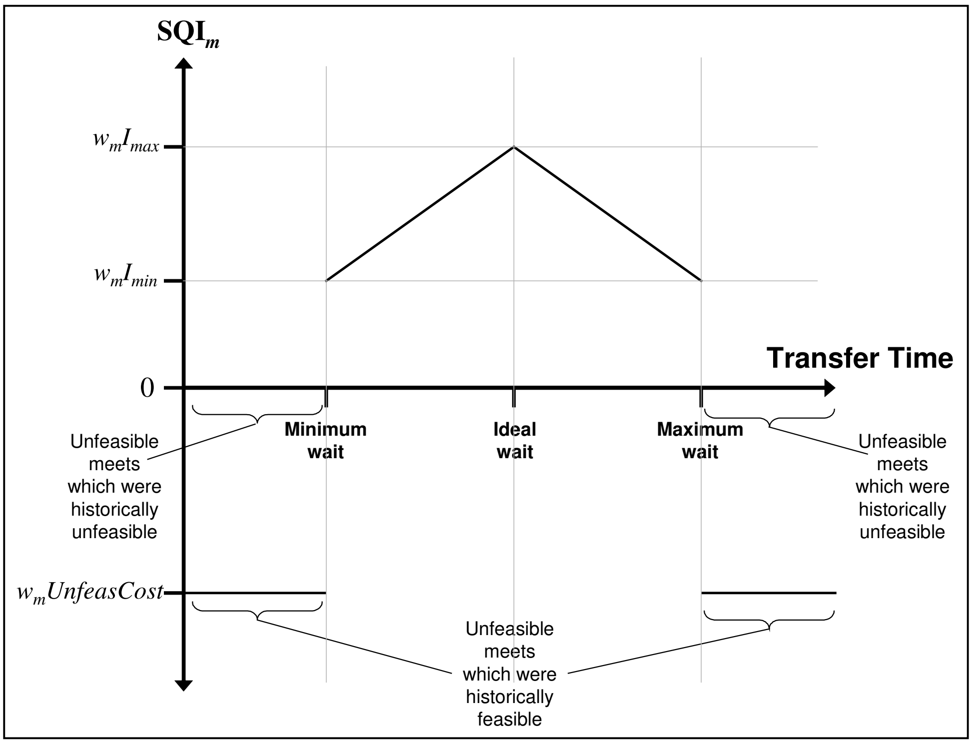

Figure 3 : Relationship Between SQI_m and Wait Time
Source: Based on Fleurent et al (2004)

The highest (and best) values of SQI_m result where the *actual wait time* is closest to the *ideal*. The index is zero if the *trip meet* is *unfeasible* and has always been *unfeasible*. However it is a negative number i.e. the value of the penalty $UnfeasCost$ if the *trip meet* is *unfeasible* but used to be historically feasible before the change in the timetable.

4 Application of SQI

The SQI approach was applied in a simple bus rail timetable case study in Melbourne on bus route 630. Coordination quality was assessed at 3 stations between route 630 and the 3 separate rail lines it crosses at Huntingdale, Ormond and Gardenvale Railway Stations. At each station only transfers between bus route 630 and rail was considered. However this was reviewed in all directions.

Site investigation and a review of timetables suggested values for the parameters as indicated in Table 1 for the a.m. peak. Off peak values were adjusted for u_m (maximum wait time) and $UnfeasCost$ (penalty for removing a feasible trip meet) because these parameters are related to service headways.

Table 1 : Parameter Settings for SQI Application
Melbourne Bus-Rail Case Study – A.M. Peak

Parameter		Value	Basis
a_m	actual wait time	As indicated in timetable	• Based on an analysis of schedules
l_m	minimum wait time	2 mins	• Based on site review of a minimum time at a modest walk pace
i_m	ideal wait time	5 mins	• Enables reasonable walk plus a modest time on platforms
u_m	maximum wait time	10 mins	• Ideal wait time plus 6 mins which is equivalent to around 95% of late running range for rail and bus • At values over 10mins passengers would see leaving trains as the bus arrives
$UnfeasCost$	Penalty for historical feasible meets which are no unfeasible	-20 mins	• Based on the wait time which passengers would have to wait until the next train in the headway (10 mins) • Weighted by passenger valuations of wait and walk time. A weight of 2.0 is used based on Transfund New Zealand (2000)
I_{max}	Maximum quality index base value for feasible meets	10	• This is the scaling factor which determines the relative size of index values. • A simple scaling between 5 and 10 was used based on its simplicity
I_{min}	minimum quality index base value for feasible meets	5	
w_m	weight to apply to trip meet *m*	10	• High weight for CBD bound trains in the a.m. peak
		5	• Lower weight for counter peak connections

Figure 4 shows the resulting total values of SQI for each of the three stations for a weekday, Saturday and Sunday.

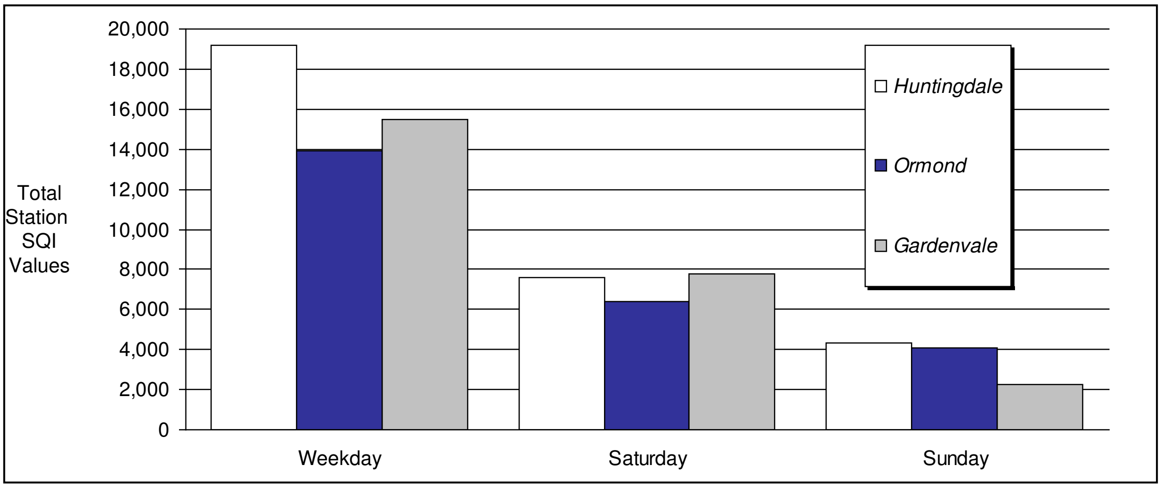

Figure 4 : Station SQI Values – Day of Week

This suggests that weekday coordination of service is better than at weekends. This might be expected because weekday headways are shorter than at weekends. Hence there is more opportunity to transfer within a reasonably low time.

Figure 4 also suggests that Huntingdale has better coordination than Ormond or Gardenvale Station on weekdays. Also that Gardenvale has better coordination than Ormond on weekdays.

Closer analysis of the SQI computations in this case suggests that these conclusions are not quite so clear. Table 2 shows the number of vehicle trips run by bus and rail at each of the stations, the number of feasible trip meets and the SQI values computed.

Table 2 : Schedule Coordination Inputs and SQI Outputs Melbourne Bus-Rail Case Study

Station	No. Vehicles Trip/ Day		Feasible Trip Meets	SQI
	Rail	Bus		
Weekday				
Huntingdale	156	152	447	19,170
Ormond	141	120	327	13,902
Gardenvale	162	117	364	15,446
Saturday				
Huntingdale	108	63	199	7,650
Ormond	107	62	184	6,662
Gardenvale	114	60	206	7,791
Sunday				
Huntingdale	90	42	121	4,448
Ormond	90	41	120	4,120
Gardenvale	94	40	79	2,310

The weekly distribution of coordination quality is driven by the number of vehicle trips where transfers can occur as much as it is by coordination quality. Hence Huntingdale Station, which has 156/152 rail/bus vehicle trips each weekday will have a much higher SQI score because there are more trips compared to Gardenvale on a Sunday with 94/40. While certainly more feasible trip meets are made in the Huntingdale case, the number of vehicle trips made at each station biases the results towards a high SQI outcome as much as coordination quality does. The important point here is that it is possible for a very large station with many coordinating services but with poor quality of trip meets (long waiting times) to have a higher total SQI score compared to a station with only one coordinating bus at very high quality. The SQI index is measuring more than just coordination quality. It is also measuring scale of service which is not directly an aim of the measure.

Another important point is that the SQI scores themselves don't mean much. When Huntingdale has a total SQI of 19,170 (weekday) and Gardenvale 2,310 (Sunday) it is difficult to say much based on these values other than they are a long way apart.

Because of these issues the research project explored ways in which SQI might be adjusted to create a more meaningful measure.

5 Development of the Synchronisation Quality Ratio

The development of an improved SQI measurement sought to remove the bias which high volumes of trip meets makes to the output index. A Synchronisation Quality Ratio (SQR) approach was developed which identified the maximum possible SQI which could be computed. This includes any trip meet weighting and would assume all meets are feasible and waiting times are 'ideal'. The SQR is thus calculated as the proportion of actual SQI in relation to this potential maximum as shown in Formula 2.

$$SQR = \frac{SQI}{SQI_{Max}}$$ **Formula 2**

The SQI ratio thus returns a ratio or percentage which is representative of the quality of coordination relative to the maximum possible quality which could ever be achieved i.e. every bus meets every train at the ideal waiting time. While SQI_{max} may never be achievable on a network wide basis, it is still an interesting number to be aware of, since it sets a standard which is high.

Figure 5 shows how the results from the SQR compare with the absolute values in the SQI formula for the stations in the Melbourne bus-rail example.

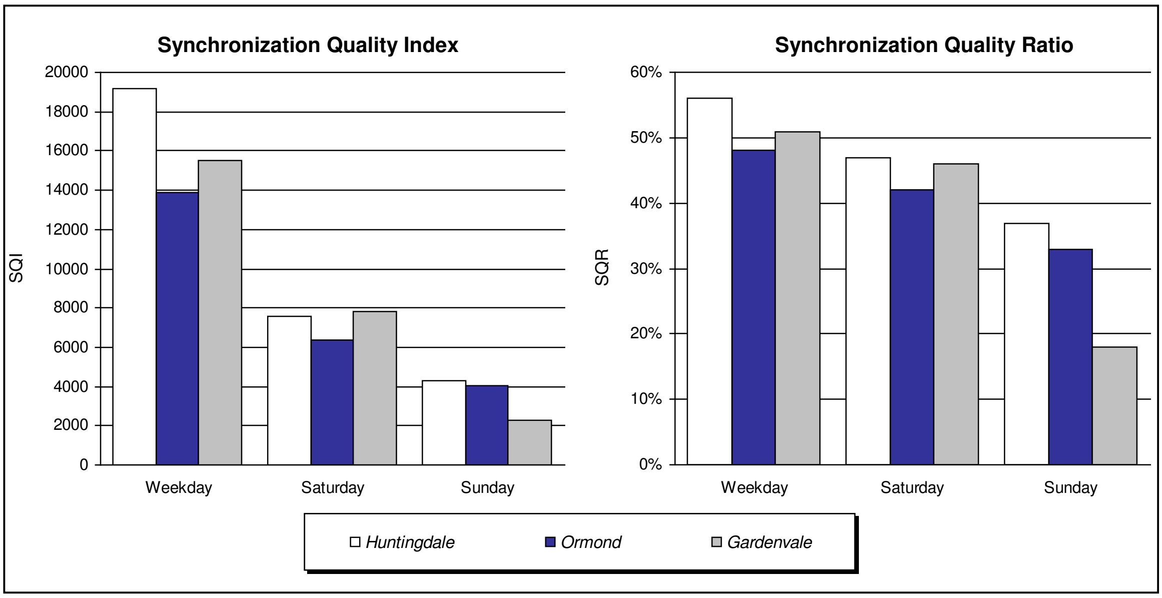

Figure 5 : Comparison of SQI and SQR Measures of Schedule Coordination

The two approaches suggest rather different values for coordination quality at each station by time period. SQR acts to bring together weekend and weekday valuations although the poorer relative quality of weekend day to weekday is retained, it's just smaller. The same is true about the relative gaps in coordination quality between stations. Interestingly the rank of station coordination quality on Saturdays changes according to the method used. The best SQI for Saturday coordination is at Gardenvale while SQR has Huntingdale with the best coordination quality.

Overall SQR was considered a better measure of relative coordination quality therefore was adopted for further investigation.

6 Exploring the Synchronisation Quality Ratio

A series of tests were undertaken to explore how the SQR would perform in terms of sensitivity to changes in key parameters and variation in relation to the adjustment of timetables. Sensitivity tests examined variation in *minimum wait time* (l_m), *maximum wait time* (u_m) and *ideal wait time* (i_m). A test of timetable adjustments was also undertaken for peak bus services.

6.1 Variation in Minimum Wait Time (l_m)

Figure 6 shows the impacts of increasing minium wait time on the SQR at each station.

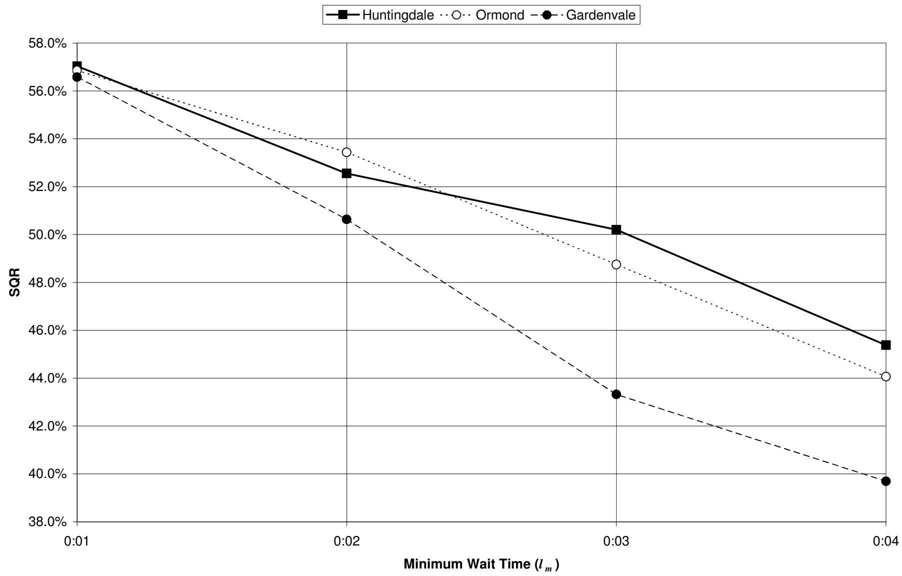

Figure 6 : Variation in Minimum Wait Time (l_m) and SQR

Increasing minimum wait time acts to reduce SQR because more trip meets become unfeasible. Stations are impacted differently depending on the distribution of transfer times. Ormond is less impacted by an increase in l_m from 1 minute to 2 minutes than Gardenvale is. This is because there are less transfer meets affected at Ormond.

6.2 Variation in Maximum Wait Time (u_m)

Figure 7 shows the impacts of variation in maximum wait time on the SQR at each station.

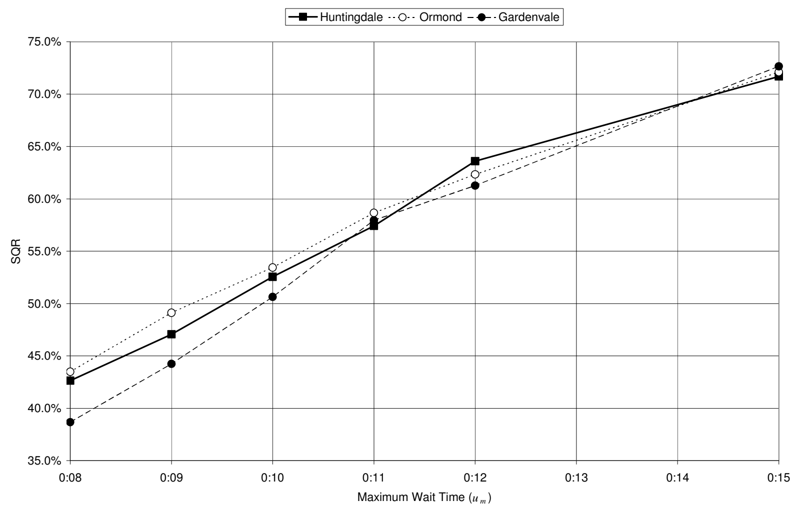

Figure 7 : Variation in Maximum Wait Time (u_m) and SQR

As maximum wait time increases more trip meets become feasible and SQR increases as a result. The rate of increase flattens out at higher maximum wait times because there is only a finite number of feasible trip meets so the benefit of getting additional meets to be feasible reduces. Even when all trip meets are feasible SQR is not 100% because this can only happen when the actual waiting times are equal to the ideal.

Figure 7 shows that stations are affected differently by variation in maximum wait parameters. This is because the number of trip meets which are not feasible is different at each station.

6.3 Variation in Ideal Wait Time (i_m)

Figure 8 shows the impacts of variation in ideal wait time on the SQR at each station.

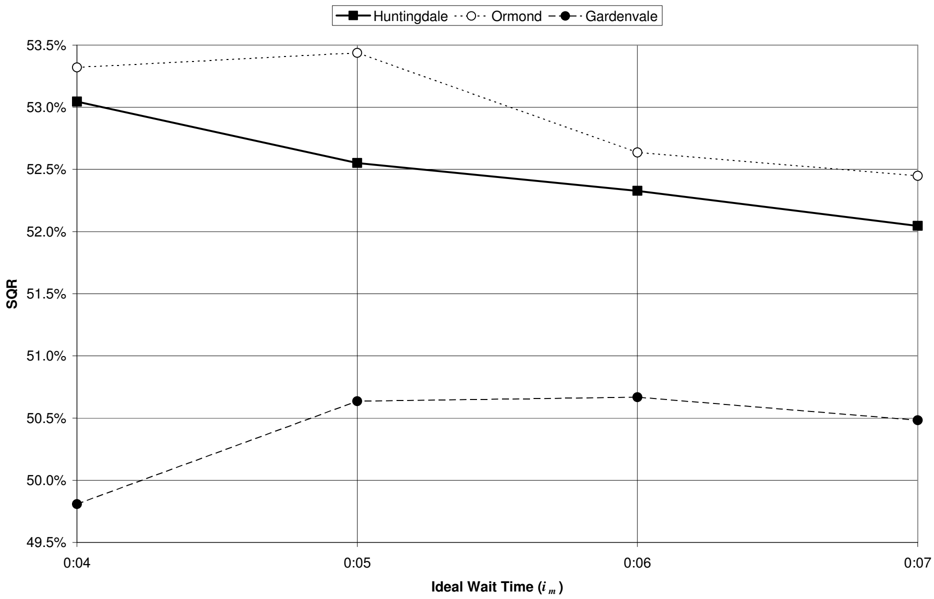

Figure 8 : Variation in Ideal Wait Time (i_m) and SQR

In general, Ormond and Gardenvale have better performance when ideal wait times are set at 5 mins while Huntingdale has an optimal ideal time at 4 minutes. This illustrates that transfer times at different stations are distributed in different ways.

6.4 Impacts of Adjusting Peak Bus Schedules

A separate set of SQR models were set up to model trip meets for these stations in the a.m. peak. Some 8 sets of bus vehicle trips were modelled (trips A to H) and a trip shifting function added such that shifting the timings of an individual vehicle trip adjusted trip meet times at each station. The model computed SQR values for adjusting each of the 8 vehicle trips separately. A separate model was used to compute total SQR values for combinations of trip shifts.

Figure 9 shows the outputs from the individual trip shifting model. Higher values for SQR are achieved by :

- Shifting the bus G timetable by – 1 minute
- Shifting the bus C timetable by +2 minutes.

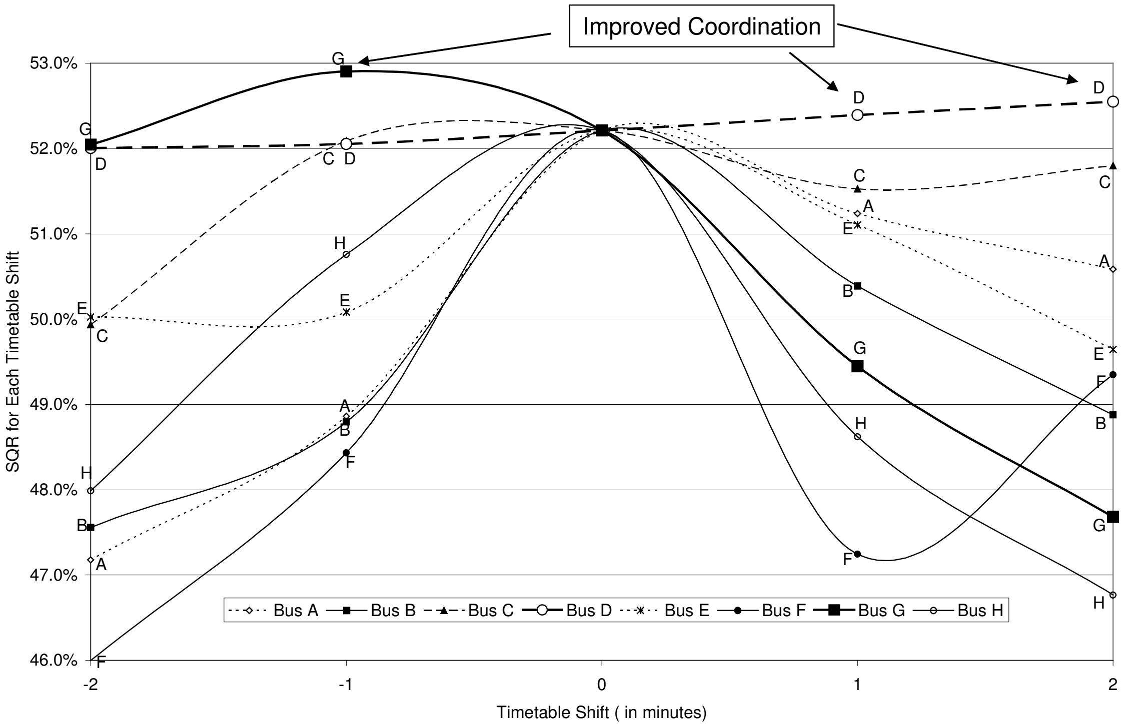

Figure 9 : Variation in Maximum Wait Time (u_m) and SQR

Tests indicated that by combining these two adjustments the SQR could be increased to 53.2% an overall increase of about 2% in total from the base timetable. Although this benefit is not to be ignored it is hardly substantial. The small scale of this benefit and the larger range of negative impacts associated with other timetable shifts suggests that the base timetable is relatively robust and well coordinated.

7 Conclusions

This paper has reviewed a series of issues associated with schedule coordination. From a user perspective good schedule coordination is a balance between allowing enough time to complete a transfer against minimising the wait time between connections. In designing schedules many other factors including tangible resource cost implications must be traded off against factors such as transfer quality.

The complexity of transfer coordination is not well understood by users who express concerns over tangible localised mismatches at local interchanges. Planners understand the issue of coordination but lack effective tools to measure coordination quality. Most planning for schedule coordination is intuitive as a result.

The use of system wide network schedule coordination software to 'optimise' bus, rail (and tram) schedule coordination is not a feasible option for most cities. In practice separate operators have different approaches to scheduling and solutions for schedule coordination will require a tool which can compare schedules between transit modes, services and separate operators in order to understand and measure the overall quality of coordination. Without an open and defendable basis for measuring the problem, user complaints about coordination will always be difficult to retort. Planners are open to much criticism because they have no technical defence.

Measures of coordination quality were reviewed. Use of passenger wait time and the SQI approach were shown to have weaknesses. A new approach termed the Synchronisation

Quality Ratio was developed and tested under a range of sensitivity tests. It has a number of benefits in that:

- It only requires timetable data – which is generally readily available as a result of the increased digitisation of web based schedule information systems.
- It can be used to measure coordination quality for multi-operator situations.
- There is an opportunity to develop a 'meta-system' where schedules from many sources can be combined and assessed to determine overall coordination quality.
- It is sensitive to coordination quality and not the volume of services.
- It can be weighted to highlight important transfer connections and be representative of passenger volume or scale of interchange importance.

SQR requires calibration to identify appropriate parameter setting for individual interchange sites. A range of potential settings were explored by sensitivity testing in a small case study.

A number of steps are required to further develop the approach. There are also a number of research questions to be explored:

- A wider exploration of parameter sensitivity is warranted.
- SQR needs to be tested on a larger data set. Its implementation on a city wide basis will require software development and standardisation of schedule data formats.
- A computational challenge is that most timetables only show arrival times at a few points 3-5 on most routes. In addition they often do not indicate dwell times, times indicted are averaged and are often not accurate. SQR needs a good estimate of arrival and departure times for all locations where coordination is possible.
- The increasing development of timetable information tools such as trip planners has made schedule data of this type more readily available. The researchers have already had discussions with MetLink in Melbourne exploring the availability of such data.
- The development of a computer package which measures coordination quality and can easily assess timetables of many formats would be an obvious long term objective. Such a tool could be developed to highlight problem locations and even undertake a preliminary assessment of where better coordination might be feasibly achieved. Use of large scale scheduling systems to undertake such a task would be expensive but is possible. A smaller scale system to quickly identify opportunities which individual operators may then go on to explore and implement using their own tools would be a more pragmatic and cost effective approach to the problem.
- It would be beneficial to explore the relationship between passenger wait time measures of schedule coordination with SQR. Passenger wait time measures have the benefit of using the volume of users as a measure. This is a better measure than the weighted optimisation applied in SQR however SQR remains a more practical way of tackling the problem. Exploring ways to calibrate SQR so it is a better representation of passenger wait time will be an effective advance in the approach.

Acknowledgments

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