

SUPPLEMENTARY MATERIALS

Scoring and Classifying Regions via Multimodal Transportation Networks

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Further Data Details

For our interests in this paper, many features of the transportation networks are left out of the main paper to keep focus on our machine learning application. However, these details may be of interest to readers with a broader research agenda. We therefore present some analysis results of these networks here.

Degree Distributions

One such feature is the degree distributions of the single-mode transportation networks. Unsurprisingly the degree distributions of the train network (Table 2) and bus network (Table 4) exhibit fat tails, but the road network (Table 5) does not. Clearly a road intersection is tightly physically constrained in how many roads can join there, whereas a station (which covers a larger physical area as well as vertical stacking) can include many more connecting lines. This is amplified by our encoding of different kinds of train routes (e.g., local vs express) as separate lines. So a station with a degree of 44 may only have 12 separate railway lines connected to it with multiple kinds of trains running on each line.

For the train network, a bigger surprise than the frequency of highly-connected stations is the high frequency of stations with one link (see Table 1). In a standard rail system representation (i.e., an undirected simple graph with stations nodes connected directly by line links) these would all be stations at the end of a line. Even for Tokyo's extensive train network this number is would be impossible. The explanation comes from our representation of the physical stations as separate from the platforms for each line/type. The large number of $k = 1$ station nodes reflects stations with only one kind of train link rather than having one link. Most of the platform nodes connected to these $k = 1$ station nodes have two links meaning that the most common type of station is one for which only local trains pass through. Although such stations are rare in the city center, they are common along commuter lines that radiate into the suburbs.

The bus network degree distribution (see Table 4) is much more as expected, with end-of-the-line stops being fairly rare (990), while simple along-a-single-route stops being highly prevalent (23,992). In Japan, most bus depots and transfers are located at train stations, and share similar degree distribution characteristics as a standard, simple network representation. In the current work that is the representation we use for the buses, but this does not foster the inclusion of transfer and wait times, so future work will adopt a bus network representation following our train network.

The nodes in the street network represent intersections, and their degree distribution is shown in Table 5. Because we limit our road network to tertiary or higher

Table 1 Tokyo area train network station node degree distribution. In our representation this is the number of different lines and line types (e.g., local vs. express) connecting to that station.

Degree	Count
44	1
39	3
38	1
23	2
22	3
21	2
20	5
19	2
18	1
17	3
15	5
14	5
13	7
12	14
11	15
10	15
9	32
8	40
7	49
6	73
5	61
4	125
3	159
2	304
1	591

roads plus uncategorized “roads” the road network by itself is highly disconnected. Although this accurately reflects characteristics of the Japanese urban road network in which road widths/types fluctuate highly along its course, it results in the large number of dead-ends (10,983). In our main analyses the network becomes connected when we “glue” it to the hexagonal grid with “walking” links, but the disconnected nature explains why for the road network itself there are so many nodes with single edges. Double-edged roads can’t really count as intersections; in fact, we removed intermediate nodes from the OpenStreetMap road path data[1]. The remaining 1,154 $k = 2$ intersection nodes represent joints connecting roads of different types. The remaining figures capture a fairly typical road network when only fairly large roads are considered, but it is likely skewed from the distribution we would see if we included all roads.

The hex (walking) network is generated from the hexagonal grid, and because it is a *hexagonal* grid each node has six links unless it is on a border. As is clear from Table 6, the percent of perimeter nodes compared to internal nodes is small (1.5%).

Speed Limits

OpenStreetMap data for Japan is sparse, so we had to make assumptions based on typical values where information was lacking (see Table 7). There is no direct connection between the OpenStreetMap highway types and the Japanese rules for speed limit determination, but we made our best approximations based on the available delimitations [2]. Rather than assume people can always drive at the posted speed limit, we reduced driving speeds to capture features such as traffic, turning, waiting at lights, etc. Future work will refine these driving speeds based on local features, traffic/congestion patterns, etc.

Table 2 Tokyo area rail network platform node degree distribution. In our representation this is the number of adjacent station connections across all tracks and line types (local, rapid, express, etc.), plus the number of other line types at the same station, plus one for the access link to the associated station.

Degree	Count
50	1
49	1
48	3
47	8
46	22
45	10
44	2
43	2
42	9
41	56
40	76
39	9
29	1
28	1
27	7
26	6
25	40
24	54
23	45
22	93
21	49
20	23
19	39
18	37
17	44
16	86
15	105
14	157
13	164
12	150
11	294
10	313
9	314
8	463
7	293
6	512
5	456
4	596
3	604
2	34

Table 3 Tokyo area rail network platform node degree distribution isolated to include only route links. In our representation this is the number of adjacent station connections for each line type. A value of 1 implies a line terminus, 2 is a standard stop along a line, and higher numbers represent lines that either split courses (such as the Marunouchi subway) or for which trains of the same type have alternative routes/stops (such as the Narita Express).

Degree	Count
8	2
7	6
6	18
5	35
4	189
3	198
2	4114
1	617

Table 4 Tokyo area bus network bus stop degree distribution. We represent the bus network in the traditional manner, so the degree distribution matches intuitive values.

Degree	Count
58	1
57	1
51	1
46	1
27	2
26	1
20	4
19	2
17	3
16	1
15	9
14	6
13	7
12	7
11	9
10	25
9	23
8	48
7	112
6	308
5	741
4	2,233
3	5,128
2	23,992
1	990

Table 5 Tokyo area road network degree distribution. Nodes in the OpenStreetMap data with 2 links representing curves in the road were eliminated, thus the remaining $k=2$ nodes reflect connections between two different road types (i.e., a road that changes its type).

Degree	Count
7	5
6	63
5	565
4	17,100
3	28,363
2	1,154
1	10,983

Table 6 The degree distribution for the hex grid covering the Tokyo area. The deviations from 6 are only due to hexes being on the boundaries or coastline.

Degree	Count
6	259339
5	1142
4	1725
3	1118
2	15

Table 7 Default speed limits and drive speeds in kph by road type when data was unavailable.

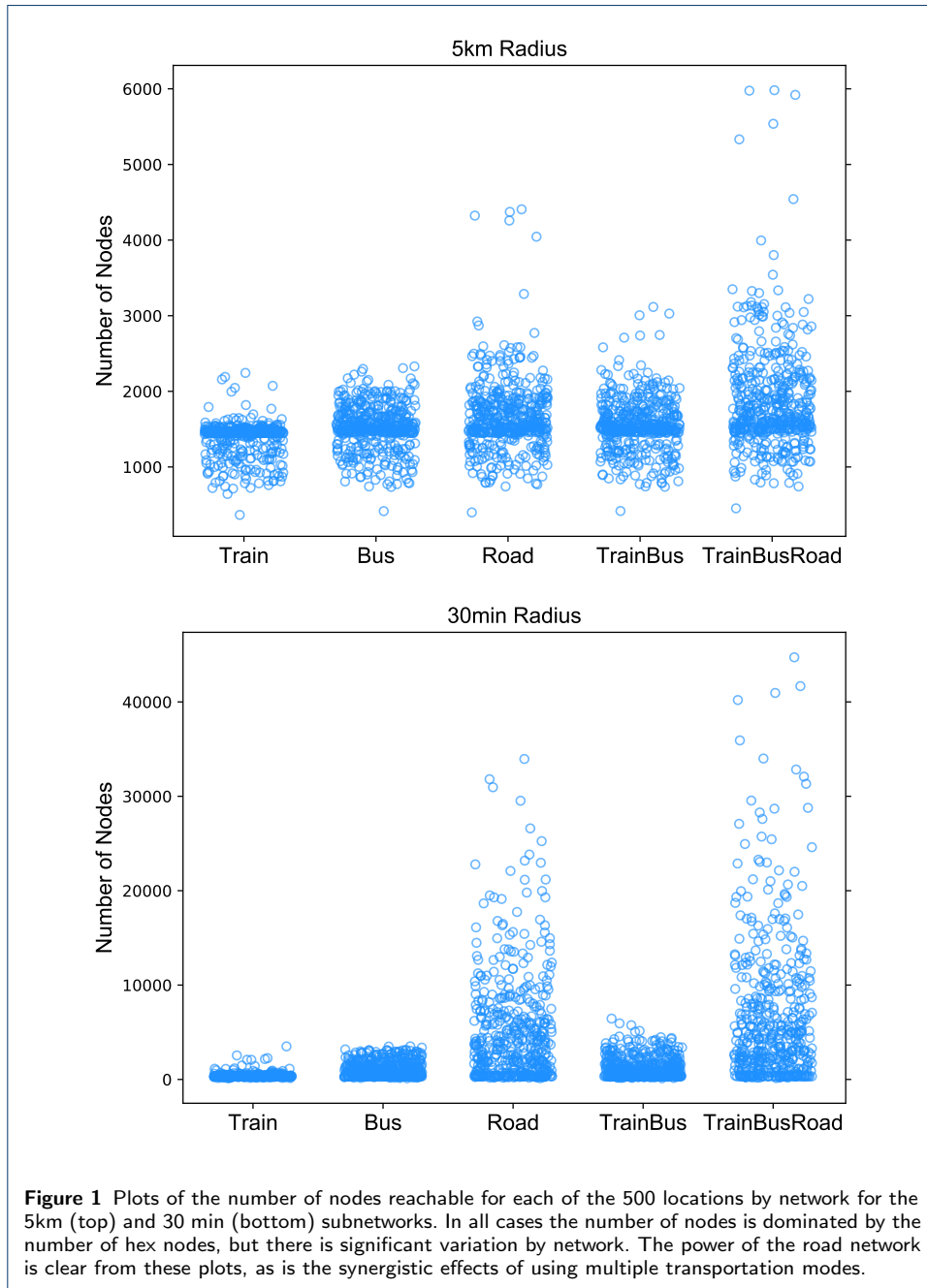
Road Type	Speed Limit	Drive Speed
Motorway	80	70
Motorway Link	60	40
Trunk	60	30
Trunk Link	50	30
Primary	50	30
Primary Link	50	30
Secondary	40	30
Secondary Link	40	30
Tertiary	30	30
Tertiary Link	30	30
Road	30	25

Further Result Details

We furthermore include plots, tables, and results from the combined networks beyond, but related to, the main focus of the paper to fill in the picture and aid in reproduction and extension studies.

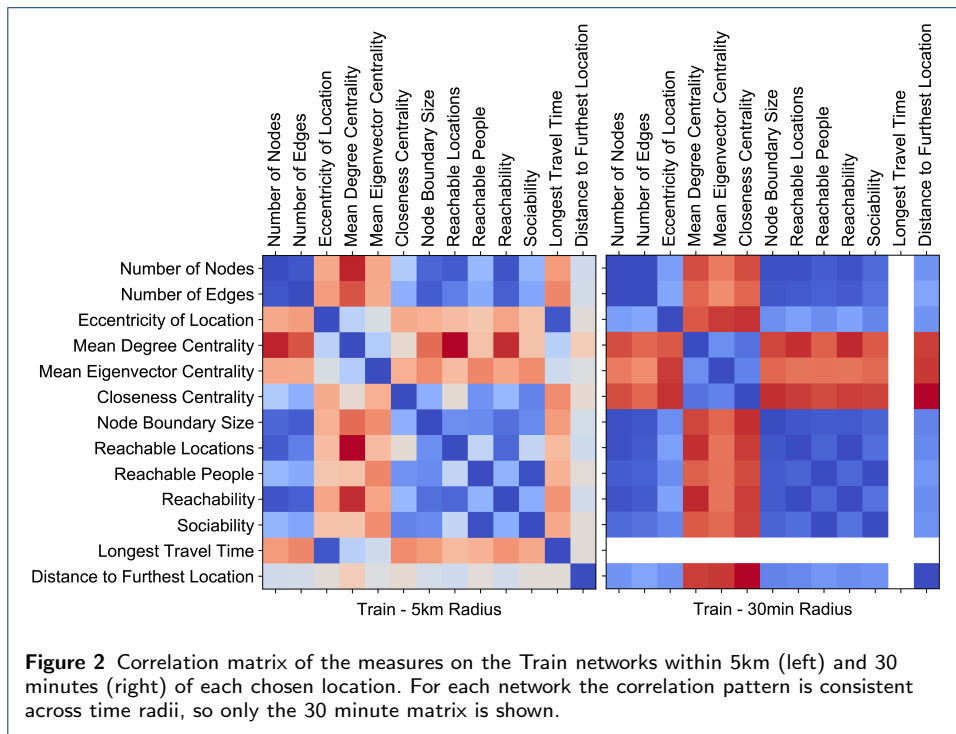
Scatter Plots

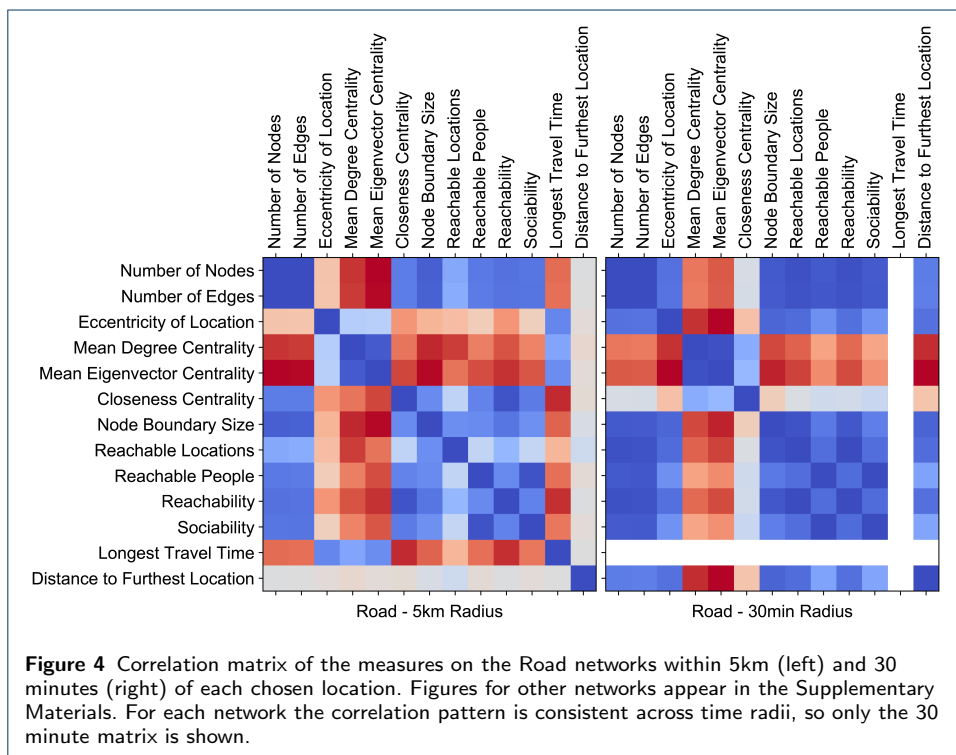
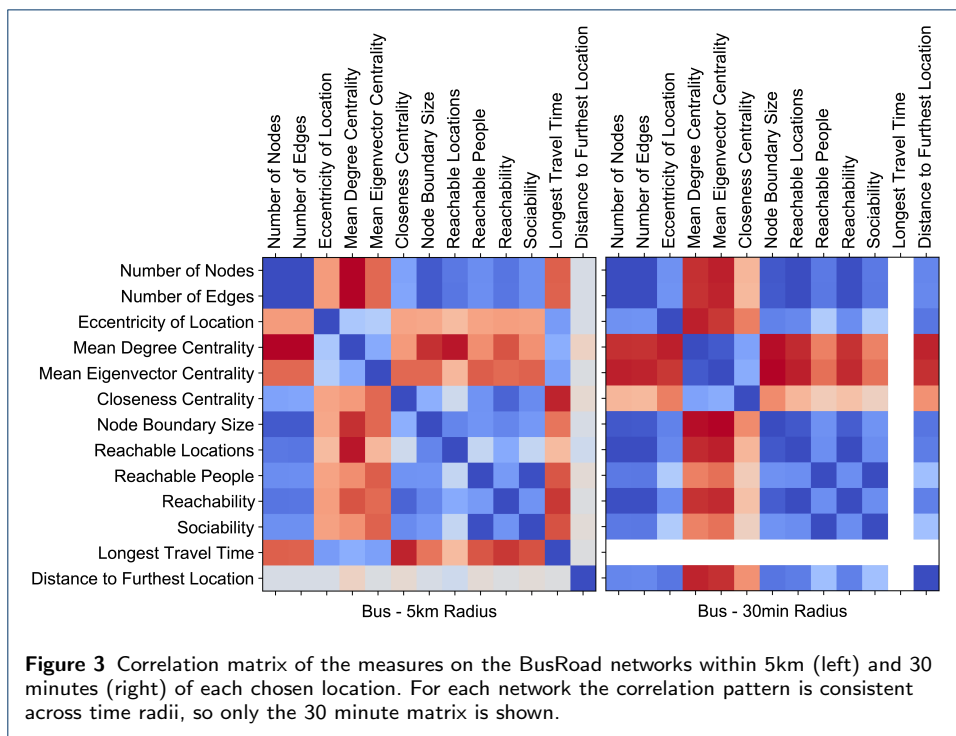
We have scatter plots such as those shown in Figure 1 of all the variables by network separated by subnetwork in order to understand relationships in the data and spot features that are likely to be useful for clustering and plotting. The included plots for the number of nodes reflect an important result of the relative power of transportation modes on the reach achievable as well as how those modes reinforce each other.



Correlation Plots

The main paper included the correlation matrix plot for all three transportation networks combined, reproduced here as Figure 6. Here we also include the correlation matrix plots for the other networks for both the 5km and 30 min subnetworks. The other time radius subnetworks are very similar to the 30min network, so they have been excluded, but are available upon request.





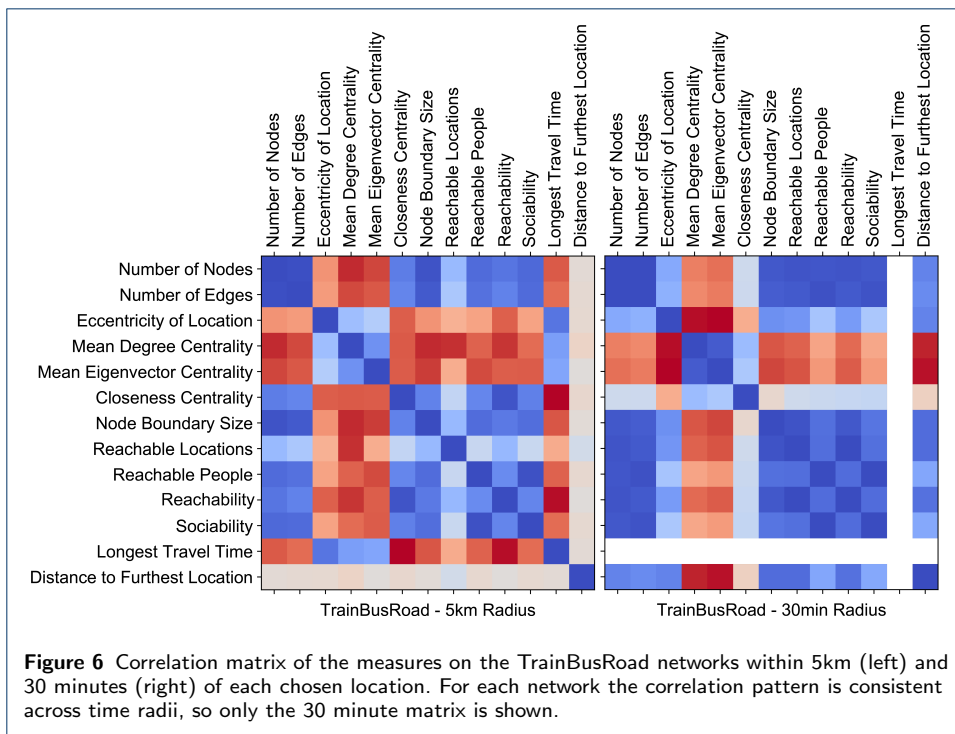
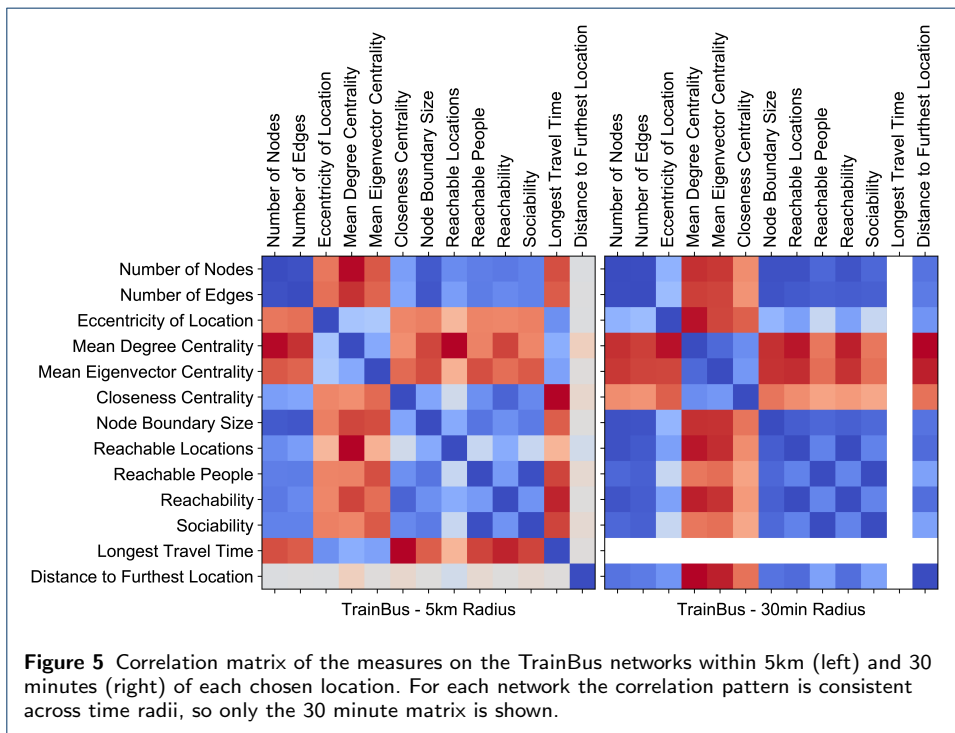


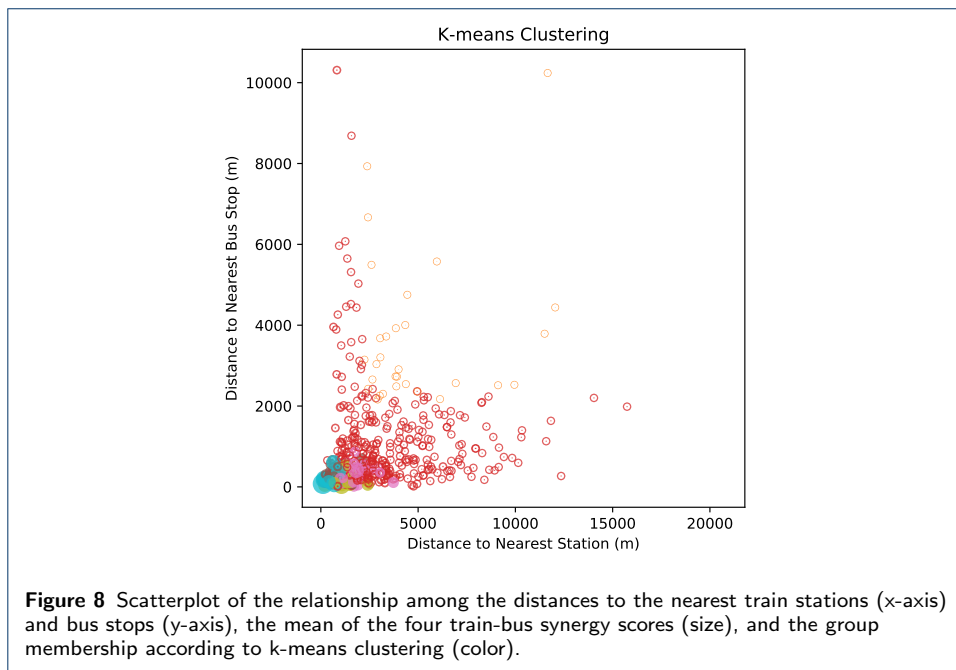
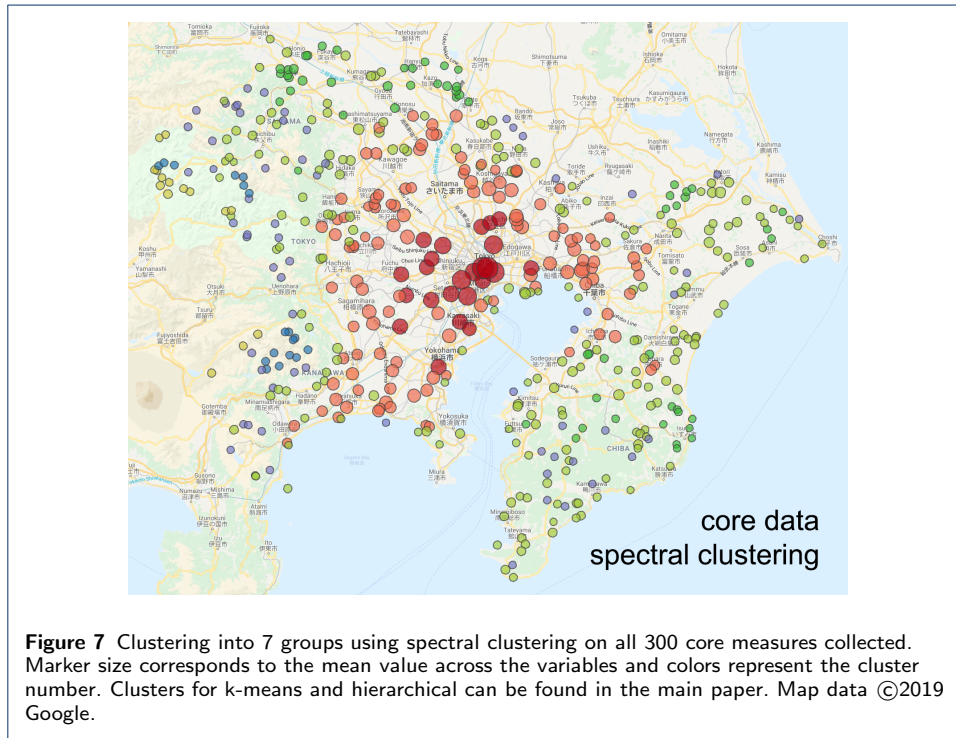
Table 8 The percent of possible difference in correlation matrices for each distance-based subnetwork pair for each network. Unsurprisingly the more distance the time (e.g., 20min vs 60min) the greater the difference in correlation matrices.

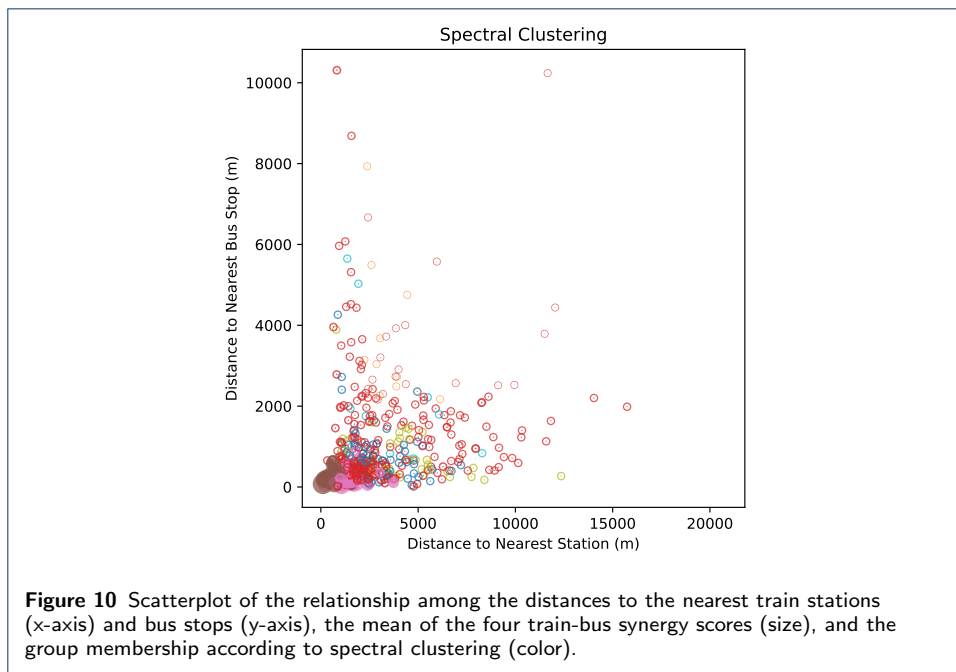
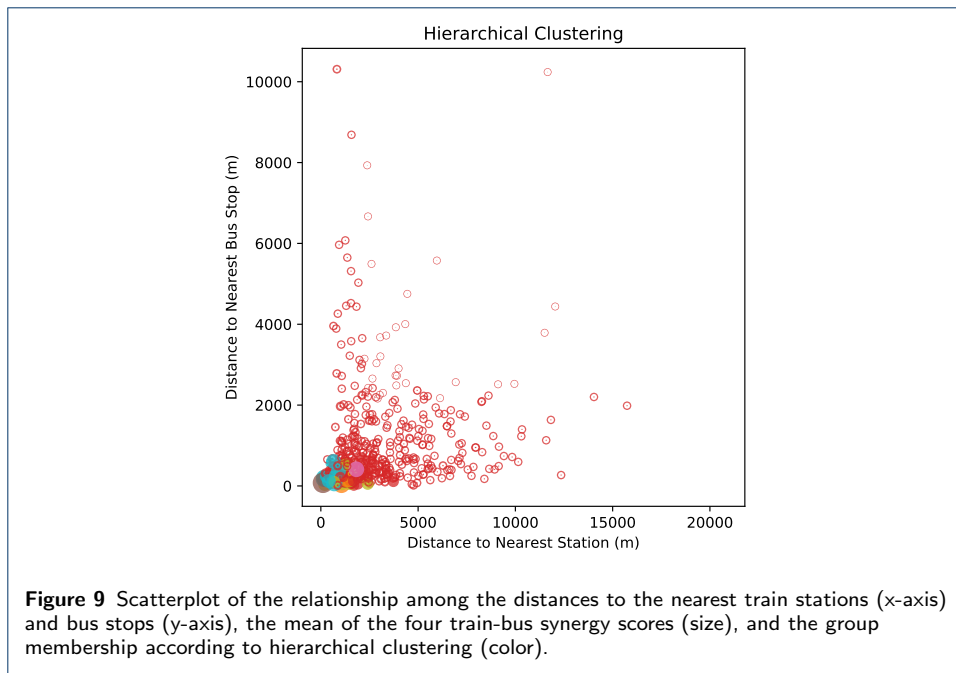
First Network-Subnetwork	Second Network-Subnetwork	Frobenius Norm of Difference
Train-20m	Train-30m	6.6
Train-20m	Train-45m	8.79
Train-20m	Train-60m	9.45
Train-30m	Train-20m	6.6
Train-30m	Train-45m	3.05
Train-30m	Train-60m	4.22
Train-45m	Train-20m	8.79
Train-45m	Train-30m	3.05
Train-45m	Train-60m	1.49
Train-60m	Train-20m	9.45
Train-60m	Train-30m	4.22
Train-60m	Train-45m	1.49
Bus-20m	Bus-30m	6.26
Bus-20m	Bus-45m	8.89
Bus-20m	Bus-60m	11.34
Bus-30m	Bus-20m	6.26
Bus-30m	Bus-45m	3.16
Bus-30m	Bus-60m	6.66
Bus-45m	Bus-20m	8.89
Bus-45m	Bus-30m	3.16
Bus-45m	Bus-60m	3.9
Bus-60m	Bus-20m	11.34
Bus-60m	Bus-30m	6.66
Bus-60m	Bus-45m	3.9
Road-20m	Road-30m	6.15
Road-20m	Road-45m	9.6
Road-20m	Road-60m	11.41
Road-30m	Road-20m	6.15
Road-30m	Road-45m	3.5
Road-30m	Road-60m	5.34
Road-45m	Road-20m	9.6
Road-45m	Road-30m	3.5
Road-45m	Road-60m	1.9
Road-60m	Road-20m	11.41
Road-60m	Road-30m	5.34
Road-60m	Road-45m	1.9
TrainBus-20m	TrainBus-30m	5.38
TrainBus-20m	TrainBus-45m	9.89
TrainBus-20m	TrainBus-60m	13.26
TrainBus-30m	TrainBus-20m	5.38
TrainBus-30m	TrainBus-45m	5.4
TrainBus-30m	TrainBus-60m	8.8
TrainBus-45m	TrainBus-20m	9.89
TrainBus-45m	TrainBus-30m	5.4
TrainBus-45m	TrainBus-60m	3.69
TrainBus-60m	TrainBus-20m	13.26
TrainBus-60m	TrainBus-30m	8.8
TrainBus-60m	TrainBus-45m	3.69
TrainBusRoad-20m	TrainBusRoad-30m	6.22
TrainBusRoad-20m	TrainBusRoad-45m	9.7
TrainBusRoad-20m	TrainBusRoad-60m	12.15
TrainBusRoad-30m	TrainBusRoad-20m	6.22
TrainBusRoad-30m	TrainBusRoad-45m	4.21
TrainBusRoad-30m	TrainBusRoad-60m	7.19
TrainBusRoad-45m	TrainBusRoad-20m	9.7
TrainBusRoad-45m	TrainBusRoad-30m	4.21
TrainBusRoad-45m	TrainBusRoad-60m	3.18
TrainBusRoad-60m	TrainBusRoad-20m	12.15
TrainBusRoad-60m	TrainBusRoad-30m	7.19
TrainBusRoad-60m	TrainBusRoad-45m	3.18

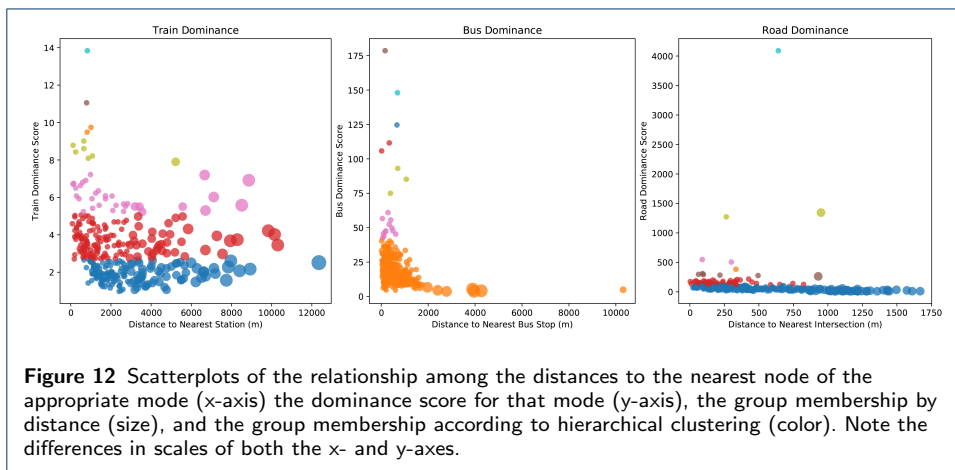
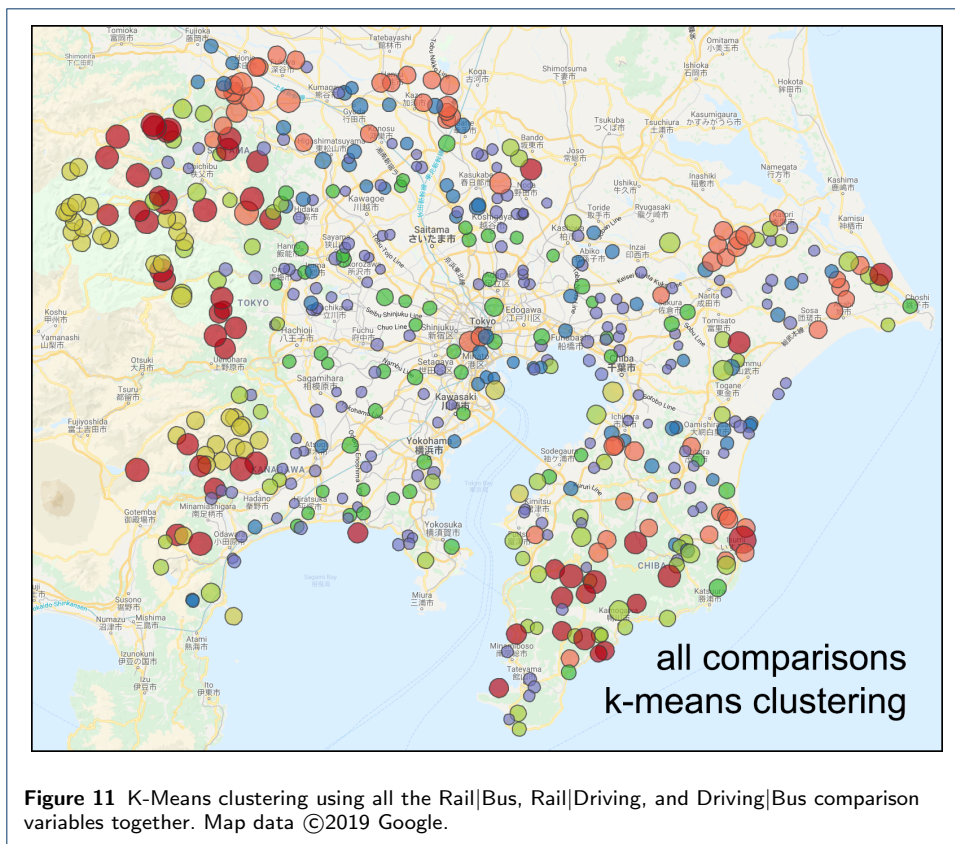
Table 9 The percent of possible difference in correlation matrices across transportation networks for each distance-based subnetwork. Unsurprisingly the more distance the time (e.g., 20min vs 60min) the greater the difference in correlation matrices on average. Similarly unsurprising is that the 5km has the highest level of correlation similarity because the hex grid is (excepting boundary locations) the same and dominant within 5km.

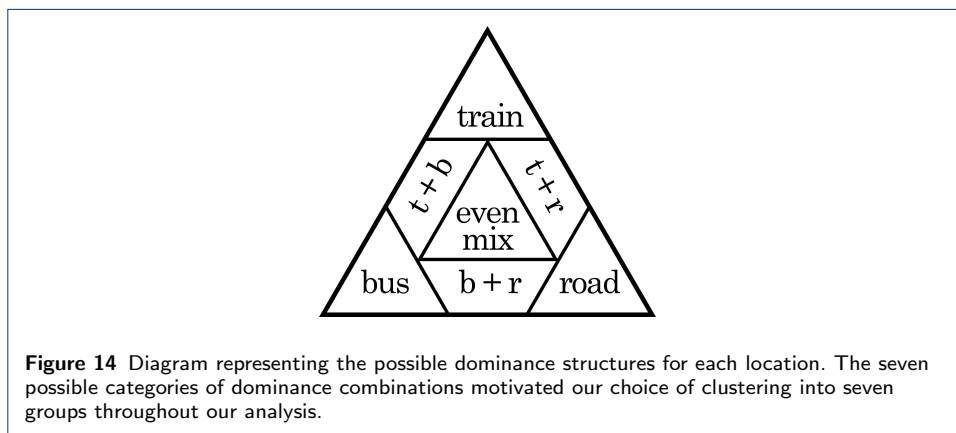
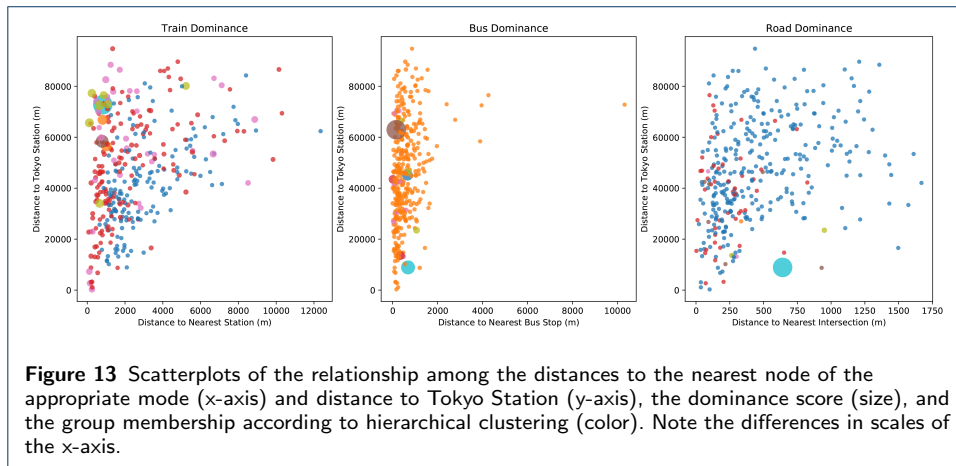
First Network-Subnetwork	Second Network-Subnetwork	Frobenius Norm of Difference
Train-5km	Bus-5km	9.54
Train-5km	Road-5km	13.15
Train-5km	TrainBus-5km	10.4
Train-5km	TrainBusRoad-5km	12.29
Bus-5km	Road-5km	6.65
Bus-5km	TrainBus-5km	3.32
Bus-5km	TrainBusRoad-5km	6.32
Road-5km	TrainBus-5km	7.15
Road-5km	TrainBusRoad-5km	5.45
TrainBus-5km	TrainBusRoad-5km	4.73
Train-20m	Bus-20m	8.94
Train-20m	Road-20m	13.01
Train-20m	TrainBus-20m	8.35
Train-20m	TrainBusRoad-20m	13.87
Bus-20m	Road-20m	8.73
Bus-20m	TrainBus-20m	2.15
Bus-20m	TrainBusRoad-20m	10.33
Road-20m	TrainBus-20m	8.41
Road-20m	TrainBusRoad-20m	2.83
TrainBus-20m	TrainBusRoad-20m	9.67
Train-30m	Bus-30m	10.86
Train-30m	Road-30m	14.87
Train-30m	TrainBus-30m	8.08
Train-30m	TrainBusRoad-30m	15.9
Bus-30m	Road-30m	8.65
Bus-30m	TrainBus-30m	5.22
Bus-30m	TrainBusRoad-30m	9.81
Road-30m	TrainBus-30m	10.79
Road-30m	TrainBusRoad-30m	4.75
TrainBus-30m	TrainBusRoad-30m	10.86
Train-45m	Bus-45m	11.57
Train-45m	Road-45m	17.05
Train-45m	TrainBus-45m	9.27
Train-45m	TrainBusRoad-45m	17.61
Bus-45m	Road-45m	10.57
Bus-45m	TrainBus-45m	8.24
Bus-45m	TrainBusRoad-45m	10.16
Road-45m	TrainBus-45m	15.64
Road-45m	TrainBusRoad-45m	7.85
TrainBus-45m	TrainBusRoad-45m	12.78
Train-60m	Bus-60m	11.49
Train-60m	Road-60m	17.97
Train-60m	TrainBus-60m	11.14
Train-60m	TrainBusRoad-60m	18.34
Bus-60m	Road-60m	13.48
Bus-60m	TrainBus-60m	7.21
Bus-60m	TrainBusRoad-60m	10.3
Road-60m	TrainBus-60m	17.91
Road-60m	TrainBusRoad-60m	10.52
TrainBus-60m	TrainBusRoad-60m	12.37

Clustering Results









Sociability Comparisons

Table 10 Travel pattern AMI pairwise comparisons of Sociability for K-means clustering groups for the 5km subnetworks.

	Train	Bus	Road	TrainBus	TrainBusRoad
Train	1.0	0.719	0.658	0.724	0.685
Bus	0.719	1.0	0.616	0.967	0.729
Road	0.658	0.616	1.0	0.616	0.64
TrainBus	0.724	0.967	0.616	1.0	0.742
TrainBusRoad	0.685	0.729	0.64	0.742	1.0

Table 11 Travel pattern AMI pairwise comparisons of Sociability for K-means clustering groups for the 60m subnetworks.

	Train	Bus	Road	TrainBus	TrainBusRoad
Train	1.0	0.358	0.293	0.392	0.298
Bus	0.358	1.0	0.545	0.717	0.54
Road	0.293	0.545	1.0	0.574	0.899
TrainBus	0.392	0.717	0.574	1.0	0.609
TrainBusRoad	0.298	0.54	0.899	0.609	1.0

Table 12 Travel pattern AMI pairwise comparisons of Sociability for Hierarchical clustering groups for the 5km subnetworks.

	Train	Bus	Road	TrainBus	TrainBusRoad
Train	1.0	0.801	0.63	0.824	0.761
Bus	0.801	1.0	0.657	0.938	0.733
Road	0.63	0.657	1.0	0.648	0.629
TrainBus	0.824	0.938	0.648	1.0	0.75
TrainBusRoad	0.761	0.733	0.629	0.75	1.0

Table 13 Travel pattern AMI pairwise comparisons of Sociability for Hierarchical clustering groups for the 60km subnetworks.

	Train	Bus	Road	TrainBus	TrainBusRoad
Train	1.0	0.285	0.232	0.29	0.252
Bus	0.285	1.0	0.53	0.581	0.54
Road	0.232	0.53	1.0	0.596	0.747
TrainBus	0.29	0.581	0.596	1.0	0.552
TrainBusRoad	0.252	0.54	0.747	0.552	1.0

Table 14 Travel pattern AMI pairwise comparisons of Sociability for Spectral clustering groups for the 5km subnetworks.

	Train	Bus	Road	TrainBus	TrainBusRoad
Train	1.0	0.773	0.758	0.77	0.753
Bus	0.773	1.0	0.737	0.942	0.72
Road	0.758	0.737	1.0	0.726	0.761
TrainBus	0.77	0.942	0.726	1.0	0.716
TrainBusRoad	0.753	0.72	0.761	0.716	1.0

Table 15 Travel pattern AMI pairwise comparisons of Sociability for Spectral clustering groups for the 60km subnetworks.

	Train	Bus	Road	TrainBus	TrainBusRoad
Train	1.0	0.398	0.411	0.469	0.405
Bus	0.398	1.0	0.521	0.655	0.516
Road	0.411	0.521	1.0	0.53	0.795
TrainBus	0.469	0.655	0.53	1.0	0.556
TrainBusRoad	0.405	0.516	0.795	0.556	1.0

Reachability Comparisons

Table 16 Travel pattern AMI pairwise comparisons of Reachability for K-means clustering groups for the 5km subnetworks.

	Train	Bus	Road	TrainBus	TrainBusRoad
Train	1.0	0.219	0.213	0.232	0.171
Bus	0.219	1.0	0.244	0.836	0.315
Road	0.213	0.244	1.0	0.258	0.585
TrainBus	0.232	0.836	0.258	1.0	0.331
TrainBusRoad	0.171	0.315	0.585	0.331	1.0

Table 17 Travel pattern AMI pairwise comparisons of Reachability for K-means clustering groups for the 60m subnetworks.

	Train	Bus	Road	TrainBus	TrainBusRoad
Train	1.0	0.103	0.157	0.223	0.166
Bus	0.103	1.0	0.224	0.47	0.257
Road	0.157	0.224	1.0	0.289	0.766
TrainBus	0.223	0.47	0.289	1.0	0.329
TrainBusRoad	0.166	0.257	0.766	0.329	1.0

Table 18 Travel pattern AMI pairwise comparisons of Reachability for Hierarchical clustering groups for the 5km subnetworks.

	Train	Bus	Road	TrainBus	TrainBusRoad
Train	1.0	0.18	0.139	0.17	0.141
Bus	0.18	1.0	0.248	0.799	0.318
Road	0.139	0.248	1.0	0.265	0.651
TrainBus	0.17	0.799	0.265	1.0	0.325
TrainBusRoad	0.141	0.318	0.651	0.325	1.0

Table 19 Travel pattern AMI pairwise comparisons of Reachability for Hierarchical clustering groups for the 60km subnetworks.

	Train	Bus	Road	TrainBus	TrainBusRoad
Train	1.0	0.124	0.147	0.248	0.139
Bus	0.124	1.0	0.238	0.466	0.263
Road	0.147	0.238	1.0	0.3	0.686
TrainBus	0.248	0.466	0.3	1.0	0.315
TrainBusRoad	0.139	0.263	0.686	0.315	1.0

Table 20 Travel pattern AMI pairwise comparisons of Reachability for Spectral clustering groups for the 5km subnetworks.

	Train	Bus	Road	TrainBus	TrainBusRoad
Train	1.0	0.034	0.022	0.031	0.067
Bus	0.034	1.0	0.048	0.178	0.061
Road	0.022	0.048	1.0	0.036	0.171
TrainBus	0.031	0.178	0.036	1.0	0.048
TrainBusRoad	0.067	0.061	0.171	0.048	1.0

Table 21 Travel pattern AMI pairwise comparisons of Reachability for Spectral clustering groups for the 60km subnetworks.

	Train	Bus	Road	TrainBus	TrainBusRoad
Train	1.0	0.016	0.041	0.046	0.048
Bus	0.016	1.0	0.17	0.427	0.209
Road	0.041	0.17	1.0	0.299	0.726
TrainBus	0.046	0.427	0.299	1.0	0.348
TrainBusRoad	0.048	0.209	0.726	0.348	1.0

Table 22 The correlation and group member mutual information between reachability and sociability for selected subnetworks.

Radii	Travel Pattern	Correlation	k-means group AMI	hierarchical group AMI	spectral group AMI
5km	Train	0.527	0.178	0.123	0.03
5km	Bus	0.673	0.203	0.201	0.031
5km	Road	0.753	0.221	0.219	0.084
5km	TrainBus	0.682	0.199	0.22	0.085
5km	TrainBusRoad	0.75	0.262	0.235	0.16
60m	Train	0.956	0.443	0.421	0.188
60m	Bus	0.727	0.217	0.218	0.27
60m	Road	0.88	0.345	0.338	0.475
60m	TrainBus	0.881	0.345	0.437	0.418
60m	TrainBusRoad	0.881	0.357	0.284	0.45

Clustering Comparisons

In the main paper we presented only the summary of the clustering technique differences. In Table 23 we show the results from each pairwise comparison for all 42 experiments. From the summary data one can see that kMeans and spectral clustering are most similar on average, but that kMeans and hierarchical clustering achieve the highest similarity score. What one couldn't see from the summary data is for which experiments the comparisons achieved relatively higher or lower scores. For example, that high kMeans \leftrightarrow hierarchical results occurs for the results of mean eigenvector centrality for the 60 min subnetwork bus data (an uninformative measure for our purposes). The minimum similarity (0.059) is for networkSynergy (the synergy for both TrainBus and TrainBusRoad using all four measures) which is a very important result for our purposes.

Table 23 The adjusted mutual information between all pairs of clustering methods presented for each experiment. Core data refers to the measures of the networks and subnetworks (excluding the combined measures).

Experiment	kMeans vs hierarchical	kMeans vs spectral	spectral vs hierarchical
allData	0.356	0.63	0.324
coreData	0.484	0.575	0.547
core5km	0.297	0.66	0.234
core20m	0.471	0.608	0.477
core60m	0.603	0.622	0.557
Core-Train-5km	0.283	0.751	0.22
Core-Bus-5km	0.486	0.644	0.436
Core-Road-5km	0.293	0.752	0.265
Core-TrainBus-5km	0.403	0.618	0.306
Core-TrainBusRoad-5km	0.383	0.712	0.33
Reachability-Train-5km	0.616	0.351	0.202
Reachability-Bus-5km	0.633	0.21	0.159
Reachability-Road-5km	0.672	0.232	0.213
Reachability-TrainBus-5km	0.629	0.241	0.228
Reachability-TrainBusRoad-5km	0.655	0.421	0.401
Reachability-Train-60m	0.617	0.244	0.045
Reachability-Bus-60m	0.686	0.613	0.506
Reachability-Road-60m	0.791	0.773	0.715
Reachability-TrainBus-60m	0.637	0.63	0.539
Reachability-TrainBusRoad-60m	0.699	0.717	0.674
Sociability-Train-5km	0.626	0.478	0.317
Sociability-Bus-5km	0.526	0.562	0.294
Sociability-Road-5km	0.581	0.377	0.225
Sociability-TrainBus-5km	0.526	0.565	0.293
Sociability-TrainBusRoad-5km	0.576	0.513	0.324
Sociability-Train-60m	0.55	0.25	0.13
Sociability-Bus-60m	0.647	0.403	0.297
Sociability-Road-60m	0.658	0.515	0.374
Sociability-TrainBus-60m	0.647	0.433	0.375
Sociability-TrainBusRoad-60m	0.622	0.515	0.38
Eigenvector-Train-60m	0.59	0.658	0.402
Eigenvector-Bus-60m	0.872	0.447	0.43
Eigenvector-Road-60m	0.399	0.587	0.239
Eigenvector-TrainBus-60m	0.742	0.55	0.424
Eigenvector-TrainBusRoad-60m	0.765	0.527	0.447
network6030Scaling	0.093	0.671	0.104
train6030Scaling	0.101	0.681	0.107
bus6030Scaling	0.61	0.633	0.518
road6030Scaling	0.367	0.65	0.323
networkSynergy	0.428	0.515	0.275
trainBusSynergy	0.059	0.493	0.01
trainBusRoadSynergy	0.45	0.453	0.16
limitedComparison	0.163	0.399	0.048
accessibilityComparison	0.567	0.707	0.491
sociabilityComparison	0.55	0.64	0.519
furthestPointComparison	0.506	0.489	0.423
populationScaling-All	0.549	0.643	0.413
populationScaling-Train	0.155	0.617	0.071
populationScaling-Bus	0.216	0.545	0.102
populationScaling-Road	0.124	0.564	0.084
populationScaling-TrainBus	0.432	0.763	0.431
populationScaling-TrainBusRoad	0.339	0.623	0.237
distStation	0.401	0.651	0.293
distBusstop	0.637	0.642	0.459
distIntersection	0.461	0.562	0.317
distAnyNode	0.528	0.532	0.324
trainDominance	0.333	0.597	0.216
busDominance	0.516	0.715	0.489
roadDominance	0.15	0.598	0.042
allDominance	0.467	0.428	0.175
Minimum	0.157	0.431	0.033
Mean	0.059	0.21	0.01
Maximum	0.482	0.551	0.311
	0.872	0.773	0.715

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