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A study on the planning of through train service on metro networks

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Abstract
Based on the current and upcoming metro network of the city of S, considering the previewed passenger flow, we propose a plan with certain number of through trains operating on adjacent lines, and a train graph as well as its corresponding schedule is generated with certain constraints considered. Relative issues are discussed, including infrastructure, signal system and modes of control. Finally, a general conclusion of the feasibility and benefit on passengers and operators of the two through train services is made.

Keywords: urban rail transit, through train, train operation plan, metro network

1. Introduction
In this study, lines 11, 14 and 16 of the metro network of City S are concerned, on which through trains are intended to operate. Line 11 (abbreviated as L11 below) is a line currently in service with a total length of 51.73 km, which serves as the express metro link between the city centre and the western suburban areas as well as the airport in the west. Meanwhile, a 1.5 km eastward extension from the current terminus FUT to GXN connecting Line 14 is planned. The planned line 14 (abbreviated as L14 below) connects the eastern areas and city centre, which is also an express link measured 50.34 km, consisting of 15 stations. These two lines utilise Size A metro trains in eight car sets, whose maximum speed is 120 km/h. The junction GXN will serve as the terminus of two lines. A regional line serving eastern districts measured 29.2 km is designed to be metro line 16 (abbreviated as L16 below), consisting of 24 stations. A-type rolling stocks in six car sets are utilised, whose maximum operation speed is designed to be 80 km/h. The capacity of rolling stocks adopted on L11, L14 and L16 are 2480 passengers, 2480 passengers and 1860 passengers respectively. The station UVS will be the junction connecting L14 and L16, which is also the terminus of L16. The diagram of lines is shown in Figure 1.
Considering the potential demand of commuting from the eastern suburban areas to the central part of the city, a through-train plan is proposed and discussed in this study. In this plan, through trains operate on L11 and L14 as well as L14 and L16.

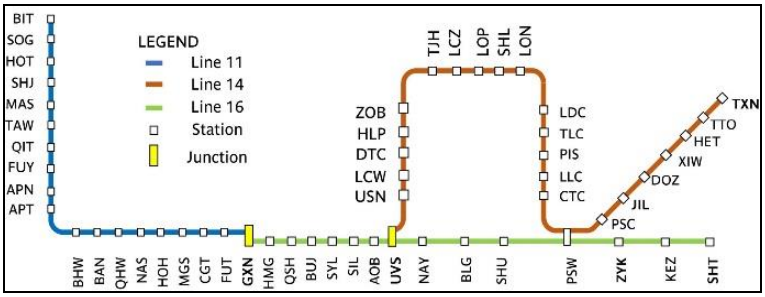


Fig 1: Diagram of Lines 11, 14 and 16.

2. Necessity of through-train service
As the urban rail transit networks expands, the demand of direct train service from one point to another keeps rocketing. Generally, such kind of demand is reflected on the congestion at transfer stations, especially stations serving as terminus of one or several lines, bringing considerable high pressure to junctions. In this study, GXN and UVS Junctions on L14 are two major junctions facing challenges brought by transfer passengers. Moreover, passengers spend more time on commuting due to transfer and sometimes, congestion at junctions, which will distract commuters from using rail transit as a commuting method.
In this study, GXN is designated as a major central junction with four interchange lines, two of which, namely L14 and L11, will terminate at this junction. According to passenger preview, in the long term, 42% of the passengers will transfer from L14 to L11 during morning peak hours, while a relatively small proportion of passengers terminate their trip at GXN. In view of the considerable demand of transfer from L14 to L11, a through train plan connecting these two

lines as an east-west corridor is proposed. Another junction UVS with three interchanging lines, welcomes transfer passengers among L16, L14 and L3 during peak hours. The statistics indicates that during morning peak hours, a considerable proportion of transfer passengers will transfer from L16 to L14 and continue their voyage going westward. In view of the potential high demand and its derivative issues in transfer at these two principal junctions, through-train services are considered and planned in this study on L11, L14 and L16.

3. The through-train plan on lines 11, 14 and 16

3.1 Interconnecting lines

In general, on Lines 11, 14 and 16, ordinary train routes are still available. Trains run on these lines between their own termini without interconnecting other adjacent lines. Considering the level of service on the entire line, these ordinary train routes will cover the entire line rather than terminating mid-route.

For routes of through train services, several factors are considered: commuting from the east to the centre, an east-west corridor and express service to and from the airport from the eastern areas. Besides, the complexity brought by interconnection and the extended operation cycle time for rolling stocks are also considered. Therefore, three interconnection plans were proposed:

- Interconnection between L11 and L14.
- Interconnection between L14 and L16.
- Interconnection of L11 and L16 via part of L14.

Among these three plans, the first plan is intended to fulfil the demand for an east-west corridor as well as passengers travelling between the eastern districts and the airport. Through trains plan 2 is aiming at the commuting demand of eastern sub-centres in order to reduce transfer at UVS Station. Plan 3 is a combination of plan 1 and 2 targeting at passengers travelling between eastern sub-centres and the airport as well as western sub-centres. Considering the complexity of the third plan, especially the diffusion of incident and delay and the extension of operational cycle time, this plan is abandoned. Therefore, there will be interconnection between L11 and L14, and between L14 and L16.

3.2 Termini of train routes

As interconnection routes require trains circulate on two lines, circulation time extends. Therefore, it is necessary to adjust termini of different train routes in order to reduce circulating time of trains running on interconnection routes, rather than turning back at termini of both lines.

The western terminus of L11-L14 through service is on the current L11. In view of the initial purpose of serving passengers heading for the airport and the future new airport terminal, the western terminus shall be APN. At present, APN station has reverse tracks at the north side of the station, and during morning peak hours, there are train services that runs between APN and the current central terminus FUT.

When focusing on L14, this interconnection route can be regarded as a short-run train route compared to the ordinary train route. Therefore, it is practical to adopt to the method used to choose the terminus for short-run routes. According to relative research [1], when the figure of passengers per hour per direction of two adjacent sections fulfils the criterion shown in formula (1), the station between them canbe a mid-route terminus for short-run routes.

$$D = [(100\%—P_1) + (200\%—P_2)]/2 \quad (1)$$

In this sense, several possible turn-back stations are considered and, the station ZYK is selected as the eastern terminus of the L11-L14 through service. Therefore, the through train service on L11 and L14 operates between APN on L11 and ZYK on L14.

Based on the previous considerations, the L14-L16 through service aims at offering a direct liaison between the eastern sub-centres and the city centre, and to minimise the complexity in operation as well as the circulating time of rolling stocks, this through service will terminates at GXN on L14. As for its eastern terminus, the method is similar to that used in the decision of the eastern terminus of L11-L14 through service. The result indicates that JIL is a better choice for the eastern terminus of L14-L16 through service.

To sum up, five train routes on Lines 11, 14 and 16 can be listed as follows after analysis, two of which are through-train service routes.

- BIT to GXN on L11.
- GXN to SHT on L14.
- UVS to TXN on L16.
- APN to ZYK on L11 and L14.
- GXN to JIL on L14 and L16.

As for the frequency of train service, the interval of train service between BIT and GXN refers to the current data. The through trains from L14 via GXN will be inserted in the intervals between trains on L11. For L14 and L16, the frequency of train service depends on the preview of passenger flow and the scale of transfer passengers. Considering the capacity of rolling stocks used on three lines, the number of trains of each route is listed as follows:

- 10 trains per hour from BIT to GXN on L11.
- 4 trains per hour from GXN to SHT on L14.
- 8 trains per hour from UVS to TXN on L16.
- 6 trains per hour from APN to ZYK on L11 and L14.
- 4 trains per hour from GXN to JIL on L14 and L16.

3.3 Impact of Lines 14-16 through service

The difference in maximum speed in rolling stocks between L14 and L16 poses considerable impact on the through-train service. Defined as a trans-regional express rail link, L11 and L14 adopt a higher criterion in terms of maximum speed; they are designated for a maximum operational speed of 120 km/h. Meanwhile, due to the limitation of platform length, it is not practical for 8 car trains entering L16 whose platforms can only accommodate 6 car trains. Therefore, L14-L16 through service can only operate by L16 six-car rolling stocks. As is mentioned above, the maximum speed of L16 rolling stocks is 80 km/h. Because of the difference in maximum speed, the operating time between GXN and UVS of L14-L16 through service will be longer than that of other train services on the same section. It is possible that in certain cases the train with higher speed will take over the 6 car train. However, due to the limitation of infrastructure, it is not feasible for trains to take over on the entire Line 14. Before planning the timetable and train graphs, it is necessary to restrict the interval between the 8 car trains and 6 car interconnection trains to avoid take-overs, thus the

interval should fulfil the following criterion [2]:

$$T_{\text{interval}} + T_2 - T_1 \geq h \quad (2)$$

where T interval refers to the interval between trains of different maximum speed of operation. T1 and T2 are, respectively, the travel time of 6-car trains and 8-car trains departing after the six-car train, and h is the headway, which is 100 seconds on L14. After calculation, T interval should be no less than 305.46s. In other words, to avoid the take-over of eight-car trains, a six-car train should depart at least 305.46 seconds before the departure of an eight-car train at either GXN or UVS Junctions. Timetables and train graphs should be planned according to this criterion.

From this problem, we can preview that the interconnection of lines whose rolling stocks operate at different speed may cause a loss in passing capacity, which may turn into a restriction for the future development. The dilemma of the RER Lines B and D in Paris is one of the case that has the same problem [3].

3.4 Concurrent operation at junctions

Two major junctions where trains turn back or go through will be critical points in operation. Therefore, it is necessary to analyse the concurrent operation and the minimum headway at junctions GXN and UVS.

3.4.1 UVS junction

To fulfil the requirements for concurrent turn-back of ordinary L16 trains and the passage of L14 trains as well as the L14-16 through train, a plan for platforms is proposed for this situation, as shown in Figure 2.

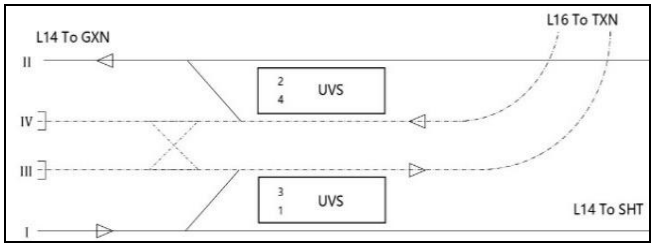


Fig 2: Track diagram of UVS Junction.

At this junction, the most critical scenario occurs when westbound L16 trains arrive continuously and are about to turn back at UVS, while an eastbound through-train is arriving at the junction and continue its mission on L16 just before the arriving of the latter L16 train. The following diagram (Figure 3) illustrates the procedures of concurrent turn-back and passage operation at UVS Junction.

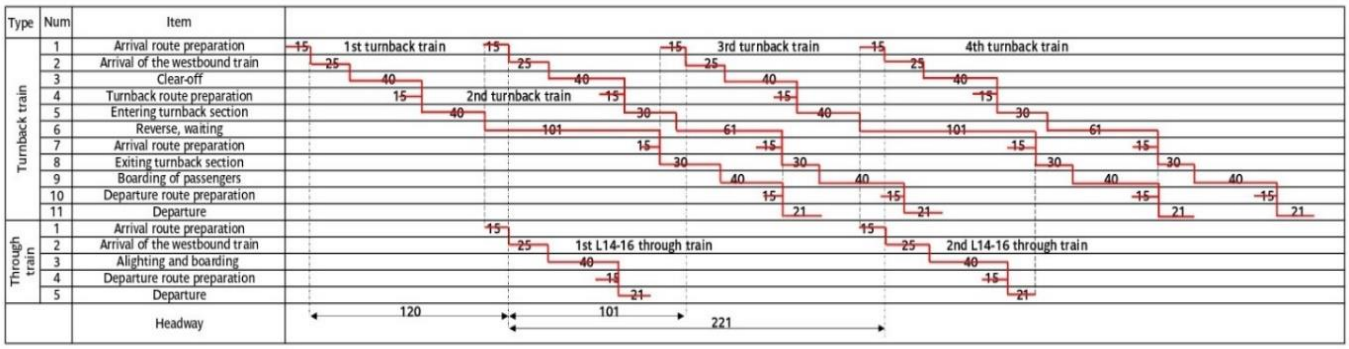


Fig 3: Procedures of concurrent operation at UVS Junction.

The calculation in Figure 3 reveals that the concurrent operation of the arrival of eastbound through train and the westbound reversing train is feasible and practical. This is based on a condition in which the first train should enter reverse track III via a scissors crossover before reversing, while the following train enters track IV for reversing and exit to track III after turning back. In this way, the concurrent operation of turn-back and passage is achieved. The interval between two adjacent turn-back trains is 120 s. It fulfils the requirement of 30 trains per hour.

3.4.2 GXN Junction

This junction is the terminus of L11 and L14, and through trains continue service on adjacent lines. Besides, L14-L16 through service terminates here as well. The track diagram is shown in Figure 4. Note that a depot shared by two lines is connected to this junction as well.

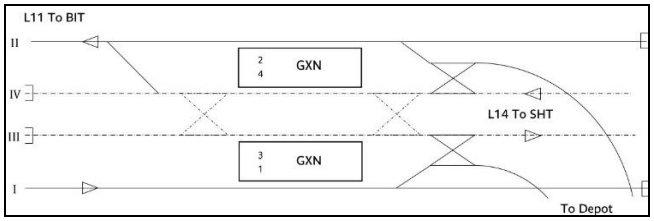


Fig 4: Track diagram of GXN Junction.

At this junction, the trains of L11 (not through train) have to turn back using the inlet/ outlet line, and trains terminating at GXN Junction utilise the reverse tracks III and IV after arriving. At this point, the eastward direction towards L14 faces more crucial situation than the opposite direction, especially when turn-back trains on L14 is departing just after the eastward through train. Figure 5 illustrates the concurrent operation of eastbound direction at GXN Junction.

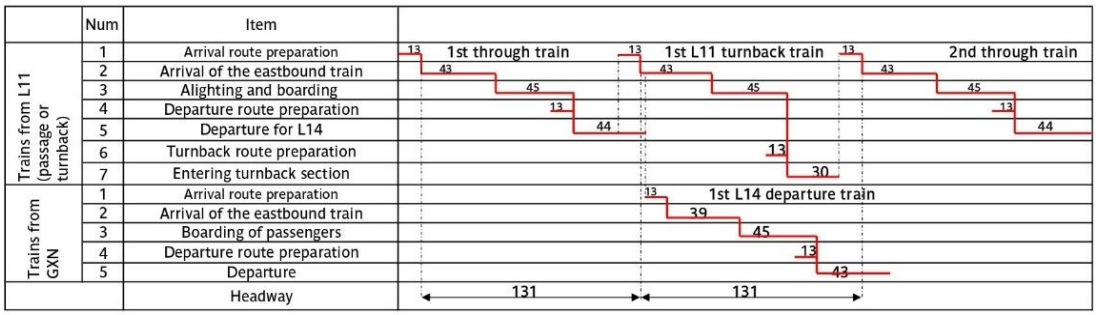


Fig 5: Procedures of concurrent operation at GXN Junction.

Figure 5 illustrates the procedures of concurrent operation at GXN Junction. Two eastbound through trains arrive at GXN Junction and enter L14 in turn. Between the arrivals of these two trains, a L11 non-interconnection train terminates at GXN Junction, and meanwhile, a train from GXN Junction departs. It shows that the departure of the L14 train and the arrival of the L11 train can operate concurrently without disturbance. The headway is 131 seconds.

3.5 Planning of time tables and train graphs

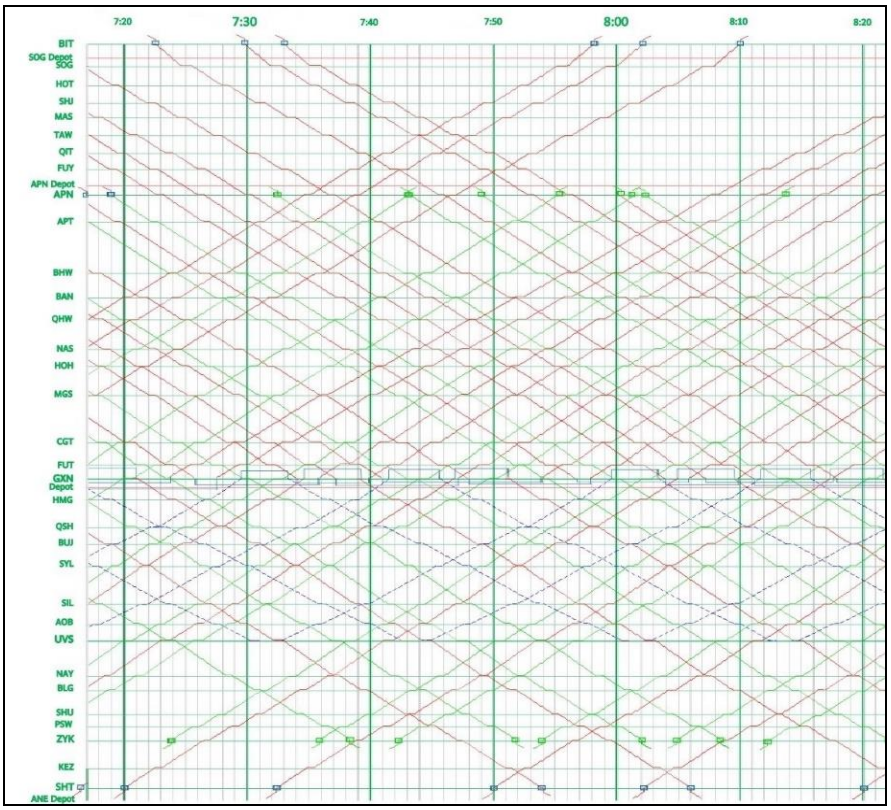
The analysis gave necessary constraints on the planning of timetables and train graphs. Other constraints including the minimum turn-back time and the minimum headway are considered as well. Due to the complexity of train organisation in GXN-UVS section, the timetable of this section shall be settled down in priority. Once the timetable of this section is generated, train missions of other sections including L11, part of L14 and the entire L16 will be clear. Therefore, we chose the westbound train from UVS as the starting point of planning.

According to the number of trains defined above, 4 trains of L14, 6 trains for L11 and 4 interconnection trains from L16 depart from UVS Junction per hour. Considering the interval constraint, the L14-L16 through trains depart between two 8-car trains operating in 120 km/h. Therefore, the departure of trains at UVS Junction follows the cycle per half an hour; the cycle of intervals of departure trains is illustrated in Table 1.

As the timetable of through trains generated with the cycle listed below (Table 1), on the one hand, the schedule of L11, L16 and other part of L14 (Westbound direction) can be drew out thereafter. On the other hand, by considering the minimum turn-back time and the constraint of intervals, the timetable of GXN-UVS section will be settled. Figure 6 shows the generated train graph according to the analysis and intervals decided above.

Table 1: Cycle of westbound departure trains of UVS junction per thirty minutes

Type of train	Terminus	Interval
L11-L14 through train	APN	3min
L14 train	GXN	3min
L11-L14 through train	APN	6min
L14-L16 through train	GXN	6min
L11-L14 through train	APN	3min
L14 train	GXN	3min
L14-L16 through train	GXN	6min
L11-L14 through train	APN	6min



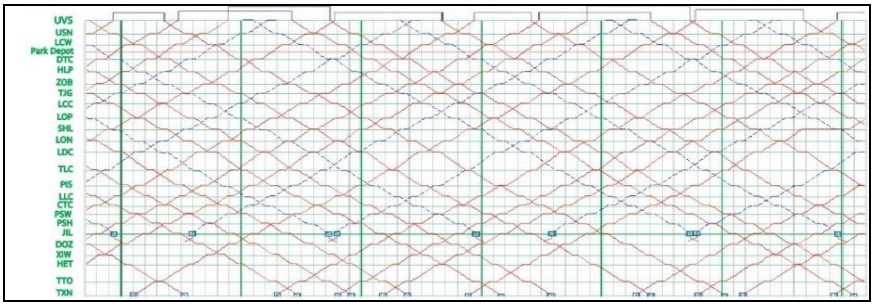


Fig 6: Train graph at peak hours.

4. Impact and relative critical issues

4.1 Pros and cons of through train service

It is apparent that through train service will bring considerable benefit for passengers, as they are able to spend less time on transfer and waiting for the train from another line after alighting, which will improve the level of service by reducing the time on commuting, and therefore attract more commuting passengers. According to relative research in through-train service, the time spent on transfer appears to be longer to that spent on travelling on board in terms of personal feelings, even though the time is, de facto, the same [4].

Moreover, for operators, the brutal large number of transfer passenger at termini brings considerable pressure to the organisation of the crowd. In this study, the two junctions will doubtlessly face this problem. This problem will deteriorate due to the coexistence of several connected lines, especially on the platform. With the help of interconnection, or through train service, the transfer passengers of interconnected lines are, de facto, turned into passing passengers who do not have to transfer; this will greatly relief the pressure of junctions. It will reduce the security risk caused by large passenger flow of major junctions.

It needs to point out that in case of disturbance or delay on a single line, the influence will doubtlessly diffuse on other interconnected lines. At this time before the problem is settled, it is suggested that the through train service be suspended.

Besides, considering the relative low speed of L16 trains, as is seen from the train graph (Figure 6), the interconnection L14-16 restricts the future development of the faster train services on L14. In terms of travel time, the benefit brought by this through service is not as apparent as that of the other one. In view of general profit, it needs more consideration of this service.

4.2 The sharing and the adaptability of rolling stocks

At present, rolling stocks are owned by a single line; trains of a certain line do not goes into the tracks and depots of other lines in most cases, even though they are connected by connected lines. In this case of interconnection, to reduce the time of starting from depots, it is necessary for different lines to share rolling stocks.

The adaptability of lines is another critical issue that affect the feasibility of through train service. From infrastructure like gauge and track gauge, to the compatibility of signal system, these issues should be considered in advance before interconnecting. The interconnected lines should be equipped with the same type of rolling stocks and fulfils the same gauge requirement in order to assure the entry of trains and, stopping at stations. Trains should utilise the same method of electrification. If the formation of train sets utilised on interconnected lines is different, necessary adaptation from platform screen doors to certain modification in signal system should be made.

4.3 A compatible signal system, a unique control centre

As for the signal system, the interconnected lines are subjected to use the same type of signal system. Trains equipped with two types of devices is also feasible, which may increase cost in installation, training and maintenance. It is suggested to use the communication-based train control (CBTC) system in order to improve train service and the level of automation.

It needs to point out that the interconnection of the three lines mentioned in this study will face the problem of the compatibility between an ordinary automatic train operation (ATO) system and an unattended train operation (UTO) system. Therefore, all lines should be accessible for UTO and ordinary ATO system, which requires certain modification in the signal system on L11. The interconnection of Lines 2 and 3 of Nürnberg U-Bahn is a successful usage in the combination of ordinary ATO system and UTO system.

Besides, the control centres of three lines shall be the same in order to achieve the unity of train control, or at least connected. In the case of interconnection of RER Lines A and B, they adopt different control mode in terms of centralised control. RER A has separated control centres owned by the two operators, while these two are connected both physically, while RER B adapts a unique control centre [5]. It is suggested to share the same centre by the interconnected lines to improve the communication and handling in operation as well as the problem-shooting in case of disturbance.

5. Conclusion

From the study above, we can conclude that the through train service of L11-L14 is feasible and is of considerable benefit to passengers considering the scale and the demand of through-service passengers. We could not preview an equal profit on the L14-L16 through service, considering the lower demand of interconnection and above all, the impact to passing capacity. The latter factor pose a considerable impact not only on the loss of capacity in the interconnection sector, but also on the capacity on the two junctions.

6. Acknowledgments

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