Case Study I – Stockholm Railway Network Analysis

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2013-3-30

1 Introduction

Except for bus system and airport transport, public transport in Stockholm includes metro system, light rail system, tram system, commuter rail system and boat/ferry system. Particularly, in Case Study I we focused on Stockholm rail traffic, consisting of metro, light rail, tram and commuter rail as demonstrated in **Figure 1** and **Table 1** below.

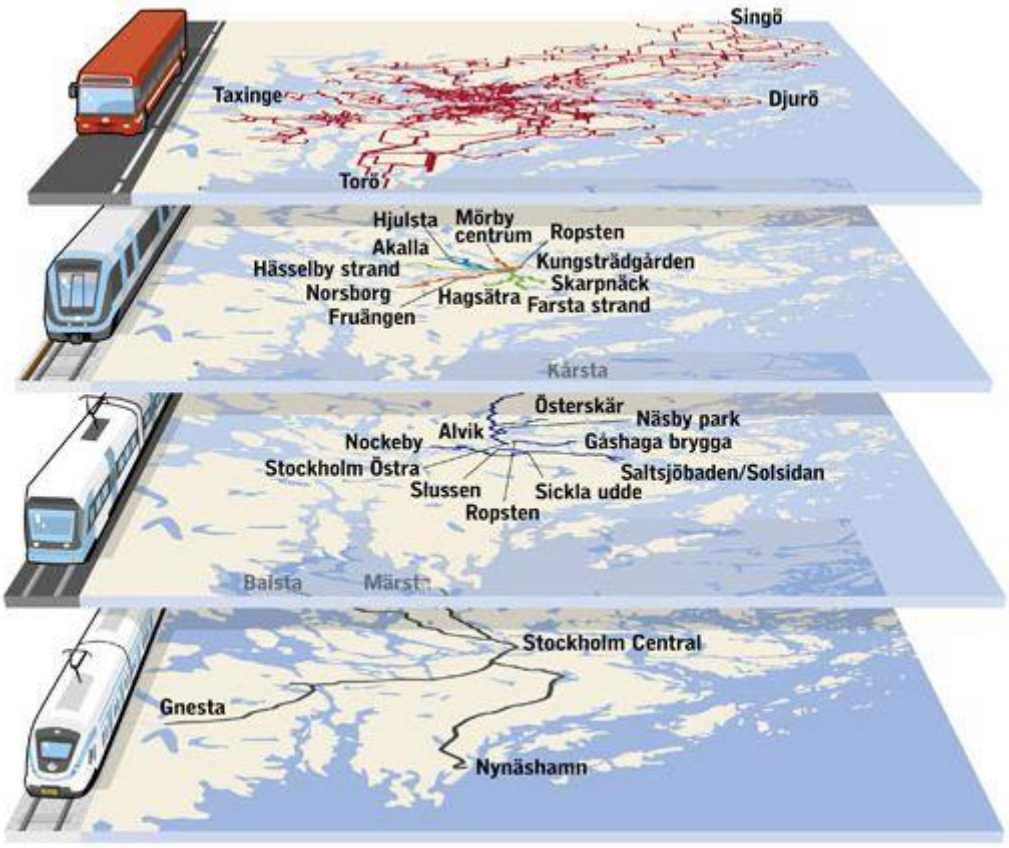

Figure 1 Stockholm Public transport *(Source: SJ.se)*

In order to learn how to systematically analyse public transport networks, with Excel plugin NodelXL, Stockholm rail traffic above is abstracted into Stop-level and Transfer-level scheme graphs. In these network representations, descriptions on the network from different aspects are generated to explore the network characteristics and thus implement Stockholm rail system development. Consequently, transfer relationships among stations and extent of line overlapping are calculated. As well, comparisons between the two schemes metrics are summarized to examine potential implications. In addition, any influential factors are taken full account of and incorporated for further investigation on impacts.

Table 1 Stockholm Rail Traffic System

System	Catergoty	Line	Starting station	Ending station	Station number
Metro	Blue line	T10	Hjulsta	Kungsträdården	14
		T11	Akalla	Kungsträdården	12
	Red line	T13	Ropsten	Norsborg	25
		T14	Mörby centrum	Fruängen	19
	Green line	T17	Åkeshov	Skarpnäck	24
		T18	Alvik	Farsta strand	23
		T19	Hässelby strand	Hagsätra	35
Light rail	Nockebybanan	L12	Alvik	Nockeby	10
	Lidingöbanan	L21	Ropsten	Gåshaga brygga	14
	Roslagsbanan	L27	Stockholms östra	Kårsta	18
		L28	Stockholms östra	Österskär	18
		L29	Stockholms östra	Näsbypark	11
	Saltsjöbanan	L25	Slussen	Saltsjöbaden	14
		L26	Igelboda	Solsidan	5
	Trärbanan	L22	Alvik	Solna centrum	24
Tram	Spårväg City	S7	Sergels torg	Waldemarsudde	7
Commuter rail		J35	Bålsta	Nynäshamn	27
		J36	Märsta	Södertälje centrum	24
		J37	Södertälje centrum	Gnesta	6
		J38	Uppsala	Älvsjö	16

2 Methodology

2.1 Create Network

In this case study, the Stockholm railway network is represented using two alternative schemes. One is Stop-level scheme regarding each station as a node in the network; the other one is Transfer-level scheme in which each transfer station is a node. Based on the characteristics of the network, some assumptions were made to clear some problems.

2.1.1 Stations

In Stockholm railway network, stations are named geographically, which distinguishes the according nodes from each other. However, there exist some stations locating at the same place where passengers can achieve transfers without gap but are assigned with different names in different lines. For example, train station Stockholm C, enables no-gap transfers with T-bana station T-centralen. So here we regarded Stockholm C and T-centralen as the same station, using the same name Stockholm C. Similarly, we made the terminal station for Roslagsbana L27-L28-L29 station Stockholm östra and T-bana T13-T14 station Tekniska högskolan as the same one Tekniska högskolan, L27-L28-L29 station Universitetet and T13-T14 station Universitetet as one station Universitetet, also S7 station Kungsträdården and T11-T10 station Kungsträdården as one station Kungsträdården.

2.1.2 Direction

In reality, Stockholm rail system runs in both 2 directions, but here we take into account only one direction, regarding all the links as undirected.

2.1.3 Distance

In Stockholm rail system, the stop distances in different categories of lines are set not exactly not the same. For example, the stop distance of the commuter rail is 4 km on average, while metro rail is around 2 km on average. However, in this project we focused on the network, to simplify the calculation, all the link distances between two nodes are regarded as a constant 1.

2.2 Generate Network Indicators

2.2.1 Network size

After creating the network, the overview size of the network can be gained from the number of nodes and the number of links.

2.2.2 Node centrality

- Degree (k)

Degree is the number of links that are directly connected to a certain node.

- Closeness (c)

Closeness is the inverted average distance from a certain node to all other nodes. The formula is

$$\mathrm{c}(u) = \sum_v f(u,v) \Big/ \sum_v f(u,v) \cdot d(u,v)$$

- Betweeness (b)

Betweeness is the share of shortest paths between other node pairs which traverse through a certain node.

$$\mathrm{b}(u) = \sum_{v,w} f(v,w,u) \Big/ \sum_{v,w} f(v,w)$$

2.2.3 Network topology

- Line overlapping

Line overlapping is an index calculated from the ratio of the sum of line lengths to the network length. The network length is the sum of line length minus lengths of the multiple spacing.

- Directness (τ)

This is the indicator that reflects the proportion of paths that can be reached without transfers.

$$\tau = |L| \Big/ \max_{u,v} d(u,v)$$

In order to show the directness of the service, we need to create the network in terms of transfers. Here we created the minimum transfer number matrix between each station (each pair of nodes). Due to the various number of stations, we group the station by lines, in each group every nodes has the same OD-reach matrix as others. Transfer stations

need to be taken into account in each line calculation separately.

- Local clustering(C)

Local clustering indicates how much are a node's neighbours to be a clique (complete graph). NodeXL uses the clustering efficiency to indicate the local clustering.

$$C_i = {}^{2M_i}/_{N_i(N_i-1)}$$

3 Results

3.1 Network

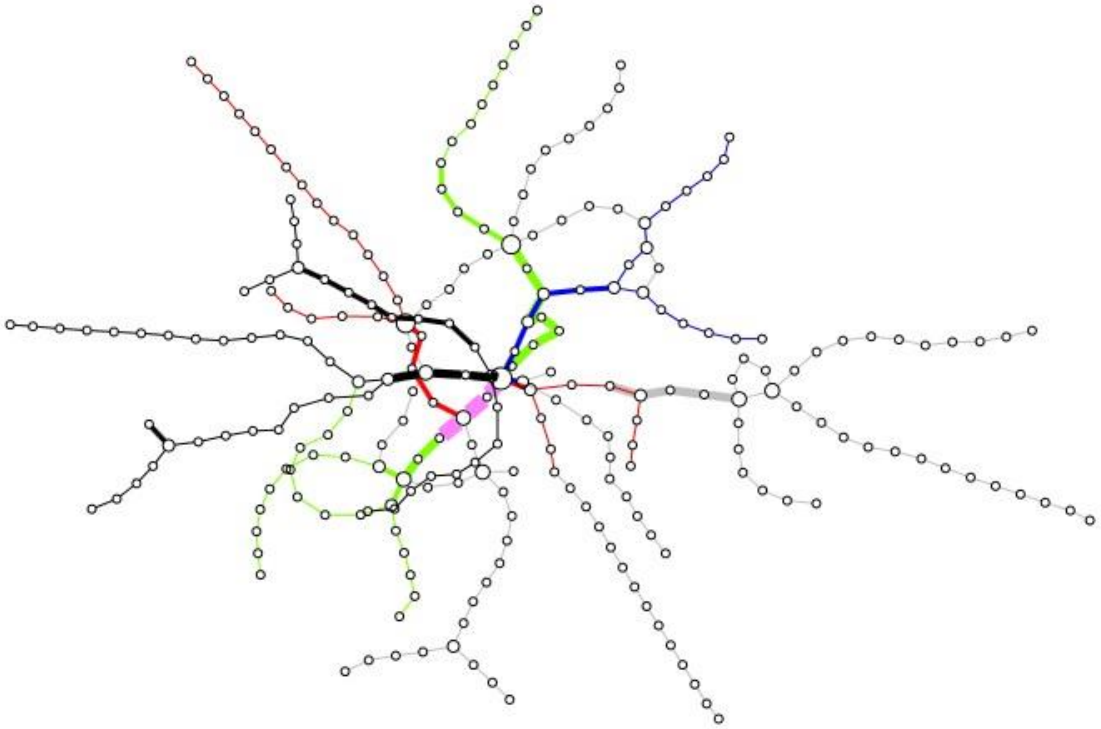

Figure 2 Stockholm Railway Network (stop-level, Harel-Koren Fast Multiscale layout)

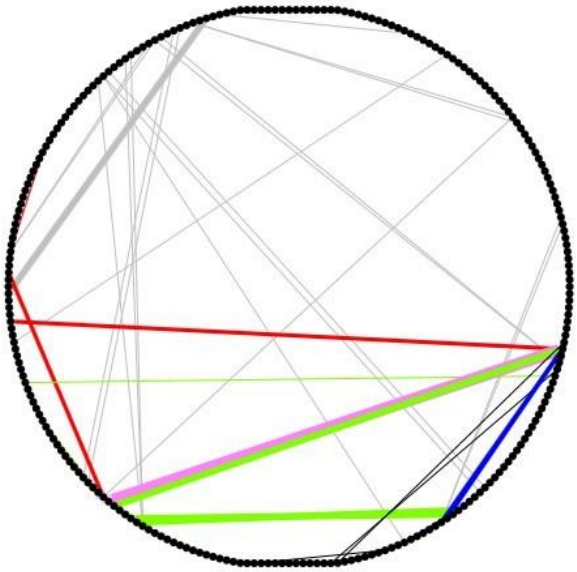

Figure 3 Stockholm Railway Network (stop-level, Cycle layout)

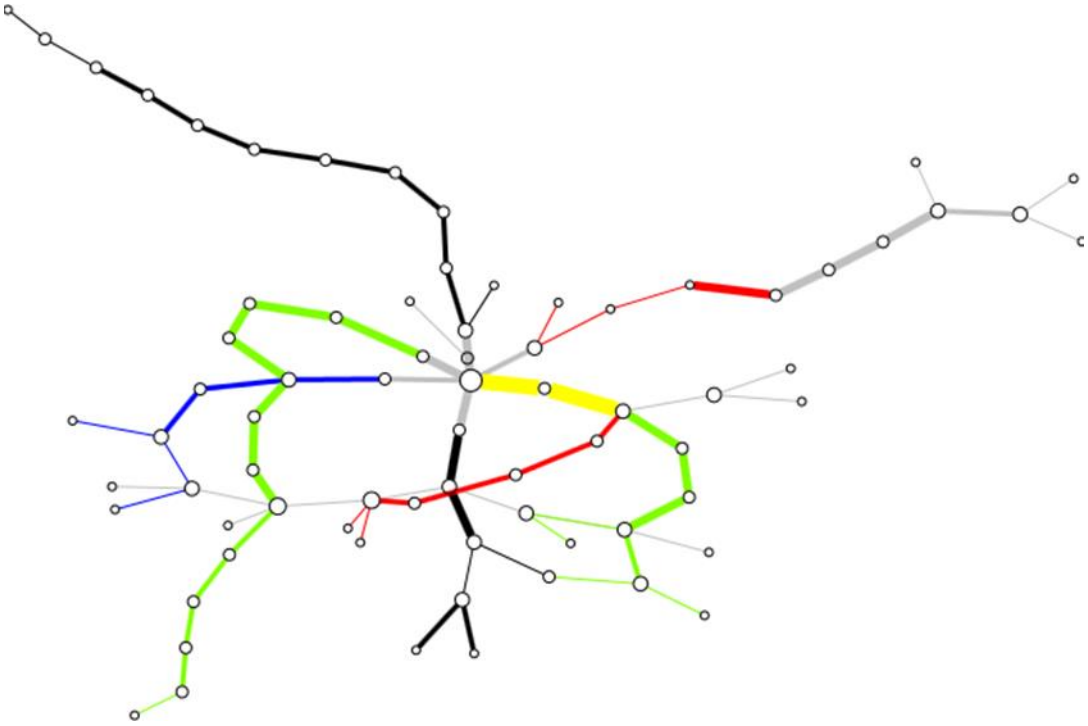

Figure 4 Stockholm Railway Network (Transfer-level, Harel-Koren Fast Multiscale layout)

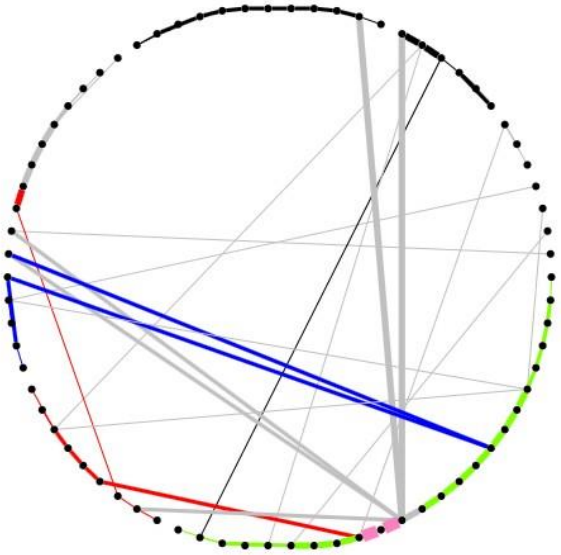

Figure 5 Stockholm Railway Network (Transfer-level, Cycle layout)

3.2 Network size

The table below shows the basic network size indicator value of stop-level and transfer level networks.

Table 2 Network size indicators

Scheme	Stop-level	Transfer-level
Node	252	74
Link	264	81

3.3 Node centrality

-Degree

The tables and figures below illustrate the statics summary, distribution and extreme cases of the networks.

Table 3 Degree statics summary of the networks

Scheme	Stop-level	Transfer-level
Minimum Degree	1	1
Maximum Degree	7	7
Average Degree	2.063492063	2.135135135
Median Degree	2	2

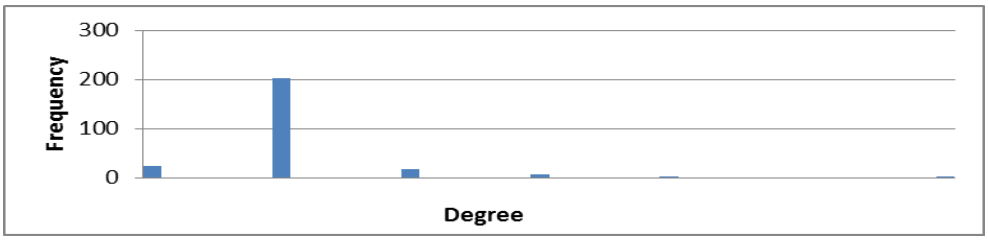

Figure 6 Histogram of stop-level degree

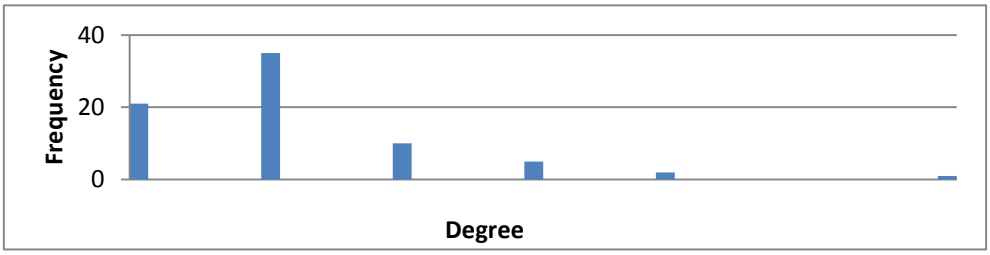

Figure 7 Histogram of transfer-level degree

Both levels have the same highest and lowest cases. The highest degree is Stockholm C (T-centralen), with the degree value of 7. The following are Liljeholmen with degree 5 and Slussen, Gullmarsplan, Sundbybergs centrum and Årstaberg with degree of 4. Most of the stations have the degree of 2 while network end stations have degree 1.

-Closeness

Table 4 Closeness statics summary of the networks

Scheme	Stop-level	Transfer-level
Minimum Closeness Centrality	0.00015	0.000999
Maximum Closeness Centrality	0.000459	0.003115
Average Closeness Centrality	0.000274421	0.002035338
Median Closeness Centrality	0.000265	0.0021165

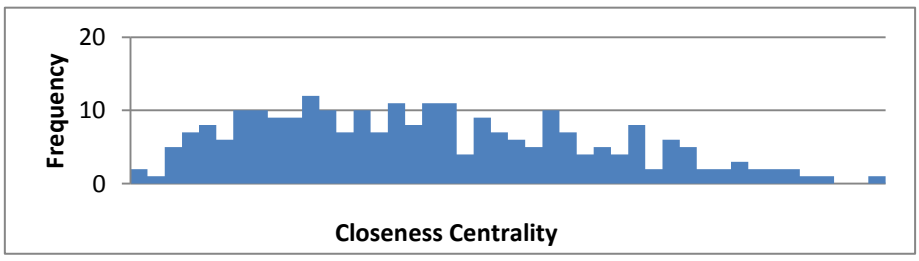

Figure 8 histogram of closeness centrality of stop-level

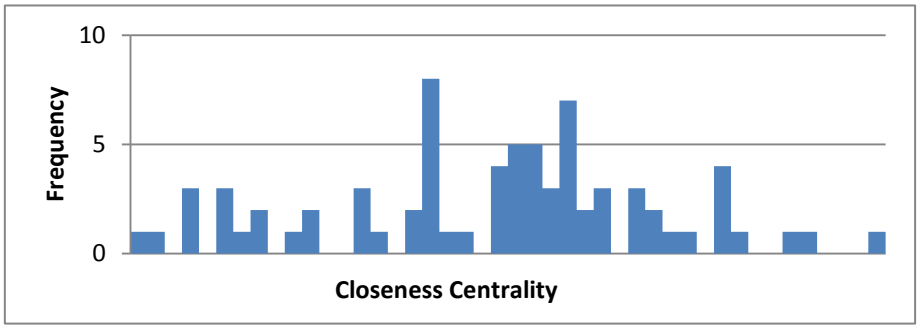

Figure 9 Histogram of closeness centrality of transfer-level

Table 5 Extreme cases of closeness centrality for the networks

Scheme	Highest cases		Lowest cases	
Stop-level	Stockholm C	0.000459	Frösunda	0.000162
	Stockholms södra	0.000438	Ekskogen	0.000156
	Östermalmstorg	0.000433	Kårsta	0.00015
Transfer-level	Stockholm C	0.003115	Näsbypark	0.001156
	Stockholms södra	0.002959	Österskär	0.001156
	Årstaberg	0.002882	Uppsala C	0.001076

-Betweeness

Table 6 Summary statics of betweeness

Scheme	Stop-level	Transfer-level
Minimum Betweeness Centrality	0	0
Maximum Betweeness Centrality	21512.48333	1667.833333
Average Betweeness Centrality	1814.880952	225.7837838
Median Betweeness Centrality	1230	126.8333335

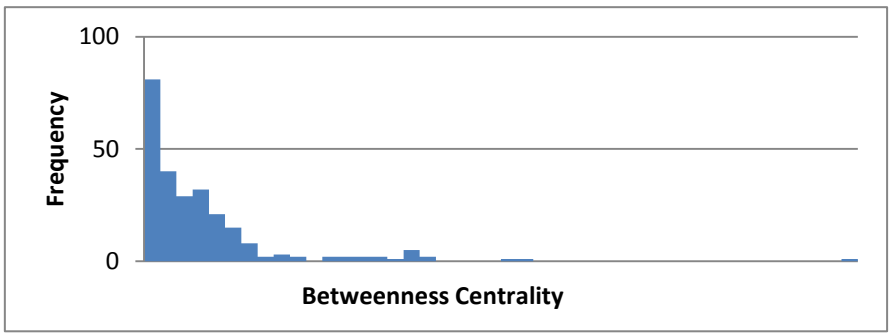

Figure 10 Histogram of betweeness of stop-level

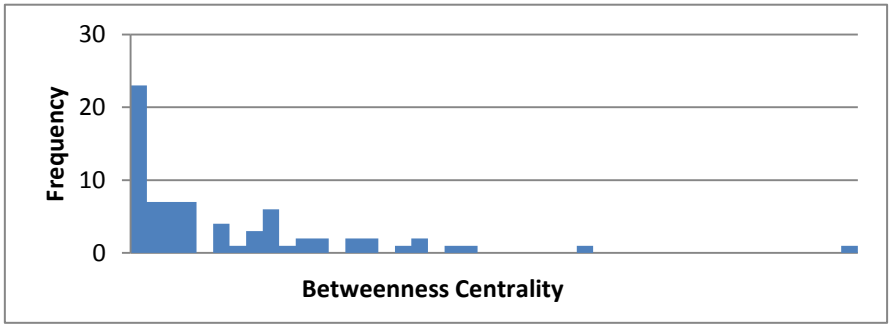

Figure 11 Histogram of betweeness of transfer-level

Table 7 Extreme cases of betweeness of the network

Scheme	Highest cases		Lowest cases	
Stop-level	Stockholm C	21512.48333	Ropsten	0
	Årstaberg	11012.11667	Fruängen	0
	Östermalmstorg	11866	Norsborg	0
Transfer-level	Stockholm C	1667.833333	Ropsten	0
	Stockholms södra	805	Fruängen	0
	Årstaberg	1054.666667	Norsborg	0

3.4 Network topology

-Overlapping ratio

For Stop-level network the ratio is 1.269 while Transfer-level network 1.84.

-Directness

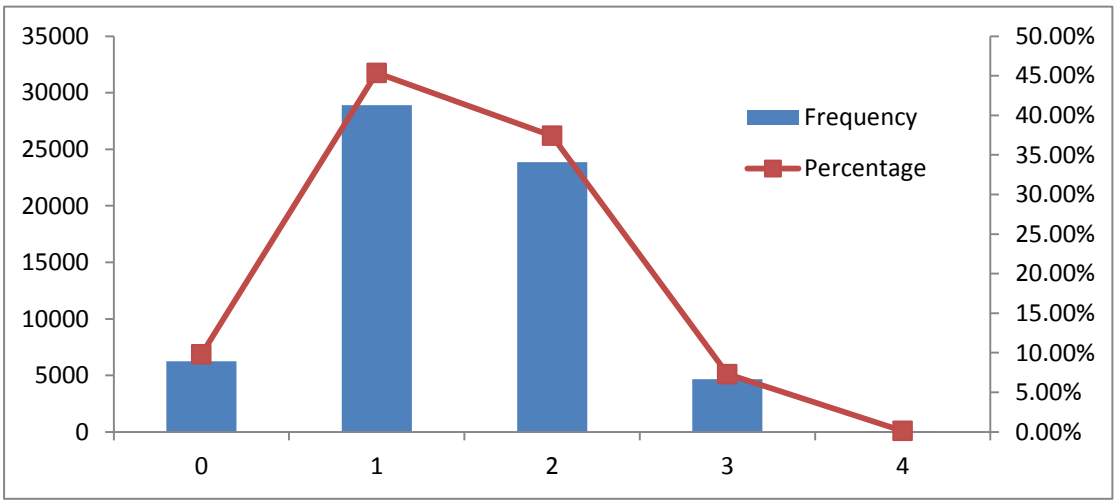

Figure 12 Network Total Minimum Number of Transfer and Percentage

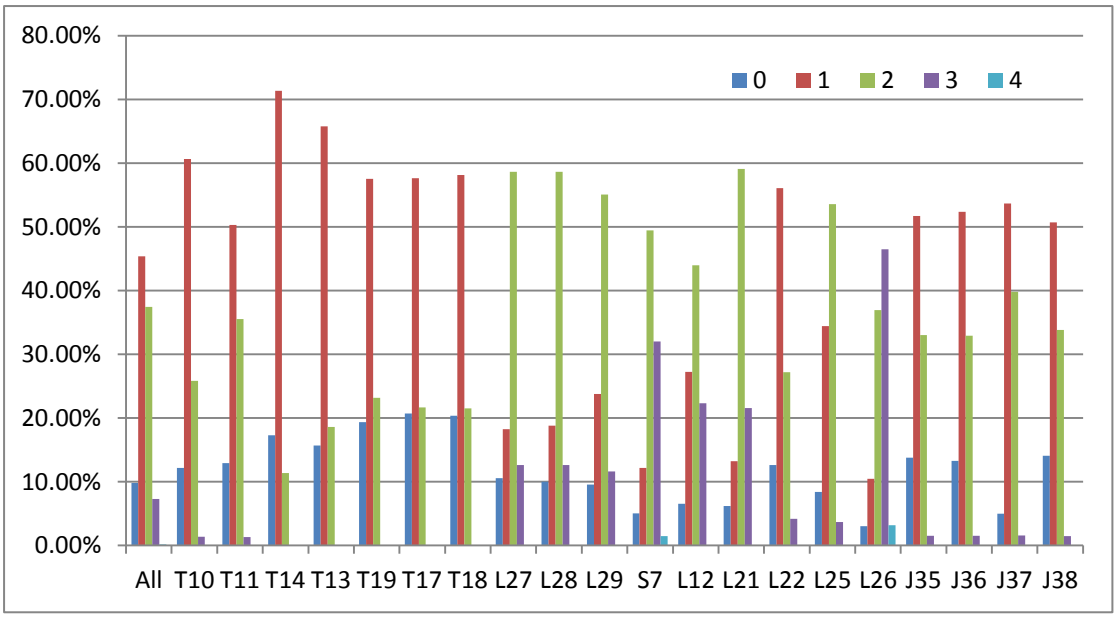

Figure 13 Line Total Minimum Number of Transfer and Percentage

- Local Clustering

All clustering coefficients are zero, indicating that there is no local clustering existing in

both scheme networks.

4 Analysis

4.1 Minimum number of transfer distribution

As illustrated above in **Figure 12**, for any pair of nodes in the network, minimum transfer number ranges from 0 to 4 and is not evenly distributed, centred on middle value 1 and 2. This in turn means that for most trips in the network, travellers only need to transfer once or twice, which indicates a relatively high efficiency of the network. Besides, few cases are that travellers transfer four times in trips between remote ends of rail network such as light rail line 26 stations to tram line S7 stations. For further investigation, the distribution can be abstracted into **Figure 14** below. The minimum transfer behaves as a normal distribution with the mean between 1 and 2.

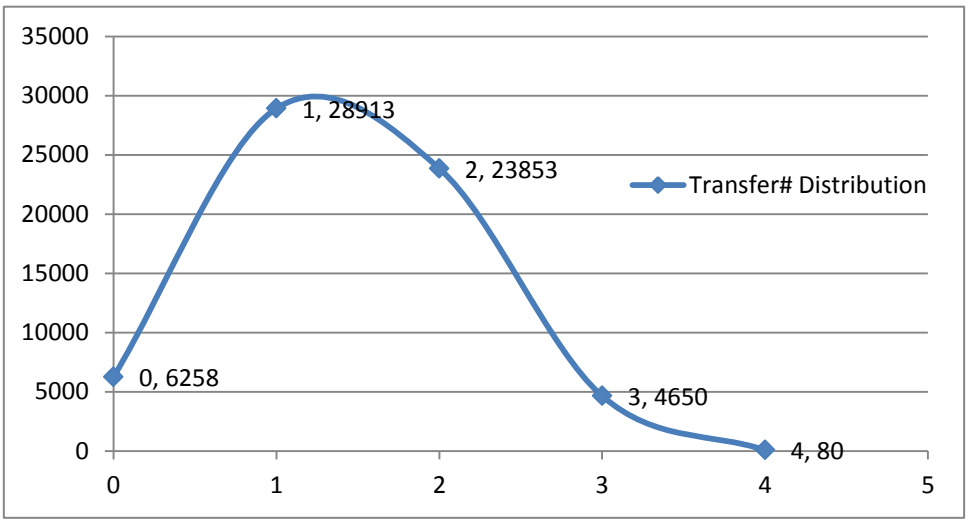

Figure 14 Minimum Transfer number distribution

Specifically, in **Figure 13** above, differences among lines are inferred. Blue and red bars representing fewer transfers appear extraordinarily in metros and commuter rails while green and purple bars representing more transfers in tram and light rails. In other words, Metro lines are better directly connected in the network than both the commuter rail and the worse light rail lines. However, there is an exception in light rail, Line 22 from Alvik to Solna centrum, proved to stand out from other light rail lines.

According to Stockholm rail characteristics, almost all rail routes, especially all metro rails via Stockholm C, implying that transfer can occur there for stations along any lines including Stockholm C station even though the minimum transfer route via Stockholm C is not the desired shortest path. In addition, all metro lines pass by Slussen station, which is start of light rail L25 and extended light rail line L26, and hence cut down directness among these lines. Meanwhile, metro lines in the same colour group share majority common stations. Say for green line group T19-T17-T18, 14 stations out of T17 line 24 stations, T18 line 23 stations and T19 line 35 stations are the same. Above two facts joint metro rail tightly through more shared stations and spread out the directness to end stations, thus reduce the minimum transfer times among stations. The same theory applies for commuter rails that once transfer in Stockholm C enables minimum transfers for stations along any lines including Stockholm C station. In contrast, light

rails are normally the implement of metro lines, locating at the stretching out branches in the network. Consequently, trips origins or ends at stations on such branches must firstly change trains at connection stations with metro and commuter rails before transfer on main lines. No doubt, the minimum numbers of transfers for light rails turn out greater than metro and commuter rails. As mentioned, L22 stands out for transfer stations included along this rail such as Alvik , Liljeholmen and Gullmarsplan are already connections in the network, then in turn link L22 with the existing lines.

4.2 Maximum number of transfers

On the foundation of minimum number of transfer analysis, it's demonstrated that more transfer occur among stations on light rails. Taking no account of unnecessary transfers, the maximum number of transfers among light rail stations should be 4 as indicated in **Table 8** below. Apparently, once in origin light rail ends, once in metro transfer station, once in commuter rail transfer station or once more metro transfer station, once in destination light rail ends.

Table 8 Maximum transfer numbers

Line		L22			
	Station	Tippen	Tattby	Erstaviksbadet	Solsidan
	Sergels torg	4	4	4	4
	Nybroplan	4	4	4	4
	Styrmansgatan	4	4	4	4
	Djurgårdsbron	4	4	4	4
S7	Nordiska museet Vasamuseet	4	4	4	4
	Liljevalchs Gröna Lund	4	4	4	4
	Skansen	4	4	4	4
	Djurgårdsskolan	4	4	4	4
	Bellmansro	4	4	4	4
	Waldemarsudde	4	4	4	4

Of course, in reference to boring twist transfers, there will no limitation on maximum numbers. Say, from Alvik to Gullmarsplan, such dummy transfers can obtained at every stop by switching among T19- T18-T17 lines, which leads to unpredictable amount of twists in preferred routes. In the same way, travellers can even take roundabout routes between stations on the same line. Controversially, rational travellers seldom sacrifice travel time to take such dummy paths rather than take the shortest or more convenient paths in reality.

4.3 Extent of line overlapping

The ratio of line overlapping in stop-level scheme 1.269 reflects the merge and collinear degree in the network. On basis of calculation formula, the line overlapping extent indicates the weight of lines linking transfer stations in the network. For metro rails, say green line group T19-T17-T18, share 14 stations out of T17 line 24 stations, T18 line 23 stations and T19 line 35 stations, almost taking up the majority. Line overlapping ratio is calculated as below,

$$Green\ metro\ line\ overlapping = (23 + 22 + 34)/(23 + 22 + 34 - 13) = 1.197$$

Obviously, the ratio is smaller than the network ratio, meaning that more multiple spacing percentage exist in metro lines and the transfer stations dominate more than in the network.

As mentioned above, the ratio in transfer-level scheme is 1.84, higher than 1.269 in stop-level. Reasonably, transfer-level network is consist of transfer nodes, origin stations, ending stations and connections among them while stop-level network contains non-transfer stations and their relative connections except for elements in transfer-level scheme.

4.4 Comparison between Stop-level and Transfer-level schemes.

Generally, node and link numbers are different and thus lead to different graph attributes.

Table 9 Comparison of the two networks

Scheme	Stop-level	Transfer-level
Node	252	74
Link	264	81
Graph Density	0.008221084	0.028878193
Average Degree	2.063492063	2.135135135
Average Betweeness Centrality	1814.880952	225.7837838
Average Closeness Centrality	0.000274421	0.002035338

The higher density in transfer-level than stop-level scheme captures the concentration of transfer stations in central areas. The stop-level density can be improved like L22 by extending or connecting light rails to metro and commuter rails.

Due to such concentration of transfer station, stations are better connected in transfer-level graph and hence the influence and popularity are so much larger that average degree in transfer-level is no doubt greater than stop-level.

Betweeness centrality describes the communication role of station in paths between other nodes. Therefore, with all stations considered, the distances between stations those are not neighbours are largely further than only transfer stations scheme. This sharp contrast provides an evidence for boundary spanner performance. Closeness centrality captures the distance from one station to every other station in the network. Definitely, this distance score is higher in transfer-level than in stop-level.

From all the difference analysis above, we can conclude that Stockholm rail system covers almost whole areas while transfer stations are gathered in central. From another side, the transfer stations expansion is proved possible. Transfer stations shall be added in outer space and network capacity is relieved in central areas at the same time.

4.5 Influential factors

There is one shortcoming during the process of the network analysis. According to the assumption, real distances between the stations are not referred in the analysis. As is mentioned previously, the distance varies from any components of Stockholm rail system. Commuter trains tend to have longer distance while trams in city have shorter distances. This may affect the network size to some extent. For instance, the network

length is longer than obtained above since the commuter rails stretch much longer to the suburban areas in reality. What's more, in the network topology, the line overlapping extent would be affected since the calculation evolves the stop distances and line lengths. In contrast, other indicators will remain steady since it's actually the relationships among nodes that really matters in calculation.