Directed Readings

Railway network design and transfers in Greater Tokyo and London

Due: 3 May 2022

Student number: 1931393

3971 words

Contents

1 Introduction

The aim of this report is to visualize the origin-destination characteristics of railway networks, especially for journeys with interchanges (transfers). Greater Tokyo and Greater London are used as case studies to demonstrate the visualizations, and some comparisons will be made. There are fundamental differences in the network: Tokyo has greater reliance on "heavy rail" than London, railway fares are much cheaper overall, and Greater Tokyo is a metropolis that includes several cities beyond Tokyo Prefecture. Because of these differences, comparison will not be extensive, as the primary aim is still the visualization of OD characteristics of railway networks.

This is important not just for existing rail networks that seek further optimizations, but also for growing and emerging cities of the future looking for transportation planning. Studies on current, developed cities help inform the practices and governance of future cities.

2 Data and Methods

The data for Greater Tokyo is from the MLIT's (Ministry of Land, Infrastructure, Transport and Tourism) transportation census in 2016. The transportation census involved a survey of origin-destination (OD) data, which is the basis for this report. There are significant language barriers because the data, the report, and the specification is entirely in Japanese, so machine translation was used when necessary. Because the language style from the government publication is formal, machine translations should not have grave inaccuracies. This is perhaps an unconventional limitation for spatial data analysis, but English is not used universally, so it is important to recognize the potential of language barriers in deterring widespread international analysis and literature review.

The London data is from the TfL (2017). It includes an OD survey, which is again the core data used. The data is for London Underground, not National Rail or other rail services. In contrast, the Tokyo data includes both metro and heavy rail. On one hand, it is difficult to compare between London and Tokyo because vital information regarding National Rail is missing. On the other hand, heavy rail has a different purpose in Tokyo, especially in the centre, where it is used in conjunction and almost interchangeably with the metro system. The heavy rail fares are as cheap as the metro (Ueno to Akihabara is 168 yen by metro and 136 yen by JR), and both are much cheaper than rail transport in London overall. Analysis focusing only on Tokyo Metro would be even more misleading because the "heavy" rail network in central Tokyo is deeply integrated to the metro system. Furthermore, through-services are common; they are metro services that, at the terminus of the metro line, continue further service as a heavy rail line. For example, the Hibiya Line serves Naka-meguro to Kita-Senju; some Hibiya Line trains will continue beyond Kita-Senju to Kurihashi station via the Tobu Nikko Line. Excluding "heavy rail" services would lose vital information on journeys in the Hibiya Line – should journeys from Naka-meguro to Kurihashi be excluded? "Heavy rail" plays different roles in the two cities, so a comparison would capture the effects of the differences in services and fares. It is precisely the point to evaluate the transportation network of the two cities as it is, and not exclude information. Therefore, the biggest limitation is not the integration of heavy rail in Tokyo's network, but the exclusion of National Rail and other services in the TfL data. Nevertheless, the aim of this report is not strictly to make a comparison, but to provide more than one case study to demonstrate the methodology. Therefore, the two cities will have two separate sub-sections, and only refer to each other when appropriate, instead of presenting every figure for both cities simultaneously.

The analysis first examines the basic characteristics of the origin-destination matrix to get a basic understanding of the network. This involves plotting out the most frequent OD pairs on a map, identifying the busiest stations and key interchange hubs. The second step is to plot the routes for journeys to and from the busiest stations. Routes means the entire journey is plotted, from the origin through any interchange stations to the destination station. The maps for the major stations are separated to reduce visual clutter, so to facilitate direct comparison the routes are overlaid on each other in a pairwise matrix. For transfers-only journeys, the average number of transfers for every station is calculated and mapped, identifying the easiest and hardest stations to commute to and from. If necessary, the journeys with the most transfers are tabulated and their routes visualized with a diagram, to identify the most inconvenient journeys sorted by the number of trips made.

3 Analysis and discussion

3.1 Basic characteristics of the Tokyo network

Figure 1 shows a flow map of OD pairs in Tokyo, with Figure 2 zoomed into central Tokyo. The arrows only connect the starting and ending station, not the intermediate transfer stations. To reduce clutter, only the first 300 pairs sorted by trip frequency are shown. In Central Tokyo, the most frequent clusters are on the west, which corresponds to Shinjuku station. The smaller cluster on the East is Tokyo, Shimbashi, and Shinagawa stations. Despite its namesake, Tokyo Station is eclipsed by Shinjuku in terms of passenger flow, because Shinjuku station is actually a combination of multiple stations by multiple railway operators. The major stations on the western side of central Tokyo are Ikebukuro, Shinjuku, and Shibuya. Tokyo station has a lower concentration of arrows compared to Shinjuku, because there are more stations around Tokyo that act as alternatives. Destinations that are close to Tokyo station no longer need to use it if there is a closer metro station nearer to the destination. An extensive underground mall also connects the surrounding metro stations to Tokyo station, including Otemachi, Nijubashimae, Hibiya, Ginza. The density of activi-

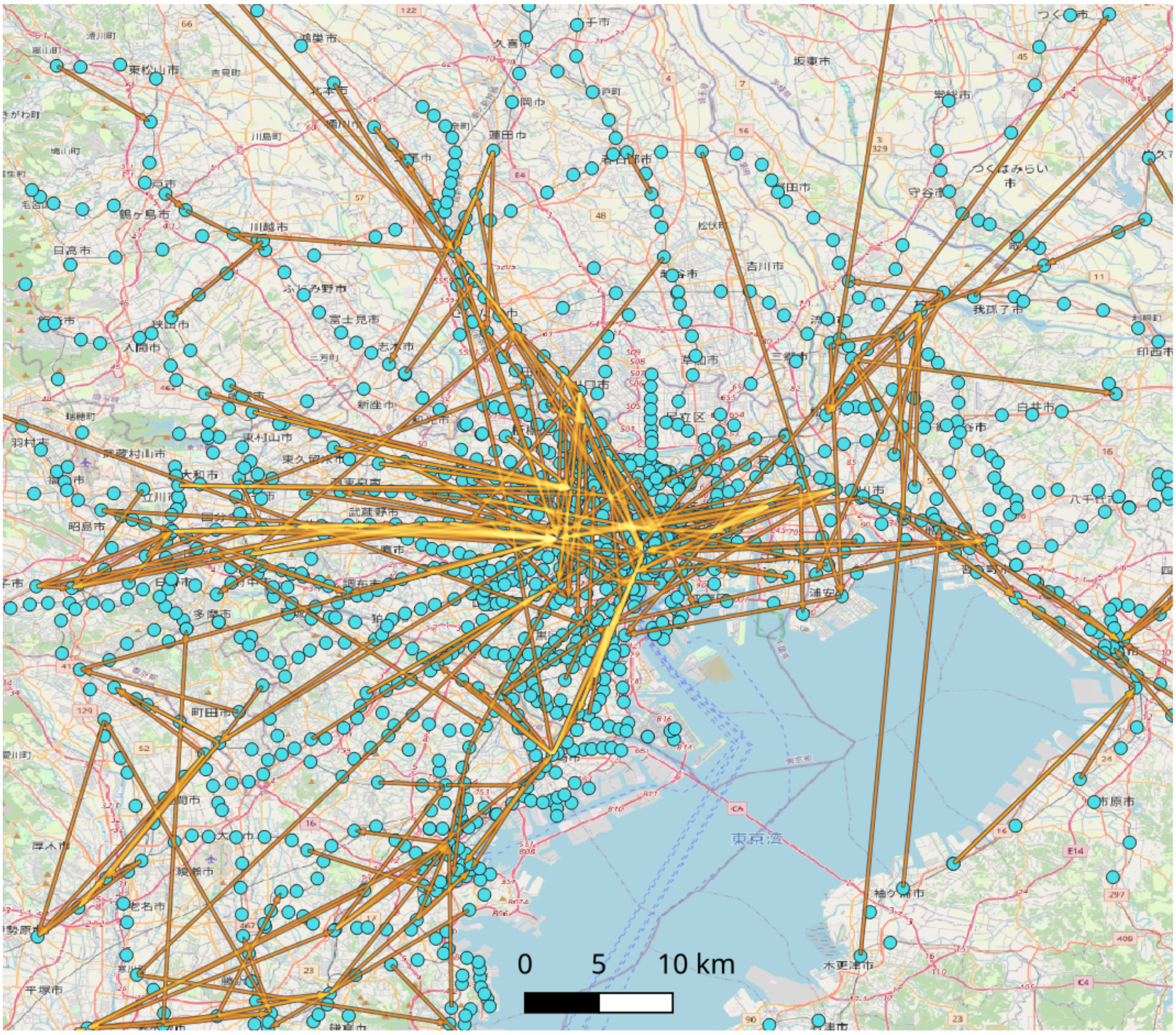

Figure 1: Tokyo: Flow map of OD pairs

ties around Tokyo station lead to a high density of metro stations, which counter-intuitively causes those metro stations to be excluded in this map, because they collectively divided the frequency of journeys to the area, reducing the individual station passenger counts, leaving Tokyo station rather isolated. Shinjuku and Ikebukuro does not have as much stations around it, so journeys to/from the general area must use Shinjuku or Ikebukuro station. Furthermore, while Tokyo station is the terminus of all Shinkansen routes, there are only 9 non-Shinkansen routes from JR and Tokyo metro. Compared to this, Shinjuku station has 12 lines from five operators.

The map verifies that OD pairs for Shinagawa and Shimbashi station are in a north-south

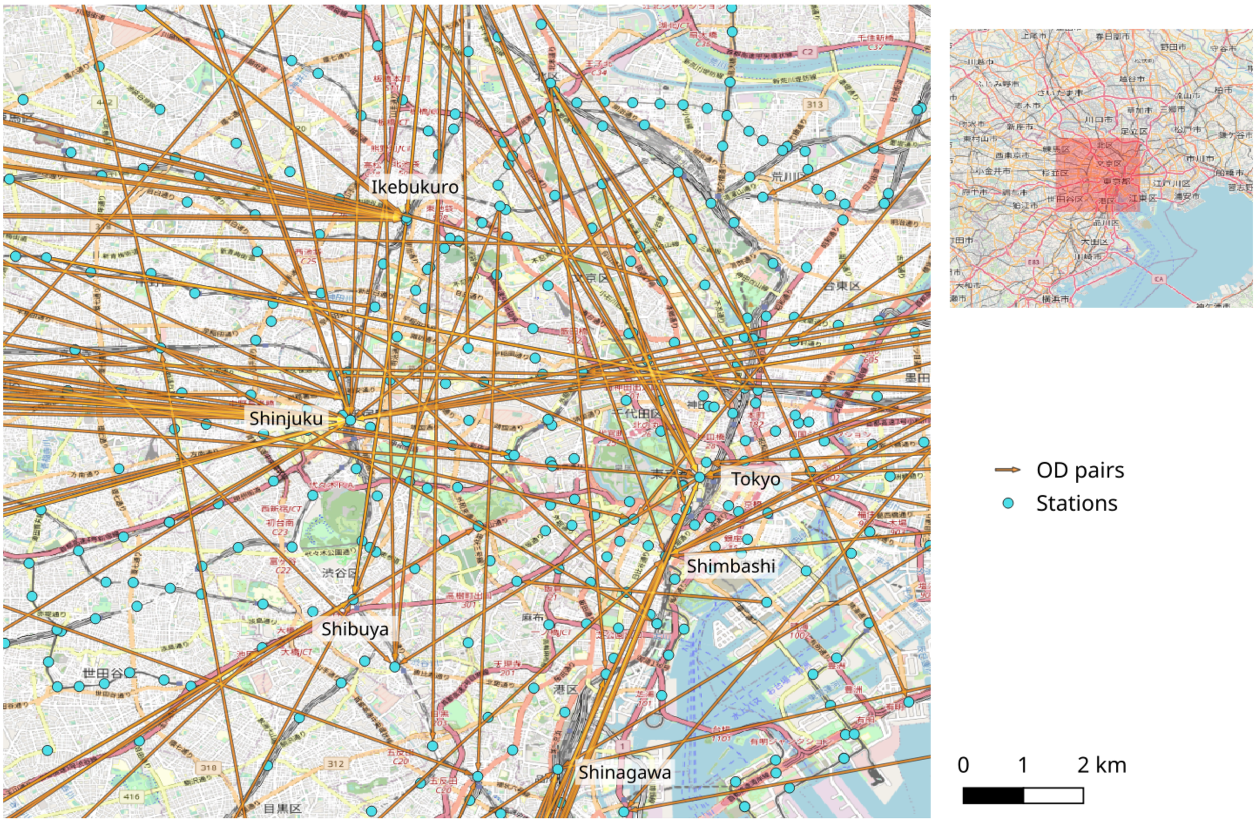

Figure 2: Tokyo: Zoomed in flow map of OD pairs

manner, whilst Tokyo station is more mixed and has some east-west journeys. There are prominent journeys to/from Shibuya from the southwest, because Shibuya is the terminus of the Tokyu lines that serves southwestern Tokyo. In a similar vein, a significant number of journeys to/from Ikebukuro are from the northwest, because Ikebukuro is a terminus of the Seibu Railway, which serves northwestern Tokyo. There is a noticeable lack of traffic to the northeast, and stations within central Tokyo, especially within the Yamanote line, are not often important. This map also shows a limitation of highlighting arrow intersections. For example, there is seemingly a cluster of light colors north of Tokyo station, but it is a grid of overlapping arrows. The arrows "passing through" the area are intersecting with each other, but does not show a cluster around a station. The arrows also does not represent the actual geographical route of the journey along the train tracks, so intersections does not indicate the physical density of lines are high in that area.

3.2 Journeys to/from major stations of Tokyo

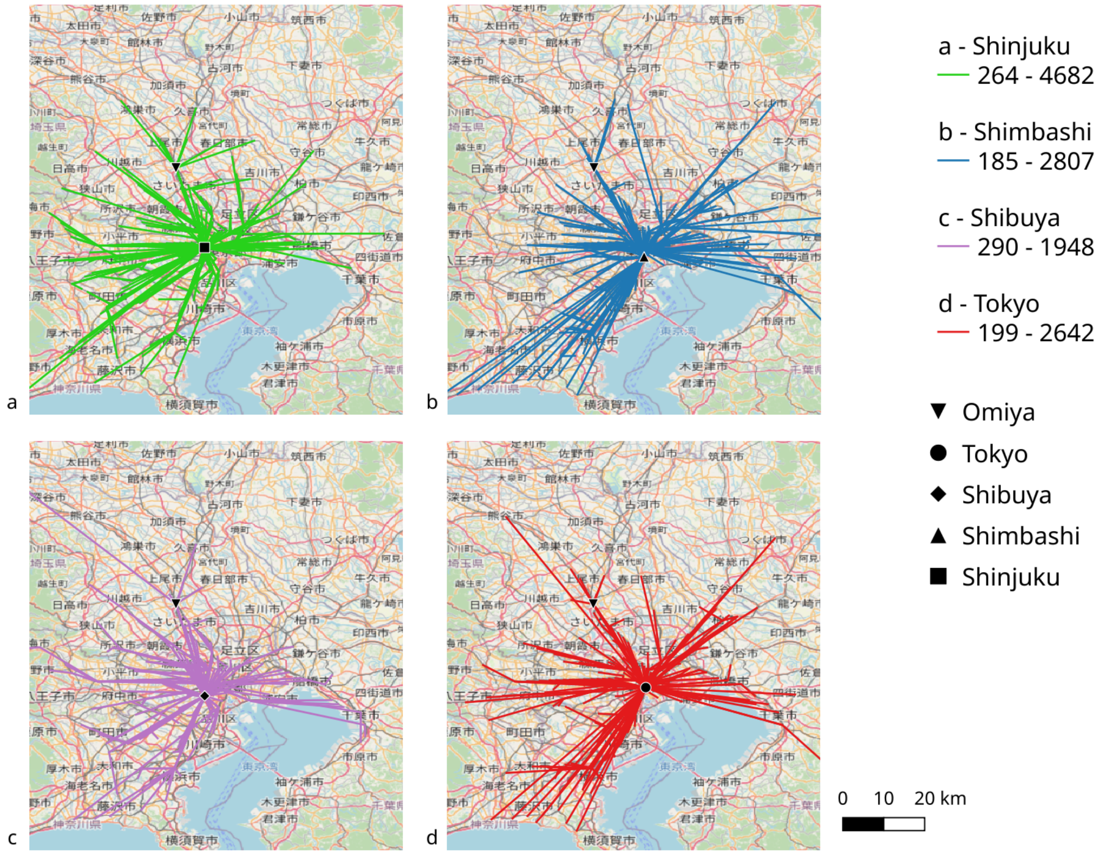

Figure 3: Routes containing each of the four major stations in Greater Tokyo

Figure 3 shows journeys routes to/from each of the four major stations in Tokyo, represented by straight lines. The journeys are classified into five equal-quantile quadrants, and only the highest quadrant is shown. The extent of the quadrant is shown by the numbers in the legend. Omiya station is indicated by an upside-down triangle, because it is an important hub connecting all four stations to stations in the north. While Omiya is in the Greater Tokyo area, it is not in Tokyo Prefecture but in Saitama Prefecture, highlighting the size of the metropolis. Tokyo station has the most extensive connections to the north, stretching to Kumagaya via the Takasaki Line.

Shibuya also has a connection to Honjo, Saitama (out of bounds in the map), but it involves transfers to Akabane. Otherwise, Shibuya does not serve the northeast very well because of the lack of connecting lines. Tokyo and Shimbashi has a good coverage in the northeast, but only Shinjuku had covered some of the area east of Omiya, so it is still lacking in rail coverage overall. Tokyo and Shimbashi stations has a very distinct northeast-southwest pattern, in contrast to the western stations which are more directionally uniform, which makes sense because the train tracks are arranged in a north-south direction. The significance of the Tokaido Main Line is exemplified by Tokyo and Shimbashi's coverage of the southern edge of Greater Tokyo.

Although Shibuya is the terminus of the southwestern-serving Tokyu railways, it was able to serve stations on the west as far as Shinjuku, and as far as Tokyo on the east. This shows that Shibuya's position on the Yamanote line clearly helped access to western stations through Shinjuku and Ikebukuro. Shibuya journeys to Chiba on the East is significant because it does not have any direct connections.

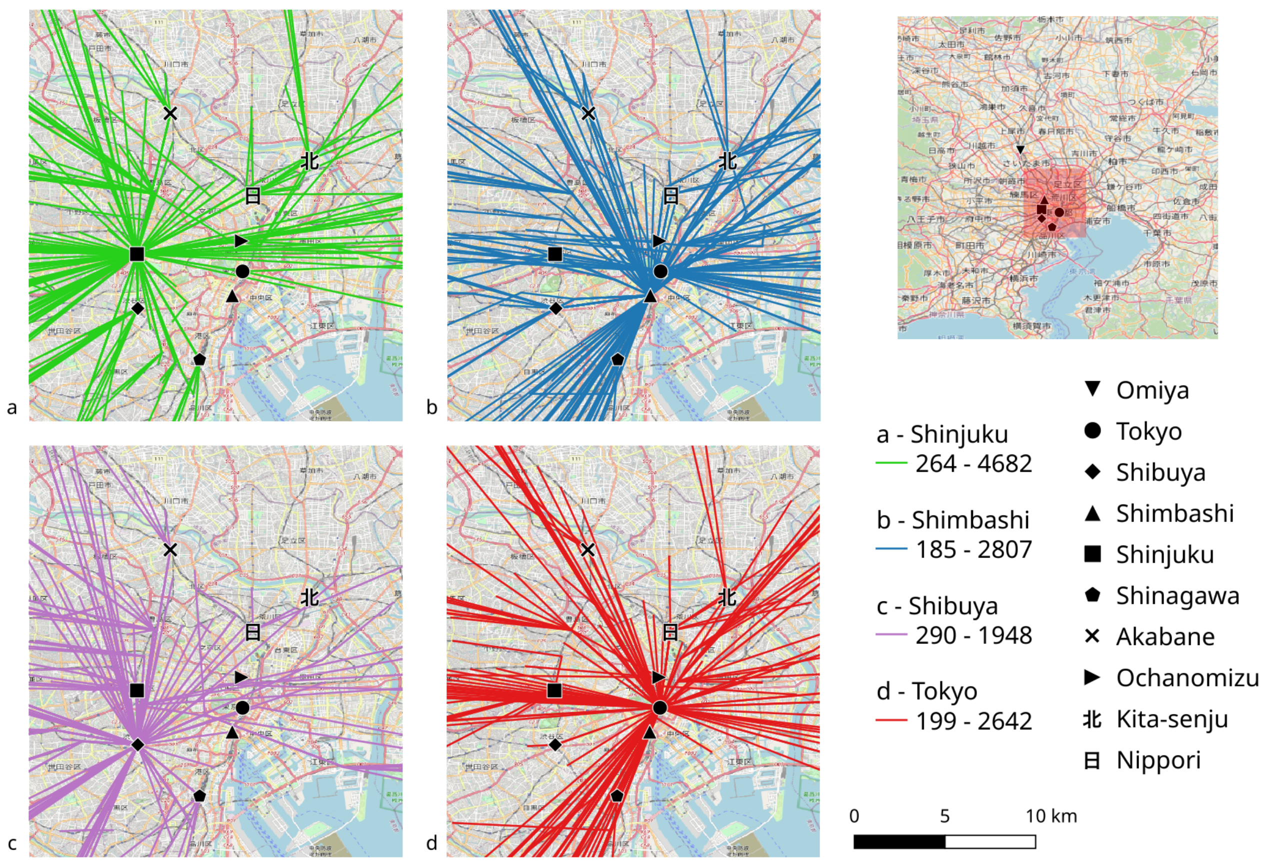

Figure 4: Routes containing each of the four major stations in central Tokyo

Figure 4 is the previous map zoomed into central Tokyo. Shinjuku routes also involve

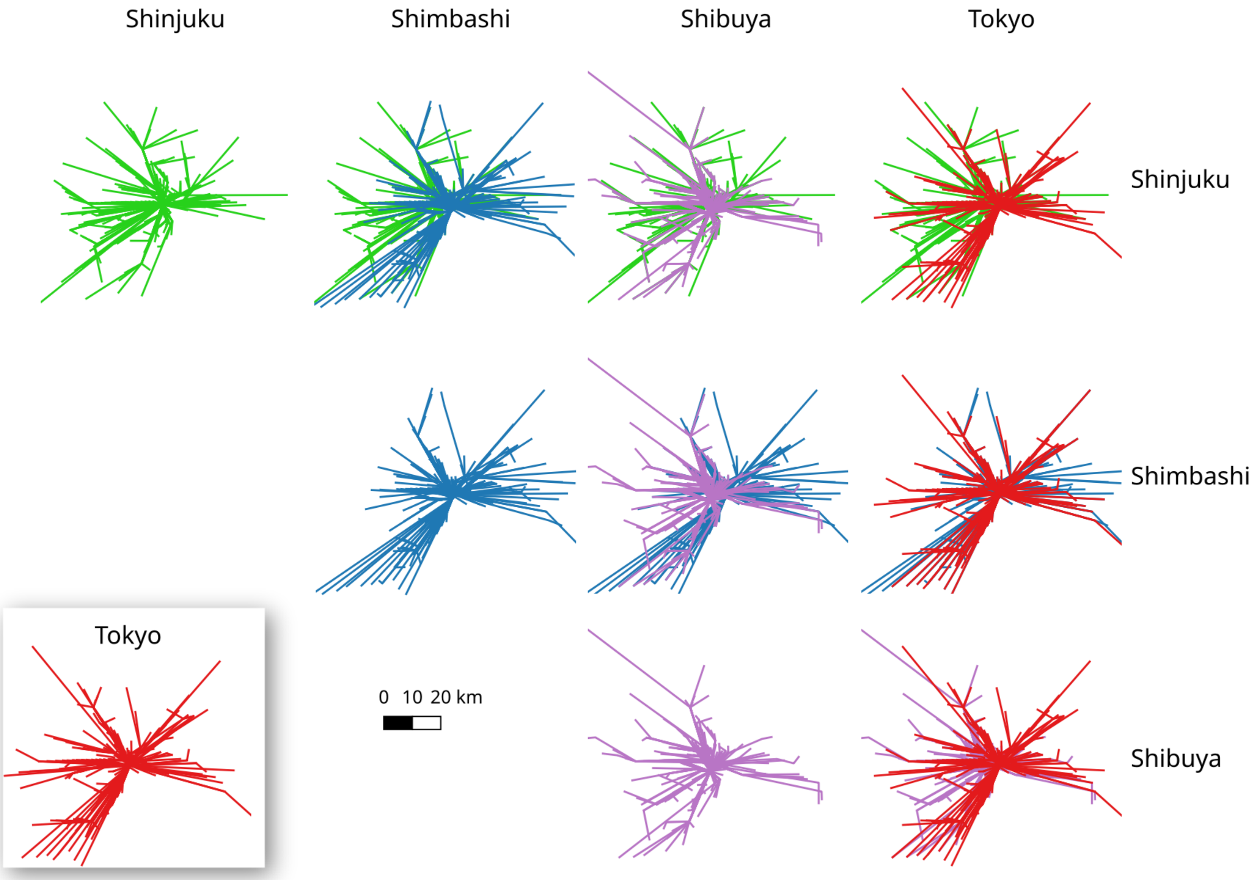

Figure 5: OD pairs matrix for major stations in Tokyo

significant transfers at Ikebukuro, Shibuya, and Shinagawa. Whilst Ikebukuro and Shibuya complemented Shinjuku in the west, Shinagawa complements it in the south. There is also a considerable number of Shinjuku journeys interchanging at Nippori and Kita-Senju stations, which serves as a hub to northeastern Tokyo. Shinjuku's advantage in the west through the Chuo Line is not that large, as Tokyo is the terminus of the Chuo Line. Shibuya, despite needing a transfer to go west, is able to compete with Shinjuku. Shinjuku also does not have the Tokaido Main Line, limiting its effectiveness in coverage of the south (Figure 5). Even Shibuya is able to serve the southern stations via the Tokyu lines to Yokohama and transferring to JR.

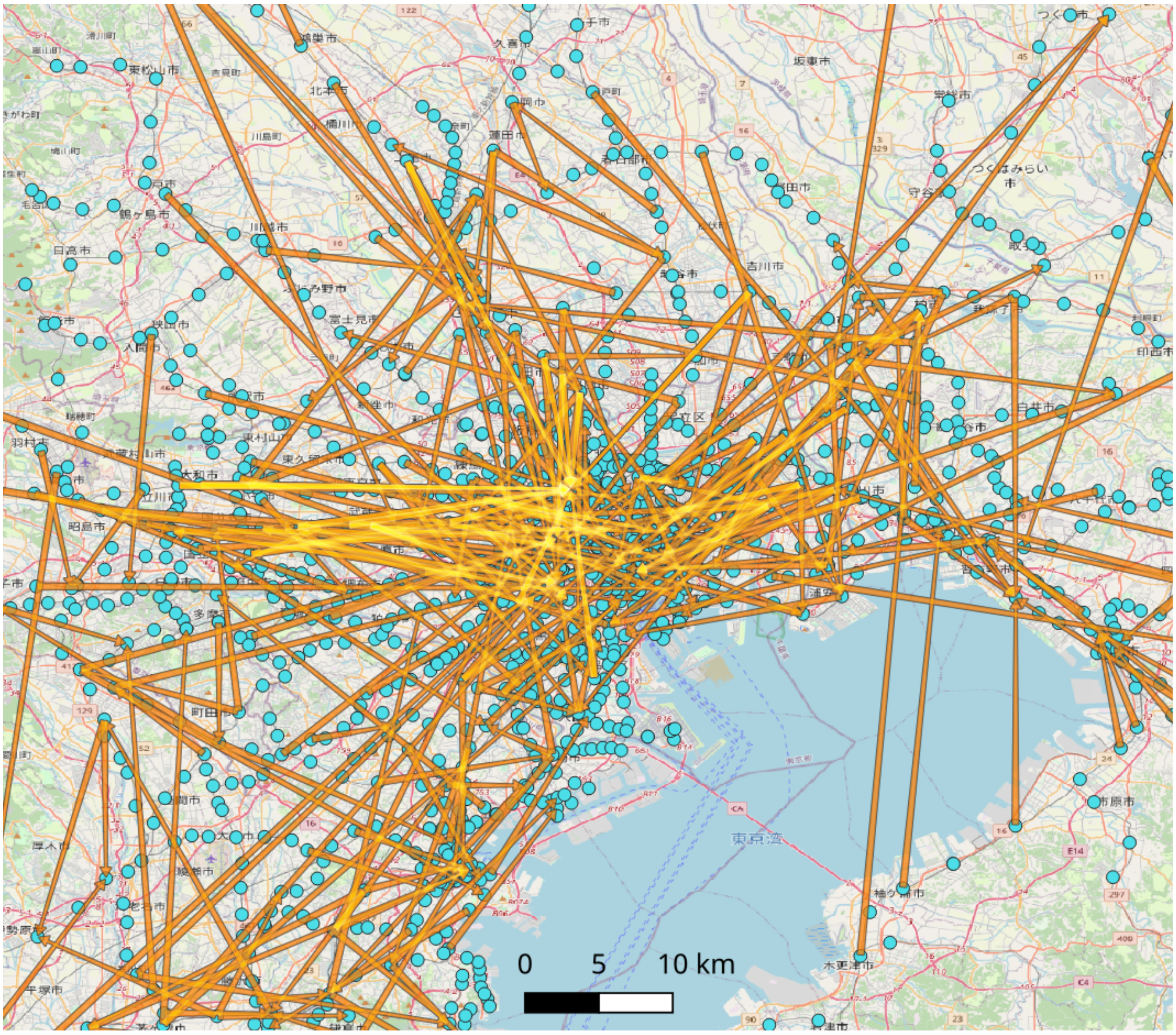

Figure 6: Greater Tokyo: Flow map of OD pairs involving transfers

3.3 Tokyo journeys with transfers

Figure 6 shows the OD pairs flow map only for journeys with transfers. The top 300 pairs are shown, but because the cutoff number is different (1252 versus 899 people per day), the two maps cannot be directly compared. Nevertheless, some basic properties can be investigated. The flow map for all journeys appear quite linear, in the sense that the OD pairs roughly followed the train tracks, and connect the stations in the outskirts to Central Tokyo, roughly following a concentric city model. This map shows more intersecting OD pairs, revealing a more multi-centric metropolis. Cities in Greater Tokyo but outside Tokyo Prefecture such as Yokohama in the south and Chiba in the east are not just mere connector stations to inner Tokyo, but cities in their own right, as indicated by the grid of journeys from elsewhere in the metropolis. For example, there are journeys from western Tokyo to Yokohama, indicating that Yokohama is a city that has attractive forces by itself, and not just a satellite of inner Tokyo. These nodes do not necessarily have to be large cities; for example there journeys from Akabane in the north to Kashiwa in the northeast, even though Akabane is a just neighbourhood in Kita ward of Tokyo Prefecture.

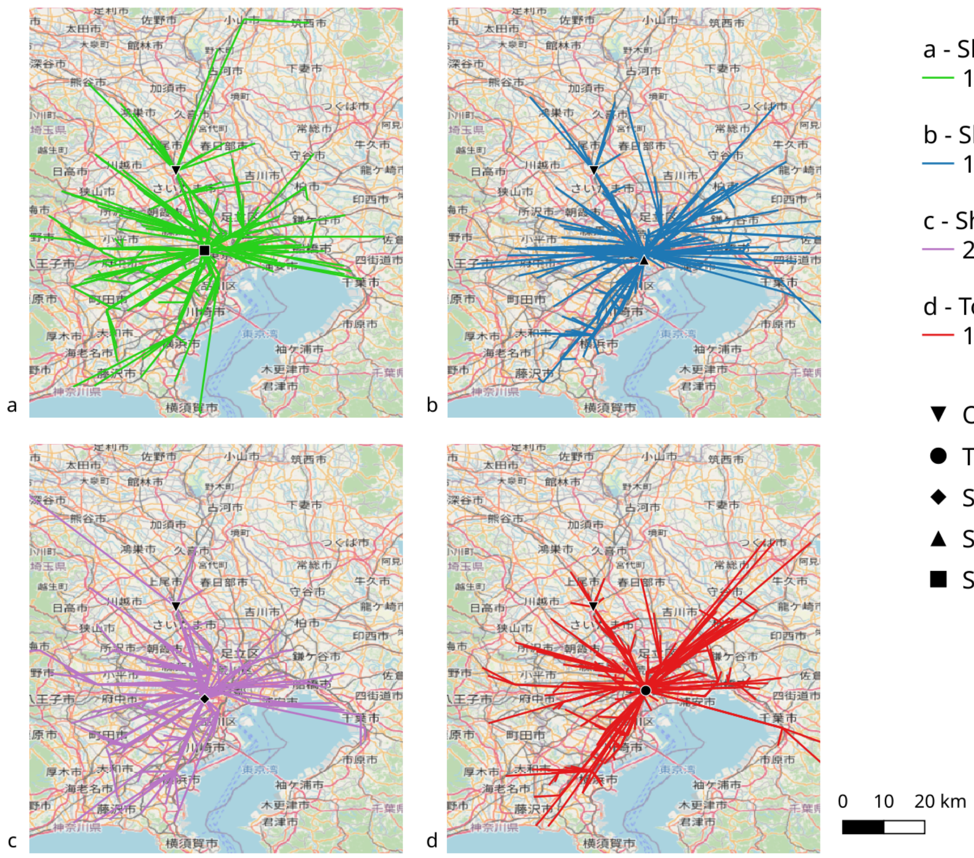

Figure 7: Routes containing each of the four major stations in Greater Tokyo

Figure 7 shows the routes for each of the four major stations, for journeys with transfers. Note that Tokyo station no longer in the top 4 busiest stations, which is now Shinagawa. However, the four stations are unchanged so that it can be compared to the previous maps. Because this map excludes journeys without transfers, many of the connections from Tokyo and Shimbashi to the southern stations are excluded as they are directly connected through the Tokaido Main Line. Instead, this map reveals potential weaknesses, inconveniences, and inefficiencies in the network. Shimbashi is able to connect to the north through transfers at Omiya. There were less routes connecting Tokyo to the west and south, indicating that these areas do not have trouble in accessing Tokyo station. Rather, there are more connections between Tokyo and the northeast, indicating a potential to improve there. On the other hand, Shibuya still lacks connections to the northeast outside Tokyo Prefecture.

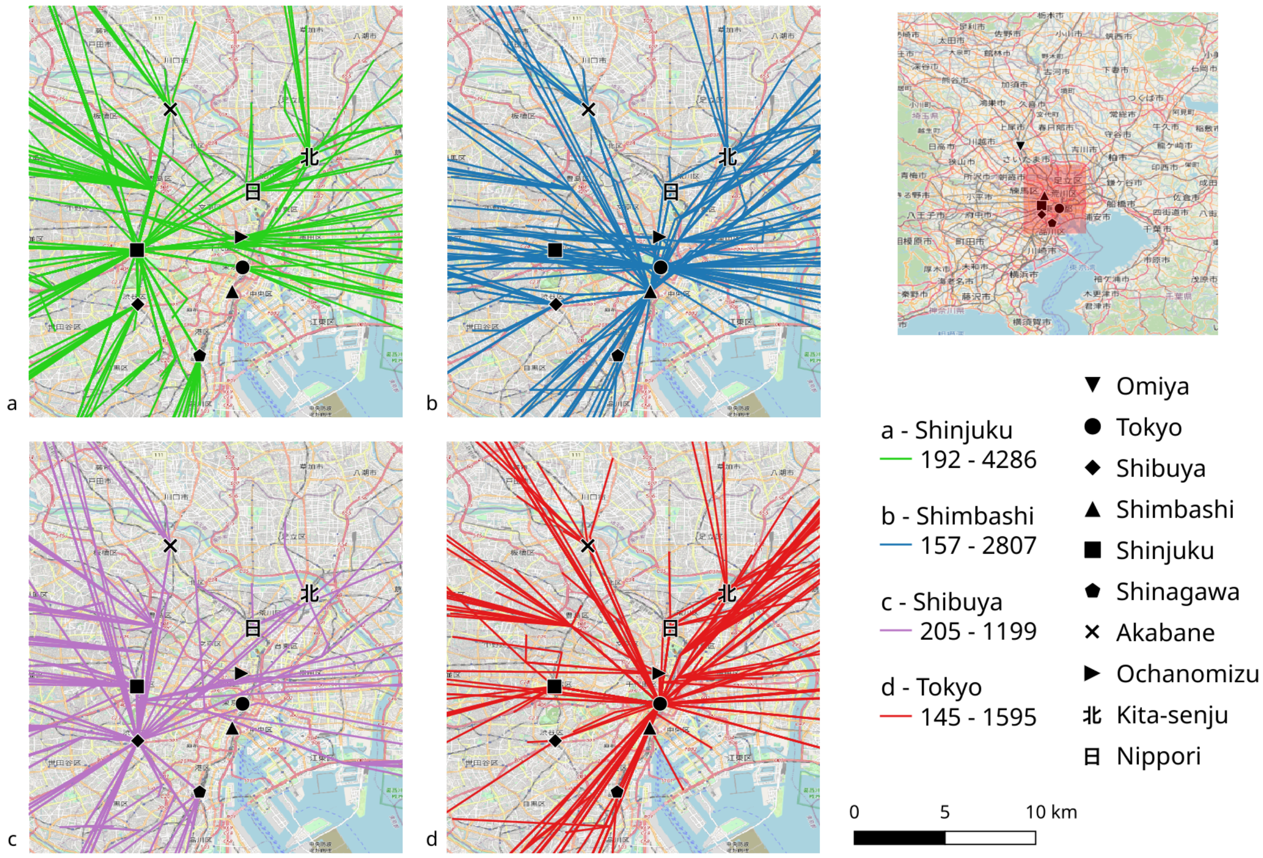

Figure 8: Routes containing each of the four major stations in central Tokyo

Figure 8 shows the same routes map zoomed into Central Tokyo. Without the direct connection from Shinjuku to western stations on the Chuo Line, Shinjuku journeys that required a transfer did so at Ikebukuro for the northwest and Shinagawa for the south. Shinjuku serves the west by interchanges at both Tokyo and Ochanomizu. The Chuo-Sobu Line from Shinjuku arrives at Ochanomizu then Tokyo in that order, so it is slightly more convenient to change at Ochanomizu for journeys from Shinjuku. For journeys via the Sobu Line, which does not stop at Ochanomizu, Tokyo station must be used to connect to Shinjuku.

Shibuya actually had direct coverage of northern central Tokyo via the Fukutoshin Line, which was excluded in this transfers-only map. Other than a slight increase in transfers through Kita-Senju, Shibuya had little change. Shimbashi has an increase in routes to the west, which indicates a greater reliance on interchanges for journeys between the west. Shimbashi and Tokyo is again a strong hub for direct journeys to the south, as shown by the significant decrease in transfers-only routes to the south. The denser lines to the northeast from Tokyo confirms that even for the best hub for the northeast, it has greater reliance on transfers compared to other areas Tokyo covers. The Joban Line that connects Tokyo to the northeast is integrated to the Tokaido Main Line as the Ueno-Tokyo Line, but the Tokaido Main Line is clearly better at serving the south than the Joban Line on the northeast. This means the network inefficiency is not about the number of lines to the northeast but the quality. For example, the Joban Line does not serve Tsukuba city in Ibaraki Prefecture; the Tsukuba Express terminates at Akihabara, which requires a transfer to Tokyo station.

3.4 Tokyo average transfers analysis

Figure 9 shows the average number of transfers for each origin station in a journey. The stations in central Tokyo has the lowest average number of transfers, and as the station gets further away from the centre, the more likely it is to have more transfers. This means journeys beginning in central Tokyo tend to arrive at their destination with few transfers, which makes sense intuitively. Journeys beginning further away tend to require transfers to reach their destination, even if it is in central Tokyo, because only a few lines serve the suburban areas, and those lines only has a limited number of termini in central Tokyo. The number of transfers would also increase for journeys not going to or from central Tokyo, because it faces the same limitation in termini and route choice. The lowest band of stations in central Tokyo fits the Yamanote loop remarkably well. The notable stations with a low average

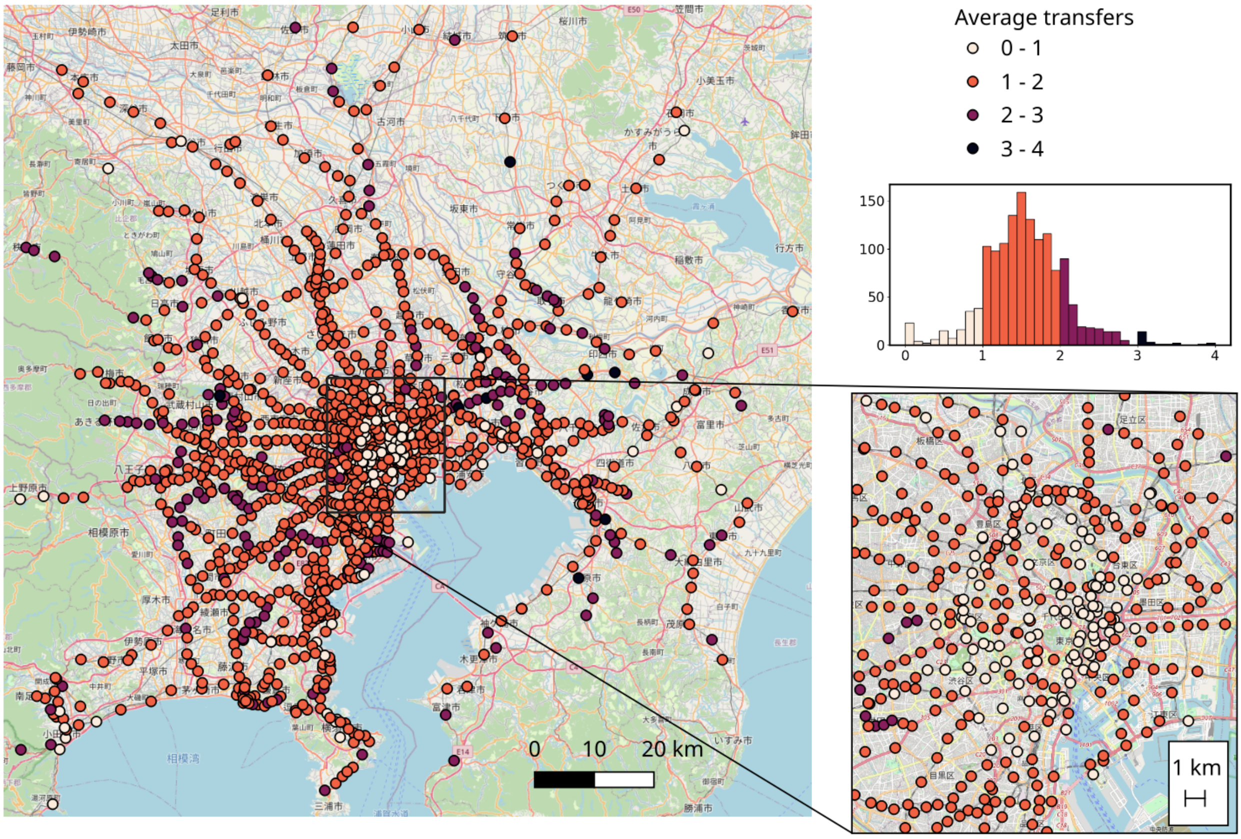

Figure 9: Tokyo: Average transfers for every origin station

outside the Yamanote line is Akabane, Oji, Kita-Senju in the north, which are important interchange stations. On the other hand, Setagaya-Daita station on the Odakyu Line in the west has a low average only because it is usually used by travellers on other stations on the Odakyu Line.

3.5 Basic characteristics of the London network

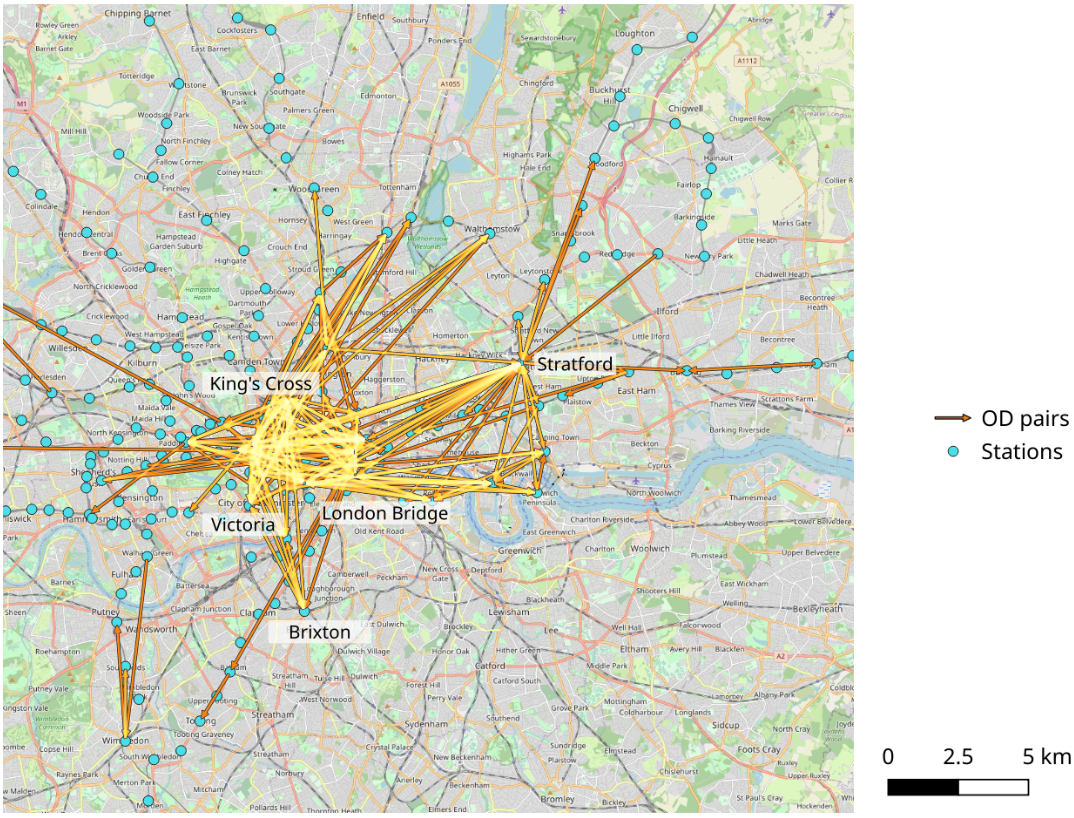

Figure 10: London: Flow map of OD pairs

The above analysis is repeated for London. Figure 10 shows a flow map of OD pairs. Only the 300 most frequent journeys are shown. Even though this is Greater London, Greater Tokyo is more populous and has a more expansive railway system. There are stations all over Greater Tokyo and it was only limited by natural barriers such as Tokyo Bay. In contrast, Greater London has a significant lack of underground stations in the south, despite not having natural barriers. There is a noticeable cluster on the east, which is Stratford station. The distance between Tokyo and Shinjuku stations is around 5.3 km, but the distance from Stratford to London Bridge is nearly 7 km. Stratford is further away from central London (and indeed it is in Zone 2) but in terms of journey frequency ranking, it is as important as Tokyo station.

The map is slightly misleading because the high density in central London creates the

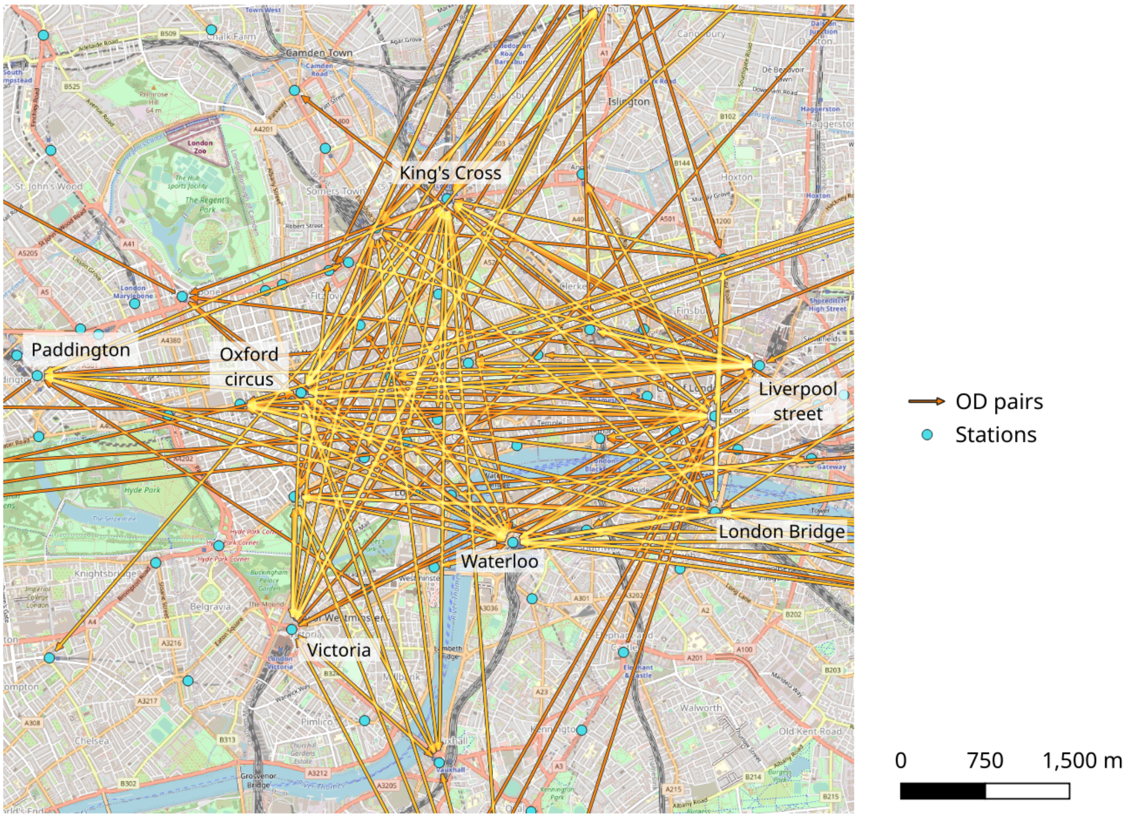

Figure 11: London: Zoomed in flow map of OD pairs

illusion that the entire Zone 1 has evenly high traffic. Upon zooming in, Figure 11 shows a more accurate map at the expense of hiding Stratford, Brixton, Canary Wharf, and other Zone 2 stations. Compared to Tokyo, the major stations in London also distributed in a circular manner around the core. Whereas Tokyo's Yamanote line is more elongated vertically, London's "circle" is more elongated horizontally. Additionally, the major stations in London are not connected by a single line.

3.6 Journeys to/from major stations of London

Figure 12 shows the OD pairs containing the four major stations in London, and Figure 13 zooms into central London. Compared to Tokyo, they look more uniform around the city. Destinations are from all spatial directions and almost uniformly radial around the station, but all of them have significant gaps in serving southern London. The only gap for King's

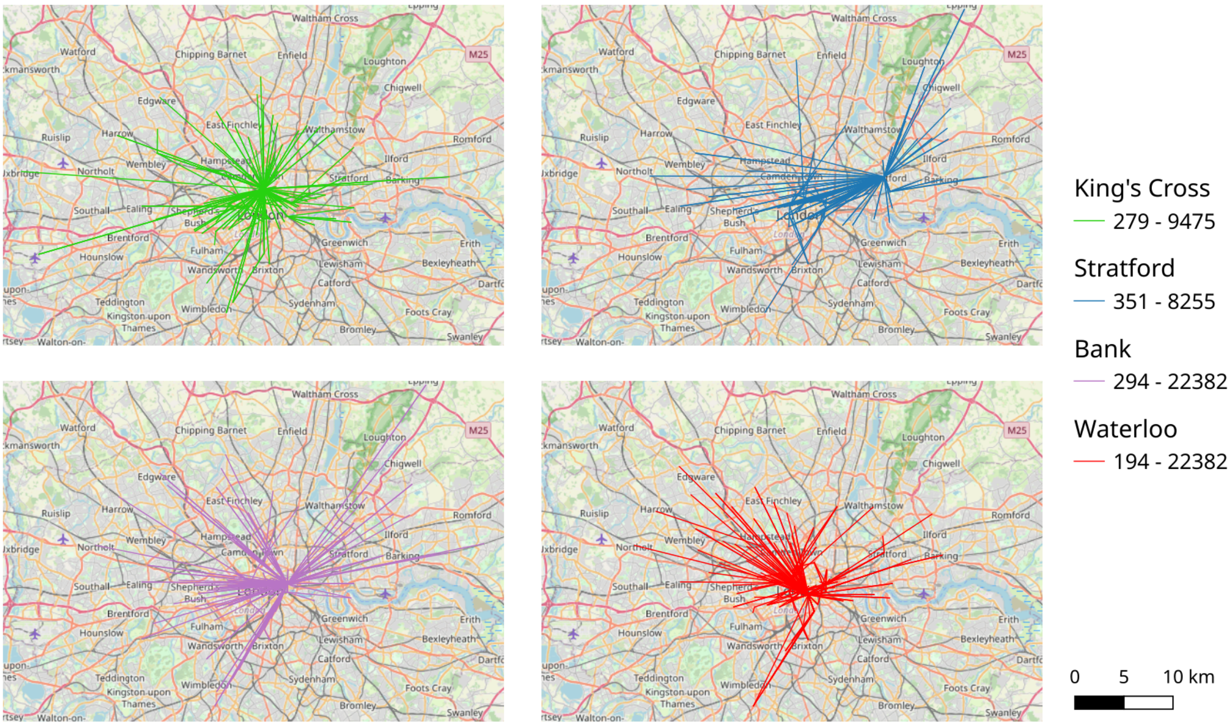

Figure 12: Greater London: Routes containing each of the four major stations

Cross is the northeast, which is covered by Stratford and Bank stations. Despite Waterloo's position south of the Thames, it has as much service to the northwest as King's Cross, as well as southern London (Figure 14).

Compared to the others, Waterloo has more journeys to central London, because southern London does not have alternative railway hubs other than London Bridge, whilst there are many alternative railway hubs north of the Thames that compete for journeys from their respective direction. This is similar to Tokyo station having less traffic than Shinjuku, because eastern Tokyo has much more stations than the west.

3.7 London journeys with transfers

Figure 15 shows the routes of journeys containing each of the four major stations, with at least one transfers. Note that the busiest station for transfers-only traffic is Victoria, not King's Cross. Nevertheless, the four stations are still used so that it can be compared to the

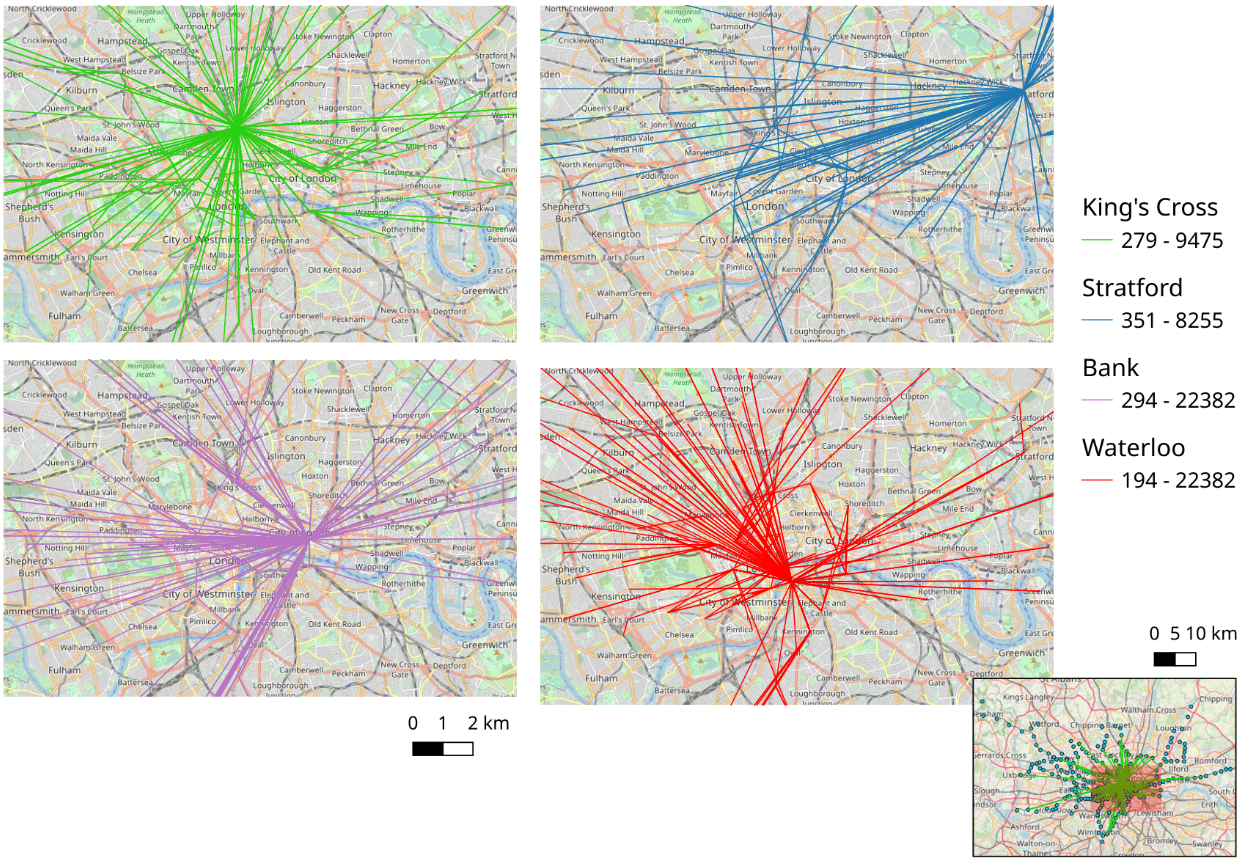

Figure 13: Routes containing each of the four major stations with at least one transfer, showing central London

original map. The original maps are quite uniform by direction and structured in a hub-and-spoke model. This map shows that the hub-and-spoke structure is primarily because of journeys without transfers. By ignoring such journeys, we get a more interesting map. King's Cross does have good coverage of northeastern London, they just require transfers. Stratford also has coverage in central London, not just in the west. The western stations are because of the Central line; by ignoring direct journeys containing Stratford, this map reveals that the most frequent connections to Stratford from central London requires transfers. Whilst coverage from Stratford returned to central London, journeys containing Bank with transfers are almost exclusively north of the Thames. This makes sense because the only connection Bank has to the south is from the Northern Line, which does not require transfers.

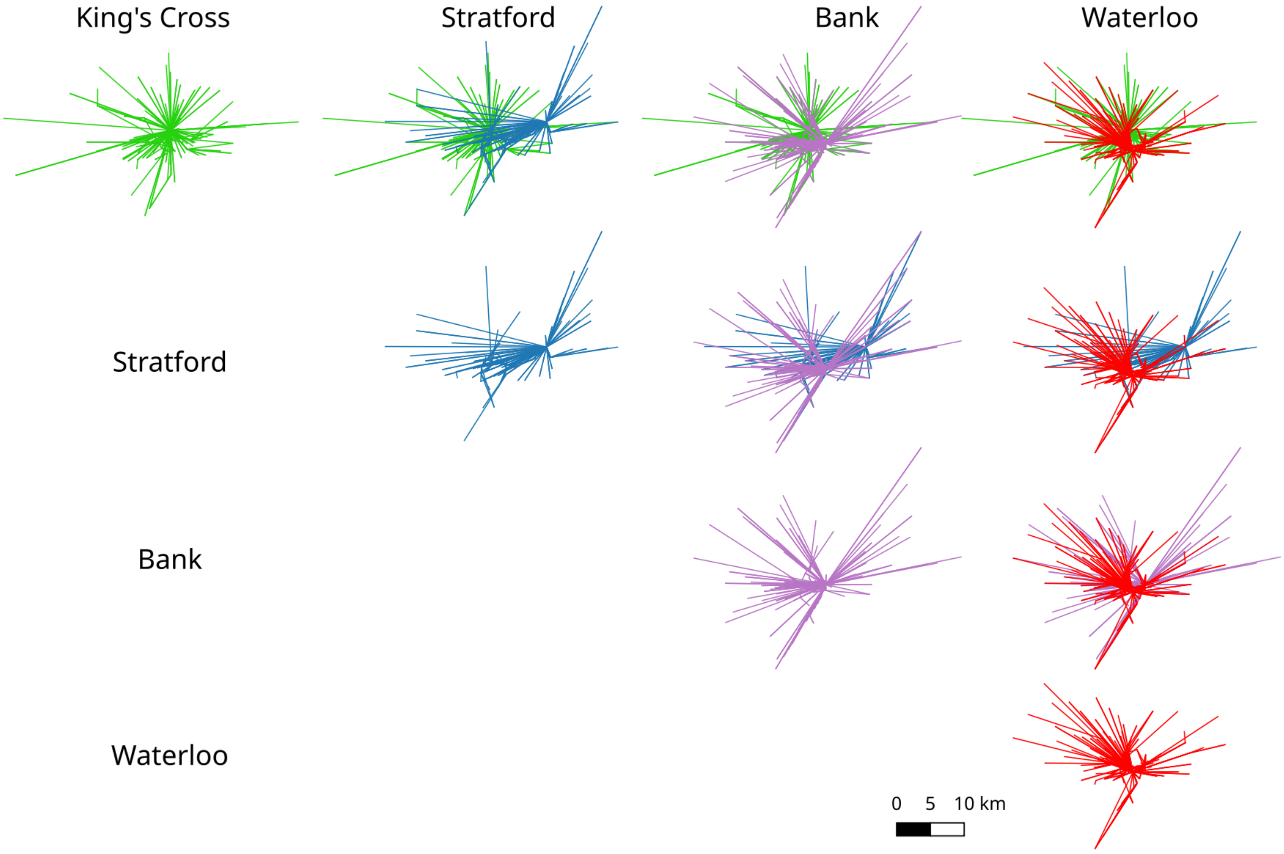

Figure 14: OD pairs matrix for major stations in London

Figure 16 is the same map but zoomed into Central London. It reveals several important transit stations that complement the major stations. In the north, Finchley Road and Marylebone stations acts as a transit station for journeys containing King's Cross to northwest London. Liverpool Street, which was the fifth most frequent origin station for journeys with transfers, is the key node that connects northeastern London to King's Cross. For Stratford, the Central Line is vital to connecting it with the rest of Central London, especially at Liverpool Street, Bank, and Holborn. In particular, Holborn connects it to the Kensington area via the Piccadilly Line, and the south is connected through Bank using the Central Line, and London Bridge, using the Jubilee Line. The Central Line is clearly more frequently used than the Jubilee line, so the heavy reliance of Stratford on the Central Line means it is a potential bottleneck and source of risk if the Central Line is out of service. The opening of the Crossrail would therefore help mitigate risk and reduce congestion, as well as extending the

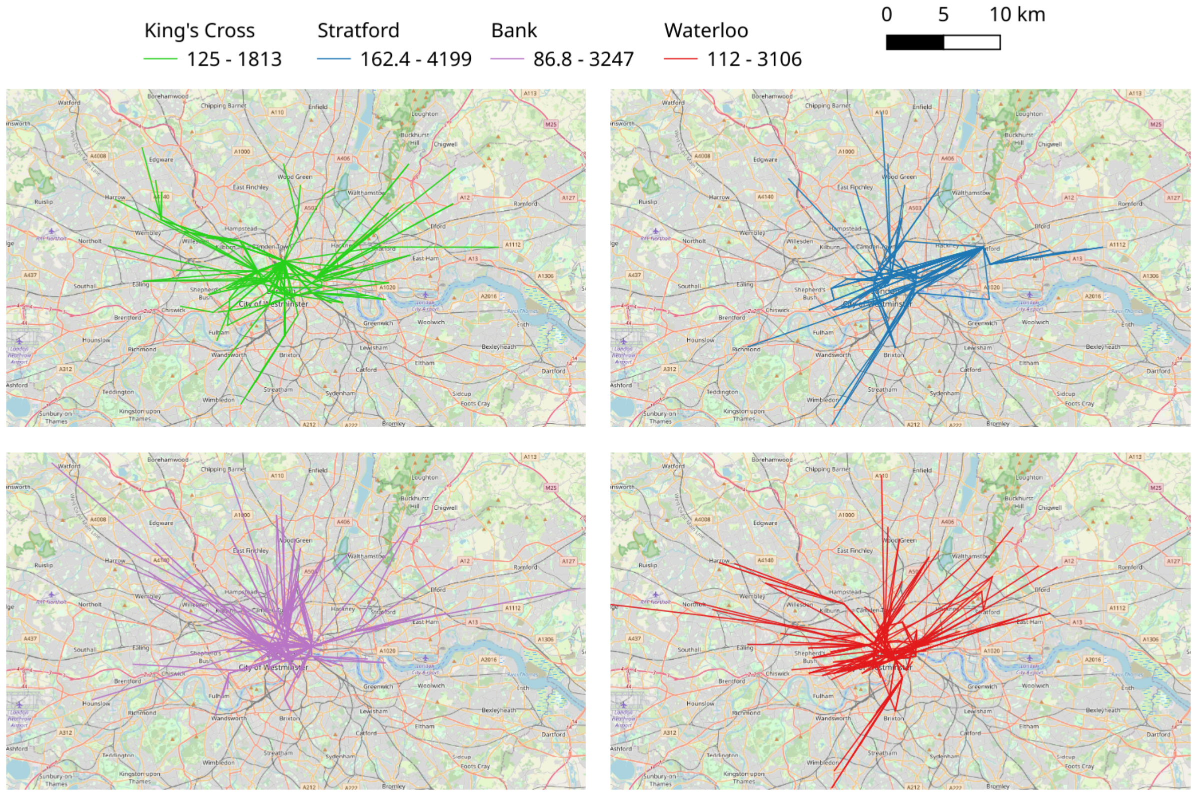

Figure 15: Routes containing each of the four major stations with at least one transfer, showing Greater London

already impressive direct coverage of Stratford to western London.

3.8 London average transfers analysis

Figure 17 shows the average number of transfers for every origin station in London. Compared to Tokyo, there is no consistent spatial trend. Stations on the Central Line in the northeast has a low average, presumably because journeys are either only on the Central Line due to adjustments by the traveller, or the convenience of the Central Line in directly reaching destinations. In contrast, the stations in the northwestern and southern outskirts has a higher average number of transfers. This could mean that the Northern Line is less effective than the Central Line in terms of network efficiency. Despite splitting into two branches in central London, the Northern Line by itself is inadequate at covering enough destinations, and the interchange stations it serves are also not as efficient as the Central

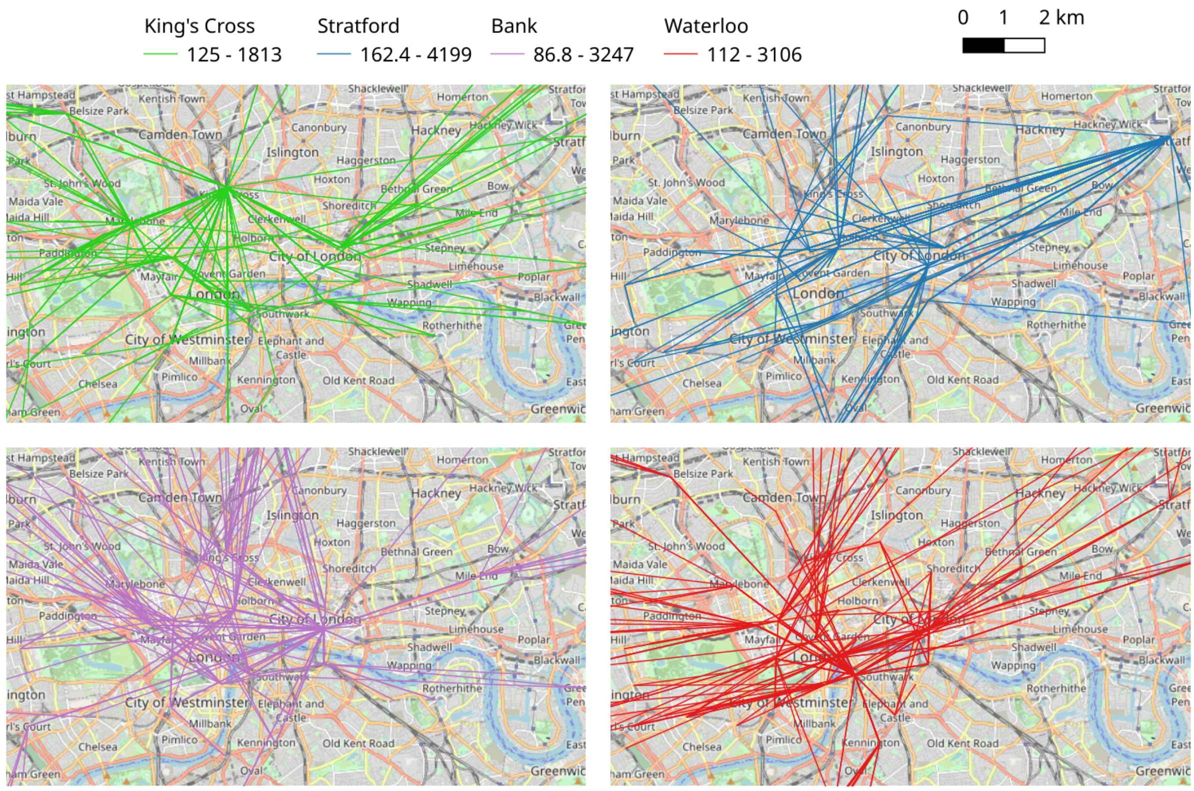

Figure 16: Routes containing each of the four major stations with at least one transfer, showing central London

Line. The Metropolitan Line does not cross central London as efficiently as the Central and Northern lines does, and it does not have two branches like the Northern Line, so it is perhaps not too surprising that stations has a higher average. Some stations on the highest band are as close as Preston Road, but as the histogram shows, this is potentially misleading as there are very few stations exceeding 1.4 transfers on average, so stations like Preston Road are usually on the low end of the band (1.2 for Preston Road). This is therefore a reminder that the colour scheme is different from Tokyo because of the less skewed distribution. The difference is because rail transportation in Tokyo is much more reliant on heavier rail rather than metro in the outskirts. This is indeed a limitation on the comparisons that can be made between Tokyo and London, but it is also important to not shy away from comparisons when it is how people travel around the city in reality. There are many stations on the highest band even in Central London, but this is still comparable to Tokyo because the highest

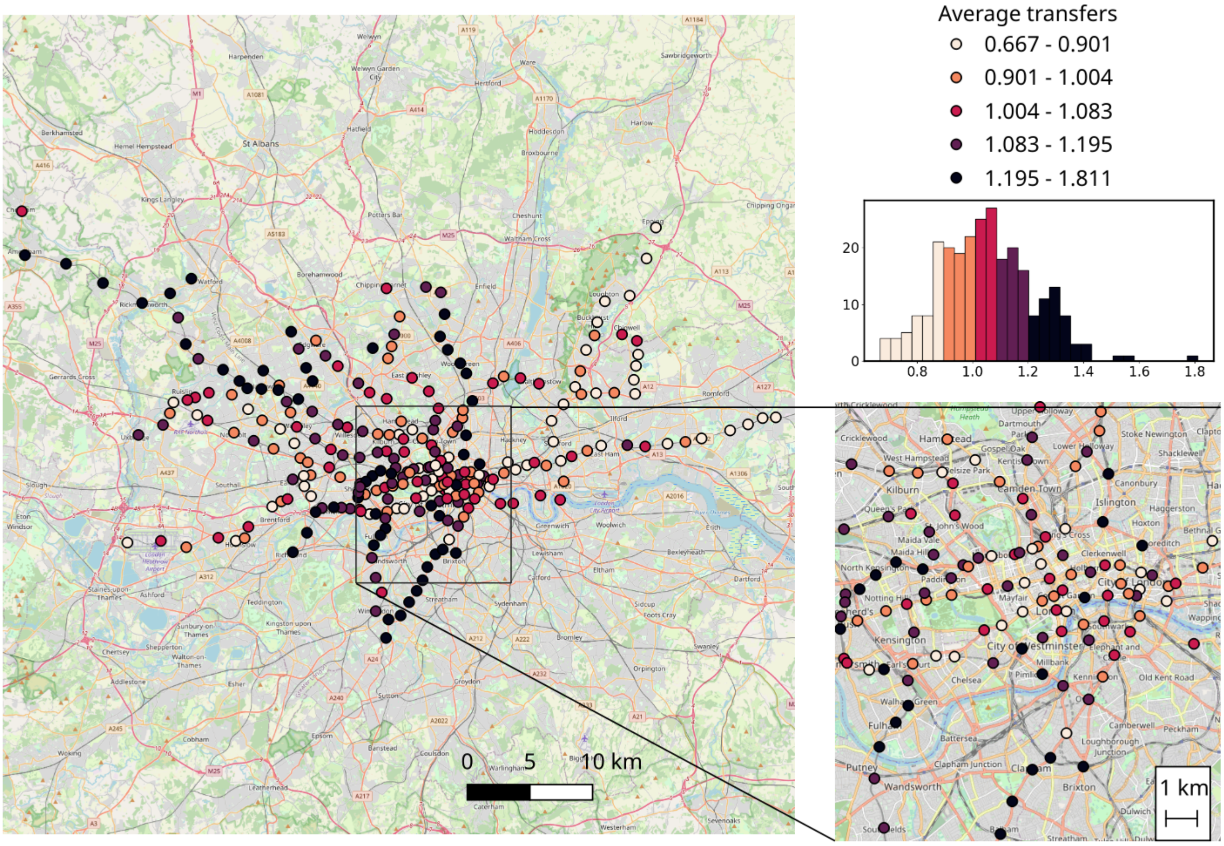

Figure 17: London: Average transfers for every origin station

band in London corresponds to under 2 transfers on average.

4 Conclusion

The aim of this report is to visualize the origin-destination characteristics of railway networks, especially for journeys with interchanges (transfers). It supports existing passenger flow and train frequency data with OD data. It provided numerical evidence for the rail traffic patterns – Tokyo and Shimbashi stations benefited greatly from the Tokaido Main Line in serving southern Tokyo. Nippori and Kita-Senju are key proxies for northeastern Tokyo, while Omiya and Akabane functions as gateways to the north. The Tokyu lines are vital to Shibuya's coverage in southwestern Tokyo.

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