Residential proximity to transport facilities as urban determinants of individual-level per- and poly-fluoroalkyl substance (PFAS) exposures: Analysis of two longitudinal cohorts in Singapore

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Summary

Background The spatial determinants of human exposures to Perfluoroalkyl Substances (PFAS), a broad class of persistent environmental contaminants affecting pregnancy and early childhood development, amenable to policy are poorly understood because of the diversity of potential sources of exposure. This is especially true for modern, dense urban settings, which contain numerous built environment- and behavioral-related inputs (e.g., road traffic, run-off, wastewater, etc.) but few high-profile sources (e.g., manufacturing, agriculture, military).

Methods We quantify exposure based on residential proximity to transport facilities and its parcel size and evaluate the association of exposure with plasma PFAS concentrations analyzed in human blood from two geographically- and demographically- diverse cohorts of pregnant women in urban Singapore (n = 784 aged 19–47 in 2009–2011 and n = 384 aged 18-45 in 2015–2017). To rule out behavioral confounding, we exploit future residential addresses among individuals who moved (negative control exposures). Transport facilities were ground-truthed through automated extraction of Google streetview data.

Findings Adjusting for known predictors, within-neighborhood and unobserved spatial heterogeneity, a standard deviation (SD) increase in transport facility exposure (approximately 10,000m^2) is linked to 0.12, 0.17, 0.11 SD increases in residents' perfluorobutane sulfonic acid (PFBS), perfluorobutanoic acid (PFBA), and perfluorononanoic acid (PFNA) concentrations, respectively in the 2009 cohort. We found similar positive associations in the more recent 2015 cohort.

Interpretations Transport facilities are prevalent near residences in urban settings and may be potential sources of PFAS emissions due to their presence in automotive-related lubricants, parts, and materials. Our findings that exposure was robustly related to individual-level concentration over and above behavioral and other factors highlight the importance of monitoring these and other urban sources of exposure.

Key words and phrases PFAS, built environment, biomarkers, environmental epidemiology, Singapore, GUSTO, geospatial

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1 Introduction

Per- and poly-fluoroalkyl substances (PFAS) include thousands of chemically stable and highly persistent substances used in consumer products and industrial applications,[1] with a long trail of studies suggesting adverse health effects.[2,3] For pregnant mothers, higher PFAS exposure is associated with lower fertility.[4] Prenatal exposure to PFAS (and other persistent organic pollutants) is adversely linked to maternal thyroid functioning.[5] In children, PFAS is linked to airway and respiratory infections,[6,7] emotional-behavioral problems,[8] and cognitive performance.[9] Newborns with in-utero exposure to perfluorooctanoic acid (PFOA) have lower birth weight.[10–12]

Despite the known adverse effects of PFAS in general,[2,3,13] PFAS have essential functions in industrial uses and consumer products, making a blanket ban impractical.[1] Consequently, outside of populations with known occupational exposures,[14,15] PFAS has also been detected in the general population (including mothers and children) across different contexts with less known exposure sources.[4,8,9,16–23]

Many studies on PFAS exposure come from environmental samples taken near water or wastewater,[24–34] and industrial sites.[24–27,29,35] Few studies focus on urban and non-industrial areas,[30] even though significantly higher PFAS has been found in urban areas.[27] Studies with human samples in highly urban contexts are far fewer. Barton et al. (2020) found higher serum PFAS concentrations in adults near affected water districts linked to aqueous film-forming foams from a nearby Air Force base.[36] Across US states, Sun et al. (2018) found higher plasma PFAS in participants living in inland states (as opposed to coastal states).[15]

In urban environments, transport facilities (e.g., transit depots and petrol stations) are of potential concern because of the PFAS burden from industrial-related activities and automotive products. Glüge et al. (2020) identify 12 use categories of PFAS in automotive products and applications (car bodies, automotive waxes, windshield wiper fluid, engine and steering systems, engine oil coolers, cylinder head coatings and hoses, electronics, fuel lines, steel hydraulic brake tubes, interior components, and brake pad additives).[1] These use categories are more than any other known industrial branch (such as the chemical or semiconductor industries).[1] A related industrial use is the oil and gas industry, where PFAS are used for oil and gas transportation, oil and gas storage, oil containment, and oil and fuel filtration.[1] These industrial usages are typically used in liquid form. However, there is a growing appreciation for the fact that these PFAS are present in the atmosphere, including gases, aerosols, and particulate matter,[37–39] including in urban areas.[40–47] In particular, PFAS has been detected in air samples near high-profile sites with PFAS contamination.[43,48–51]

This article, therefore, evaluates transport facilities as a potential point source of PFAS exposure in pregnant women drawn from a general population. We use a population- and geographically-representative cohort, which measures plasma PFAS concentrations in pregnant women near recruitment and birth (2009–2011). The context is Singapore, a densely built city with fairly concentrated PFAS measures.[20,31,52] Regulatory buffers mean that the known sources of exposure (e.g., heavy industrial zones) locate far from residential areas (Figure A1). On the other hand, transport facilities have high PFAS industrial usage but are non-regulated and typically located near residences. Our objective is to systematically investigate the extent to which within-neighborhood spatial proximity to transport facilities based on residence is linked to the PFAS concentrations from our human samples.

2 Methods

2.1 Study population

The study population includes pregnant women from the longitudinal cohort study "Growing Up in Singapore Towards healthy Outcomes" (GUSTO). Families undergoing first-trimester antenatal dating ultrasound scanning in two hospitals were invited to participate in the study, which aimed to understand pregnancy conditions and early childhood development. In total, 1450 women at 7–11 weeks of pregnancy were recruited into the study between June 2009 and October 2010. The participants are otherwise ethnically diverse and are located across all major areas of Singapore city (Appendix AA).[20] The age at delivery of women, near the time of blood collection, is 19–47 years old.[53] We map residences to administrative areas and correlate the recruited participants to the 2010 census count of the adult female population aged 20–49 across neighborhoods ($r = .89$, $p < .001$, $n = 166$ neighborhoods). We also compute correlation at the broader planning area level ($r = .92$, $p < .001$, $n = 33$ planning areas; see Appendix AA), confirming that the cohort is geographically representative.

2.2 PFAS measurements

Part of the inclusion criteria for GUSTO includes the willingness to donate cord blood. Our human measures of PFAS come from the analyses of these cord blood samples that reflect neonatal exposure. In total, GUSTO analyzed PFAS samples for 784 participants. Out of the PFAS measurements, eight had concentrations above limits of detection (LOD) and limits of quantification (LOQ) for at least 95% of participants (Table A1). We subsequently include these eight PFAS measurements in our analyses. These eight PFAS [LOD–LOQ] are: perfluorobutane sulfonic acid (PFBS) [0.078–5 ng/ml], perfluorobutanoic acid (PFBA) [0.41–0.5 ng/ml], perfluorononanoic acid (PFNA) [0.016–0.1 ng/ml], perfluorooctanoic acid (PFOA) [0.009–0.1 ng/ml], perfluorooctane sulfonic acid (PFOS) [0.027–0.1 ng/ml], perfluorohexane sulfonic acid (PFHxS) [0.024–0.1 ng/ml], perfluoroundecanoic acid (PFUnDA) [0.011–0.1 ng/ml], and perfluorodecanoic acid (PFDA) [0.01–0.1 ng/ml]. Other PFAS measurements are excluded because of low detection rates. The first two, PFBS and PFBA, are considered shorter-chained 4-carbon PFAS replacements for legacy PFAS, such as the 8-carbon PFOA and PFOA.[2] For the eight included PFAS measures that fall outside the limits of detection or limits of quantification (Table A1), we substitute values based on the corresponding limiting values, as is common.[4,54]

2.3 Residential exposure to transport facilities

Figure 1 illustrates how we quantify residential exposure to transport facilities for a given residential point. We first create concentric circles around the point location of residences based on a certain radius, such as a 500m radius (approximately 1,750 feet). We

Figure 1. Quantifying residential exposure to transport facilities. Residential exposure to transport facilities is computed based on the area of transport facilities parcels intersecting with the concentric circle (500-meter radius) within 500m (approximately 1,640 feet) of the residence. The footprint of the transport facility outside the circle is not counted. Illustration based on a family in the cohort data.

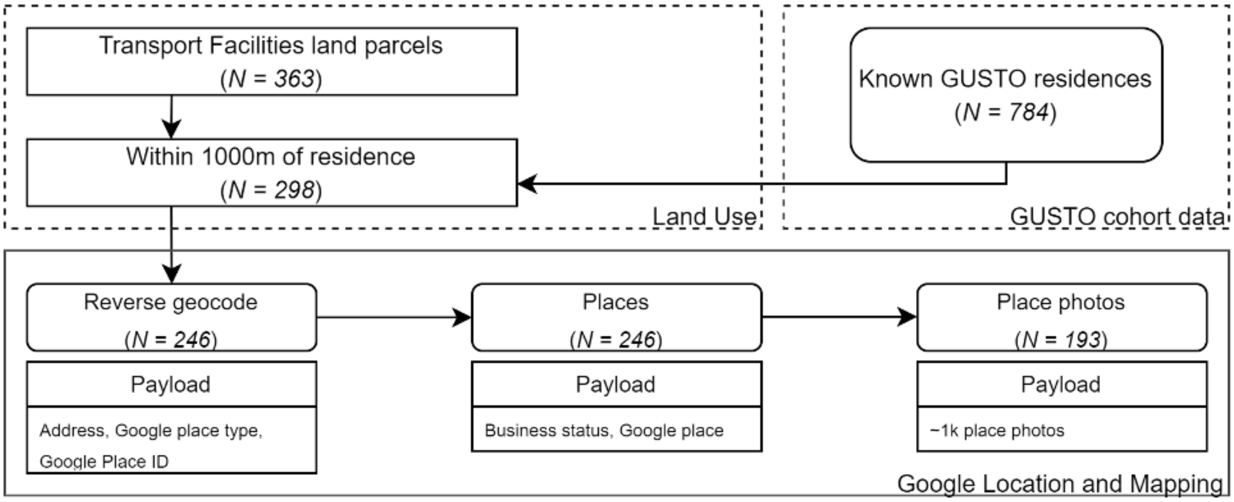
then overlay the concentric circles with the land parcels assigned to transport facilities. The exposure measure is the area of transport facilities within the circle (shaded red in Figure 1). The larger this area is, the higher the measure. We also compute and extend our analyses to alternative radiuses and years for the sensitivity analyses.

2.4 Auditing land parcels for transport facilities

Figure 2 illustrates how we improve interpretation and construct validity by curating street-level public-contributed images. Using the geo-referenced land parcels, we query the Place API using the Place ID before finally querying the Photos API to obtain the street images of the relevant transport facility parcels. We then manually scan all images. From this approach, most transport facilities appear to be petrol kiosks/gas stations and larger transport depots (e.g., bus depot in Figure 2). Appendix B provides more details.

2.5 Maternal baselines

The GUSTO cohort collected demographic characteristics from interviews, which we use to adjust for known predictors of PFAS measurement. These include age at delivery,[36,55,56]



(a) Geocoding land use parcels and retrieving place photos

(b) Woodlands Bus Depot

Figure 2. Auditing land parcels for transport facility land use. Panel A shows a schematic representation of geo-referenced parcels used to obtain street-level photos of the location. Panel B shows an example of a large transport depot (with residential buildings in the backdrop).

place of birth/legacy effects,[18,20,21] ethnicity (Chinese, Malay, Indian, or Others/Mixed),[18,20,36,55,57] education,[17,20,55] occupation,[14,18,36,58,59] and socioeconomic baselines such as housing type, marital status, maternal monthly income, and household monthly income (see also Appendix AA).[60,61]

2.6 Supplementary data

To map participants to areas, we use the 2008 publicly available data on administrative borders (in increasingly fine-grained levels—regions, planning areas, and subzones). We also supplement our analyses using commute time data to construct alternative spatial instruments of exposure (more details on travel time in Appendix D). The analyses with future residences use the 2019 versions of administrative borders and land use (Appendix E). The 2008 version of land use aligns more closely with residences at the time of recruitment, while the 2019 version aligns more closely with future residences (see Section 2.9).

Our replication study uses a separate younger cohort in Singapore, and these use the 2014 versions of administrative borders and land use (more details in Appendix F).

2.7 Descriptives and summary statistics

For basic statistics, we compute the total number, land area, and percentage of land cover across the three plans (2008, 2014, 2019). We map land zones to postal codes to compute the percentage of certain land types near given points of location. To better characterize land use around residential spaces, we also restrict these computations to known public and geocoded buildings (around 10k postal codes and close to 80% of the resident population). Euclidean distance between residences and land parcels is computed both point-to-edge and point-to-centroid. For PFAS measurements, we also compute summary statistics, including quantile categories. Where relevant, we point to visual patterns using spatial plots of residences and transport facilities.

2.8 Statistical analyses

The estimand of interest is how exposure to transport facilities (Section 2.3), by total surface area within 500 meters of residence occupied by transport facilities, is linked to PFAS concentration. Our outcome measures are plasma PFAS measurements from cord blood, which passes through to fetuses. We model the relationship between the plasma PFAS concentrations and exposure to transport facilities by fitting a series of multivariable regression models that adjust for variation in PFAS originating from maternal characteristics and unobserved and time-invariant spatial heterogeneities. The model we estimate is of the form:

$$\text{PFAS}_{ic} = \beta(\text{Exposure to transport facilities})_{ic} + \gamma X_i + \delta_c(\text{administrative area})_c + \varepsilon_{ic} \quad (1)$$

where PFAS measure varies by individual i and the administrative area c. The assumption is that PFAS can be found beyond immediate source sites but has relatively quick decay in exposure past a certain radius.[21,30] X_i is the vector of controls for observed maternal characteristics described in Section 2.5 so PFAS can vary by known predictors of PFAS such as age, ethnicity, education level, and socioeconomic status. Equation (1) adjusts for various levels of administrative areas (details below).

Model 1 is unadjusted (setting $\gamma = 0$, $\delta_c = 0$). Model 2 adjusts for the maternal baselines (setting $\gamma \neq 0$, $\delta_c = 0$). Models 3–5 subsequently adjust for the geographical units (setting $\gamma \neq 0$, $\delta_c \neq 0$) in increasingly fined-grained order: regions (n = 5, see Figure A2), planning areas (n = 32), and subzones (n = 147, hereon *neighborhoods*, see Figure 3). For example, adjusting for the neighborhood unit allows all participants in the same unit to have a constant effect, accounting for differences between neighborhoods, such as drinking water sources or proximity to coasts and water catchments.[15,31,36]

Models 1–4 do not account for neighborhood-level heterogeneities. Model 5 adjusts for neighborhood-level heterogeneities and captures within-neighborhood effects (please see Appendix AA for an example of confounding without this adjustment). Standard errors are clustered at the planning area level to allow for correlation in exposure within towns (especially considering that the planning area delineation heavily informs urban planning).

We focus on PFBS as the unregulated shorter 4-carbon PFAS industrial replacement of the longer-chained legacy PFAS with growing data points raising health concerns (Appendix AB).[2,62–65] Besides having good data coverage (Table A1), PFBS is also known to have high concentrations in the region and can remobilize into the air. From analyses of environmental samples collected from the same city, and likely reflecting industrial shifts to the shorter-chain PFAS, PFBS (followed by PFBA) has the highest concentration,[31] and is one of the most frequently detected PFAS in different matrices with concentrations up to 100 times those reported in other cities.[52,66] A study in the region also reports PFBS as the most concentrated PFSA (perfluorosulfonic acids) in air samples,[49] and air samples from nine Asian cities (albeit excluding Singapore) indicate a relative affinity of PFBS to be aerosolized into fine particulate matter.[52,67] We later extend our evaluations to other PFAS.

2.8.1 Secondary model

A secondary model allows for a stepped effect in exposure to transport facilities. This model is motivated by three pieces of evidence: i) where we see two main types of transport facilities (Section 2.4), gas stations and transport depots, with large differences in footprint; ii) where a standard deviation increase in exposure is larger than the areal footprint of a typical gas station (Table A3), and iii) from detected influential points around a large transport depot (later in Figure 4). Therefore, we use a secondary model as an open-ended investigation, using indicators for various thresholds of the total area of transport facilities:

$$\text{PFAS}_{ic} = \beta^{(t)} \mathbb{1}\{\text{Exposure to transport facilities} > t\}_{ic} + \gamma X_i + \delta_c (\text{administrative area})_c + \varepsilon_{ic}, \tag{2}$$

for a range of t values (0 to 20,000m^2, in steps of 2,000m^2). Adjustments are otherwise similar to Equation (1).

2.9 Sensitivity analyses

2.9.1 Model specifications

We perform an assortment of sensitivity analyses to ground our non-experimental estimates. First, we include an additional Model 6, which is Model 5 with additional adjustments for income with a smaller sample size (Appendix AB).[60,61] Second, we perform tests to detect influential points using a jackknife approach at the individual level and separately for planning areas and neighborhoods, where participants of an entire area are excluded in each iteration (Appendix AB). Third, in Appendix C, we systematically rule out other geographical variations in transport facilities as simply capturing other land use types (Figure C25). Fourth, we consider and rule out other spatial instruments related to our main spatial instrument (defined in Section 2.3) but should otherwise have no association with PFAS levels (Appendix D).

2.9.2 Negative control exposure

As a falsification test, we exploit the trail of participant residences and compute their future exposure to transport facilities using their future addresses (approximately ten years later). The concern is that some unmeasured family-level characteristics related to PFAS exposure also systematically place families near areas with certain spatial properties (e.g., near edges of neighborhoods or near arterial roads) that happen to be where transport facilities are located. In Appendix E, we test if future exposure can predict past plasma concentrations among the subset of participants who have since moved to a different location.

2.9.3 Replication study

Finally, we use a different set of 384 participants (aged 18–45 at recruitment) in the same context from a more recent 2015 Singapore cohort—the S-PRESTO study—as a replication study.[4,68] This cohort is suitable for replication as (i) it also analyzed plasma PFAS measurements from blood samples collected at recruitment and collected basic maternal demographics, and (ii) it allows us to construct the exposure measure the same way using the 2014 transport facilities data. Models are as defined in Equation (1) in Section 2.8 to similarly allow exposure to transport facilities to be associated with PFAS measurements in this cohort. The substantial value of this replication is that it allows us to examine whether our general findings can be replicated at a different time point. More details in Appendix FB.

3 Results

From the PFBS measurements, the median (IQR) is 18.2 (13.28–28.97) ng/ml, and the mean is 24.16 (standard deviation (SD) 15.93) ng/ml (Table A1). These numbers are higher than human samples in other studies, which find a mean of 0.070 ng/ml in US adults,[69] and a median of 0.035 ng/ml in women with GDM in the Shanghai cohort.[54] However, our measurements are consistent with other studies of human and environmen-

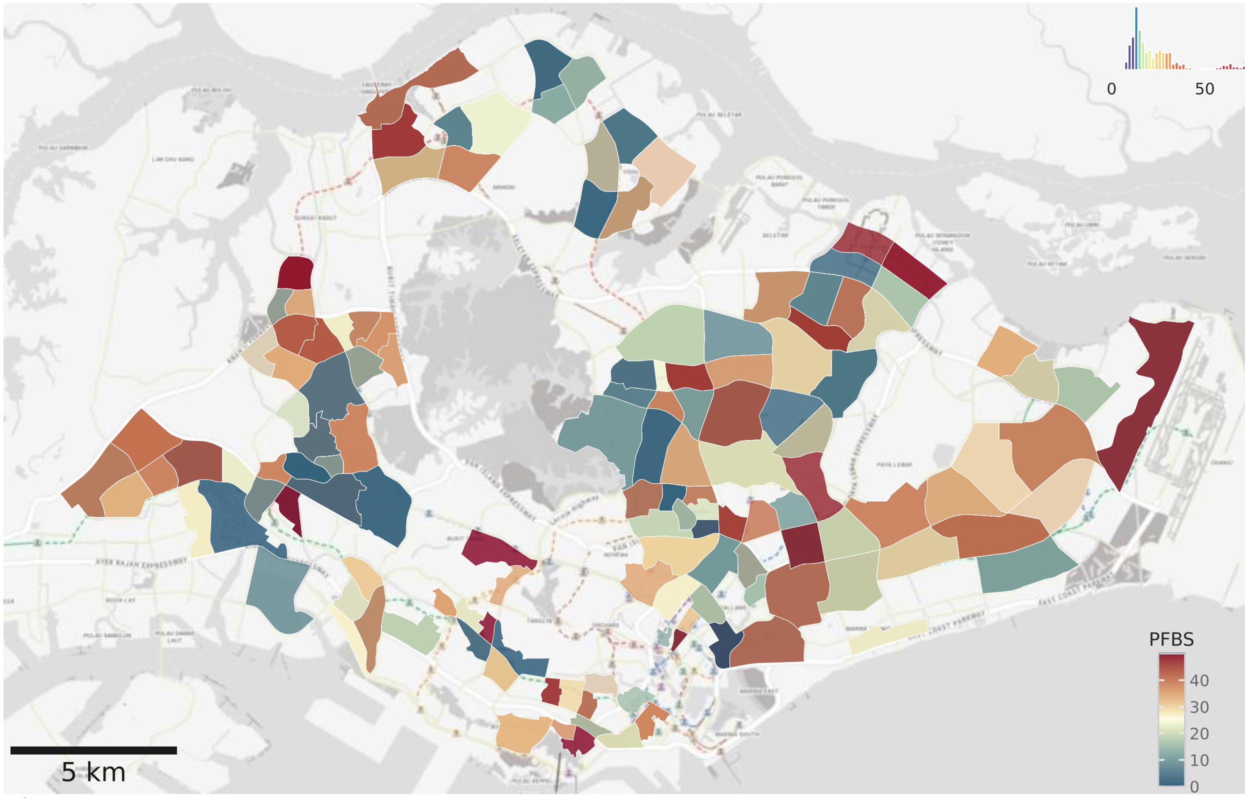


Figure 3. PFBS averaged across neighborhoods (n = 147). Legend indicates underlying distribution.

tal samples in the same region that find fairly concentrated measures of PFAS.[20,31,52,54,67]

Figure 3 plots the PFBS measurements across the city. One area with high PFBS measurements is the right-most area next to the only commercial airport. Airports are high-profile sites.[13,27,33,36] Another area with high PFBS measurements is in the northwest region, where the residential point from Figure 1 lies. In Appendix AA, Figures A2 to A7 provide more visual aids depicting the spatial distribution of PFAS concentrations around the location of transport facilities.

The example in Figure 1 is a participant with unusually high plasma PFAS concentration, with PFBS near the 95th percentile (between the 75th and 100th percentile for the other seven PFAS measurements). From Figure 1, we observe that this participant lives near two transport facilities as potential points sources of PFAS, one of which is a large bus depot (see also Table A2 and Table B7). While this observation is anecdotal, we next present results that systematically quantify whether living near transport facilities is associated with higher PFAS concentrations.

3.1 Main results

We estimate Equation (1) and report the estimates from modeling the plasma PFBS measurements as dependent on exposure to transport facilities. Models 1–4 estimates, which do not adjust for neighborhood-level heterogeneities, have weak statistical evidence of association, although they are always positive. From Model 5, which additionally adjusts for neighborhood-level heterogeneities, we observe statistical evidence of an association (0.158, SE 0.056, p = .016, Table A3). The estimate from Model 6, which adjusts for income available for a smaller sample, is comparable (0.149, SE 0.058, p = .016, Table A3). Hence, we observe within-neighborhood associations of PFBS and transport facilities exposure. In Appendix AA, we report statistical evidence of confounding without the adjustments in Model 5 (income and housing types are associated with PFBS, except with the stated adjustments), The estimate 0.153 implies that a 10,000m^2 increase in exposure to transport facilities (approximately 1 SD) is associated with a 1.6 ng/ml increase in PFBS (0.1 SD). We observe similar findings with exposure computed using a 1000m radius (Table A4), but not with the 1500m (Table A5) and 100m radius (Table A6).

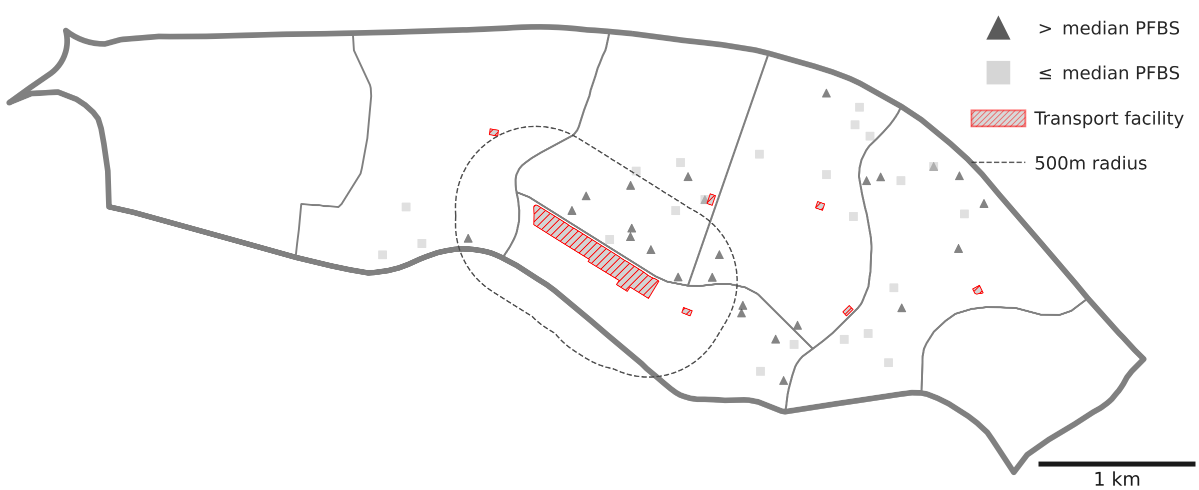


Figure 4. Participants around a transit depot in the area identified in the neighborhoods-level influential point analysis (Figure A15). Each triangle and square marker corresponds to a participant living in this area. Lines delineate administrative borders.

The influential point analyses (Appendix A) reveal that a single neighborhood disproportionally shrinks the estimate towards zero when excluded (Figure A15). Only one participant changes the estimate by over half the standard error when excluded (Figure A14). We find no influential planning areas (Figure A15). Figure 4 plots the area corresponding to the influential neighborhoods. A large transport depot with nearby participants having higher detected PFBS. Motivated in part by this finding and that a standard deviation increase in transport facility is larger than the typical land parcels of gas stations (Appendix B), we use the secondary model Equation (2) which flexibly allows for a stepped effect in the exposure to transport facilities.

3.2 Thresholds

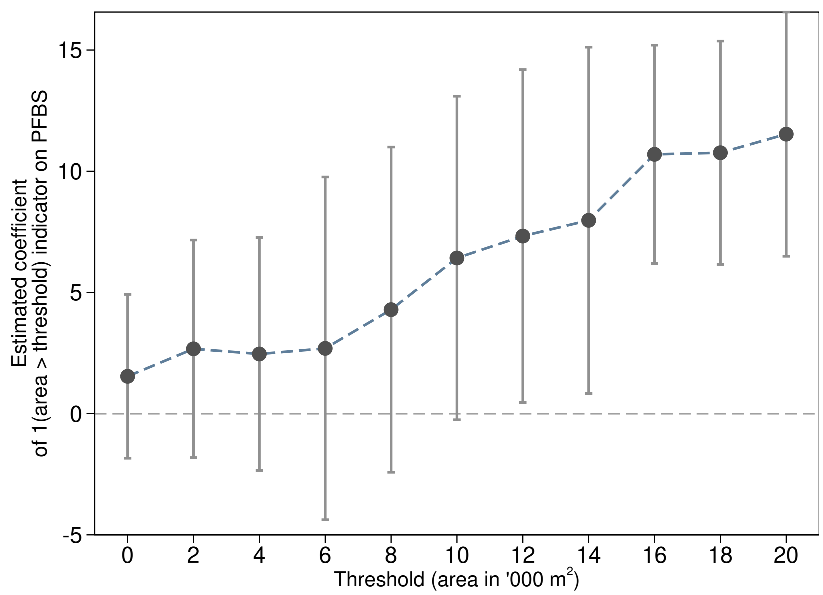


Figure 5. The estimated effect of exposure to an area of transport facilities based on cutoffs from estimating Equation (2). Each point is the point estimate from a model regressing PFBS on an indicator for whether the area of transport facilities within a 500m radius is more than the area indicated on the horizontal axis. For instance, the first point is the estimate of the binary for area of transport facilities > 0 m^2, the second point for area > 2,000 m^2, etc. After 20,000 m^2, fewer than 50 households would be binned into the exposed group. Capped vertical lines are 95% confidence intervals from clustered standard errors. Please see Appendix F for the other PFAS.

Figure 5 reports the estimated coefficients at each equal-sized interval in thresholds for the exposure measure (Section 2.8.1). We observe statistical evidence of association once the threshold reaches 10,000m^2, which is typically linked to the larger train and bus depots based on our audits (Section 2.4). The estimated coefficients past the 10,000m^2 mark are statistically significant and larger (threshold of 12,000m^2, 7.326, SE 3.352, $p = .037$; threshold of 20,000m^2, 11.530, SE 2.459, $p < .001$). The estimate at the 20,000m^2 threshold implies a higher PFBS of 11.5 ng/ml (approximately 0.72 of the SD). We observe a similar pattern with PFDA (Figure F29 in Appendix F).

3.3 Sensitivity analyses

In other sensitivity analyses, we also evaluate other land uses (Appendix C). The spatial distribution of transport facilities does not capture other land use types (Figure C25). To help rule out nuanced spatial confounders and exposure mechanisms, we compute alternative spatial instruments of the exposure defined in Section 2.3 and find no associations between these and PFBS concentrations (Appendix D). We also test and rule out that future exposure using future addresses can predict PFBS concentrations using the subset of GUSTO participants who have relocated since study enrollment (Appendix E).

PFAS	N	< LOD	< LOQ	LOD value	LOQ value	Est. (95% Conf. Int.)	P-value
PFBS	784	0	0	0.078 ng/mL	5.000 ng/mL	0.117(0.030 to 0.203)	0.01[a]
PFNA	784	0	0	0.016 ng/mL	0.100 ng/mL	0.113(0.037 to 0.189)	0.005[a]
PFOA	784	0	0	0.009 ng/mL	0.100 ng/mL	0.063(-0.108 to 0.235)	0.455
PFOS	783	0	1	0.027 ng/mL	0.100 ng/mL	0.103(-0.027 to 0.234)	0.115
PFHxS	777	1	6	0.024 ng/mL	0.100 ng/mL	0.029(-0.021 to 0.080)	0.244
PFBA	773	11	0	0.410 ng/mL	0.500 ng/mL	0.169(0.063 to 0.274)	0.003[a]
PFUnDA	754	2	28	0.011 ng/mL	0.100 ng/mL	0.022(-0.024 to 0.069)	0.334
PFDA	750	0	34	0.010 ng/mL	0.100 ng/mL	0.072(-0.042 to 0.185)	0.207

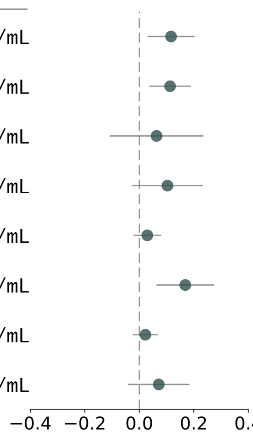


Figure 6. Figure reports all estimates from modeling PFAS measurement (from cord blood) as dependent on exposure to transport facilities. Horizontal axis of the plot reports the $\hat{\beta}$ coefficients from estimating

$$\text{substance}_{ic}^{\text{(scaled)}} = \beta(\text{Exposure to transport facilities})_{ic}^{\text{(scaled)}} + \gamma X_i + \delta_c(\text{neighborhood})_c + \varepsilon_{ic},$$

where $\text{substance}_{ic}^{\text{(scaled)}}$ is the PFAS substance (indicated in the first column). The PFAS substances and the exposure to transport facilities variable are scaled to have a standard deviation of one The specification is otherwise identical to that in Equation (1). Measurements below LOD and LOQ values (indicated in the second and third columns) are first imputed by the LOD/LOQ values (indicated in the fifth and sixth columns) divided by $\sqrt{2}$. Gray horizontal lines are the 95% confidence intervals constructed from standard errors clustered at planning areas. Significance levels: ^{c} 0.1 ^{b} 0.05 ^{a} 0.01.

Finally, we extend our analyses to other plasma PFAS measurements that are well-detected. We include the eight PFAS measurements with at least 95% detection rate in our participants (Table A1). Figure 6 reports the estimates. All units are scaled so that Figure 6 reports the standardized regression coefficients. We observe statistical evidence of positive associations in two emerging PFAS: PFBS (0.117, SE = 0.042, p = .010) and

PFBA (0.169, SE = 0.052, p = .003), and the legacy PFNA (0.113, SE = 0.037, p = .005). We also replicated our evaluations using a separate cohort study with separate analytes and detection rates (PFBS is poorly detected and not included). This cohort uses maternal (instead of cord) blood as the participants are not pregnant yet at the time of recruitment. There, we find statistical evidence of positive associations with PFNA, PFOS, and PFHpS (Figure F30, Appendix F).

4 Discussion

Using a sample of pregnant women in Singapore, a densely urban city, this study finds statistical evidence of positive associations between residential proximity to transport facilities and plasma PFAS concentrations. In the eight PFAS measures that were well detected (at least 95% of participants analyzed), we observe statistically significant associations in three PFAS. We find that a one SD increase in exposure to transport facilities (approximately 10,000m^2) is associated with a 0.12 SD increase in PFBS, a 0.17 SD increase in PFBA, and a 0.11 SD increase in PFNA. From our systematic evaluation of geo-referenced transport facility images, we find two main types of transport facilities, gas stations and large transport (bus and train) depots, with vast differences in footprint between the two types. An influential point assessment at the neighborhood level reveals that many participants live near a specific transport depot and have above-average PFBS measurements. These results suggest that the larger depots substantially contribute to observed associations, which ties in with the fact that an SD increase in exposure is larger than the footprint of the typical gas station. By modeling a stepped effect, participants with disproportionately large exposures ($>$ 10,000m^2) have more than a 0.46 SD increase in PFBS.

In line with other findings from the same region,[20,31,52,54,67] we note relatively high concentrations in some PFAS measurements in our sample. Human concentrations of environmental chemicals are generally not well studied in Singapore. However, a few other studies have verified higher PFAS from human samples in the Southeast Asia and East Asia regions,[20,54] as well as high concentrations of PFAS from environmental samples in the same city, especially PFBS in various matrices (e.g., bulk water, pore water, suspended particles, and benthic sediments).[31,52,67] Specifically, from analyses of urban catchment environmental samples targeting 22 PFAS in Singapore, the most abundant PFAS is PFBS.[31] Another study in Singapore finds a high environmental concentration of PFBS, up to 100 times higher than prior findings.[52] This study exhibits similarly high concentrations, albeit in human samples,[20], and we add to this by explaining its geographical variation by linking to transport facilities.

Transport facilities are a potential point of PFAS exposure because of the known uses of PFAS products in transport and automotive applications.[1] Some of the uses [functions] of PFAS in automotive-related activities include car body [weather resistance paint, no-wax brilliant top coat], engine and steering system [sealants and bearings], and engine oil coolers [heat transfer].[1] Glüge et al. (2020) also identify the oil and gas industry with seven PFAS uses [functions] such as transport [lining of the pipes, oil viscosity reduction], storage [prevention of evaporation loss], and containment [prevent spreading of oil or gas on water].[1] In our setting, residences can be as near as within 18 meters of a transport facility.

Several potential contamination routes exist, such as groundwater contamination by motor vehicle-related fluids, including lubricants, cleaning agents, fire-suppressing chemicals, etc. Additionally, it is increasingly understood that the aerosolization and airborne dispersal of PFAS are much more substantial than previously appreciated.[40–42,44–47,67] A recent extensive field study demonstrated that PFAS can remobilize into the air, amplifying the risk of atmospheric presence and potential exposure in areas beyond the original point source.[47]

We conduct an array of sensitivity tests to rule out spurious findings and obtain coincided evidence (Section 2.9). Although we cannot definitively state transport facilities as a source of airborne exposure, our sensitivity analyses exhaustively rule out systematic associations with all other land use types (Appendix C), and adjusting for the neighborhood of residence subsume other regional patterns relating to drinking water and proximity to other well-documented sites of contamination (Equation (1)). We also rule out a specific type of behavior regarding residential choice as a confounder with null results when we use future addresses to compute exposure (Appendix E). Finally, we replicated our findings in a separate cohort (Appendix F).

Of the three PFAS with evidence of associations, perfluorobutane sulfonic acid (PFBS) and perfluorobutanoic acid (PFBA) are newer emerging PFAS replacing the legacy PFAS with known adverse health effects such as perfluorooctanoic acid (PFOA) and perfluorooctanesulfonic acid (PFOS).[2,3,6–8,70–73] Manufacturing companies, for example, no longer manufacture the 8-carbon PFOS by switching to shorter-chained 4-carbon PFBS.[2,62] From environmental samples in the same city, PFBS and PFBA are the two most concentrated short-chain PFAS.[31,52] Using a study on rabbits, Crute, Landon, Garner, et al. (2023) report links between PFBS and adverse maternal outcomes such as renal injury and placenta functioning.[74] However, studies of PFBS and PFBA on human health effects are rare. Three studies using the same sample of children found links between serum PFBS concentration and asthma, immunological markers, and hyperuricemia.[63–65] These emerging PFAS, otherwise, have limited data about health effects,[2,3,13] partly because animal-based studies are limited by the vast differences in toxicokinetic disposition of animals and humans.[3,62,75]

The third PFAS with evidence of association, Perfluorononanoic acid (PFNA), has been an understudied legacy PFAS until recent years.[2] Past studies with mice find a link between PFNA and developmental toxicity.[76,77] More recent studies with mothers find an association between PFNA and fertility in mothers, and PFNA and low birth weight,[78–82] suggesting that the understudied PFAS can adversely affect newborns in utero.[2] PFNA has also been reported to contribute to metabolic syndrome in humans.[83]

A primary contribution of the study is how we systematically investigated the non-regulated transport facilities (and other land use types) as potential point sources of PFAS exposure. We link these facilities to plasma PFAS concentrations in a general urban population, a relatively novel approach compared to previous studies. Past studies using human samples typically evaluate known and regulated sources.[15,25,35,36,84] Studies evaluating non-regulated sources using human samples are rare.[42] Moreover, we reduce the likelihood of spurious findings by systematically considering the geographical distribution of other land uses around participants' residences.

Our findings demonstrate that even in a well-planned, densely urban setting, there can be sources of PFAS that are located near dense residences. For a sense of urban density in Singapore, there are approximately 3.7 million residents over 126km^2 of purely residential land use parcels in 2010 (approximately 26k residents per 1km^2). In particular, based on the 2010 census, the neighborhood identified as an influential point with the large transport depot (Figure 4) has a population of 30k residents (approximately 20k/km^2). Based on the later 2020 census, density in this neighborhood has increased to 32k/km^2. On the other hand, land use and transport facilities are static over time. Our computations suggest that total transport facilities changed by less than 0.03% between 2008 and 2019 for areas within a 500m radius of known public housing points. This built environmental inertia, contrasted with increasing population density, suggests that the potential risk of PFAS exposure will only intensify with time.

A corollary finding that may be of interest is that we observe no associations with the general industrial areas (Appendix C), which are known point sources of PFAS.[24–27,29,35] Given the regulatory buffers, one reason could be that few residents (including cohort study participants) live near those industrial sites. Only one participant resides within 100 meters of an industrial site. In addition, there is a heavy skew in exposure to industrial sites because of their location far away from neighborhoods (Figure A1). Combined with our findings, this urban distribution underscores the need to examine and monitor other potential and under-sampled point sources without such regulatory residential buffers in a highly urban setting.

We note several limitations to our study. First, given our sample and context of analyses, we cannot precisely characterize whether pathways occur indoors at home or outdoors around the neighborhood vicinity. Previous studies have highlighted indoor air pollutants, potentially through heating, ventilation, and air conditioning systems.[37,41,60] We are cognizant that occupation is an important determinant of PFAS exposure, and we adjust for it. However, the cohort occupation classification may not align directly with related occupational hazards.[14,18,36,58,59] Not all PFAS are well detected, and we only report PFAS that were well detected. A related issue is that while PFAS is a large mixture of compounds, we study only a few separately.[72] Future studies should examine PFAS collectively as a mixture in such studies of spatial determinants. Finally, we lack concrete priors about the exposure to transport facilities and thus modeled it linearly with the primary evaluation buffer at 500 meters. The upshot is that we find coincided evidence with different buffers and with different model specifications.

More than half of the world's population lives in urban areas, and the number is rising still. This study addresses a critical research gap in understanding urban determinants of non-classic but ubiquitous contaminants, which may have wide-ranging adverse health effects. We find robust evidence that transport facilities may be an otherwise unrecognized source of urban PFAS exposures, a class of chemicals with wide-ranging potential health effects. While Singapore has lower geographical disparities in poverty and minority status, reducing the likelihood of confounding, this also means that our findings may have more stark implications for many other regions with greater segregation and issues of environmental injustice. Since transport facilities are much more prevalent than, e.g., factories or airports in urban areas, the contribution of differential exposure of PFAS and other understudied chemicals to geographic health disparities from these common built environment features warrants far more attention.

Data sharing

The GUSTO cohort study was approved by the SingHealth Centralized institutional Review Board (2018/2767/D) and by the National Health Care Group Domain Specific Review Board (D/2009/00021). The S-PRESTO cohort study was approved by the SingHealth Centralized institutional Review Board (2019/2143/D).

The data that support the findings in this study are available upon request. Code to reproduce results will be made publicly available online.

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Supplementary Materials (Not for Publication) for
“Residential proximity to transport facilities as urban determinants of individual-level per- and poly-fluoroalkyl substance (PFAS) exposures: Analysis of two longitudinal cohorts in Singapore”
(Authors here August 2024)

Table of Contents

A. Supplementary materials for results

A.A Descriptive and summary results

This appendix provides supporting tables, figures, and details for descriptive results. All distributions, including spatial distribution of the land parcels of interest, are reported here.

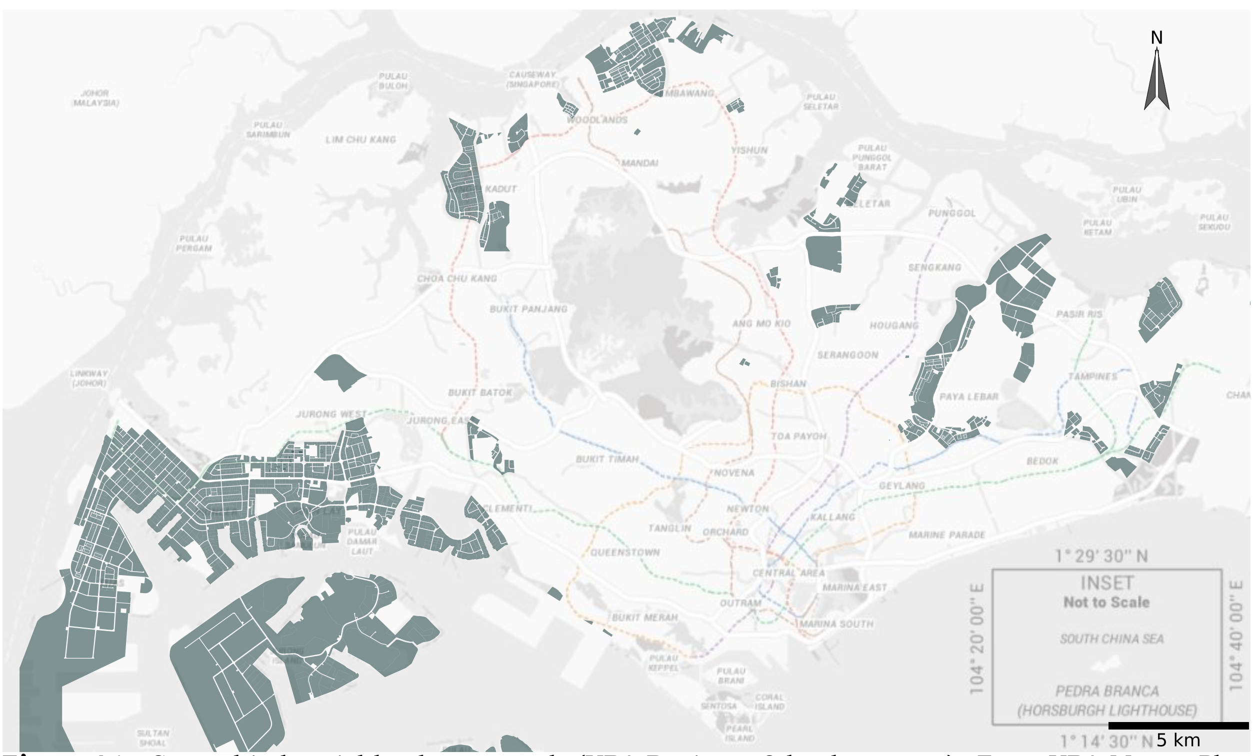


Figure A1. General industrial land use parcels (URA Business 2 land use type). From URA Master Plan 2008

Figure A2 plots the land parcels most closely related to heavy industrial sites (Urban Redevelopment Agency "Business 2" land use). Most are scattered on the outskirts of residential areas, in particular the large parcels. A minority of smaller land parcels classified as "Business 2" are near or within neighborhoods (referenced in https://www.ura.gov.sg/-/media/Corporate/Planning/Master-Plan/MP19writtenstatement.pdf).

Table A1 reports all chemicals sent for analysis using the collected cord blood samples, and the number of samples below limits of detection (LOD) or below limits of quantification (LOQ). Figure A2 plots the transport facility land parcels across the island. These are much smaller (in comparison to Figure A1), but tend to be scattered close to residential neighborhoods. The lines in the figure delineate the five regions (central, north, north-east, east, and west). Figures A3 to A7 plot the same map by the five regions. Participants with above median plasma PFBS concentrations ($\sim$18.2 ng/ml) are shown as black triangles while participants with below median concentrations are in gray squares. Transport facilities are shaded red. The distribution in exposure to transport facilities measure (defined in Section 2.3) is reported in Figure A8 and Figure A9. Table A2 lists the eight types of transport facilities. See Appendix B for how we get more details that most transport facilities are gas stations/petrol kiosks and transit depots.

In our other auxiliary descriptive analyses (not documented in this manuscript), we find correlations between the plasma PFBS concentrations and a set of maternal factors. All findings below are correlations of the data without any adjustments, unless reported otherwise, and are subject to data coverage. We find that low-income mothers (less than SGD2000 in monthly income; 67.3%; n = 739) have higher PFBS measurements. Mothers with no university degree (73.1%, n = 772) have higher PFBS measurements. We also find that mothers living in public housing (90.7%; n = 772), which corresponds to more affordable housing from government housing subsidies, have higher PFBS measurements. We consider public housing as those living in 1–5-room HDB (Housing and Development Board). While the executive condominiums are also under the Housing and Development Board, at least for the first 10 years, we classify these as private (non-public) housing. Living in public housing is associated with approximately 4.01 ng/ml (SE = 1.63; $p < .05$) higher plasma PFBS concentration. The association between public housing and higher PFBS measurements persists even with the other maternal baselines and attenuates only when we include the neighborhoods areal fixed effects. In this case, the estimated coefficient is still positive but no longer statistically significant at conventional levels (adjusted $\hat{\beta} = 2.4$, SE = 1.67, $p > .1$). This motivates the importance of including the neighborhood areal fixed effects to adjust for unmeasured spatial heterogeneity. For administrative borders and movement between neighborhoods, see Lee, Lim, and Shen 2021,[1] and Lim and Shen 2022.[2]

Correlation of GUSTO participants with base population. While GUSTO was not designed to be representative by geography,[53] we compute a simple correlation and find that

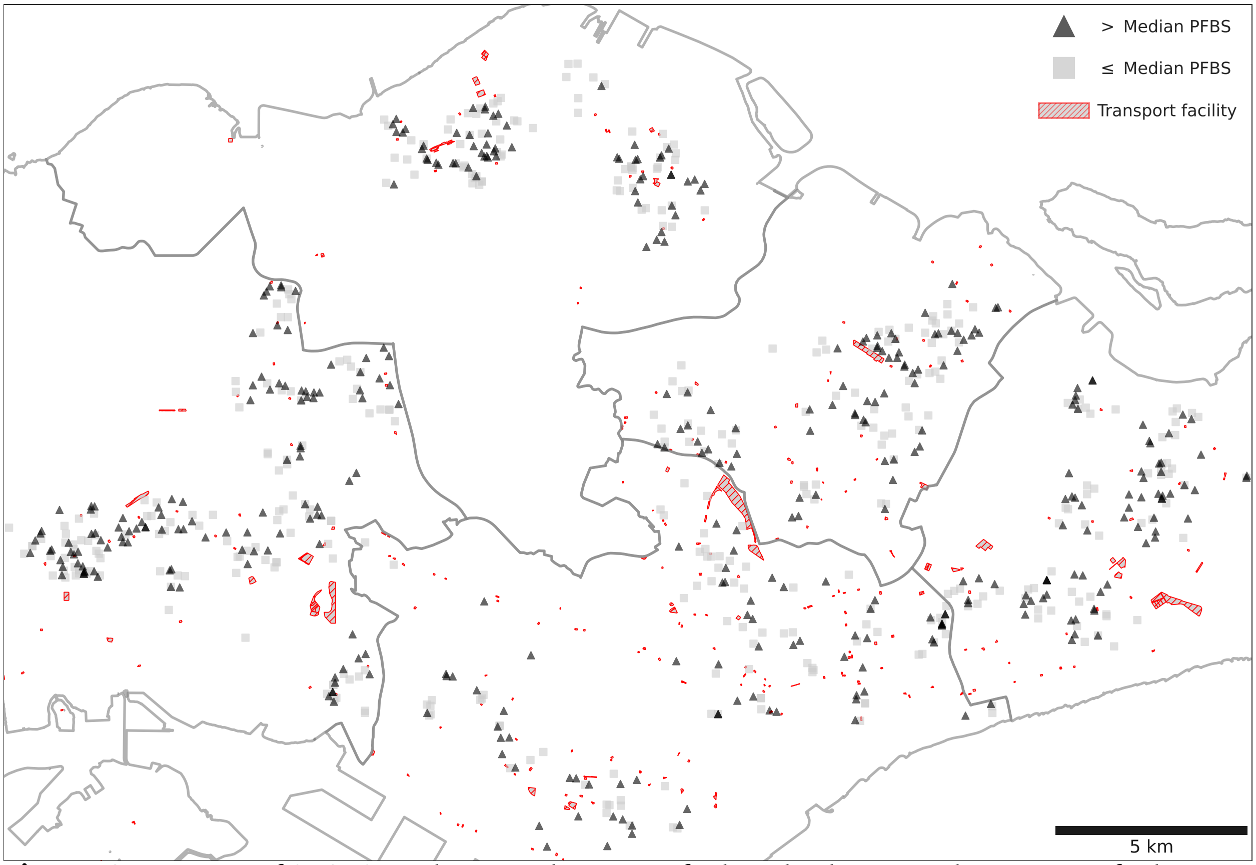


Figure A2. Locations of GUSTO residences and transport facilities land use parcels. Transport facilities are shaded in red. Gray lines delineate the five regions (central, west, east, north, north-east). See Figures A3 to A7 for a breakdown of the same figure by the other five regions.

our sample of GUSTO participants vary closely with the base population by region. We start by retrieving the Department of Statistics population census numbers (https://www.singstat.gov.sg/find-data/search-by-theme/population/geographic-distribution) for the 2010 census which is available by planning areas and subzones (*neighborhoods* in the main body). The participant age range at delivery is approximately 19–47. We therefore filter the population census figures for females who fall in the six 5-year bins (age 20–24, age 25–29, age 30–34, age 35–39, age 40–44, age 45–49). We then ground-truthed the official subzone of each GUSTO participant by first geocoding their location using the postal code before map-matching their point locations to the official 2008 version of the subzone delineation map. This yields a subzone (and planning area) ID tag for each GUSTO participant which we use to match to the subzone tags in the population census figures. Finally, we compute the correlation, by planning areas and separately by subzones, between the number of GUSTO participants and the number of women aged 20–49 in the base population (planning area correlation = .895, p-value < $.001 \times 10^{-13}$, planning areas = 33; subzone correlation = .89, p-value < $.001 \times 10^{-58}$, subzones = 166; GUSTO participants = 1,488).

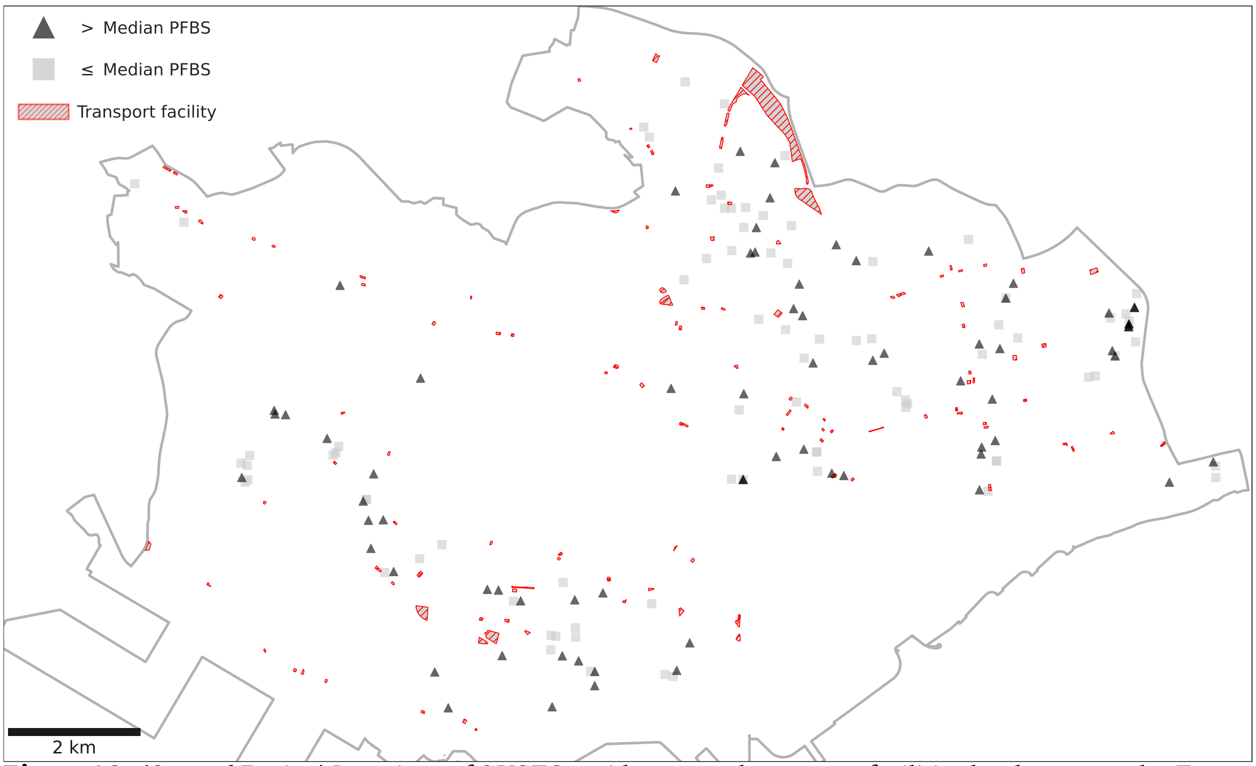


Figure A3. (Central Region) Locations of GUSTO residences and transport facilities land use parcels. Transport facilities are shaded in red. GUSTO residences are in triangles (above median plasma PFBS concentration) and squares (below median plasma PFBS concentrations). See Figure A2 for the map of the whole city. See Figures A4 to A7 for the other four regions.

Figure A4. (West Region) Locations of GUSTO residences and transport facilities land use parcels. Transport facilities are shaded in red. GUSTO residences are in triangles (above median plasma PFBS concentration) and squares (below median plasma PFBS concentrations). See Figure A2 for all five regions.

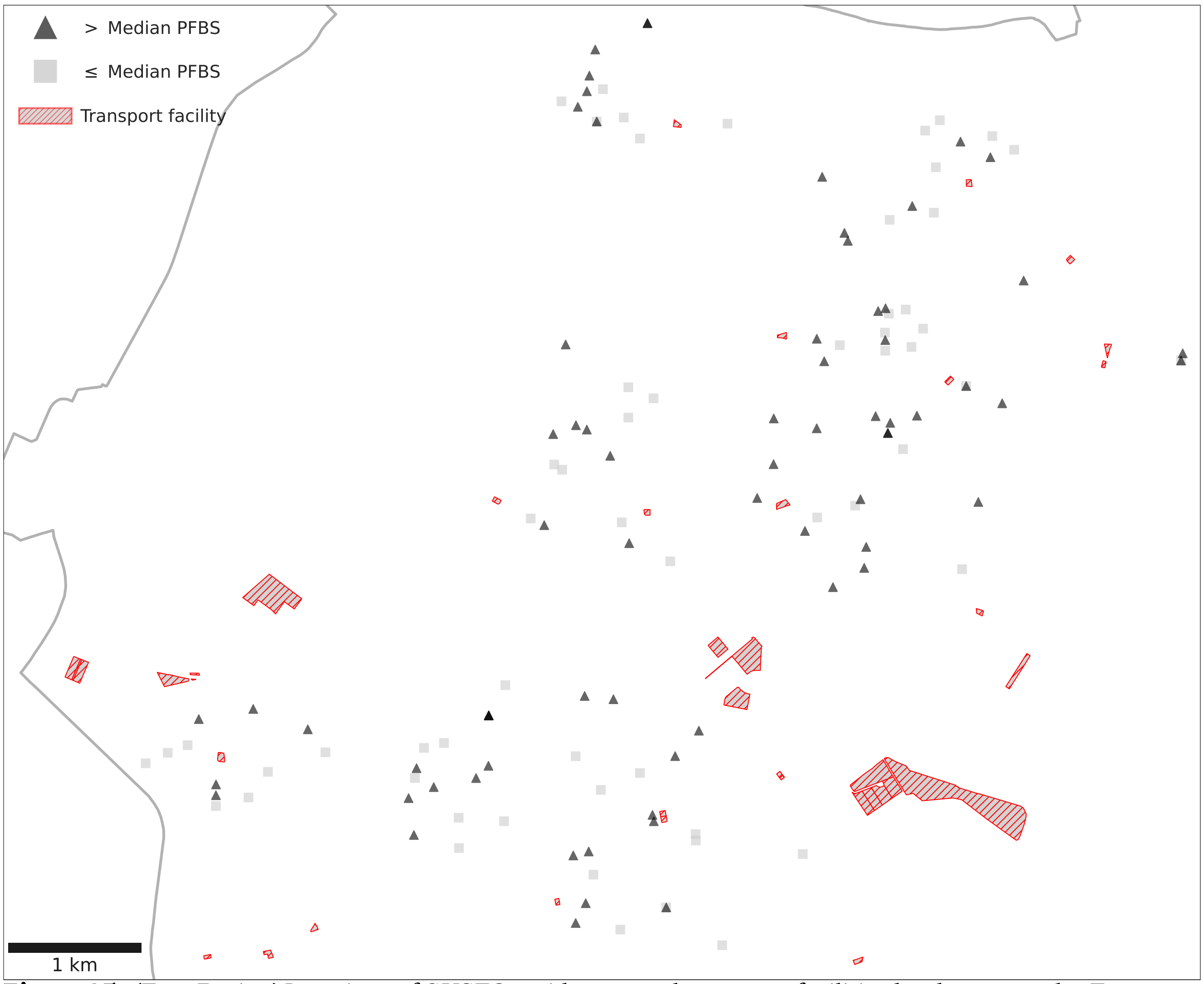


Figure A5. (East Region) Locations of GUSTO residences and transport facilities land use parcels. Transport facilities are shaded in red. GUSTO residences are in triangles (above median plasma PFBS concentration) and squares (below median plasma PFBS concentrations). See Figure A2 for all five regions.

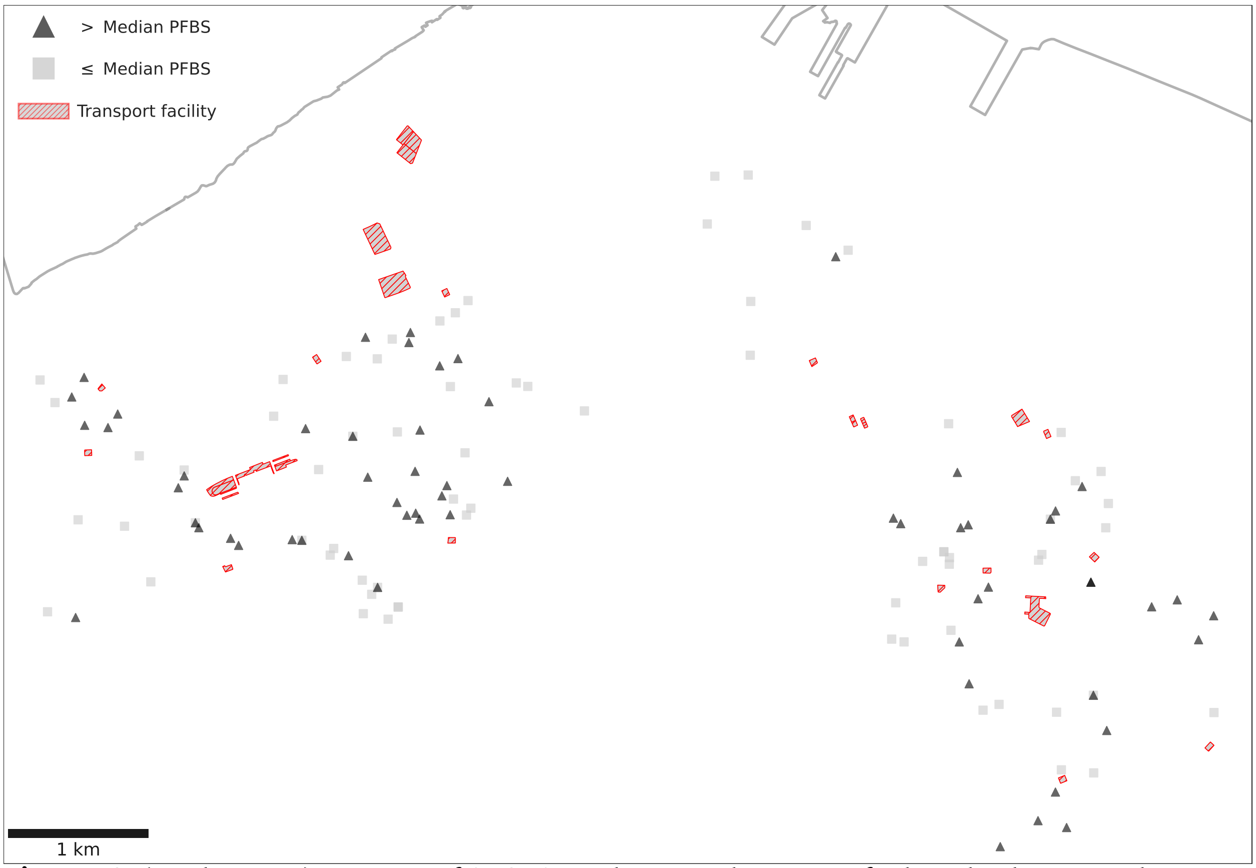


Figure A6. (North Region) Locations of GUSTO residences and transport facilities land use parcels. Transport facilities are shaded in red. GUSTO residences are in triangles (above median plasma PFBS concentration) and squares (below median plasma PFBS concentrations). See Figure A2 for all five regions.

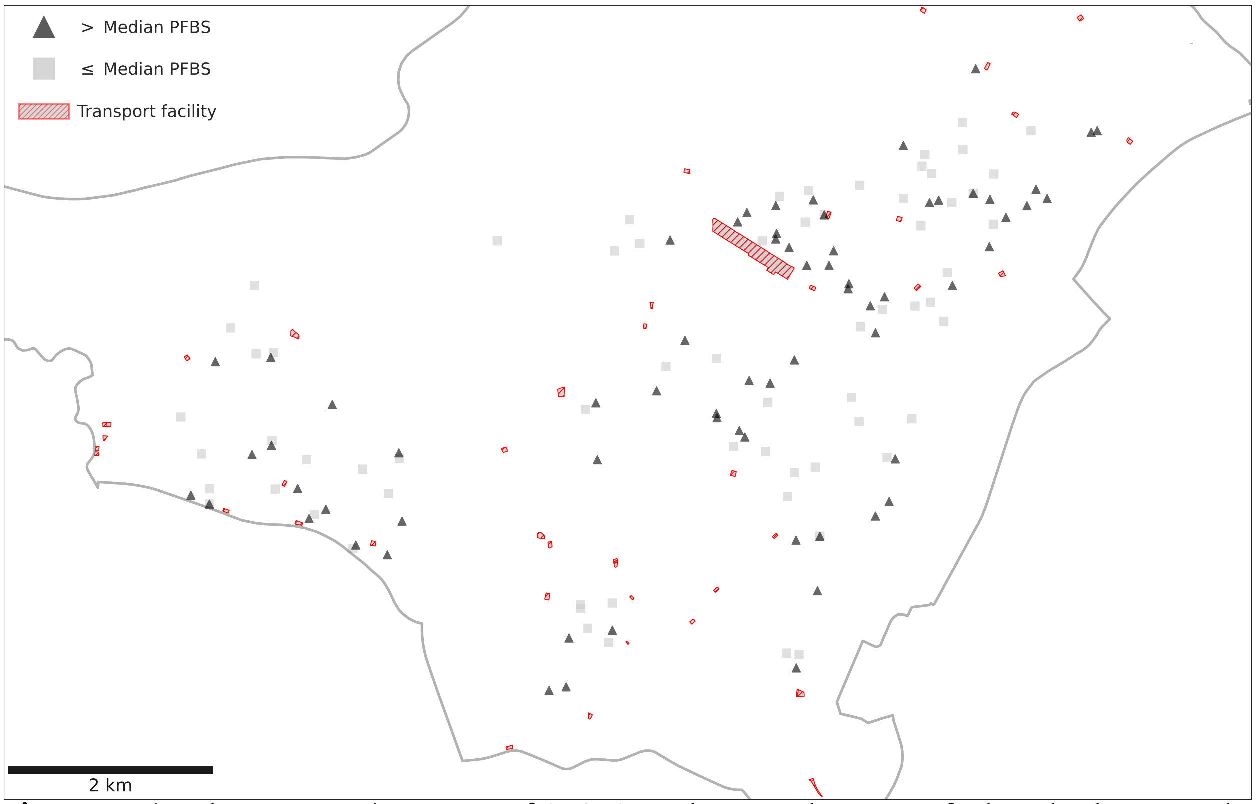
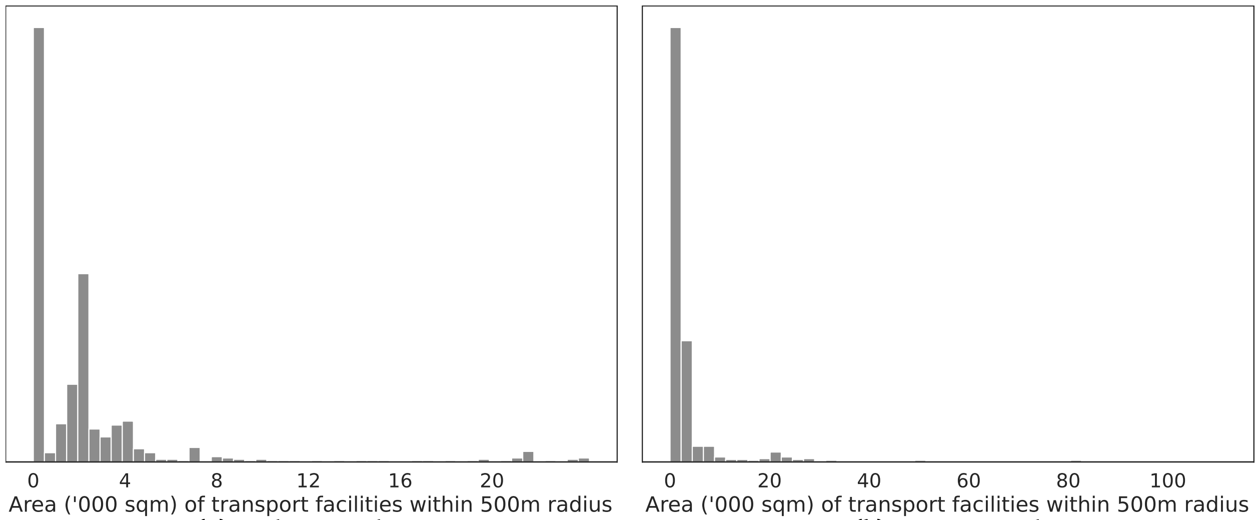


Figure A7. (North-East Region) Locations of GUSTO residences and transport facilities land use parcels. Transport facilities are shaded in red. GUSTO residences are in triangles (above median plasma PFBS concentration) and squares (below median plasma PFBS concentrations). See Figure A2 for all five regions.

Table A1. Completeness of GUSTO EDC measures

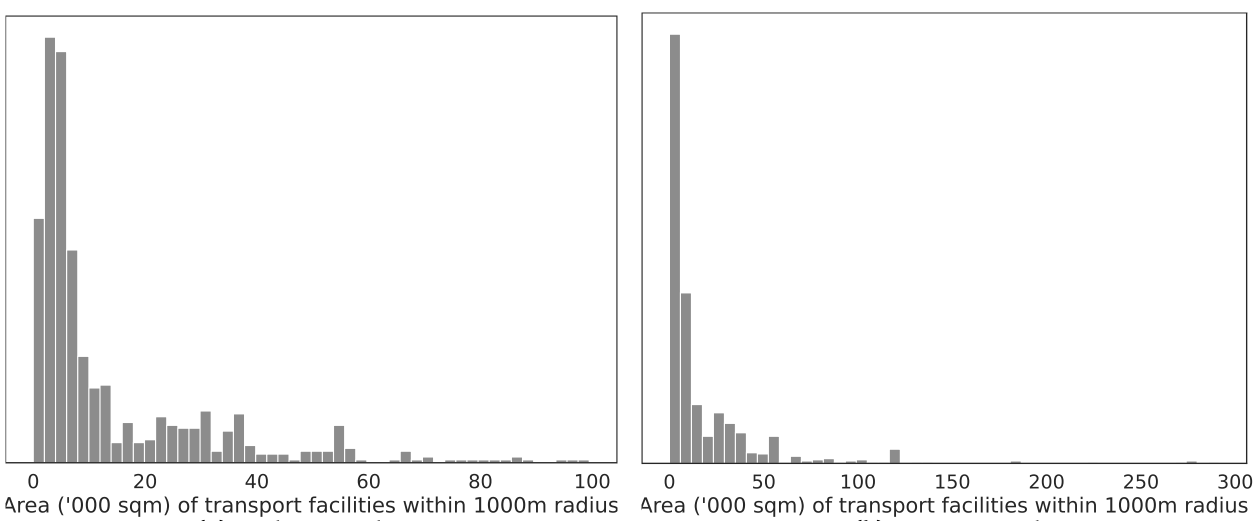
		Not measured			Summary statistics				
	Measured (1)	< LOD (2)	< LOQ (3)	Total (4)	Mean (5)	SD (6)	Q1 (7)	Median (8)	Q3 (9)
PFBS	784	0	0	0	24.162	15.929	13.28	18.23	28.95
MBP	784	0	0	0	2.71	1.61	1.75	2.29	3.122
PFOA	784	0	0	0	1.982	1.544	1.0	1.485	2.415
PFNA	784	0	0	0	0.951	0.528	0.59	0.79	1.212
MEHP	784	0	0	0	10.712	7.614	6.77	9.065	12.24
Oxyben	784	0	0	0	2.269	0.784	1.77	2.11	2.68
PFOS	783	0	1	1	1.326	0.986	0.77	1.11	1.58
PFHxS	777	1	6	7	0.579	0.359	0.33	0.5	0.73
Benzophe	775	9	0	9	57.943	157.356	2.74	6.89	39.045
PFBA	773	11	0	11	2.076	4.34	1.25	1.58	2.06
PFUnDA	754	2	28	30	0.256	0.222	0.14	0.2	0.29
PFDA	750	0	34	34	0.162	0.1	0.11	0.14	0.19
Methylp	663	119	2	121	6.889	7.171	2.39	5.47	9.1
MECPP	655	129	0	129	0.597	0.615	0.29	0.42	0.685
MEP	558	209	17	226	1.93	3.335	0.582	0.9	1.725
PFHpA	555	139	90	229	0.196	0.169	0.11	0.15	0.21
MMP	526	258	0	258	0.911	1.469	0.61	0.75	0.93
MCINP	515	269	0	269	2.972	2.994	1.41	2.15	3.32
Propylp	506	278	0	278	0.366	0.437	0.19	0.25	0.39
BPS	437	326	21	347	0.179	0.22	0.09	0.12	0.19
Ethylp	388	359	37	396	0.26	0.245	0.13	0.2	0.29
PFPeA	207	577	0	577	0.175	0.117	0.12	0.15	0.19
PFDoDA	82	139	563	702	0.109	0.096	0.07	0.09	0.11
BPA	58	726	0	726	10.544	17.001	3.885	5.315	9.608
Butylp	11	756	17	773	0.125	0.084	0.07	0.1	0.13
MCPP	10	661	113	774	0.583	0.411	0.375	0.425	0.488
MBzP	9	773	2	775	1.477	0.756	0.81	1.35	1.85
PFHxA	7	776	1	777	0.933	0.449	0.64	0.85	1.195
MNOP	0	784	0	784	—	—	—	—	—

Note: Table reports the completeness of PFAS measurements. Measurements in nanograms per millilitre (ng/ML). LOD = limit of detection. LOQ = limit of quantification. Samples flagged as < LOD and < LOQ are imputed with the corresponding LOD/LOQ values divided by $\sqrt{2}$ in Appendix F.



(a) Without outliers **(b)** Untruncated

Figure A8. Distribution of area of transport facilities land parcel within 500m radius of residence. Vertical axis is density. Left figure cuts off at approximately 97th percentile. See Figure A9 for the distribution based on a 1000m radius.



(a) Without outliers **(b)** Untruncated

Figure A9. Distribution of area of transport facilities land parcel within 1000m radius of residence. Vertical axis is density. Left figure cuts off at approximately 97th percentile. See Figure A8 for the distribution based on a 500m radius.

Table A2. Eight types of transport facilities

Facility Type
Car Park
Heavy Vehicle Park
Trailer Park
Bus Depot/Terminal
Transport Depot
MRT/LRT Marshalling Yard/Depot
Driving Circuit/Test Centre
Petrol Station/Kiosk

Type of establishment in transport facilities land use parcels. Official source: https://web.archive.org/web/20230207075239/https://www.ura.gov.sg/maps/media/mp/MPUG_2014_for_map_legend.htm.

A.B Main results

This appendix supplements figures and tables for the main results where we evaluate the adjusted associations between plasma PFBS concentrations with exposure to transport facilities. Models are as described in Section 2.8 of the main body.

Table A3 reports the estimates from modeling the plasma PFBS measurements as dependent on exposure to transport facilities. We have GUSTO 784 participants with blood samples sent for PFAS analysis. 13 participants reported postal codes not found from an official source (https://www.onemap.gov.sg/apidocs/apidocs/#search). These 13 participants drop out in Model 1 of Table A3. In Model 2, 29 more participants drop out when we add the maternal baselines. 21 drop out because of missing maternal baselines:

`ethnicity(1) <-> age at birth(1) -> highest education(12) <-> housing type(12) -> place of birth(20) -> marital status(21).`

The above implies that one participant has missing ethnicity *and* age at birth data (tally 1). 11 more have missing data on education (tally 12). These same 11 participants also have missing housing type data. A further 8 have missing place of birth records (tally 20). One more participant also has missing occupation data (tally 21). On top of these 21 participants, a further 8 more dropped out as singleton observations.[3] In Model 4, an additional participant drops out as a singleton observation when the planning area fixed effects are included. In Model 5, 21 more participants drop out as singleton observations when the subzone (neighborhood) fixed effects are included. A further 50 participants dropped out in our last model, Model 5, when the income measures with lower coverage were included.

We fail to observe any statistically significant associations in Models 1–4. Model 4, which adjusts for maternal baselines and for the planning areas, is marginally significant. From Model 5, which adjusts for the maternal baselines and for subzone-level effects, we observe a positive and statistically significant association with an estimate of 0.153 (SE 0.056, $p < 0.05$). Hence our modeling captures only within-subzone associations in PFBS and transport facilities exposure but we observe no such associations across regions of the city. See also Lee, Lim, and Shen (2021) and Lim and Shen (2022) for variation in day-to-day movement across neighborhoods.[1,2] Figure A10 plots the estimated fit from Model 5 with the baseline covariates partialed out from both the plasma PFBS concentration and from the exposure measure. The estimated coefficient of 0.15 implies that a 10,000m^2 increase in exposure to transport facilities is associated with an approximately 1.58 ng/ml increase in PFBS (approximately 0.1 SD). Model 6, which adjusts for maternal and household income, has comparable estimates. Tables A4 to A6 reports the results for the alternative buffer radiuses of 1000m, 1500m, and 100m. Figures A11 to A13 plot the corresponding estimated best-fitted models for Model 5.

Figures A14 to A16 report the results from evaluating which points are influential using the change in the estimated coefficients when certain observations are excluded from estimation. As before, we focus on Model 5. Figure A14 reports the results where each point corresponds to the change in estimated coefficient from Model 5 when the observation indexed on the horizontal axis is omitted from the estimation. The rule of thumb we use is to flag runs where the change is larger than $2/\sqrt{n}$ in absolute terms. More influential points increase than decrease the estimate. One influential point decreases the estimate by more than half the standardized error in the estimate. In Figure A15, we repeat a similar analysis but omit entire groups of individual-level observation by the subzone they are residing in. We detect one influential subzone from this analysis. We visually analyze this subzone in Figure 4. Figure A16 repeats the above analysis for the broader planning areas. We detect no influential planning areas.

Figure A17 provides three illustrating examples of participants from our GUSTO sample living in the east region. Two participants have exposure to transport facilities, and one does not, as defined using a 500-meter radius using the exposure defined in Section 2.3. The inset in Figure A17 shows the actual gas station identified in the image. The participant with no exposure has a plasma PFBS measurement of 16.93 ng/ml. Based on our estimated (adjusted) coefficient of 0.153 (from Model 5 of Table A3) and the exposure measure of 4.03, together, imply that with all else equal, there would be an estimated 0.62 ng/ml increase in plasma PFBS. In reality, the plasma PFBS concentrations for the two participants with exposure to transport facilities are 18.42 and 23.05, which is slightly higher (by 5% and by 31%, respectively).

Figure A18 provides another illustrating example with a separate pair of participants from the west region. The inset in Figure A18 showing the large transport facility, a bus depot, also shows a heavy industrial area in the backdrop, underscoring the importance of evaluating within-neighborhood variation instead of across-neighborhood variation in our preferred model. The participant in red has exposure to a large transport facility land parcel, while the other participant in gray square has exposure to a smaller transport facility. This latter participant has a plasma PFBS concentration of 11.27 ng/ml. Based on our estimated (adjusted) coefficient of 0.153 (from Model 5 of Table A3) and the difference in exposure measure of 12.65 (14.653 - 2.003), together, imply that with all else equal, there would be an estimated 1.935 ng/ml increase in plasma PFBS. In reality, the difference in PFBS for these two participants is slightly lower at 1.83.

We conduct an array of sensitivity tests. Our analyses are careful about the fact that unmeasured spatial heterogeneities are potentially linked to both unobserved behavior contributing to PFAS exposure and to the distribution of land use, such as transport facilities. We adjust for these spatial properties by modeling participants from the same neighborhoods to be similar and to correct the standard errors to allow for within-neighborhood correlation of land use distribution. We find no associations without adjusting for neighborhoods (e.g., city-wide and across the five regions). Where possible, we develop alternative exposure measures to rule out the main analyses capturing nuanced unmeasured spatial patterns relating to the geographical location of transport facilities that would be independent of any hypothesized PFAS exposure pathways. Our measure of exposure is justified to the extent that the burden of PFAS directly corresponds to the two-dimensional areal footprint of transport facilities, without accounting for the third dimension of facility height. In Section 2.4 (and Appendix B), we observe that transport facilities tend to have only a single level, and so PFAS burden should correspond most to the land area of transport facilities. We also systematically examine other land use types, in addition to transport facilities, to examine whether we were capturing the spatial correlation of transport facilities with some other land use types, such as train stations, roads, and general industrial areas (Appendix C). We develop a placebo test using the trail of future residence in the GUSTO cohort and show that exposure using future addresses is unable to predict plasma PFAS measurements from blood samples taken years earlier (Appendix E). We also extend our analyses to a separate cohort study with different plasma PFAS analytes from blood samples collected at a separate time point with broadly similar findings (Appendix F).

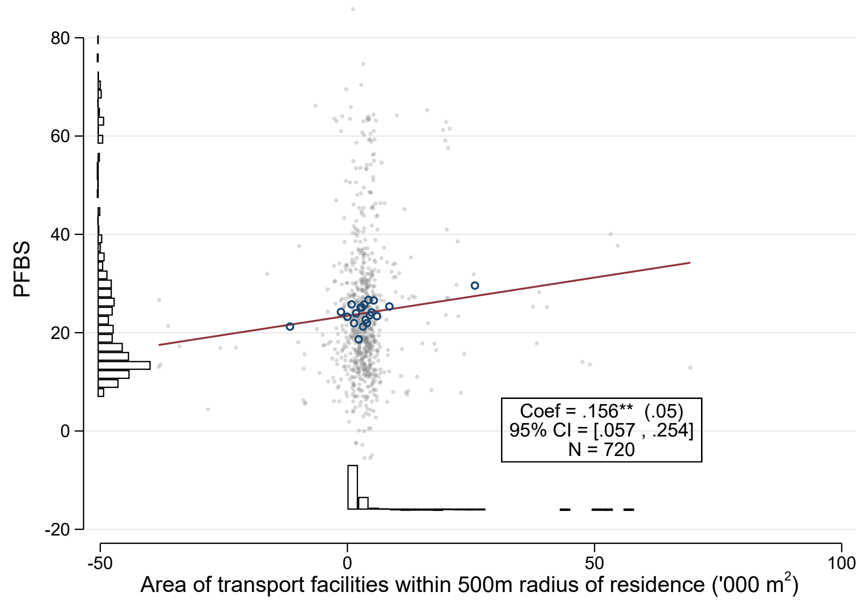


Figure A10. PFBS and transport facilities. See also Figure A8 for the distribution of area of transport facilities. Corresponds to column (5) of Table A3. Standard errors clustered at planning areas. Binned data in blue hollow circles. Significance levels: + 0.1 * 0.05 ** 0.01 *** 0.001.

Table A3. PFBS and transport facilities within 500m radius of residence.

	Dependent variable is PFBS (ng/mL)					
	(1)	(2)	(3)	(4)	(5)	(6)
Transport facilities (area) within 500m buffer	0.052	0.076	0.085	0.129^c	0.153^b	0.149^b
	(0.039)	(0.046)	(0.052)	(0.063)	(0.056)	(0.058)
Constant	23.935^a	9.980	9.946	14.848	23.386	17.255
	(0.579)	(17.920)	(17.155)	(17.000)	(21.277)	(27.469)
R^2	0.001	0.056	0.066	0.096	0.193	0.214
Maternal baselines		Yes	Yes	Yes	Yes	Yes
Income						Yes
Area fixed effects: Region			Yes			
Area fixed effects: Planning area				Yes		
Area fixed effects: Subzone					Yes	Yes
Mean Dep Var.	24.1	24.1	24.1	24.1	24.0	23.7
Std. dev. of X	10.6	10.2	10.2	10.2	10.3	10.6
n(Transport facilities (area) within 500m buffer > 0)	458	439	439	439	426	399
n(Clusters)	–	30	30	29	29	28
N	771	742	742	741	720	670

Note: Transport facilities area within 500m buffer is in 1,000 square meters. See Section 2.5 for the maternal and income controls. Figure A10 shows Model 5. Standard errors in (2)–(6) clustered at the planning areas. Significance levels: ^{c} 0.1 ^{b} 0.05 ^{a} 0.01.

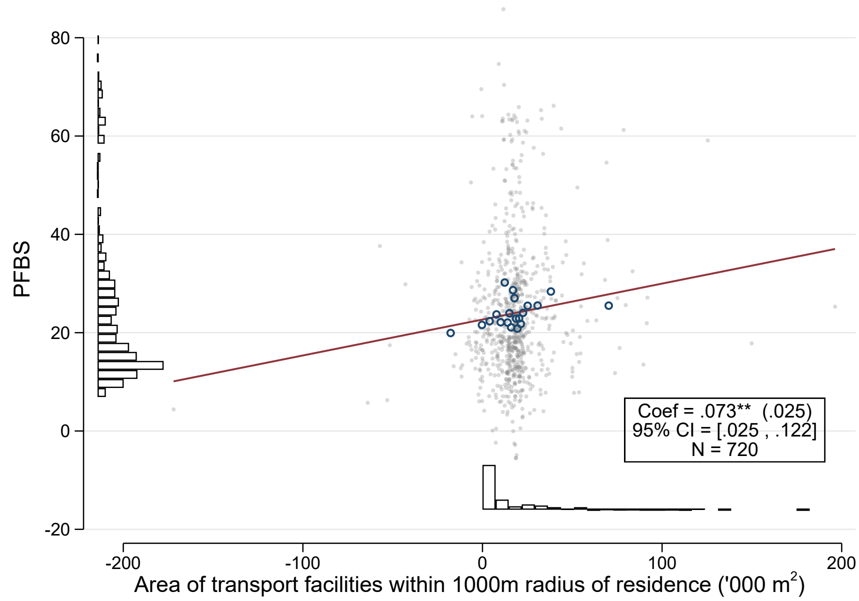


Figure A11. PFBS and Transport Facilities area within 1000m radius. Reported estimates are from regressing PFBS on the area (1,000) of transport facilities within 1000m radius of residence, with subzone fixed effects and maternal characteristics partialed out. Model corresponds to column (5) of Table A4. Standard errors clustered at subzones. Raw data in small gray circles. Binned data in blue hollow circles. Fitted line from the estimated model. Marginal histograms indicate the underlying distributions. Significance levels: + 0.1 * 0.05 ** 0.01 *** 0.001.

Table A4. PFBS and transport facilities within 1000m radius of residence

	Dependent variable is PFBS (ng/mL)					
	(1)	(2)	(3)	(4)	(5)	(6)
Transport facilities (area) within 1000m buffer	0.013	0.019	0.023	0.046^b	0.075^a	0.071^a
	(0.014)	(0.016)	(0.016)	(0.019)	(0.026)	(0.024)
Constant	23.888^a	10.429	10.372	16.229	25.683	19.761
	(0.624)	(17.754)	(17.061)	(17.107)	(21.334)	(27.395)
R^2	0.001	0.055	0.065	0.096	0.196	0.216
Maternal baselines		Yes	Yes	Yes	Yes	Yes
Income						Yes
Area fixed effects: Region			Yes			
Area fixed effects: Planning area				Yes		
Area fixed effects: Subzone					Yes	Yes
Mean Dep Var.	24.1	24.1	24.1	24.1	24.0	23.7
Std. dev. of X	32.1	31.8	31.8	31.8	32.1	32.7
n(Transport facilities (area) within 1000m buffer > 0)	723	694	694	694	678	631
n(Clusters)	–	30	30	29	29	28
N	771	742	742	741	720	670

Note: Transport facilities area within 1000m buffer is the area (in 1,000 square meters) of the buffer area residence that is allocated to transport facilities land use. Figure A11 shows Model 5. Standard errors in (2)–(6) clustered at subzones. Significance levels: ^{c} 0.1 ^{b} 0.05 ^{a} 0.01.

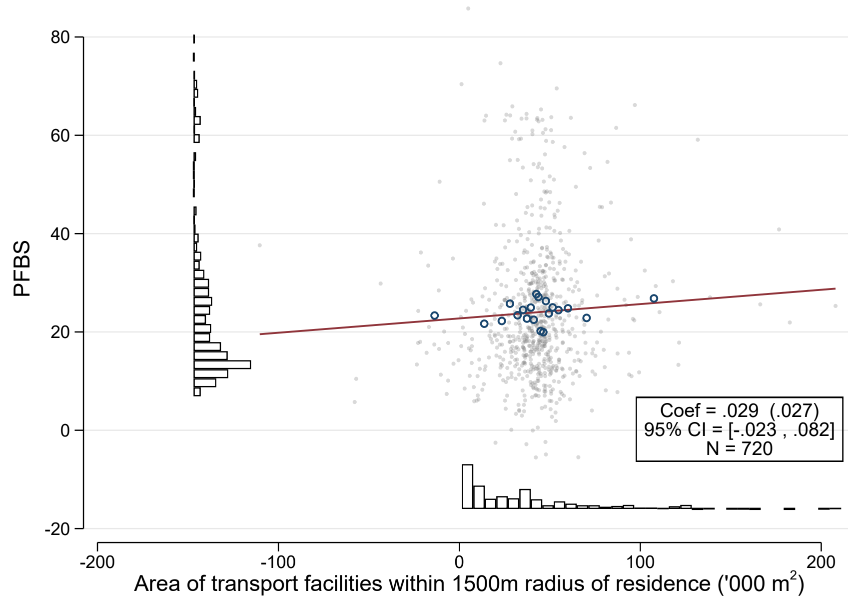


Figure A12. PFBS and Transport Facilities area within 1500m radius. Reported estimates are from regressing PFBS on the area (1,000) of transport facilities within 1500m radius of residence, with subzone fixed effects and maternal characteristics partialed out. Model corresponds to column (5) of Table A5. Standard errors clustered at subzones. Raw data in small gray circles. Binned data in blue hollow circles. Fitted line from the estimated model. Marginal histograms indicate the underlying distributions. Significance levels: + 0.1 * 0.05 ** 0.01 *** 0.001.

Table A5. PFBS and transport facilities within 1500m radius of residence

	Dependent variable is PFBS (ng/mL)					
	(1)	(2)	(3)	(4)	(5)	(6)
Transport facilities (area) within 1500m buffer	0.002	0.003	0.004	0.018	0.033	0.029
	(0.011)	(0.013)	(0.012)	(0.016)	(0.026)	(0.026)
Constant	24.063^a	10.578	10.420	15.855	24.955	18.952
	(0.762)	(17.422)	(16.705)	(16.921)	(21.523)	(27.304)
R^2	0.000	0.054	0.063	0.092	0.190	0.211
Maternal baselines		Yes	Yes	Yes	Yes	Yes
Income						Yes
Area fixed effects: Region			Yes			
Area fixed effects: Planning area				Yes		
Area fixed effects: Subzone					Yes	Yes
Mean Dep Var.	24.1	24.1	24.1	24.1	24.0	23.7
Std. dev. of X	55.1	54.7	54.7	54.7	55.1	55.1
n(Transport facilities (area) within 1500m buffer > 0)	770	741	741	740	720	670
n(Clusters)	–	30	30	29	29	28
N	771	742	742	741	720	670

Note: Transport facilities area within 1500m buffer is the area (in 1,000 square meters) of the buffer area residence that is allocated to transport facilities land use. Figure A12 shows Model 5. Standard errors in (2)–(6) clustered at subzones. Significance levels: ^{c} 0.1 ^{b} 0.05 ^{a} 0.01.

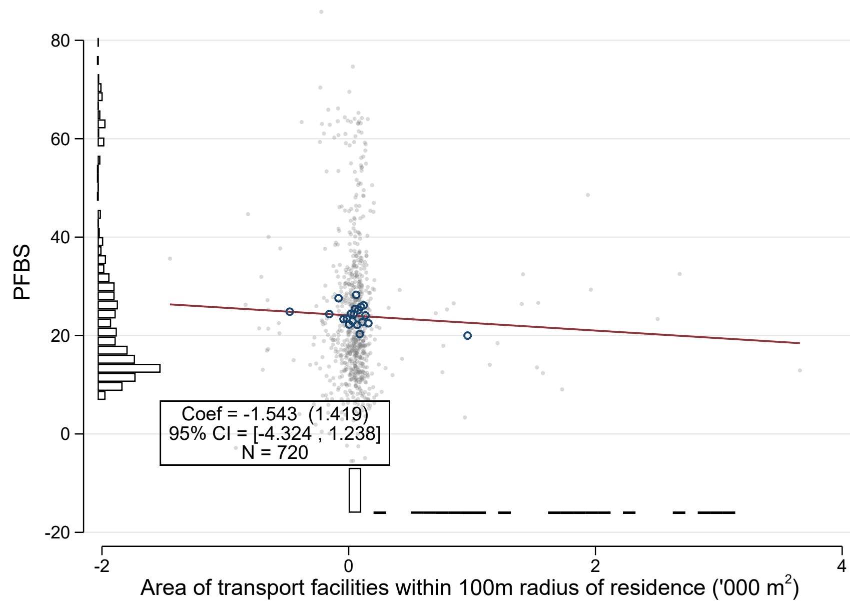


Figure A13. PFBS and Transport Facilities area within 100m radius. Reported estimates are from regressing PFBS on the area (1,000) of transport facilities within 1500m radius of residence, with subzone fixed effects and maternal characteristics partialed out. Model corresponds to column (5) of Table A6. Standard errors clustered at subzones. Raw data in small gray circles. Binned data in blue hollow circles. Fitted line from the estimated model. Marginal histograms indicate the underlying distributions. Significance levels: + 0.1 * 0.05 ** 0.01 *** 0.001.

Table A6. PFBS and transport facilities within 100m radius of residence

	Dependent variable is PFBS (ng/mL)					
	(1)	(2)	(3)	(4)	(5)	(6)
Transport facilities (area) within 100m buffer	−0.959	−1.766	−1.885	−1.424	−1.569	-2.899^c
	(1.326)	(1.390)	(1.361)	(1.349)	(1.572)	(1.569)
Constant	24.186^a	10.252	10.048	15.969	23.216	16.254
	(0.498)	(17.940)	(17.026)	(17.145)	(21.461)	(27.150)
R^2	0.000	0.055	0.065	0.091	0.189	0.212
Maternal baselines		Yes	Yes	Yes	Yes	Yes
Income						Yes
Area fixed effects: Region			Yes			
Area fixed effects: Planning area				Yes		
Area fixed effects: Subzone					Yes	Yes
Mean Dep Var.	24.1	24.1	24.1	24.1	24.0	23.7
Std. dev. of X	0.4	0.4	0.4	0.4	0.4	0.4
n(Transport facilities (area) within 100m buffer > 0)	34	34	34	34	33	30
n(Clusters)	–	30	30	29	29	28
N	771	742	742	741	720	670

Note: Transport facilities area within 100m buffer is the area (in 1,000 square meters) of the buffer area residence that is allocated to transport facilities land use. Figure A13 shows Model 5. Standard errors in (2)–(6) clustered at subzones. Significance levels: ^{c} 0.1 ^{b} 0.05 ^{a} 0.01.

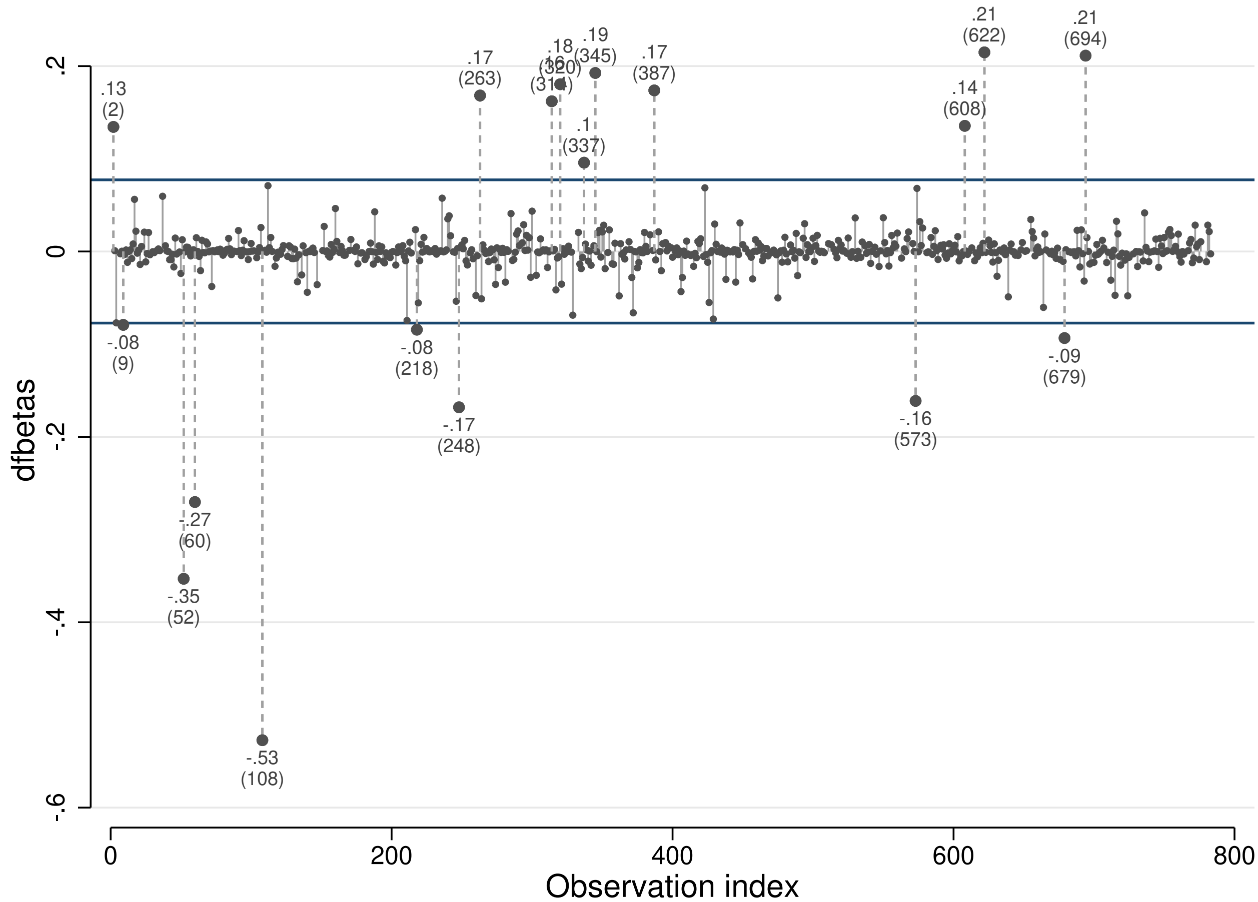


Figure A14. Figure shows the influence of each observation on the estimate of area of transport facilities within 500m radius of residence. Results corresponds to Figure A10 and Table A3. Vertical axis is the dfbeta measure standardized by the standard error of the estimate:

$$\text{dfbetas}_{(i)j} = \frac{\hat{\beta}_j - \hat{\beta}_{(i)j}}{SE(\hat{\beta}_j)}. \tag{A1}$$

where $\hat{\beta}_j$ is the estimate from omitting observation i. The paired horizontal lines are rule-of-thumb thresholds computed as $\pm 2/\sqrt{n}$. Observations falling outside the rule-of-thumb threshold highlighted with the dfbeta and observation index (in parentheses).

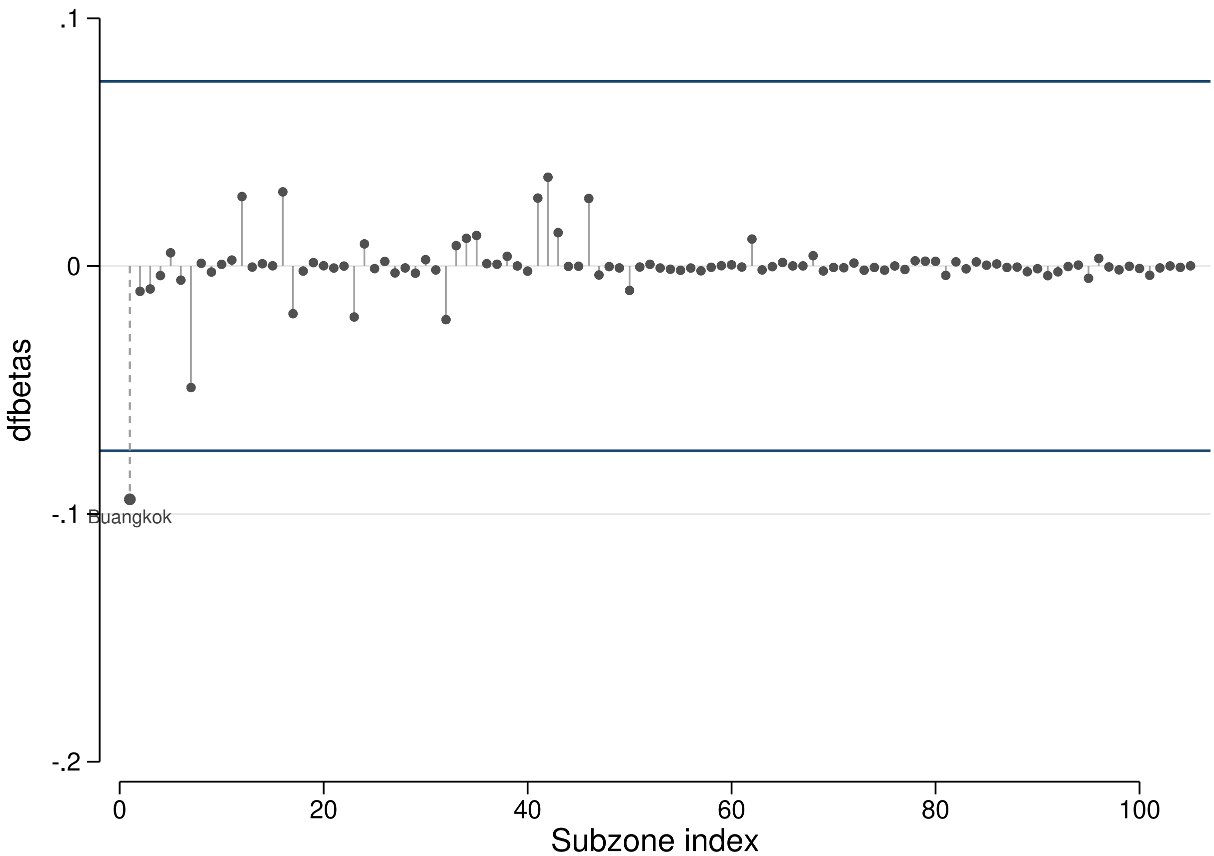


Figure A15. Figure shows the influence of each subzone on the estimations of model (5) in Table A3. Vertical axis is the dfbetas measure standardized by the standard error of the estimate:

$$\text{dfbetas}_{(c)j} = \frac{\hat{\beta}_j - \hat{\beta}_{(c)j}}{SE(\hat{\beta}_j)}.$$

where $\hat{\beta}_c$ is the estimate from omitting all observations from subzone c. The paired horizontal lines are rule-of-thumb thresholds computed as $\pm 2/\sqrt{n}$. Subzones falling outside the rule-of-thumb threshold highlighted with the dfbeta and observation index (in parentheses).

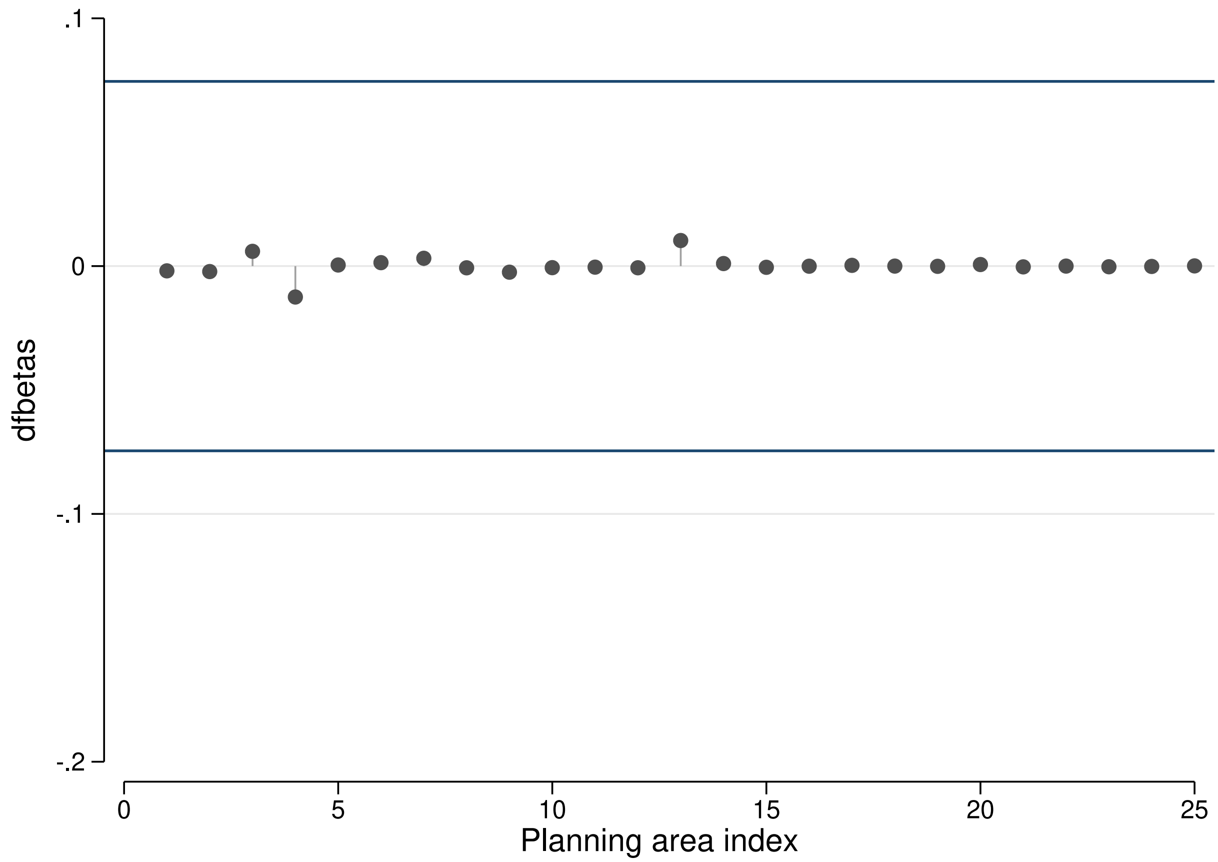


Figure A16. Figure shows the influence of each planning area on the estimations of model (5) in Table A3. Vertical axis is the dfbetas measure standardized by the standard error of the estimate:

$$\text{dfbetas}_{(c)j} = \frac{\hat{\beta}_j - \hat{\beta}_{(c)j}}{SE(\hat{\beta}_j)}.$$

where $\hat{\beta}_c$ is the estimate from omitting all observations from planning area c. The paired horizontal lines are rule-of-thumb thresholds computed as $\pm 2/\sqrt{n}$. Planning areas falling outside the rule-of-thumb threshold highlighted with the dfbeta and observation index (in parentheses).

Figure A17. Example of three participants with and without exposure.
Image source: Google Photos.

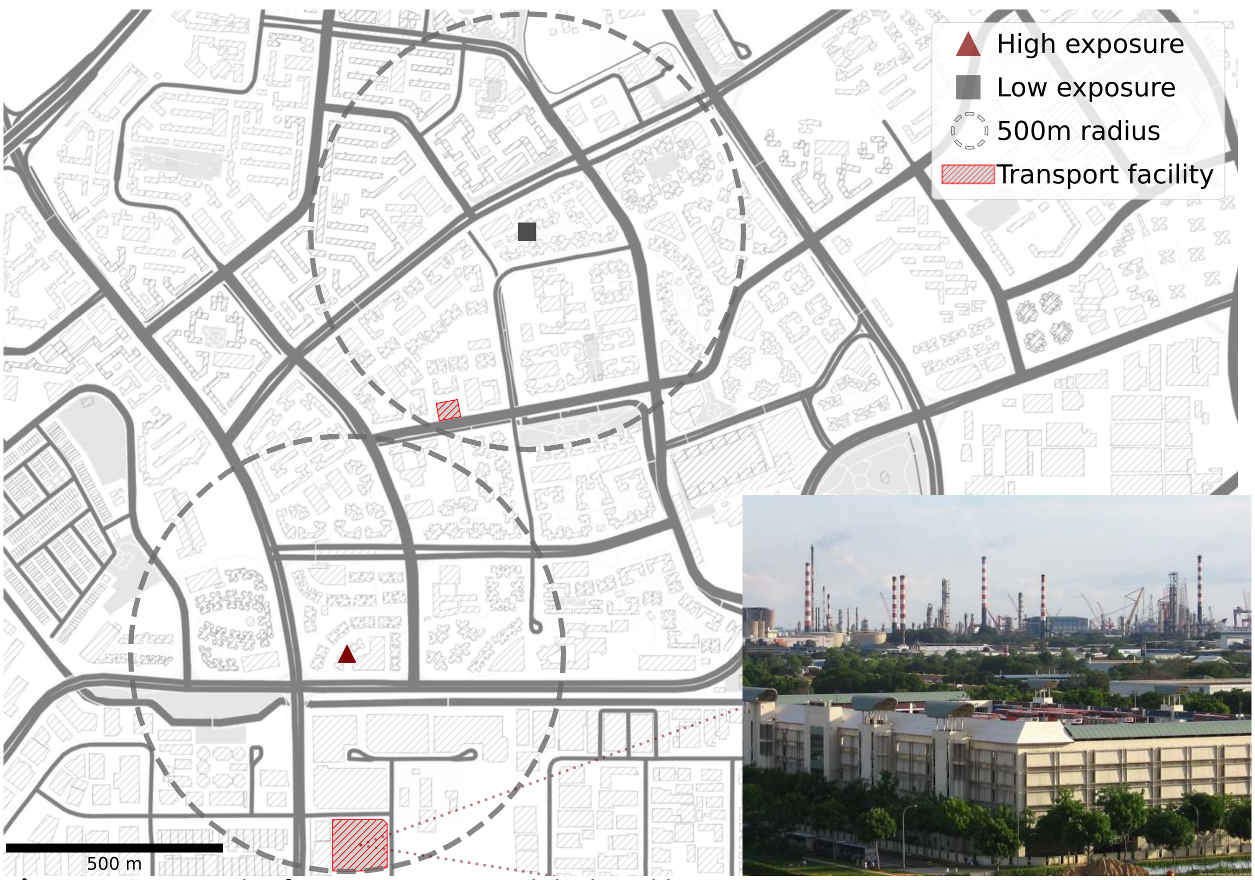


Figure A18. Example of two participants with high and low exposure.
Image source: https://en.wikipedia.org/wiki/Soon_Lee_Bus_Park#/media/File:Soon_Lee_Bus_Park_and_Jurong_Industrial_Estate_aerial_view.jpg.

B. Public-contributed street-level pictures of transport facilities

This appendix provides further details about how we attempted to pin down the specific type of transport facility using the publicly available land use data. We know where land parcels for transport facilities are located, but not the specific facility type.

To map residences to land use zones of potential hazard in our main analyses, we use the publicly-available vector data on land zones with assigned typology, such as Transport Facility. Within each land use type, there can be further breakdowns of types. For instance, a transport facility can be one of eight subtypes: 1) car park, 2) heavy vehicle park, 3) trailer park, 4) bus depot/terminal, 5) transport depot, 6) MRT/LRT marshalling yard/depot, 7) driving circuit/test centre, or 8) petrol station/kiosk (Table A2). This specificity on the subtypes, however, is not present in the public data. For instance, for a given parcel of land zone assigned for transport facilities, we do not know if this would be a gas station or a transit depot.

To address this and to partially scale the solution, we systematically obtain street-level public-contributed images geotagged to the location of the transport facilities. There are, in total, 363 land parcels assigned to transport facilities in the 2008 data. We first reverse-geocode all the 298 transport facilities whose centroids are within 1000m of a GUSTO residence, using the centroid coordinate.[1] From this, we obtain the associated formatted address, Google Place ID, and Google Place type. We successfully recovered these for 246 transport facility land parcels. The place types for these 246 are tabulated in Table A2. Each place can have more than one type. The "Establishment" and "Point of Interest" type gets tagged to most (n = 208). Store, food, and convenience stall also get tagged to many transport facility ($n \geq 58$). This does not rule out our queried land parcels as transport facilities. Virtually all gas stations/petrol kiosks in Singapore have convenience shops that also sell food (Figure B19 and Figure B20). Many of the tagged pictures we later see (Figure B20) are also of these known convenience stalls (e.g., 7-Eleven, FairPrice Xpress, etc.) commonly found in gas stations, more on the pictures below. Other observations are that 58 are typed as gas stations, 20 as car wash (which can also be found in gas stations, Figure B21), 17 as transit stations, 2 as subway station, and 1 as a bus station.

To further gain insights into the transport facility land use, we use the 246 place ID to obtain a list of photo IDs tagged to the place,[2] before finally using the photo IDs to download the photos.[3] We successfully obtained at least one street-level photo for 193 of the transport facility land parcels. In total, we have 1135 photos, and we looked

[1] Using the Google Geocoding Service: `https://developers.google.com/maps/documentation/javascript/geocoding`.

[2] Using the Google Places Service: `https://developers.google.com/maps/documentation/places/web-service/details`.

[3] Using the Google Photos Service: `https://developers.google.com/maps/documentation/places/web-service/photos`.

through all of them. Figure B19 shows an assort of photos related to gas stations while Figure B22 shows an assortment of photos broadly related to transit depots. The Places service also returns the name of the point of interest, if available, but we do not find this to be a particularly clear signal of transport facility type. For instance, one place name we recovered is "LKA Auto Parts Trading Pte Ltd," but upon inspection of the tagged photos, it became apparent that it is a gas station (image D in Figure B19).

Overall, many photos of transport facilities appear to be gas stations/petrol kiosks or transit depots. The assumption here is that the other types of transport facilities (Table A2) are rare and do not have some attribute that makes them less likely to be captured in the places and photos database or less likely to be captured in pictures by the public. Linking the photos to the underlying spatial data, we observe that gas stations occupy relatively small land areas. In Figure B19, the gas station in subfigure (a) has a known land area (and closest centroid-to-point distance to a GUSTO residence point) of 1,190m^2 (414m), the gas station in subfigure (b) is 800m^2 (180m), the gas station in subfigure (b) is 1,862m^2 (898m), and the gas station in subfigure (d) is 2,600m^2 (214m). The land parcels that appear to be transit depots are far larger. The bus depot in subfigure (a) of Figure B22 is 52,608m^2, and the closest centroid-to-point (not edge-to-point) distance to a GUSTO residence point is 963m. The bus depot in Figure 1 is 25,981m^2 with the nearest GUSTO residence within 592m. For reference, one of the larger gas stations we find is 4,055m^2 and is within 976m of a GUSTO residence (Figure B23). All street-level photos (Figures B19 to B23) in this manuscript are public contributed but taken directed via the Google Photos API (unless otherwise stated).

Table B7. Types of detected places in transport facilities parcels

	Type	Count
1	Establishment	208
2	Point Of Interest	208
3	Store	80
4	Food	67
5	Convenience Store	58
6	Gas Station	58
7	Car Wash	20
8	Atm	19
9	Finance	19
10	Transit Station	17
11	Car Repair	14
12	Restaurant	13
13	Grocery Or Supermarket	6
14	Supermarket	6
15	Place Of Worship	4
16	Park	3
17	Meal Delivery	3
18	Parking	3
19	Subway Station	2
20	Cafe	2
21	Bakery	2
22	Clothing Store	1
23	Tourist Attraction	1
24	Street Address	1
25	Health	1
26	General Contractor	1
27	Bus Station	1
28	Car Rental	1
29	Home Goods Store	1
30	Car Dealer	1

Note: Types come from the Google Geocoding API. See Figure 2. For n = 246 Google places. Types are not mutually exclusive, places can have multiple types. Types are not necessarily accurate nor complete.

(a) Cencon Bldg

(b) 76 Yio Chu Kang Rd

(c) 324 Thomson Rd

(d) 603 Tiong Bahru Rd

Figure B19. Petrol Stations. Selected illustrations of petrol stations and kiosks in transport facilities land parcels within 1000m of known (GUSTO) residences. Photos are from the Google Place Photo service which source from photos that are user-submitted and photos from managers of establishments.
Image source: Google Photos.

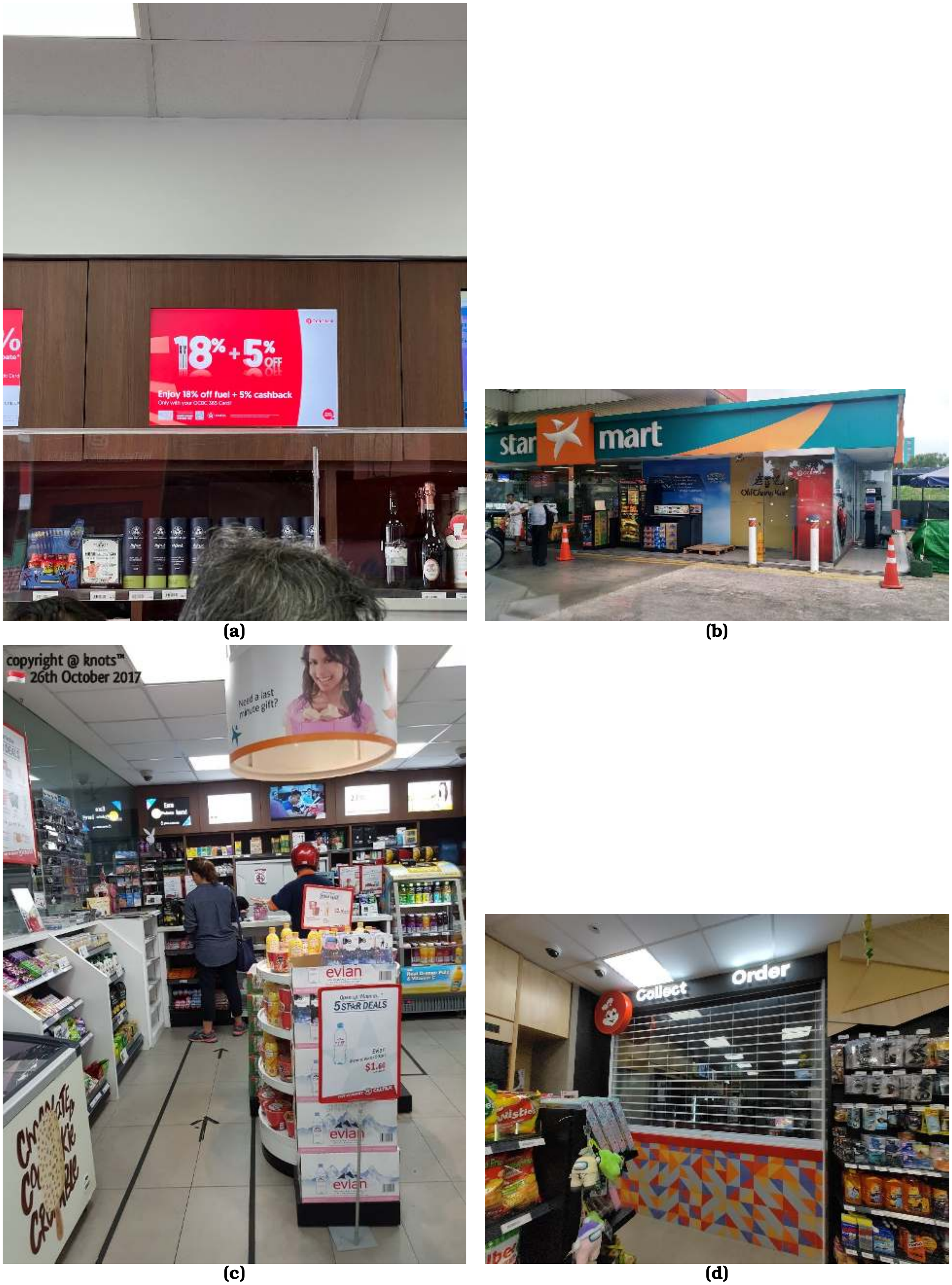
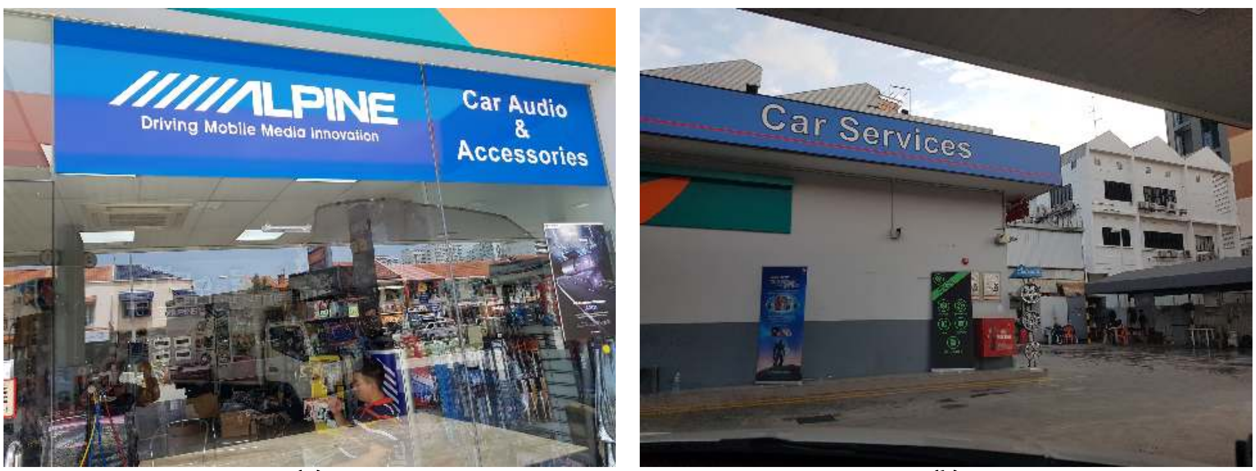


Figure B20. Food and convenience shops in gas stations.
Image source: Google Photos.



(a) (b)

Figure B21. Car wash and car repair services in gas stations.
Image source: Google Photos.

(a) Bukit Batok Bus Depot

(b) Yio Chu Kang Bus Interchange

(c) Bukit Merah Interchange

(d) (Before) Jurong East Station

(e) St. Michael's Terminal

(f) Bangkit Station

Figure B22. Transport depots, terminals, and stations. Selected illustrations of transport depots in transport facilities land parcels within 1000m of known (GUSTO) residences. Photos are from the Google Place Photo service which source from photos that are user-submitted and photos from managers of establishments.
Image source: Google Photos.

Figure B23. Larger gas station at 4,055m^2.
Image source: Google Photos.

C. Other land uses

This appendix considers and reports results for all other land use types. The spatial vector data on land parcels and their land uses come from the URA official land use data in Singapore. The master plans are released on a roughly five-year cadence. For the main evaluations, we use the 2008 version, which is closest to when blood samples were collected. In the 2008 version, there are more than 110k delineated land parcels of 32 land types over 776km^2 of land in the 2008 plan.

Figure C24 reports the within-subzone correlation of transport facilities with all other land use types. The measures of the land uses are as defined in Section 2.3 of the main article and share the same units. We observe that four land use types—Place of Worship, Residential, Business 1 - White, and Port/Airport—are negatively correlated with the transport facility land use. Another four land use types—Residential/Institution, Business 2, Business Park - White, and Business 2 - White—are positively correlated with the transport facility land use. Business 1 and Business 2 broadly refers to light and heavy industry uses, respectively (see https://web.archive.org/web/20240717071728/https://www.ura.gov.sg/-/media/Corporate/Planning/Master-Plan/MP19writtenstatement.pdf?la=en#page=11.) The estimated coefficients are adjusted for subzone areal effects and standard errors are clustered at the planning areas.

Figure C25 reports the estimated association between the plasma PFBS concentration with all the other land uses, in addition to transport facilities. We observe statistically significant and fairly large estimated coefficients for Business 2 - White and Light Rapid Transit (LRT). Although it may be interpreted as a signal of potentially hazardous sites, we also note that in 2008, there were only three Business 2 - White land parcels (14 today) with a collective land area of 0.09km^2 (0.17km^2 today). For the LRT, in 2008 there were only 14 parcels (15 today) with a collective land area of 0.01km^2 (0.02km^2 today).

General industrial areas. Factories and industrial plants are the known land parcels of concern. However, residences near industrial sites in our urban setting are rare. General industrial ("Business 2") areas have a regulatory minimum nuisance buffer of 100m (approximately 330 feet). In 2008, there were 5,576 land parcels used for heavy industry with a collective land area of 118km^2 (approximately 15.2% of total land area), but most are geographically clustered outside residential neighborhoods (Figure A1). In practice, the industrial areas also usually more than clear the regulatory minimum. The nearest distance from our participants to a general industrial land use parcel is 45 meters by edge of the land parcel 70 meters by of land parcel, and only 163 participants have an industrial land use parcel intersecting within 500m of their residence. For that single residence within 45 meters of a industrial land parcel, we checked and the corresponding industrial site is small on average—with a land parcel of approximately 2,000m^2—which is small relatively to the collectively areas of industrial sites on the outskirts of neighborhoods (see Figure A1). Using distance to centroid, only one residence is within 100 meters. For distance to edge, 18 residences are within 100 meters.

Transport facilities do not share these regulatory buffers and can locate right next to residential buildings (Figure A17 and Figures A2 to A7). For distance to centroid, 33 residences are within 100 meters of a transport facility. For distance to edge, 72 residences are within 100 meters of a transport facility. By distance to edge (distance to centroid), residences in our sample with blood collections live as near as within 18 meters (40 meters) of a transport facility. There are 363 transport facility land parcels with a collective land area of 2.3km^2 (approximately 0.3% of total land area). Base on distance to edge (distance to centroid), the nearest transport facility is within 18 meters (40 meters) of a residence. While the collective land area is fairly small, these transport facilities are scattered geographically. For additional context, we use about 120k of known postal codes and compute the percentage of area attributed transport facilities and industrial land parcels within a 500m concentric circle as 0.38% (SD 1.1%) and 4.83% (SD 15.79%), respectively. When we subset postal codes to known public residences, the numbers change to 0.41% (SD 1.27%) and 1.63% (SD 1.27), suggesting that the industrial areas tend to be placed further away from residential areas.

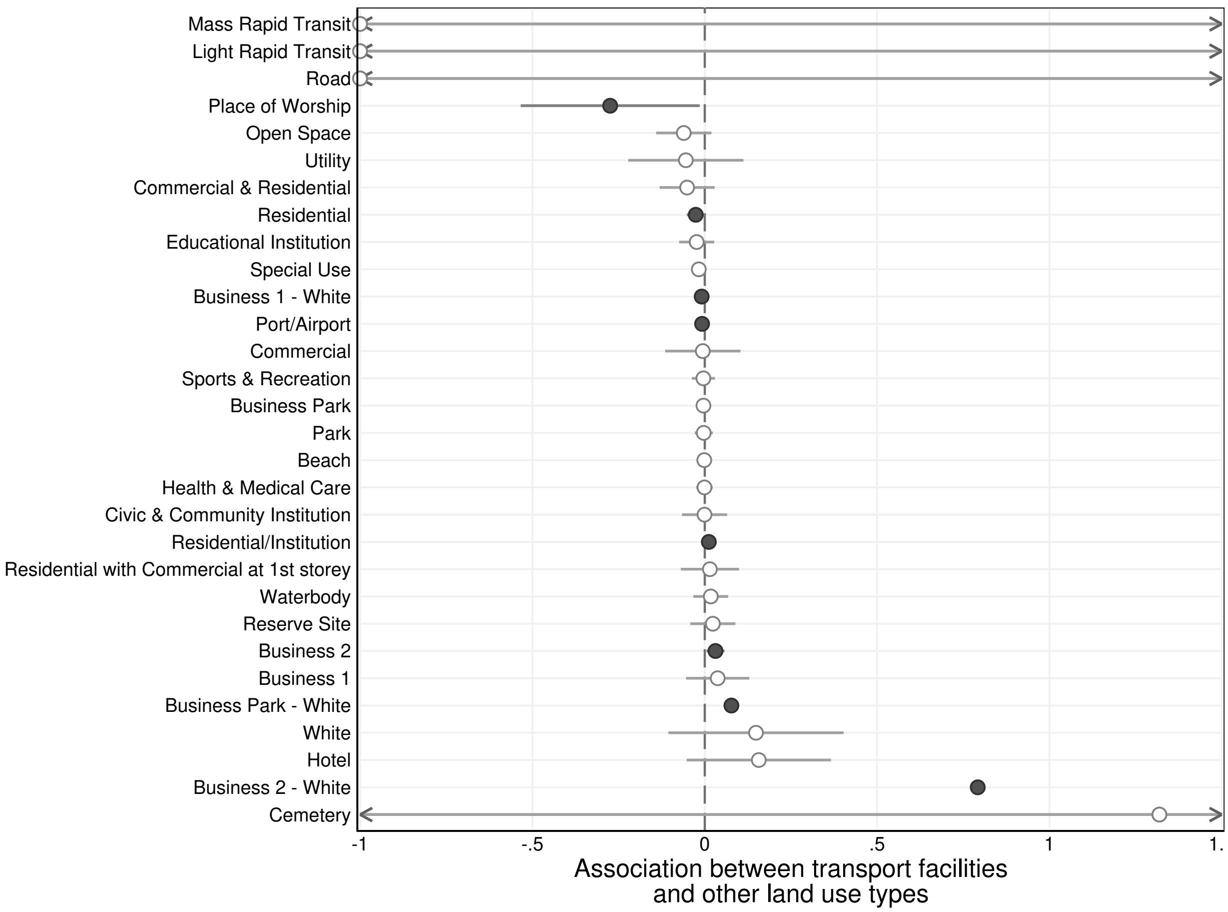


Figure C24. Correlation of transport facilities to other land use types. Horizontal axis reports the $\hat{\beta}$ coefficients from estimating

$$\text{transport facilities}_{ic} = \beta(\text{land use})^{\text{j}}_{ic} + \delta_c(\text{subzone})_c + \varepsilon_{ic}, \tag{C2}$$

where $(\text{land use})^{\text{j}}$ is one of the land use types indicated on the vertical axis. All variables are area within 500m radius of residence. Estimates significant at the 5% level have black markers; the remaining estimates have hollow markers. Gray horizontal lines are the 95% confidence intervals constructed from standard errors clustered at planning areas. Arrows indicate truncated confidence intervals.

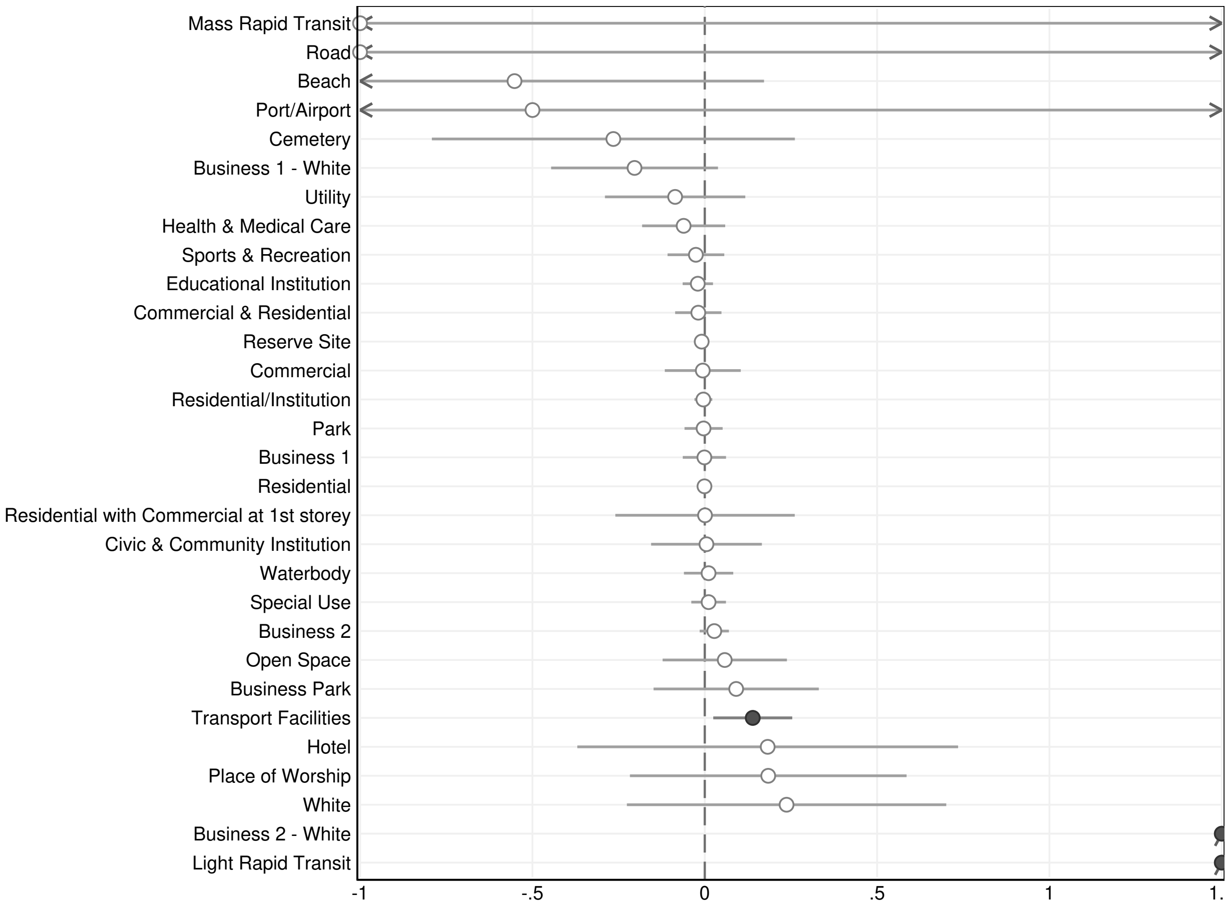


Figure C25. Association between PFBS and land use types. Horizontal axis reports the $\hat{\beta}$ coefficients from estimating

$$\text{PFBS}_{ic} = \beta(\text{land use})^{\text{j}}_{ic} + \gamma X_i + \delta_c(\text{subzone})_c + \varepsilon_{ic}, \tag{C3}$$

where (land use)$^{\text{j}}$ is area (units in 1'000m^2) of the land use type indicated on the vertical axis. Model is equivalent to model (5) of Table A3. Estimates significant at the 5% level have black markers. Gray horizontal lines are the 95% confidence intervals constructed from standard errors clustered at planning areas. Arrows indicate truncated confidence intervals.

D. Other spatial instruments

To help examine nuanced spatial patterns in the areal proximity to transport facilities, and as an auxiliary exploration of the exposure mechanism, this appendix evaluates a handful of alternative spatial instruments of the exposure measure defined in Section 2.3.

The four alternative instruments are: i) distance to nearest transport facility by a point-to-edge distance from the point of residence to the edge of the land parcel, ii) distance to nearest transport facility by a point-to-centroid distance from the point of residence to the geometric centroid of the land parcel, iii) number of transport facilities within the concentric circle, and iv) accessibility-based area around residence based on areas within 10–20-minute reach by public transit (including walking). As a caveat, the public travel time data was collected around 2021. These alternative spatial instruments that are potentially linked to the main exposure measure defined in Section 2.3 through spatial patterns relating to where residences and transport facilities according to urban planning, but potentially have no direct pathway to PFAS exposure. More concretely, if exposure is also tied to the size of the facility, residences near transport facilities are likely similar to residences with high exposure as defined in Section 2.3 but otherwise should not share the same level of exposure. Figure D26 reports the correlation between the four key alternative instruments (p-values $< .001$).

Table D8 report the estimates for the different models for the point-to-edge distance to the nearest transport facility. Models and adjustments are otherwise similar to Equation (1) and Table A3. We observe no association between proximity measured by distance to nearest transport facility and the plasma PFBS concentration. From Model 5, the estimated coefficient is -0.676 (SE 3.38, $p = .843$, Table D8), which implies that a standard deviation decrease in distance to the nearest transport facility ($\sim$300m) is related to a -0.2 decrease in PFBS (SE 0.01). Table D9 reports the estimates for nearest distance to transport facilities measured as point of residence to the geometric centroid of the land parcel. We do not observe any statistically significant association here.

Table D10 reports the estimates using the number instead of total area of transport facilities in the concentric circle of 500m radius. The estimated coefficients here are consistently positive but not statistically significant at conventional levels. In Model 5, the estimated coefficient is 0.911 (SE 0.614, $p = .149$, Table D10), which implies that an additional land parcel for transport facility within the concentric circle is associated with a 0.9 point increase in the plasma PFBS concentration (0.06 of the SD).

Table D12 reports the estimation using a 15-min travel buffer around residences to compute exposure. The estimated coefficients across the models are negative but not statistically significant. The estimated association for Model 5 is -0.014 (SE 0.069, $p = .841$, Table D12). Using a 10-min buffer reported in Table D11 and a 20-min buffer reported in Table D13 yield similar null findings.

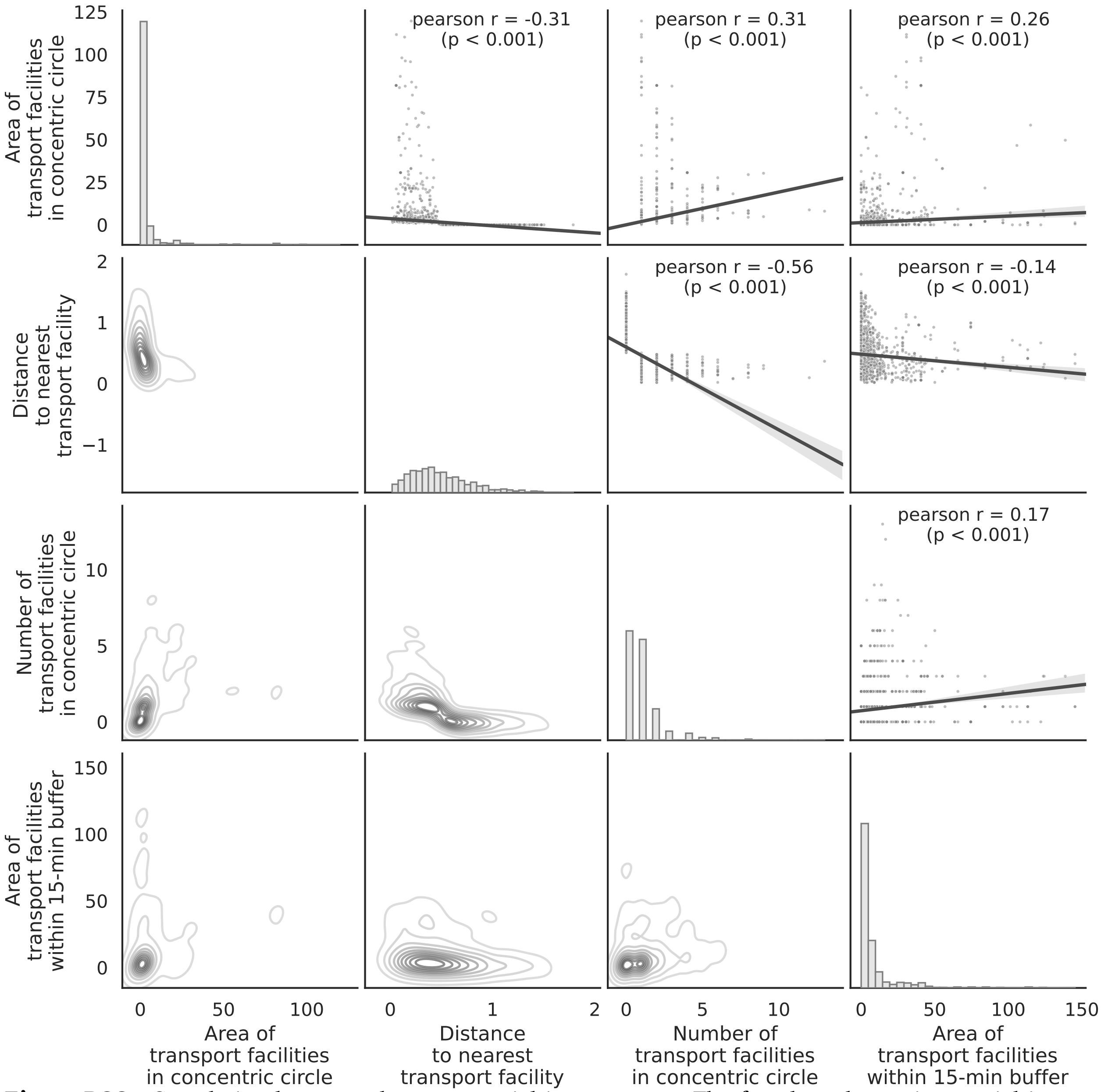


Figure D26. Correlation between alternate spatial instruments. The four key alternative spatial instruments of transport facilities are: (1) area of transport facilities within concentric cirlce (main instrument in Section 2.3), (2) distance to nearest transport facilities, (3) number of transport facilities in concentric circle, and (4) area of transport facilities within 15-minute of residence. Confidence intervals are bootstrapped (n = 1000). Main diagonal reports the univariate histogram.

Table D8. PFBS and (point-to-edge) distance to nearest transport facility

	Dependent variable is PFBS (ng/mL)					
	(1)	(2)	(3)	(4)	(5)	(6)
Distance to nearest transport facility	−1.255	−0.284	−0.978	−1.449	−0.676	1.091
	(2.056)	(2.115)	(1.911)	(2.023)	(3.384)	(3.286)
Constant	24.737^{a}	11.151	11.619	17.809	24.801	17.482
	(0.945)	(18.944)	(17.973)	(18.122)	(23.320)	(29.096)
R^2	0.001	0.054	0.063	0.091	0.188	0.209
Maternal baselines		Yes	Yes	Yes	Yes	Yes
Income						Yes
Area fixed effects: Region			Yes			
Area fixed effects: Planning area				Yes		
Area fixed effects: Subzone					Yes	Yes
Mean Dep Var.	24.1	24.1	24.1	24.1	24.0	23.7
Std. dev. of X	0.3	0.3	0.3	0.3	0.3	0.3
n(Distance to nearest transport facility > 0)	771	742	742	741	720	670
n(Clusters)	–	30	30	29	29	28
N	771	742	742	741	720	670

Note: The main independent variable—Distance to nearest transport facility—is the nearest distance from the given participant residence to the nearest transport facility land parcel computed as point-to-edge distance (in 1,000 meters). Other than the spatial instrument of exposure to transport facilities, models and adjustments are the same as in Equation (1) and Table A3. Standard errors in (2)–(6) clustered at subzones. Significance levels: ^{c} 0.1 ^{b} 0.05 ^{a} 0.01.

Table D9. PFBS and (point-to-centroid) distance to nearest transport facility

	Dependent variable is PFBS (ng/mL)					
	(1)	(2)	(3)	(4)	(5)	(6)
Distance to nearest transport facility	−0.883	0.102	−0.565	−0.810	0.123	1.872
	(2.067)	(2.116)	(1.913)	(1.994)	(3.282)	(3.145)
Constant	24.590^{a}	10.845	11.295	17.273	24.012	16.635
	(1.037)	(18.945)	(17.957)	(18.036)	(23.067)	(28.776)
R^2	0.000	0.054	0.063	0.090	0.188	0.209
Maternal baselines		Yes	Yes	Yes	Yes	Yes
Income						Yes
Area fixed effects: Region			Yes			
Area fixed effects: Planning area				Yes		
Area fixed effects: Subzone					Yes	Yes
Mean Dep Var.	24.1	24.1	24.1	24.1	24.0	23.7
Std. dev. of X	0.3	0.3	0.3	0.3	0.3	0.3
n(Distance to nearest transport facility > 0)	771	742	742	741	720	670
n(Clusters)	–	30	30	29	29	28
N	771	742	742	741	720	670

Note: The main independent variable—Distance to nearest transport facility—is the nearest distance from the given participant residence to the nearest transport facility land parcel computed as point-to-centroid distance in meters (in 1,000 meters). Other than the spatial instrument of exposure to transport facilities, models and adjustments are the same as in Equation (1) and Table A3. Standard errors in (2)–(6) clustered at subzones. Significance levels: ^{c} 0.1 ^{b} 0.05 ^{a} 0.01.

Table D10. PFBS and the number of transport facilities

	Dependent variable is PFBS (ng/mL)					
	(1)	(2)	(3)	(4)	(5)	(6)
Transport facilities within 500m	0.482	0.538	0.791	0.879^{c}	0.911	0.381
	(0.484)	(0.485)	(0.490)	(0.501)	(0.614)	(0.668)
Constant	23.636^{a}	10.484	10.127	15.898	24.112	18.389
	(0.803)	(18.292)	(17.457)	(17.614)	(22.027)	(27.758)
R^2	0.002	0.056	0.067	0.095	0.190	0.209
Maternal baselines		Yes	Yes	Yes	Yes	Yes
Income						Yes
Area fixed effects: Region			Yes			
Area fixed effects: Planning area				Yes		
Area fixed effects: Subzone					Yes	Yes
Mean Dep Var.	24.1	24.1	24.1	24.1	24.0	23.7
Std. dev. of X	1.4	1.4	1.4	1.4	1.4	1.4
n(Transport facilities within 500m > 0)	458	439	439	439	426	399
n(Clusters)	–	30	30	29	29	28
N	771	742	742	741	720	670

Note: The main independent variable is the number of transport facilities within the 500m concentric circle. Models and adjustments are the otherwise the same as in Equation (1) and Table A3. Standard errors in (2)–(6) clustered at subzones. Significance levels: ^{c} 0.1 ^{b} 0.05 ^{a} 0.01.

Table D11. PFBS and transport facilities within 10 min of residence

	Dependent variable is PFBS (ng/mL)					
	(1)	(2)	(3)	(4)	(5)	(6)
Transport facilities (area) within 10min	−0.005	−0.005	0.004	0.011	−0.109	−0.099
	(0.177)	(0.158)	(0.145)	(0.149)	(0.113)	(0.103)
Constant	24.147^{a}	10.129	9.336	14.461	22.272	16.424
	(0.600)	(18.207)	(17.389)	(17.361)	(21.962)	(26.756)
R^2	0.000	0.047	0.056	0.086	0.188	0.212
Maternal baselines		Yes	Yes	Yes	Yes	Yes
Income						Yes
Area fixed effects: Region			Yes			
Area fixed effects: Planning area				Yes		
Area fixed effects: Subzone					Yes	Yes
Mean Dep Var.	24.1	24.1	24.1	24.1	23.9	23.7
Std. dev. of X	4.2	4.2	4.2	4.2	4.0	4.1
n(Transport facilities (area) within 10min > 0)	271	263	263	263	252	230
n(Clusters)	–	28	28	28	28	27
N	744	715	715	715	695	646

Note: Transport facilities area is the area (in 1,000 square meters) within 15 minutes of residence that is allocated to transport facilities land use. Maternal characteristics include (i) age at delivery (quadratic), (ii) ethnicity, (iii) education, (iv) occupation, (v) marital status, and (vi) housing type. Income includes mother's income and household income (binned). Standard errors in (2)–(6) clustered at subzones. Significance levels: ^{c} 0.1 ^{b} 0.05 ^{a} 0.01.

Table D12. PFBS and transport facilities within 15 min of residence

	Dependent variable is PFBS (ng/mL)					
	(1)	(2)	(3)	(4)	(5)	(6)
Transport facilities (area) within 15min	−0.017	−0.005	−0.010	−0.002	−0.014	0.004
	(0.043)	(0.042)	(0.046)	(0.051)	(0.069)	(0.067)
Constant	24.276^a	10.146	9.255	14.415	22.484	16.453
	(0.727)	(18.424)	(17.561)	(17.491)	(21.991)	(26.754)
R^2	0.000	0.047	0.056	0.086	0.188	0.212
Maternal baselines		Yes	Yes	Yes	Yes	Yes
Income						Yes
Area fixed effects: Region			Yes			
Area fixed effects: Planning area				Yes		
Area fixed effects: Subzone					Yes	Yes
Mean Dep Var.	24.1	24.1	24.1	24.1	23.9	23.7
Std. dev. of X	16.3	16.3	16.3	16.3	16.2	16.5
n(Transport facilities (area) within 15min > 0)	576	553	553	553	535	496
n(Clusters)	–	28	28	28	28	27
N	744	715	715	715	695	646

Note: Transport facilities area is the area (in 1,000 square meters) within 15 minutes of residence that is allocated to transport facilities land use. Maternal characteristics include (i) age at delivery (quadratic), (ii) ethnicity, (iii) education, (iv) occupation, (v) marital status, and (vi) housing type. Income includes mother's income and household income (binned). Standard errors in (2)–(6) clustered at subzones. Significance levels: ^{c} 0.1 ^{b} 0.05 ^{a} 0.01.

Table D13. PFBS and transport facilities within 20 min of residence

	Dependent variable is PFBS (ng/mL)					
	(1)	(2)	(3)	(4)	(5)	(6)
Transport facilities (area) within 20min	−0.010	−0.004	−0.012	−0.007	−0.039	−0.028
	(0.017)	(0.018)	(0.021)	(0.021)	(0.036)	(0.034)
Constant	24.382^a	10.424	9.964	14.543	23.788	18.077
	(0.729)	(18.265)	(17.357)	(17.429)	(21.822)	(26.827)
R^2	0.001	0.047	0.057	0.086	0.190	0.213
Maternal baselines		Yes	Yes	Yes	Yes	Yes
Income						Yes
Area fixed effects: Region			Yes			
Area fixed effects: Planning area				Yes		
Area fixed effects: Subzone					Yes	Yes
Mean Dep Var.	24.1	24.1	24.1	24.1	23.9	23.7
Std. dev. of X	35.7	36.1	36.1	36.1	35.5	35.9
n(Transport facilities (area) within 20min > 0)	701	672	672	672	653	608
n(Clusters)	–	28	28	28	28	27
N	744	715	715	715	695	646

Note: Transport facilities area is the area (in 1,000 square meters) witin 20 minutes of residence that is allocated to transport facilities land use. Maternal characteristics include (i) age at delivery (quadratic), (ii) ethnicity, (iii) education, (iv) occupation, (v) marital status, and (vi) housing type. Income includes mother's income and household income (binned). Standard errors in (2)–(6) clustered at subzones. Significance levels: ^{c} 0.1 ^{b} 0.05 ^{a} 0.01.

E. Movers and future exposure

This appendix details how we focus on the subset of known movers in the GUSTO cohort since the start of the study and assess whether their future exposure is able to predict their past plasma PFBS concentration.

The fundamental concern is that the choice of residence is rarely random. Some unmeasured family characteristics might potentially correlate with lifestyle habits and non-point PFAS exposures which at the same time determines residence in a way that systematically leads to residential proximity to transport facilities, such locating near edges of neighborhoods or arterial roads. To help rule out this channel of confounding, we exploit the trail of GUSTO residence into the future (around 2022). Figure E27 provides a graph of this approach where there should be no association between future exposure and the (past) PFAS measures.[4]

We identify movers based on changes in reported residential addresses. More than half of the GUSTO participants in our sample (59%) have moved since the start of the study around 2009. We use the latest known residential address of these "movers" to compute the exposure to transport facilities, which is as defined in Section 2.3, except that residence is based on the latest residence and the spatial distribution of transport facilities is based on the 2019 versions. The plasma PFBS measurement remains the same version as the one collected during the start of the study around 2009. The regions, planning areas, and subzones are also based on the 2019 versions by mapping the postal codes onto the 2019 vector data.

Table E14 starts by repeating the model estimations defined in Equation (1) and reported in Table A3, but only for participants who moved in the future. We see that the associations are broadly comparable to the full sample (Table A3). For Model 5, the estimated association is 0.174 (SE 0.073, p = .025, Table E14) which is similar to the estimated association from the main analyses (0.153, SE 0.056, p = .019, Table A3). The estimated association from Model 6 is similar (0.174, SE 0.098, p = .090, Table E14).

Table E15 then reports the estimated associations between future exposure, as a negative control exposure, where we know that future exposure should not be able to predict pass plasma PFBS concentration through some unmeasured family characteristic(s) determining location choice. We do not see any statistically significant association for any model. The estimated coefficient under Model 5 is negative but not statistically significant (-0.057, SE 0.115, p = .623, Table E15). Model 6 has similar null findings (-0.075, SE = 0.132, p = .576, Table E15).

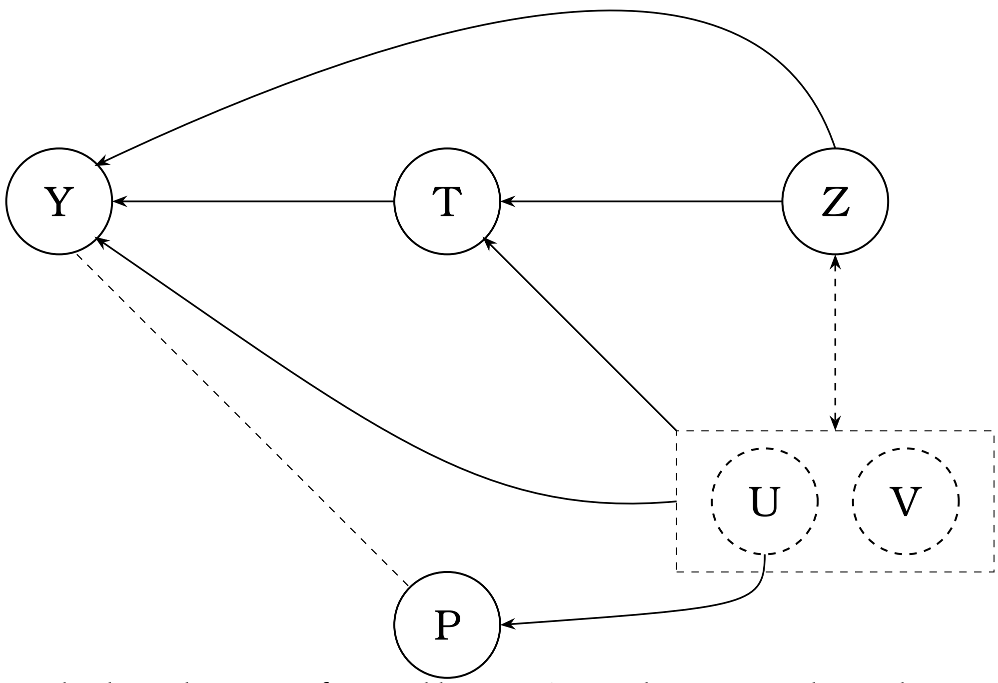


Figure E27. Placebo evaluation via future addresses. Our study is interested in evaluating the relation between plasma PFAS measures (Y) and exposure to transport facilities (T). Our models account for certain (observable) baselines (Z; Section 2.5). Our models omit certain unobserved characteristics (U and V) linked to both Y and T (and potentially Z). Part of this unmeasured baseline may capture families residential choice that might affect T (U). This U should also affect future exposure to transport facilities (P) but otherwise have no relationship to past plasma PFAS concentration (Y). V is an unobserved confounder that is intractable.

Table E14. PFBS and area of transport facilities within 500m radius (Movers only).

	Dep. var. is PFBS					
	(1)	(2)	(3)	(4)	(5)	(6)
Transport facilities (area) within 500m buffer	0.060	0.102^c	0.109^c	0.202^a	0.174^b	0.174^c
	(0.053)	(0.058)	(0.061)	(0.049)	(0.073)	(0.098)
Constant	23.896^a	10.884	9.721	1.972	4.683	12.631
	(0.654)	(24.644)	(24.029)	(21.104)	(25.023)	(32.057)
R^2	0.001	0.064	0.071	0.131	0.289	0.316
Maternal baselines		Yes	Yes	Yes	Yes	Yes
Income						Yes
Area fixed effects: Region			Yes			
Area fixed effects: Planning area				Yes		
Area fixed effects: Subzone					Yes	Yes
Mean Dep Var.	24.1	24.1	24.1	24.1	24.1	23.6
Std. dev. of X	9.9	9.9	9.9	9.9	9.9	10.0
n(Transport facilities (area) within 500m buffer > 0)	270	258	258	258	238	219
n(Clusters)	–	30	30	28	27	25
N	455	437	437	435	401	367

Note: Sample includes only known movers in the GUSTO cohort. Table is otherwise identical to Table A3. Dependent variable is PFBS (Perfluorobutanesulfonic acid) of mothers in the GUSTO sample. Transport facilities area within 500m buffer is the area (in 1,000 square meters) of the buffer area residence that is allocated to transport facilities land use. Maternal characteristics include (i) age at delivery (quadratic), (ii) ethnicity, (iii) education, (iv) occupation, (v) marital status, and (vi) housing type. Income includes mother's income and household income (binned). Standard errors in (2)–(6) clustered at subzones. Significance levels: ^{c} 0.1 ^{b} 0.05 ^{a} 0.01.

Table E15. PFBS and area of transport facilities within 500m radius (using future exposure).

	Dep. var. is PFBS					
	(1)	(2)	(3)	(4)	(5)	(6)
Transport facilities (area) within 500m buffer	−0.069	−0.081	−0.099	−0.107	−0.057	−0.075
	(0.073)	(0.085)	(0.081)	(0.081)	(0.115)	(0.133)
Constant	24.343***	8.837	9.637	13.257	−9.589	−28.506
	(0.814)	(22.177)	(21.944)	(22.725)	(26.343)	(31.363)
R^2	0.001	0.051	0.054	0.093	0.282	0.336
Maternal characteristics		Yes	Yes	Yes	Yes	Yes
Income						Yes
Region fixed effects			Yes			
Planning area fixed effects				Yes		
Subzone fixed effects					Yes	Yes
Mean of dep. var.	24.2	24.2	24.2	24.1	24.0	23.8
Std. dev. of X	6.5	6.5	6.5	6.5	6.5	6.6
Clusters	–	32	32	26	25	25
N	468	449	449	443	395	364

Note: Sample includes only known movers in the GUSTO cohort. The transport facilities area is based on the future addresses of GUSTO participants and not those around time of delivery. Table is otherwise identical to Table A3. See Table E14 for the same table but for movers only using addresses at time of delivery. Dependent variable is PFBS (Perfluorobutanesulfonic acid) of mothers in the GUSTO sample. Transport facilities area within 500m buffer is the area (in 1,000 square meters) of the buffer area residence that is allocated to transport facilities land use. Maternal characteristics include (i) age at delivery (quadratic), (ii) ethnicity, (iii) education, (iv) occupation, (v) marital status, and (vi) housing type. Income includes mother's income and household income (binned). Standard errors in (2)–(6) clustered at subzones. Significance levels: ^{c} 0.1 ^{b} 0.05 ^{a} 0.01.

F. Other PFAS

In this appendix, we test and report associations between exposure to transport facilities and the other well-measured PFAS concentrations.

F.A GUSTO PFAS measurements

The different PFAS substances have different measurement ranges (see for example, Figure 6). For ease of reporting, we scale the PFAS measurements by dividing by the standard deviation

$$\text{substance}^{\text{(scaled)}} = \frac{\text{substance}}{\sigma_{\text{(substance)}}} \tag{F4}$$

so that the interpretation of regression coefficients is how much of a standard deviation change in an input is associated with some standard deviation change in the output. For the estimates in Figure 6, where we estimate the association of exposure to transport facilities and the other PFAS substances, we also scale the area of transport facilities within residence for ease of reporting in the same scale. Importantly, we note that this linear scaling of the measurements does not aid causal inference, and separately, does not affect the t-statistics or p-values.

Figure F28 reports the correlation between perfluorobutane sulfonic acid (PFBS) and the other plasma PFAS concentrations. All measurements are scaled as described above, and the correlation is conditional on area (subzones) of the GUSTO participant. Measurements below the limit of detection (LOD) and the limit of quantification (LOQ) are first imputed by the LOD/LOQ values divided by $\sqrt{2}$. Of the other seven PFAS measurements with detection rates for at least 95% of participants (Table A1), we note a positive correlation between the plasma PFBS concentration and perfluorohexane sulfonic acid (PFHxS) perfluoroundecanoic acid (PFUnDA), and perfluorodecanoic acid (PFDA).

To test the association between the other seven plasma PFAS concentrations and exposure to transport facilities around area, we estimate

$$\begin{aligned}\text{substance}^{\text{(scaled)}}_{ic} = \beta(\text{Exposure to transport facilities})^{\text{(scaled)}}_{ic} \\ + \gamma X_i + \delta_c(\text{subzone})_c + \varepsilon_{ic},\end{aligned} \tag{F5}$$

where $\text{substance}^{\text{(scaled)}}_{ic}$ is the PFAS substance (indicated in the first column). The specification is otherwise identical to that in Equation (1) (to model (5) of Table A3). The PFAS substances and the exposure to transport facilities variable are scaled to have a standard deviation of one so that $\hat{\beta}$ is interpreted as how a standard deviation change in exposure to transport facilities is associated with a $\hat{\beta}$-times standard deviation change in the substance. Figure 6 reports the results.

Figure F29 reports the results from Equation (2) for all of the eight PFAS measures with scaled units. We see that higher thresholds are linked to higher associations for

PFBS in Figure 5 (and in Figure F29 with scaled units). We observe similar patterns with 1144
PFNA, PFOS, and PFDA. 1145

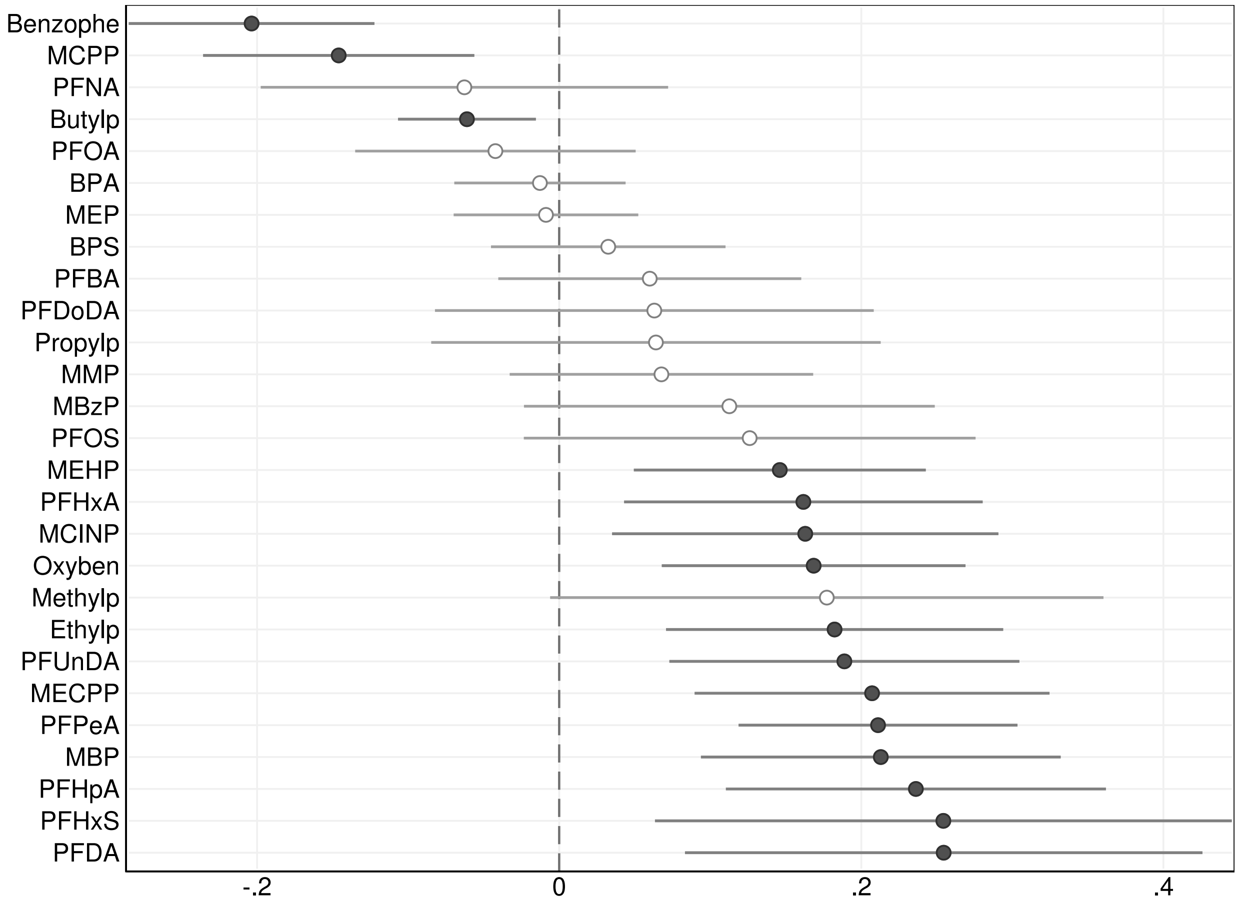
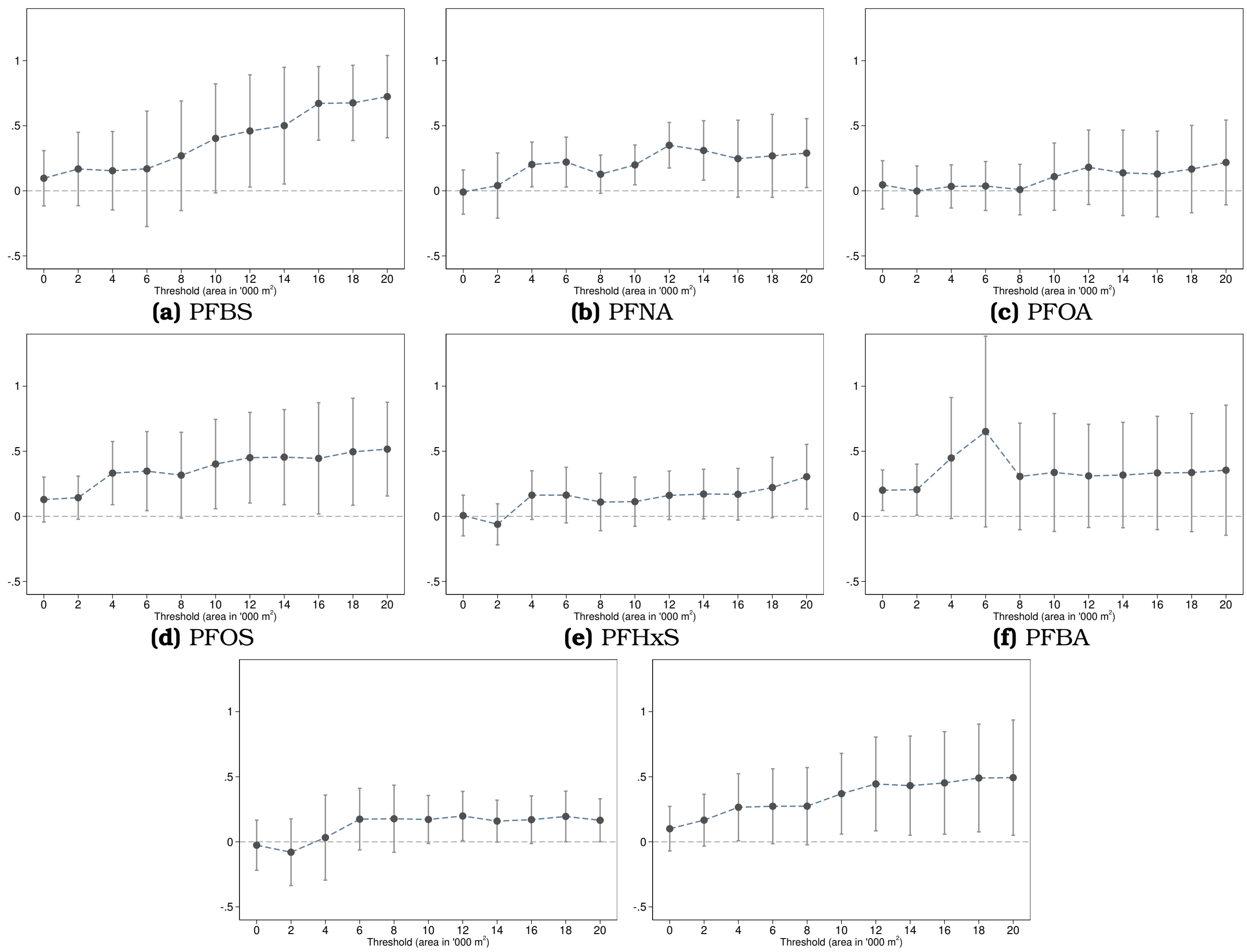


Figure F28. Correlation of PFBS (measured from cord blood) with other PFAS substances. Horizontal axis reports the $\hat{\beta}$ coefficients from estimating

$$\text{substance}_{ic}^{(\text{scaled})} = \beta \text{PFBS}_{ic}^{(\text{scaled})} + \delta_c(\text{subzone})_c + \varepsilon_{ic},$$

where substance_{ic} is one of the PFAS substances indicated on the vertical axis. Estimates significant at the 5% level have black markers; the remaining estimates have hollow markers. Gray horizontal lines are the 95% confidence intervals constructed from standard errors clustered at planning areas. Measurements that are below LOD and LOQ values are first imputed (Table A1) and then scaled to have a standard deviation of one.



(a) PFBS **(b)** PFNA **(c)** PFOA **(d)** PFOS **(e)** PFHxS **(f)** PFBA **(g)** PFUnDA **(h)** PFDA

Figure F29. Thresholds for other PFASs. PFAS measurements and the exposure measure have been scaled to have unit standard deviation. Area of transport facilities based on 500m radius.

F.B S-PRESTO PFAS measurements

We use participants from S-PRESTO, a separate cohort study in Singapore, as supplementary data for additional cross-sectional analyses. The key relevant detail to the present study is that S-PRESTO recruited participants between 2015–2017, and therefore offers a different time point for evaluation.

The S-PRESTO (Singapore Preconception Study of Long-Term Maternal and Child Outcomes) recruited N = 1,039 ethnically-diverse (Chinese, Malay, or Indian) participants aged 18–45 who intended to get pregnant and deliver in Singapore between February 2015–October 2017. Similar to GUSTO, S-PRESTO is inclusive but there were exclusion criteria for to-be mothers with existing treatments and conditions (e.g., undergoing fertility treatment or had diabetes) so that the sample included mostly healthy mother-child pairs.[4,68]

Plasma PFAS concentrations from S-PRESTO comes from a preconception plasma blood sample collected at enrollment around 2015–2017. S-PRESTO collected only maternal blood so we lack the same PFAS measurements from cord blood as a reflection of neonatal exposure. The samples were sent for testing around 2021 for 15 PFAS: perfluorohexanesulfonic acid (PFHxS), linear and branched perfluorooctanesulfonic acid (PFOS), linear perfluorooctanoic acid (PFOA), perfluorononanoic acid (PFNA), perfluoroheptanesulfonic acid (PFHpS), perfluorodecanoic acid (PFDA), perfluoroheptanoic acid (PFHpA), N-methylperfluorooctanesulfonamido acetic acid (NMeFOSAA), 6:2 polyfluoroalkyl phosphate ester (6:2 PAP), 6:2 fluorotelomer phosphate diester (6:2 diPAP), perfluorobutanesulfonic acid (PFBS), 6:2 fluorotelomer sulfonate (6:2 FTS), N-ethyl perfluorooctanesulfonamidoacetic acid (NEtFOSAA), and perfluorodecanesulfonic acid (PFDS), and perfluorooctanesulfonamide (PFOSA). The measurements data came with below LOD values replaced to half of the LOD value and this is what we use. Table F16 reports the completeness of PFAS detection and the corresponding LOD values ranked by completeness. For this set of analyses, we include the first eight measurements (seven PFAS) with detection in at least 34% of the participants. The remaining PFAS are excluded. The seven included PFAS (LOD) are: PFHxS (0.10 ng/ml), PFOS (0.20 ng/ml), PFOA (0.50 ng/ml), PFNA (0.50 ng/ml), PFHpS (0.20 ng/ml), PFDA (0.50 ng/ml), and PFHpA (0.20 ng/ml).

As far as possible, we adjust for maternal baselines in the S-PRESTO evaluations so that they are comparable to our evaluations using the GUSTO sample. For the S-PRESTO evaluations, we adjusts for age of mother during recruitment (flexibly in quadratics), education, employment, marital status, ethnicity, and household income. We note that these adjustments do not map exactly to those in the GUSTO sample. Household income, for instance, would have different stratas compared to those asked in the earlier GUSTO recruitment. All other specifications and adjustments for unmeasured spatial heterogeneity are otherwise similar as defined in Equation (1). We are unable to focus on the PFBS (perfluorobutanesulfonic acid) since only one sample had successful detection

Table F16. Completeness of S-PRESTO plasma PFAS measurements

Full analyte name	Shorthand	Measured	< LOD	LOD value
Perfluorohexane-1-sulphonic acid	PFHxS	384	0	0.1 ng/ml
Perfluorooctanesulfonic acid	PFOS-Linear	384	0	0.2 ng/ml
Perfluorooctanesulfonic acid	PFOS-Branched	383	1	0.2 ng/ml
Perfluorooctanoic acid	PFOA-Linear	374	10	0.5 ng/ml
Perfluorononanoic acid	PFNA	233	151	0.5 ng/ml
Perfluoroheptanesulfonic acid	PFHpS	186	198	0.2 ng/ml
Perfluorodecanoic acid	PFDA	159	225	0.5 ng/ml
Perluoroheptanoic acid	PFHpA	130	254	0.2 ng/ml
2-(N-Methylperfluorooctanesulfonamido) acetic acid	NMeFOSAA	6	378	0.1 ng/ml
6:2 Fluorotelomer phosphate monoester	6:2 PAP	5	379	0.1 ng/ml
6:2 Fluorotelomer phosphate diester	6:2 diPAP	2	382	0.1 ng/ml
Perfluorobutanesulfonic acid	PFBS	1	383	0.2 ng/ml
6:2 Fluorotelomer sulfonic acid	6:2 FTS	0	384	0.1 ng/ml
2-(N-Ethylperfluorooctanesulfonamido) acetic acid	NEtFOSAA	0	384	0.2 ng/ml
Perfluorodecanesulfonic acid	PFDS	0	384	0.1 ng/ml
Perfluorooctanesulfonamide	PFOSA	0	384	0.1 ng/ml

Note: Table reports the completeness of plasma PFAS measurements in the S-PRESTO sample (n = 384). Measurements in nanograms per millilitre (ng/ML). LOD = limit of detection.

above the LOD (Table F16). These estimates are reported in Figure F30.[7]

The exposure to transport facilities measure is as defined in Section 2.3, except that we map the residence of the S-PRESTO participants to the 2014 land use plans. Likewise, the regions, planning areas, and subzones are also based on the 2014 versions by mapping the postal codes onto the 2014 vector data.

PFAS	Full analyte name	N	< LOD	LOD value	Est. (95% Conf. Int.)	P-value
PFHxS	Perfluorohexane-1-sulphonic acid	384	0	0.1 ng/ml	0.038(-0.022 to 0.098)	0.207
PFOS-Linear	Perfluorooctanesulfonic acid	384	0	0.2 ng/ml	0.100(0.025 to 0.176)	0.012[b]
PFOS-Branched	Perfluorooctanesulfonic acid	383	1	0.2 ng/ml	0.061(-0.040 to 0.161)	0.222
PFOA-Linear	Perfluorooctanoic acid	374	10	0.5 ng/ml	0.028(-0.052 to 0.108)	0.473
PFNA	Perfluorononanoic acid	233	151	0.5 ng/ml	0.112(0.011 to 0.213)	0.031[b]
PFHpS	Perfluoroheptanesulfonic acid	186	198	0.2 ng/ml	0.097(0.012 to 0.182)	0.027[b]
PFDA	Perfluorodecanoic acid	159	225	0.5 ng/ml	0.031(-0.014 to 0.077)	0.171
PFHpA	Perluoroheptanoic acid	130	254	0.2 ng/ml	0.124(0.042 to 0.205)	0.005[a]

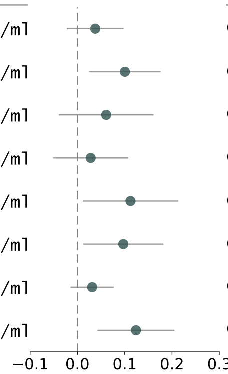


Figure F30. Figure reports estimates for PFAS measurements from the S-PRESTO cohort study. Horizontal axis of the plot reports the $\hat{\beta}$ coefficients from estimating

$$\text{PFAS}ic^{\text{(scaled)}} = \beta(\text{Exposure to transport facilities})ic^{\text{(scaled)}} + \gamma X_i + \delta_c(\text{subzone})c + \varepsilon ic,$$

where $\text{PFAS}_{ic}^{\text{(scaled)}}$ is the PFAS substance (indicated in the first column). Transport facilities and regional tags are based on the 2014 versions. All models adjust for mother's age (in quadratics), employment status, education, marital status, ethnicity, and household income collected from the S-PRESTO sample. Gray horizontal lines are the 95% confidence intervals constructed from standard errors clustered at planning areas. Significance levels: [c] 0.1 [b] 0.05 [a] 0.01.

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