Supplemental Information

Contents. S1 why the northern section, and why Paju (Figure S1). S2 how excess commuting is constructed in two steps, with the numbers of resident workers and jobs in each zone held fixed and then following each month, the benchmark for one origin, how the estimates are tested, the pre-opening trend, and Paju's estimates in both steps. S3 where the added commuting goes: the Gangnam-bound trips (Figure S2) and who is counted. S4 Seoul's subway network over the map of Figure 2B (Figure S3). S5 how the data were accessed and processed.

S1. Why the northern section, and why Paju

- *Why not the southern section.* Dongtan, at the southern end of the line, has had a 14-minute SRT link to Suseo, in Gangnam, since December 2016 (Biz Hankook, 2021), so the GTX-A opening added little new access there. Dongtan also holds 42% of Hwaseong's residents (Hankook Ilbo, 2025), and the open data give Hwaseong as one unit, so a district-level estimate would mix the station's catchment with the majority who live in the rest of the district.
- *Why Paju among the three northern districts.* The Unjeong new town, where the station is, was still growing: the registered residents of its six dong (Korean nationals) grew from 268,416 at the end of 2023 to 286,516 at the end of 2024 and 302,705 at the end of 2025, while Paju as a whole grew from 497,753 to 526,005 (Ministry of the Interior and Safety, 2026). Paju's commuters grew 4.8% in the year before the opening, against a median of 2.2% among the 44 comparison districts.
- *Prior rail.* Before GTX-A, Paju's rail link to Seoul was the Gyeongui-Jungang Line, a conventional railway; the trip from Unjeong to Seoul Station took 46 minutes by that line and 66 minutes by express bus, against 22 minutes by GTX-A (Ministry of Land, Infrastructure and Transport, 2024).
- *The two other districts on the section.* Goyang-Ilsanseo and Goyang-Deogyang already had Line 3 to Seoul (its Ilsan section opened in 1996), and Ilsanseo is a first-generation new town announced in 1989 (Goyang Newspaper, 2019) whose commuters grew 0.4% in the year before the opening.
- *Figure S1* shows where Paju's residents are. In the December 2025 resident registration (Korean nationals), the six dong of Unjeong held 302,705 of Paju's 526,005 residents (58%) on 4% of its area, 11,000 per km² against 340 in the rest of the city, and the GTX-A station lies at their southern edge, on the side facing Seoul (Ministry of the Interior and Safety, 2026).

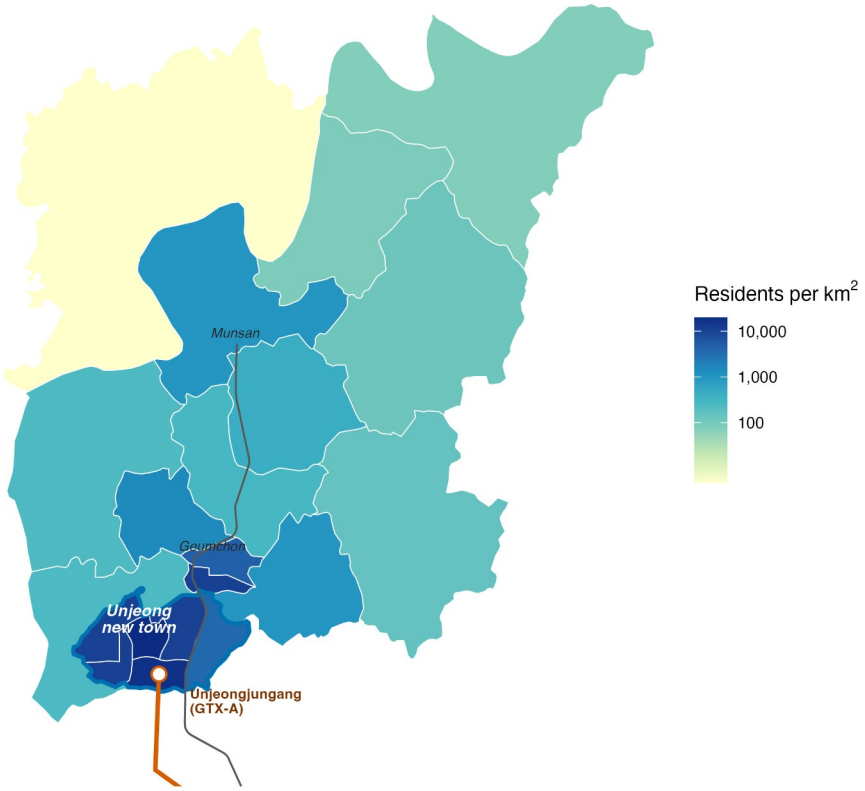


Figure S1. Residents per km² by eup, myeon and dong in Paju, December 2025 (log scale). Blue outline, the six dong of the Unjeong new town; orange, the GTX-A station and line; grey, the Gyeongui-Jungang Line. Source: Ministry of the Interior and Safety (2026), resident registration by administrative dong, accessed 3 September 2026; boundaries from the Seoul Open Data Plaza dong layer.

S2. Construction, inference, and Paju's estimates

Construction

- *Sample.* Each month is represented by one mid-month week: the Tuesday to Thursday of the week whose Wednesday lies closest to the 15th, moved to the neighbouring week when a holiday falls on one of the three days. The panel covers 36 months, January 2023 to December 2025, three days each.
- *Zones.* The zones are the 478 units the open data report: the 426 dong of Seoul and the 52 districts outside Seoul. Boundary changes within the window (Bucheon's split into three gu in 2024 and two reforms of Seoul dong) are harmonized on both the origin and the destination side.
- *The transportation problem.* Excess commuting is measured against the transportation problem (White, 1988), whose row margins O_i are the resident workers of each origin zone and whose column margins D_j are the jobs taken in each destination zone.
- *Step 1: the numbers of resident workers and jobs in each zone held fixed.* O_i and D_j are the means of the twelve pre-opening months, January to December 2024. With pair costs fixed at their 2023 means (distance, and the first time measure) the assignment is solved once, so the minimum commute is a constant for each origin and the excess moves only with that month's observed flows. With actual travel times, those reported for each month (the second time measure), the assignment is re-solved every month with the same margins, so the minimum commute moves only because travel times move.

- *Step 2: the numbers of resident workers and jobs in each zone following each month.* O_i and D_j are each month's own, so that the minimum commute moves with new residents and their workplaces. The estimates of both steps are reported below.
- *Why 2023 for the costs.* No section of GTX had opened in 2023 (the southern section, Suseo to Dongtan, opened on 30 March 2024), so 2023 pair distances and times are free of any effect of the line. The estimates compare the twelve months after the opening, January to December 2025, with the twelve before, January to December 2024; the twelve months of 2023 appear in Figure 1A only to show the trend before the pre-opening year.
- *Distance.* Distance is the mean travel distance the provider reports for each origin–destination cell (field *move_dist* in the data layout, metres; Seoul Metropolitan Government & KT, 2025). It is not a straight-line distance between zone centroids: the reported distance for a fixed pair varies from month to month. Distance costs hold each pair at its 2023 mean reported distance, pairs first appearing later keeping their own mean; the first time measure uses 2023 mean times likewise, and the second uses actual travel times, those reported for each month.
- *Excess.* Excess by origin is the actual mean commute less the minimum commute, per commuter, indexed to that district's own twelve pre-opening months.

The screen

- The minimum commute is a region-wide optimum, so an individual origin's minimum commute can exceed its actual mean commute. Two of the 46 districts without a GTX-A station, Guri and Uiwang, have non-positive pre-opening excess, for which the index to the pre-opening level is undefined; they are screened out beforehand, leaving 44 comparison districts. The screen uses only pre-opening data, gives the same 44 districts in both steps, and all six GTX-A districts have positive pre-opening excess.

The benchmark for one origin

- The assignment minimises total cost over the whole region, and an origin's minimum commute is its share of that solution: the mean cost of the commutes assigned to its resident workers. It is not the lowest mean commute the origin alone could reach, which would let its residents take the nearest jobs regardless of other origins. That own bound cannot exceed the origin's actual mean commute, while the regional share can (the screen above).

- The assignment is solved with the network simplex of the R package transport. We checked every assignment used in the paper, 146 in all (the two fixed-margin assignments, the 36 monthly assignments at actual travel times in the first step, and three per month in the second step): in each, the optimal basis is non-degenerate and every other observed pair has a strictly positive reduced cost, so the optimal assignment is unique and Paju's minimum commute, and its monthly changes, do not depend on which optimal solution the solver returns.

- For distance the two benchmarks coincide for Paju in every month (5.76 km in 2024): jobs in Paju equal 95% of its resident workers, so both put 95% of them within Paju and the rest in the nearest district. For time the regional share exceeds Paju's own bound by 0.9 minutes at 2023 travel times and by about 1 minute at actual travel times, because the nearest jobs outside Paju are taken by other origins in the regional solution. From 2024 to 2025 the regional share rose 1.04 minutes at 2023 travel times in the second step while the own bound rose 0.18.

- With the own bound as the benchmark the estimates are as follows. For distance Paju's benchmark is the same, so its estimates move only through the comparison districts' benchmarks, from +5.89 and +5.32 to +5.75 and +5.34, and remain the largest; at 2023 travel times the second-step estimate turns positive because this benchmark rises less with Paju's growth; at actual travel times excess time still falls in both steps.

Measure, own bound as benchmark	Step 1	Step 2
Excess distance (2023 pair distances)	+5.75 (largest, p = 0.022)	+5.34 (largest, p = 0.022)
Excess time (2023 travel times)	+5.69 (largest, p = 0.022)	+4.18 (second, p = 0.089)
Excess time (actual travel times)	−4.38 (p = 0.20)	−5.18 (p = 0.18)

- In the first step at fixed costs the benchmark is a constant, so it cancels from the change in excess and enters the estimate only through the pre-opening level by which the change is scaled.

How the estimates are tested

- *Intervals.* The monthly gap between Paju's index and the comparison median is serially correlated, so a twelve-versus-twelve t-test understates how much the estimate moves by chance. Intervals are therefore moving-block bootstraps: four-month blocks, 4,000 resamples, drawn within the before and after windows separately.
- *p.* p is the rank of the estimate among all 45 districts, from running the same calculation on every district without a station, against the same opening date, with the remaining districts as its comparison group. It is (1 + the number of districts whose own estimate is at least as large in absolute value) / 45, so its smallest value is 1/45 = 0.022.
- *Percentile and p.* The percentile in the tables is one-sided and signed while p is two-sided and absolute, so equal percentiles need not share a p.
- *Reading a null.* An estimate not distinguishable from the spread of the 45 district estimates is a failure to detect a change, not evidence that none occurred.
- *What each measure answers.* The interval measures how precisely the twelve-month difference is estimated from the month-to-month variation of Paju's gap within each window; it does not allow for a drift of the whole series. p asks whether Paju's estimate is significantly different from those of the districts without a station, on the assumption that without the opening Paju's change would have come from the same distribution as theirs.

The pre-opening trend and an earlier opening date

- *The threat.* A difference of differences is compromised if Paju's gap from the comparison median was already widening before the opening. Over the twelve pre-opening months the gap in excess distance rises 0.37 points per month (SE 0.14, p = 0.023); a quarter of the comparison districts trend more steeply in absolute value. The drift comes mostly from the comparison side: the comparison median index falls from 102.6 in January 2024 to 98.4 in December 2024, while Paju's index moves from 100.4 to 100.8 and stays between 97 and 103 all year.
- *An earlier opening date finds nothing.* Dating the opening twelve months early, January 2024 in place of January 2025, with a twelve-month after window that ends before the real opening, gives +1.81 points, at the 71st percentile of the district distribution (p = 0.47).
- *A later pre-opening level keeps the estimate.* Taking the gap's mean over the last six pre-opening months, instead of over all twelve, as the pre-opening level, while the index stays scaled to the full pre-opening year, removes the within-2024 drift without extrapolating it and gives +5.06 points; this is still the largest of the 45 districts (p = 0.022).
- *Extrapolating the drift removes most of it.* Subtracting the pre-opening regression line projected across the post-opening year gives +1.49 points, 25% of the raw +5.89; on the same calculation this is tenth of the 45 districts (p = 0.58). That projection assumes the gap would have kept rising at 0.37 points a month for another year.
- *A longer window gives a smaller drift.* Over the twenty-four pre-opening months, 2023 and 2024, the gap rises 0.10 points a month (SE 0.06, p = 0.11); subtracting that line projected across the post-opening year leaves +4.92 points, 83% of the raw +5.89; on the same calculation this is

the largest of the 45 districts (p = 0.067). In the second step the gap's own drifts are 0.22 points a month over the twelve months (SE 0.13, p = 0.11) and 0.06 over the twenty-four (SE 0.05, p = 0.31); projecting them leaves +2.62 points with the twelve-month drift (seventh of 45, p = 0.51) and +4.96 with the twenty-four-month drift (third, p = 0.13). The twelve-month drift comes from the comparison side: the comparison median index fell 0.34 points a month in 2024 and 0.27 in 2025, while Paju's index was flat in 2024 (+0.03 a month) and rose 0.53 a month in 2025.

- *Reading.* The earlier opening date and the later pre-opening level do not show the rise as a continuation of the pre-opening year, but neither shows what the gap would have done without the opening. The estimate is a post-opening association whose size depends on the trend assumed for the counterfactual: in the first step 1.5 points if the twelve-month drift is projected through 2025, 4.9 if the twenty-four-month drift is, and 5.9 if none is; in the second step 2.6, 5.0 and 5.3.

The two time measures

- At 2023 travel times, excess time rises with excess distance (+6.16 points, which is the largest of the 45 districts) because the destinations Paju's commuters added are farther in time as well as in distance.
- At actual travel times, excess time falls (−8.58 points, 42nd of 45, p = 0.27). Paju's actual commute time rose 1.2 minutes, from 41.0 to 42.2 (+2.22 points against the comparison median, p = 0.24), while its minimum commute at actual travel times rose 2.6 minutes, from 28.0 to 30.6, because trips within Paju became slower; so the excess fell.

Paju's estimates before rounding. Change is Paju's own change less the comparison median's, in points of the pre-opening level; intervals are moving-block bootstraps (four-month blocks, 4,000 resamples) where computed; percentile and p are the estimate's rank among all 45 districts.

Step 1: the numbers of resident workers and jobs in each zone held at their 2024 means.

Measure	Change	95% interval	Percentile / p
Excess distance (2023 pair distances)	+5.89	+2.28, +8.88	100 / 0.022
Excess time (2023 travel times)	+6.16	+2.30, +9.33	100 / 0.022
Excess time (actual travel times)	-8.58	-12.06, -7.36	7 / 0.267
Actual commute distance	+2.93	-	100 / 0.022
Minimum distance	+0.00	-	0 / 1.000
Actual commute time	+2.22	-0.96, +5.17	80 / 0.244
Minimum time (actual travel times)	+6.12	-	91 / 0.200
Commuters	+1.84	-	73 / 0.444
90th-percentile distance	+0.94	-	91 / 0.311

Step 2: the numbers of resident workers and jobs in each zone following each month.

Measure	Change	95% interval	Percentile / p
Excess distance (2023 pair distances)	+5.32	+2.39, +7.70	100 / 0.044
Excess time (2023 travel times)	-3.16	-7.15, +2.92	18 / 0.400
Excess time (actual travel times)	-16.62	-24.02, -10.55	2 / 0.178
Actual commute distance	+2.93	-	100 / 0.022
Minimum distance	+0.42	-	70 / 0.622
Actual commute time	+2.22	-0.96, +5.17	80 / 0.244
Minimum time (actual travel times)	+9.88	-	100 / 0.089
Commuters	+1.84	-	73 / 0.444
90th-percentile distance	+0.94	-	91 / 0.311

The two steps read together.

- In the first step the excess moves only with where commuters work; in the second the minimum commute also follows new residents and their workplaces. The difference between the two estimates is what new residents and their workplaces did to the minimum commute: it shows how sensitive the estimate is to the margins of the benchmark, not what their own commutes added, which are in the actual mean commute in both steps.
- For distance the difference is small: Paju's minimum commute rose 17 metres from 2024 to 2025, against a comparison median of −2 metres, and the estimate falls from +5.89 to +5.32.
- For time at 2023 travel times the difference is large: Paju's minimum commute rose 1.04 minutes (3.5%), against a comparison median of 0.00, the third largest rise of 45, because Paju's resident workers grew faster than its jobs, and the estimate falls from +6.16 to −3.16.
- In both steps the actual mean commute includes the commutes of new residents, so the first step measures the change in where commuters work, whoever they are; the data cannot separate movers from stayers (S3, Who is counted).

S3. Where the added commuting goes

The Gangnam-bound trips

- Growth in Paju's commuting was fastest toward the dong within 3 km of Samseong or Suseo station, in Gangnam, which GTX-A does not yet reach directly from Paju; from Seoul Station, Samseong is one transfer away (Line 4, then Line 2) and Suseo one transfer away (Line 4, then Line 3). In the table, the first three numeric columns are commuters to those dong over the three sampled weekdays of a month, averaged over 2024 and over 2025, and their change; the last three are the provider's reported mean travel time to those dong in minutes.

- Three checks show that this growth is specific to Paju and begins at the opening, rather than being part of a general growth of Gangnam.
- *First, the same destinations did not draw more commuters from elsewhere.* The 44 comparison districts' commuting to those dong grew 2.3% pooled (median 1.7%) against Paju's 19.1%, and Goyang-Ilsanseo, which has had Line 3 to Gangnam since 1996, grew 0.9%. Among the 35 of the 45 districts that sent at least 2,000 commuters there over the three sampled weekdays (about 700 a day) in 2024, Paju's growth is the largest.
- *Second, the growth starts at the opening.* Paju's index of commuters to those dong (2024 = 100) stays within 94 to 107 through 2023 and 2024 and rises to 112 in the first half of 2025 and 126 in the second, while the comparison districts average 105 and 100 over the two halves and Ilsanseo 105 and 97. The comparison and Ilsanseo series rise to about 115 in March and April 2025 and return to 100 in May (Figure S2A).
- *Third, the trips became faster.* The provider's reported mean travel time from Paju to those dong fell 7.1 minutes, from 118.9 to 111.8, against 0.3 minutes from the comparison districts and 2.7 from Ilsanseo (Figure S2B), as a first leg by GTX-A would produce; the data do not record route or mode.

Origin	2024	2025	Change (%)	2024	2025	Change (min)
Paju	4,054	4,829	+19.1	118.9	111.8	-7.1
Goyang-Ilsanseo (Line 3 to Gangnam already)	4,983	5,028	+0.9	109.8	107.1	-2.7
Goyang-Deogyang	14,143	14,105	-0.3	92.3	91.2	-1.0
44 comparison districts, pooled	392,946	402,108	+2.3	75.7	75.4	-0.3

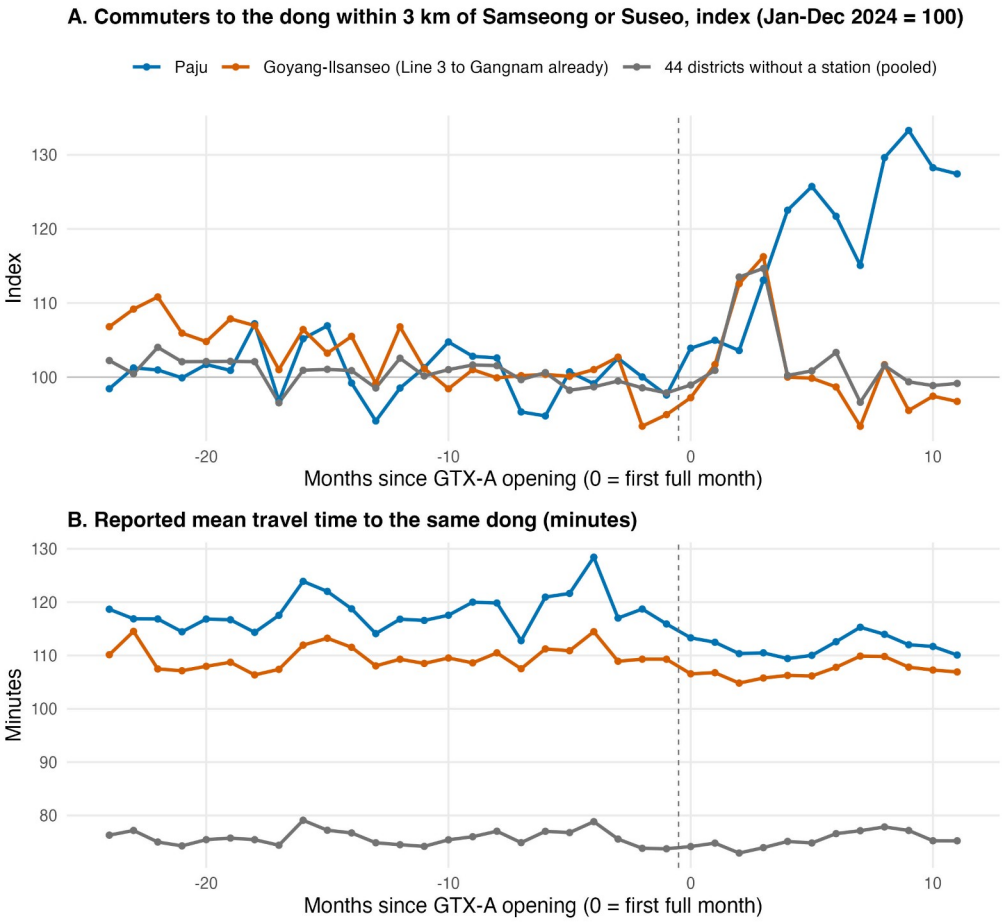


Figure S2. Paju's commuting to the dong within 3 km of Samseong or Suseo, by month. (A) Commuters over the three sampled weekdays of each month, index with January to December 2024 = 100, for Paju, Goyang-Ilsanseo and the 44 comparison districts pooled. (B) The provider's reported mean travel time to the same dong, minutes. Dashed line, the opening; representative mid-month weeks.

Who is counted

- The excess commuting index is a property of a place, not of a person: the data are monthly cross-sections of flows, not a panel of individuals, so a rise in a district's mean commute can come from existing residents travelling to farther jobs or from a change in who lives there. Four calculations bear on the second reading.
- *The district was not filling faster.* The six dong of Unjeong added 18,100 registered residents in 2024 and 16,189 in 2025 (Ministry of the Interior and Safety, 2026), and Paju's commuters grew 4.8% over the twelve months before the opening and 4.2% over the twelve after, the post-opening growth not distinguishable from the comparison districts (+1.84 points, $p = 0.44$). Excess distance rose 0.6% in 2024 and 4.6% in 2025 (annual means of the first step).
- *The shift is at the margin.* Paju's commuting grew by 16,782 trips over the three sampled weekdays of a month (about 5,600 a day) between the twelve months before the opening and the twelve after, and 31.9% of that net addition was Seoul-bound against 14.0% of the commuting already there; the comparison districts run the other way, 12.6% against a standing 18.4%.
- *Holding the numbers of resident workers and jobs in each zone at their post-opening levels gives the same answer.* With the margins fixed at their 2025 means instead of 2024, the estimate is +5.90 points for excess distance and +6.53 for excess time at 2023 travel times, both the largest

of the 45 districts; new residents and their workplaces do not produce the estimate through the minimum commute.

- *What this cannot show.* The same arithmetic would arise if existing residents took Seoul jobs while an equal number of locally working households moved in; the net addition is a residual between counts, not a set of identified people. The data cannot separate residential sorting from job switching, and the opening cannot be separated from the housing occupied around the station in the same months.

S4. Seoul's subway network

- Figure S3 puts Seoul's subway lines over the change in Paju's commuting arrivals within Seoul (the surface of Figure 2B, January to December 2025 against the twelve months before, total commuting held constant). The parts of Gangnam that grew fastest were already reachable by rail from the northern section's end at Seoul Station before the middle section, Seoul Station to Suseo, opens.

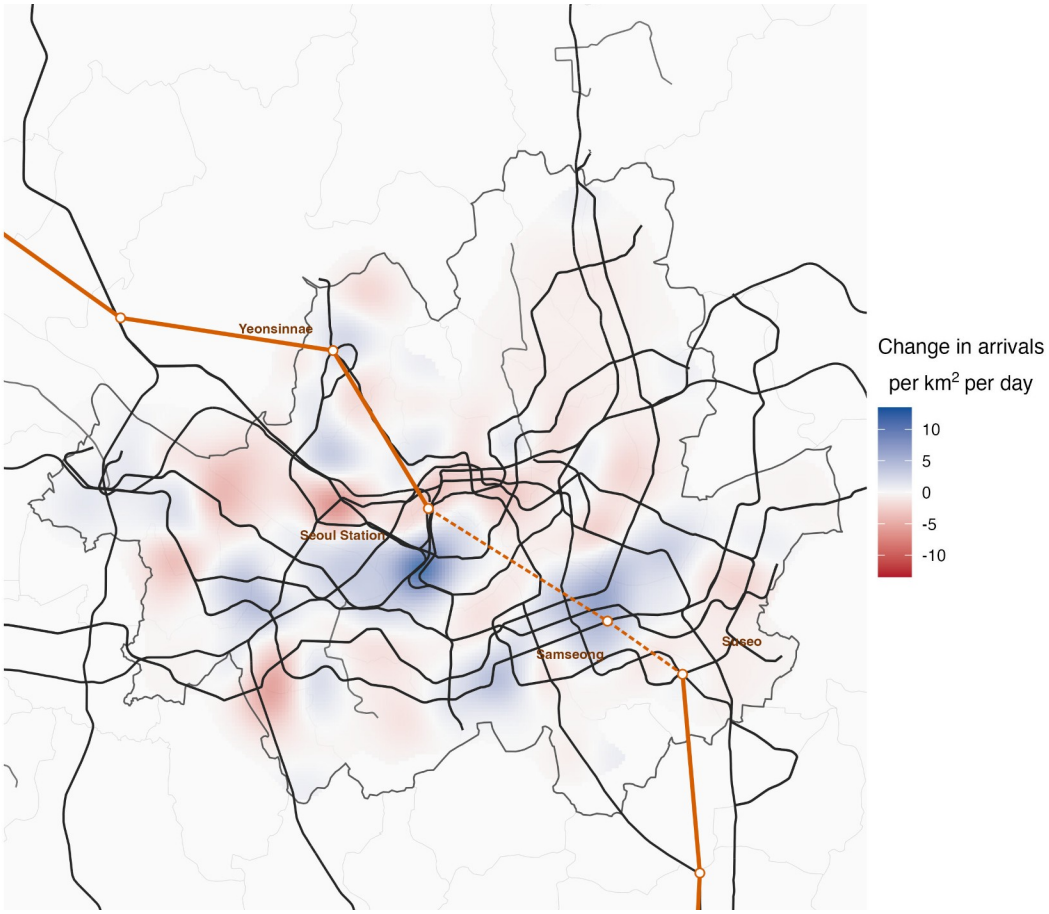


Figure S3. Seoul's subway network over the change in Paju's commuting arrivals within Seoul. Dark lines, Lines 1 to 9, the light-rail lines, and the Gyeongui-Jungang, Gyeongchun, Suin-Bundang, Seohae, Shinbundang and Airport Railroad lines (OpenStreetMap, accessed 24 August and 2 September 2026); other railway lines are not drawn. Orange, GTX-A, dotted where not yet open; circles, GTX-A stations. Surface as in Figure 2B of the main text.

S5. Data access and processing

- *Source.* The mobility data are the Seoul Metropolitan Government's open data "Seoul capital region de facto population mobility (origin–destination)", dataset OA-22300 on the Seoul Open

Data Plaza, one file per day from 1 January 2023, under the Korea Open Government License type 1 (attribution). Each row gives origin zone, destination zone, departure and destination hours, nationality group, trip purpose, mean distance in metres, mean time in minutes, and an estimated number of people weighted to the resident population by sex and age.

- *Selection.* We keep trips with purpose "work" made by Korean nationals between zones of the capital region (Seoul, Incheon and Gyeonggi) on the Tuesday, Wednesday and Thursday of one week a month: the week whose Wednesday lies closest to the 15th, moved to the neighbouring week when a holiday falls on one of the three days. The 108 sampled days, January 2023 to December 2025, and the 18 days of January to June 2026 that enter only the pair costs described below, are listed in the script.
- *Zones.* The 478 zones are Seoul's 426 dong and the 52 districts outside Seoul. Boundary changes are harmonized on both the origin and the destination side: within the window, Bucheon's three gu to one district and two Seoul dong reforms; in the 2026 files read for the pair costs, Hwaseong's four gu to one district.
- *Cells.* The provider reports estimated counts with decimals, and absent cells are treated as zero; the smallest count for a pair of zones on a day is 1.0. For each pair of zones and month, commuters are summed over the three sampled days, and the pair's distance and time are the commuter-weighted means of the reported cell means; in 2024, monthly pair counts below 3 are 3.9% of pairs and 0.06% of commuters. Within-zone commutes are the cells whose origin and destination coincide, with the provider's reported distance and time; for Paju they are 62% of its commuters, 5.73 km and 29.0 minutes in 2023.
- *Costs.* Pair distances and 2023 travel times are the commuter-weighted means over the twelve months of 2023. Of the 216,510 pairs seen in 2024 and 2025, 15,821 (7%) do not appear in 2023; they carry 0.06% of commuters in 2024 and 0.10% in 2025, none from Paju and at most 0.33% from any of the 45 districts. Their cost is the mean over the months in which they appear, through June 2026. In the first step at actual travel times, a pair of the fixed 2024 assignment that is not observed in a month takes its commuter-weighted mean time over the months in which it appears, through June 2026. Giving the pairs first seen in 2024 their pre-opening mean instead, with the pairs first seen in 2025 kept at the current rule, or dropping all of them, leaves the distance estimates within 0.01 points and the time estimates within 0.7 points of those reported, with the same ranks for distance and the same conclusions.
- *Software.* R with the packages data.table, transport (network simplex), ggplot2, patchwork, ggrepel and jsonlite. One script downloads the sampled days and reproduces every result computed from the mobility data in the main text and in this supplement, and Figure 1 and Figure S2 (https://github.com/knugislee1/gtx-excess-commuting); the map figures (Figure 2, S1 and S3) are drawn with separate scripts that need boundary and OpenStreetMap files, Figure 2B and Figure S3 from every Tuesday to Thursday outside holidays and Figure S1 from resident registration, and are available on request.

References cited in the Supplemental Information

Biz Hankook. (2021, February 23). *Dongtan–Suseo SRT tonggeun wol 30-man won… GTX yogeum bissajilkka beolsseobuteo uryeo* [Dongtan–Suseo SRT commuting at 300,000 won a month: worries that GTX fares will be high]. http://bizhankook.com/articles/21442.html

Goyang Newspaper. (2019, June 10). *(1-gi sindosi balpyo hu 30-nyeon-ui byeonhwa) Goyang-si hanhae sallim, 1991-nyeon 3600-eok → 2019-nyeon 2-jo 3000-eok* [(Thirty years of change since the first-generation new towns were announced) Goyang's annual budget, 360 billion won in 1991 to 2.3 trillion won in 2019]. https://www.mygoyang.com/news/articleView.html?idxno=51176

Hankook Ilbo. (2025, August 24). *Ingu 42-man myeong Dongtan-gu sinseol, Gyeonggi Hwaseong-si 4-gae gu chejero* [Dongtan-gu with 420,000 residents created; Hwaseong to have four gu]. https://www.hankookilbo.com/news/article/A2025082408260002063

Ministry of Land, Infrastructure and Transport. (2024, December 27). *Paju–Seoul chultoegeun 20-bundae, GTX-A Unjeongjungang–Seoul-yeok 28-il gaetong* [Paju–Seoul commutes in the twenties of minutes: GTX-A Unjeongjungang–Seoul Station section opens on the 28th] [Press release]. Korea Policy Briefing. https://www.korea.kr/docViewer/result/2024.12/27/3da94f6a4edfbc71814cfee14e3016fd/3da94f6a4edfbc71814cfee14e3016fd.view.xhtml

Ministry of the Interior and Safety. (2026). *Haengjeongdongbyeol jumin deungnok ingu mit sedae hyeonhwang* [Resident registration population and households by administrative dong] [Statistics portal]. https://jumin.mois.go.kr/

Seoul Metropolitan Government & KT. (2025). *Sudogwon saenghwal idong deiteo maenyueol* [De facto population mobility data manual for the Seoul metropolitan area]. Seoul Open Data Plaza. https://data.seoul.go.kr/dataList/OA-22300/F/1/datasetView.do

White, M. J. (1988). Urban commuting journeys are not “wasteful”. *Journal of Political Economy, 96*(5), 1097-1110. https://doi.org/10.1086/261579