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Highway Expansion and Urban Sprawl in the Jakarta Metropolitan Area

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Abstract
Transport development has been widely recognized as one of the major drivers in shaping urban forms. While recent literature has documented the urban-land use effect of transport networks between cities, little is known about the effect within cities. Using the Global Human Layer Settlement (GHSL) data provided by European Commission Joint-Project, this paper aims to find any causation between highway expansion and urban sprawl within the Jakarta Metropolitan Area, one of the most urbanized areas in the developing countries. Employing historical transport infrastructures as instruments, the result shows that areas experiencing the most improvement in highways access are converging slower than those with small improvement. This paper adds a piece of enticing evidence for urban economics literature that highway expansion may not always lead to a sprawling development of urban areas, but it can hamper its growth into a more compact urban form. Our results also confirm the existence of transport-led urban expansion in the JMA over the last three decades.

JEL Classification: O18; P25; R14

Keywords
urban development — urban expansion — urban sprawl — transport access

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1. Introduction

Transportation network and urban land use represent two interlinkage aspects that widely discussed in urban areas. The classical monocentric model suggests that transport costs play an important role in explaining urban development. As commuting costs fall, people began to move away from the city center, causing the city to expand (Glaeser & Kahn, 2003). Similarly, lower transport costs also induce a scattered development of urban areas (Burchfield et al., 2006; Garcia-López, 2019), expansion of residential land (Garcia-López, 2019) and suburbanization (Baum-Snow, 2007; Garcia-López et al., 2015; Garcia-López, 2012; Yudhistira et al., 2019).

In this paper, we examined the role of changes in transportation networks in explaining the dynamic in land use within an urban area, proxied by urban sprawl. We studied the Jakarta Metropolitan Area (JMA), one of the fastest-growing urban areas in developing Asia. The JMA experienced a dramatic sprawling process, particularly in suburban areas, that are associated with highways improvement over the last three decades. We constructed urban land expansion and sprawl index variables, introduced by Garcia-López (2019) using high-resolution spatial data from Global Human Layer Settlement (GHSL) to capture the land-use pattern within the metropolitan area. To address potential non-random process of the improvement in highways access, we exploit the access to historical transport infrastructures that were built in the early 19th century by colonial rules as potential instrumental variables. We assume that the historical transport network is strongly associated with transport network today, but less likely to correspond with today's urban land use (Baum-Snow, 2007; Duranton & Turner, 2012).

Recent literatures studying the causal impact of transport networks on urban growth have shown that highway development plays an important role. It fosters urban employment growth (Duranton & Turner, 2012), population suburbanization (Baum-Snow, 2007; Garcia-López et al., 2015), decentralization of employment (Baum-Snow et al., 2017), and induces urban sprawl (Garcia-López, 2019). Prior study by Yudhistira et al. (2019), has captured similar evidence on population growth and economic activity in the context of the JMA. The impact on urban sprawl, however, has not yet been investigated.

The study of urban sprawl has incorporated the work of geographers, economists, and urban planners. The discussion surrounding the topic continues to grow today. As summarized across the variety of literature, urban sprawl is defined as the disperse, scattered and low-density development of an urban area that resulted from market failures in the urban development process (Brueckner & Fansler, 1983; Burchfield et al., 2006; Garcia-López et al., 2015; McGrath, 2005). The first study attempting to understand the process of urban sprawl first introduced by Brueckner and Fansler (1983) using the spatial size of cities as measures of urban sprawl. An extension of this study was developed by McGrath (2005) using metropolitan area – an area with a population density of at least 1,000 people per square mile – as unit of measurement. As the development of satellite images data advanced, various studies began to investigate the presence of urban sprawl by processing and classifying these data into several urban sprawl indicators, such as urban land expansion (Deng et al. 2008; Ahrens & Lyons 2019; Oueslati et al., 2015), sprawl index (Burchfield et al., 2006) and fragmentation of urban land (Garcia-Lopez, 2019).

This paper contributes to the body of urban economic literature in three aspects. First and foremost, we provide empirical evidence on how transport infrastructures shape urban forms within-cities, more specifically related to the scattered development of urban land and urban land expansion. This expands our understanding of the fact that transport development is affecting urban sprawl differently within-cities and between-cities. While transport induced urban sprawl existed between cities in Europe (Garcia-López, 2019) and states-level in the United States (Burchfield et al., 2006), little is known about its effect within cities. We show that transport development still negatively affects the convergence of urban land, causing a slower rate of convergence in areas which experiencing better transport development.

Secondly, our study also adds to an existing body of literature by using the GHSL spatial data to measure urban sprawl in large developing countries. This data enables us to incorporate physical development in examining urban forms, instead of using only population as a proxy (Garcia-López, 2012; Yudhistira et al., 2019). In addition, the data also allow us to use multiple indicators of urban sprawl, instead of using a single measurement as conducted in prior studies (Brueckner & Fansler, 1983; Burchfield et al., 2006; McGrath, 2005). Since urban sprawl is a complex phenomenon, our study is among the first who attempt to comprehensively capture urban sprawl not only through the disperse growth of urban land, but also the scattered development of urban areas.

Lastly, to use a large metropolitan area, like the JMA, is important and an international interest to further understand the urban development process in a fast-changing urban structure. Despite numerous discussions on transport development and urban growth from economic perspectives (Henderson et al., 1996; Yudhistira et al., 2019), the study of urban sprawl in Indonesia mainly conducted by geographers and urban planners (Ambarwati et al., 2014; Hidajat et al., 2013; Wagistina & Antariksa, 2019). Our paper adds an economic perspective in examining the state of urban sprawl in Indonesia, as well as gives empirical evidence of transport-led urban sprawl in the JMA. The remainder of this paper is organized as follows. Section 2 provides background information on urban land use and highways development in the JMA. Section 3 describes the urban sprawl measurement and source of data. Section 4 identifies the strategy. Section 5 discusses the results. The last section concludes.

2. Context: Highway Development in Jakarta Metropolitan Area

Among countries undergo rapid urbanization, developing countries experienced a higher urbanization rate, approximately 2.63–3.68% annually, higher than the developed countries (0.88%) (United Nations, 2014). Indonesia has the third-largest amount of urban land in East Asia. Indonesia's urban land area increased at a rate of 1.1% each year during 2000-2010, and it is only second to mainland China. In addition, the JMA also ranks 4th as the largest metropolitan area in the world (World Bank, 2016). The JMA experienced an annual population growth of 2.8% during 2000 to 2010[1] (Statistics Indonesia, 2019). The growth, however, differs throughout the JMA. Jakarta's population grows slower than its surrounding suburbs, and the proportion of people living in the city of Jakarta has been decreased by 5% out of total JMA population (Statistics Indonesia, 2019). Urban density in the JMA also grows from 12,200 persons per square kilometer of urban land in 2000 to more than 14,600 in 2010. It indicates that the benefits of agglomeration in the JMA are still high and it still attracts people to live and work in the area. Compared to other metropolitan areas in Indonesia, Jakarta contributes to 12% of the country's built-up land, but has approximately 20% of urban population.

Extensive highway development in the JMA started with the construction of Jagorawi toll road in 1973 aiming to improve connectivity from Jakarta to Bogor. The effort to connect Jakarta and its peripheries continued with the development of new toll roads to Tangerang (1984), Cikampek (1988), and Jakarta Inner Ring Road (1989). Since 1990, no less than 150 km of highways have been built all around the JMA. The national highway authorities plan to further expand the highway networks inside the JMA until 2030, most notably through the construction of the second layer of Jakarta Outer Ring Road (JORR II) with a total length of 133 kilometers. Figure 1 depicts the proposed highway development plan in the JMA. The green line represents existing highways in 1989, the blue and red line exhibits the current highway rays and the expansion plan until 2030, respectively.

Improvements in transport infrastructures in the JMA in the last three decades have grown in line with the economic and land use development that has taken place in the JMA. It can be seen by an increase in industrial estates and residential towns in the suburbs (Hudalah et al., 2013), industrial and population decentralization (Henderson et al., 1996), and transformation of rural land to new towns in the peri-urban area of Jakarta. Over 300,000 ha of rural land has transformed into new towns, mostly located in the peri-urban area of Jakarta, causing the urban area of JMA to expand from 10 km in 1970 to 40-45 km from Jakarta in 2015 (Fitriyanto et al., 2019). In addition to toll road network, the development of the JMA also influenced by the railways network. Most of the railway lines in Indonesia, including the JMA railway network, were constructed by the Dutch during the colonial era. The JMA railways were abandoned after the independence, before being revived by national railway corporation (PNKA) during the 1970s. Since early the 1990s, the national railway authority has gradually opened the old lines, such as Tanah Abang – Serpong (1992), Jakarta – Bekasi (1992), Duri – Tangerang (1997), and Serpong – Parung Panjang (2009).

3. Measuring urban sprawl

A broad range of literature have used various measurements of urban development, particularly in examining the urban sprawl. Some basic measurements have been used by McGrath (2005), Burchfield et al. (2006), and Garcia-López

[1] Authors calculation using population census data from national bureau of statistics (Statistics Indonesia, 2019). Population growth calculated using compound annual growth rate for 10 years.

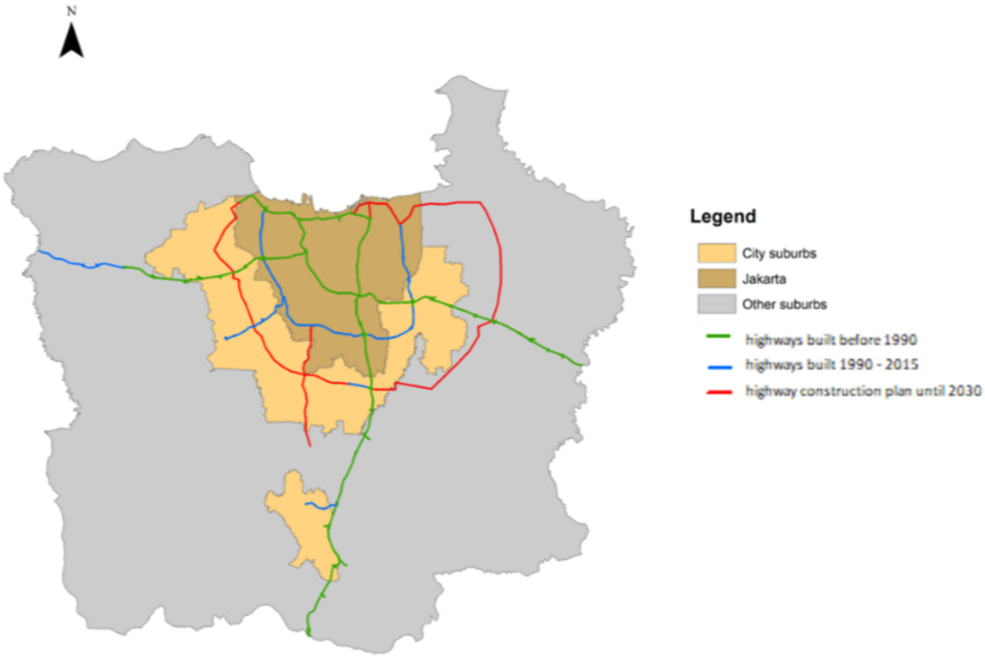

Figure 1. Highway development in the JMA
Source: Indonesia Toll Road Authority (2019)

(2019), while more complex measures also presented by Frenkel & Ashkenazi (2008). In this paper, we measure urban sprawl using two indicators, the sprawl index and the urban land expansion. Sprawl index first introduced by Burchfield et al. (2006) to test how often residential development goes beyond more than one kilometer away from other residential developments. Sprawl Index is generated by calculating the percentage of open space in the immediate square kilometer of a residential cell and then it is averaged for each unit of analysis. An increase in sprawl index over time can be interpreted as an increase in built-up cells that are isolated from other artificial lands, implying a more scattered development of a residential area. A similar indicator later used by Ahrens & Lyons (2019) and Garcia-López (2019).

The second indicator is urban land expansion, which is defined as the sum of urban settlement in a particular area. An increase in urban settlement areas indicates that a certain area experiencing land expansion during the specific period. In this study, we use the GHSL data from the Joint Research Center of European Commission. This data is derived from Landsat image collection and available for the years of 1990, 2000, and 2014. We use the GHSL urban settlement data at 38 m spatial resolution published by the JRC-EC. For each cell, it contains values of one if the cell is considered as a built-up cell and zero if otherwise. On transport development, existing pieces of literature contain different proxies of transport costs when examining their impact on urban development, such as the percentage of people using public transit and the percentage of people owning automobiles (Brueckner & Fansler, 1983), length of highways (Garcia-López, 2019; Oueslati et al., 2015), and time spent on commuting (Ahrens & Lyons, 2019). In this study, we use change in distance to highway ramp as a measure of transport improvement.

To control for exogenous distance variables (nearest distance to railway stations, district centers, and coastline), we use the transportation and road network data from OpenStreetMaps (OSM) as a baseline. The data is then cross-checked with various sources, such as the National Highways Authority of Indonesia, KAI Commuter Jabodetabek (railways authority), and geospatial information agency (BIG) to ensure there is no significant difference that causes measurement bias in our calculation. To calculate geographical variables (elevation and terrain ruggedness index), we employ official digital elevation maps data from BIG using the finest resolution of 12 m spatial unit. Lastly, to avoid the modifiable areal unit problem that arises due to substantial differences between administrative areas in Jakarta, City Suburbs, and Other Suburbs, we divide our unit of analysis into identical four kilometer-squared areas (2 km spatial unit).

4. Identification strategy

Based on the works of previous empirical studies to evaluate the effects of infrastructure development (Baum-Snow, 2007; Garcia-López, 2019; Yudhistira et al., 2019) we estimate the effect of highways expansion on urban sprawl as follows,

$$\Delta \ln(y_i) = \alpha + \gamma \Delta(dist.tohighwayramps)_i + \beta x_i + e_i \quad (1)$$

where y_i refers to two variables capturing the degree of sprawling development: (a) percentage of undeveloped land surrounding urban settlement (sprawl index), implying a scattered development and (b) urban settlement area (in km squared), indicating urban land expansion. Our main variable of interest is the change in distance to highways ramps from 1990 to 2014 which indicates the improvement in transportation access in the JMA. x_i is a set of control variables consist of initial developments, distance (distance

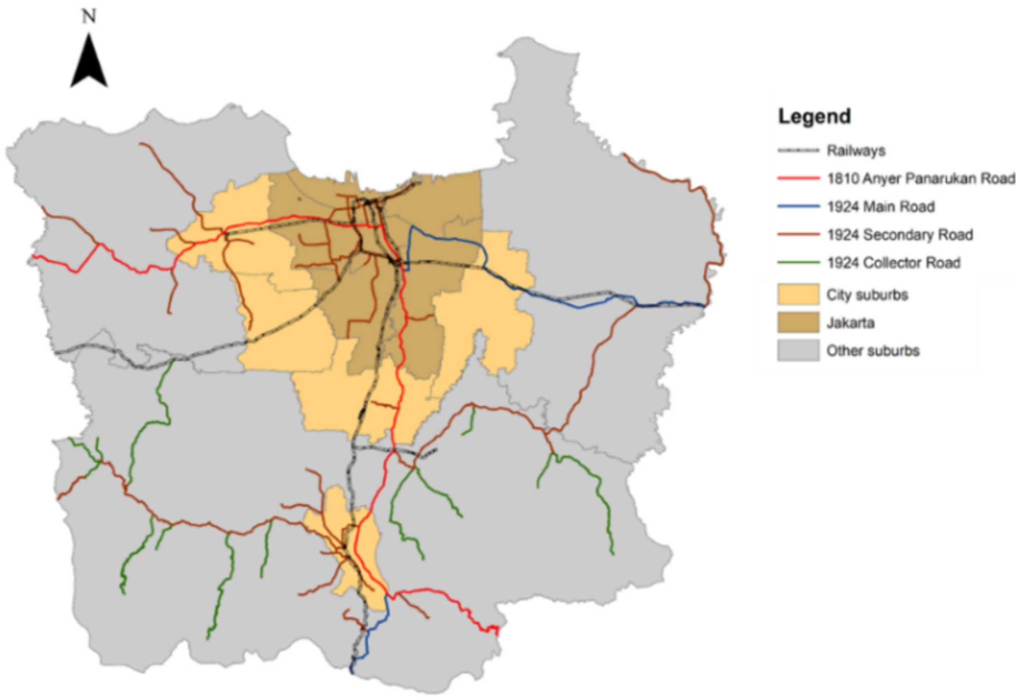

Figure 2. Historical roads in Jakarta Metropolitan Area
Source: Dutch Colonial Maps – Leiden University Library (2019)[2]

to railways station, district center, and coastline) and geographical variables (elevation and terrain-ruggedness index). The detailed explanation for each variable is presented in the Appendix 1. As the regression is expressed difference in log, the γ represents percentage point changes in the degree of sprawling development associated with a-kilometer change of the distance to highways ramps.

Estimating equation (1) using the ordinary least squares produces bias results due to reverse causality problem. It is plausible that urban development fostering highway expansion. To address this issue, we adopt IV estimation method using historical roads and railways from Figure 3 as potential instruments. To be valid, our instruments need to be relevant and exogenous to the outcome variables. The exogeneity condition requires the instruments to not directly affect the outcome variables but be channeled through the endogenous variables. In this case, we use historical transport infrastructures, since they were unlikely built anticipating the current urban spatial patterns (Garcia-López, 2012). To meet the instrument relevance condition, the instruments used in the second-stage estimation should not be weak. The K-P-F statistics of instruments used in TSLS regressions need to exceed the size and the relative bias critical value to reject the null hypothesis of weak instruments (Stock & Yogo, 2005).

In addition to validity criteria, to be suitable as instruments for our TSLS estimation, the first-best option is to choose the instruments that satisfied the following conditions: (1) it significantly affects the endogenous variables (first-stage), and (2) it significantly affects the outcome variables (reduced form). Previous studies, however, do not always provide the first-best instruments for analysis due to insignificant results on the reduced-form estimations (Garcia-López, 2012; Yudhistira et al., 2019). To overcome this problem, we prioritize the first-stage estimation results in choosing which instruments to be used. In a less restrictive way, Yudhistira et al. (2018) choose the instruments by looking at which instruments produce a stronger F-statistics in the second-stage estimations.

$$\begin{aligned}\Delta \ln(dist.tohighwayramp_i) \\ = \alpha + \gamma(dist.tohistoricaltransport)_i + \beta x_i + e_i\end{aligned} \tag{2}$$

Since these instruments may not be placed randomly due to the influence for other factors, it is important to also control for initial urban development and geographical variables (Garcia-López, 2012). Thus, we prefer to use the full-specification model controlling for initial urban development, distance, and geographical variables. In this paper, we acknowledge the role of railway network in shaping urban forms, by controlling for distance to nearest railway stations, but we ignore any potential of railways induced urban sprawl. We consider the small statistical significance in recent study by Yudhistira et al. (2019) as the main reason to ignore its causality impact.

5. Results and analysis

5.1 OLS Estimation

For descriptive purposes, we provide the OLS results for urban expansion and sprawl index presented in Table 1. Column (1) shows a negative correlation between changes in distance to nearest highway ramps and changes sprawl index. The magnitude, however, becomes smaller as we control for distance and geographical variables as shown presented in column (2) and (3). Our preferred specification in column (3) indicates that improvement in access to

[2]http://maps.library.leiden.edu/cgi-bin/iipview?marklat=-6.2358&marklon=106.7774&sid=2596434938864&svid=414005&code=04634-1&lang=1#focus.

highway corresponds to a higher degree of scattered development within the JMA by 3.8%. We provide a similar estimation for urban land expansion presented in column (4), (5), and (6). Our preferred OLS result controlling for distance and geographical variables produces a positive correlation between changes in distance to highway ramps and the sprawl index. It implies that improvement in access to the nearest highway ramps is associated with a lower level of urban expansion in the JMA. One-kilometer improvement in access to nearest highway ramp corresponds to a 1.6% reduction in urban expansion within the JMA. These results, however, are suspected to be invalid due to reverse causality bias.

5.2 TSLS Estimation

5.2.1 First-stage Estimates

Table 2 and 3 report the first-stage OLS estimates of the proximity to historical infrastructures effects on improvement in highway access. Table 2 includes the sprawl index in the 1990, while Table 3 use the initial urban settlement in 1990 as a control for the initial development of urban areas. Our results show that only 1924 secondary and collector roads are statistically significant in explaining the variation of the improvement in highway access. The estimated coefficients indicate that, consistent with Figure 3, proximity to historical roads is corresponds to a smaller improvement in distance to the nearest highway ramp. It also implies that the newly built highways tend to be located away from existing road networks, which is possible for economic or political reasons (Garcia-Lopez, 2012).

Figure 4 depicts the linear relationship between distance to historical roads and changes in urban sprawl indicators. The right figure shows a positive correlation between changes in the sprawl index and distance to 1924 collector road networks. It indicates that areas with higher reduction in sprawl index are located near the 1924 collector road networks. The left figure shows a positive relationship between changes in urban settlement area and distance to 1924 secondary road network. It implies that a larger expansion of urban land is located away from the 1924 secondary road networks.

5.2.2 Effects of transportation improvement on urban form

Table 4 reports our TSLS estimation for sprawl index and urban land expansion. We use distance to 1924 secondary and collector roads separately as instruments. Controlling for initial urban development, distance, and geographical variables, our selected instruments produce high F-statistics in all specifications, indicating that our instruments are not weak. Column (1) and (2) present the effects of improvement in highway access on the sprawl index within the JMA. On average, areas in JMA are experiencing a lower sprawl index throughout 1990–2014 (see Appendix 2), indicating that new land developments in the JMA tend to converge with the initial developments. The estimated coefficients indicate that one kilometer improvement in highway access hampers the convergence of urban land area by 6.6–9.6%. It implies that highway expansion hinders the process of forming a more compact development within the JMA.

Our preferred OLS coefficient is slightly underestimate compared to its TSLS counterpart largely due to not controlling for reverse causality bias. In terms of magnitude, by comparing the magnitude at means, our estimated coefficients are having a considerably high magnitude. Thus, it is important to be very careful in interpreting the results. In examining the effect on urban land expansion, our TSLS coefficients show no statistical evidence of transport-led urban land expansion in the JMA. Our estimated coefficient provide different effect than its OLS counterpart indicating an overestimated result in our OLS coefficient due to reverse causality bias.

To further examine the effect of transport development on urban land expansion, we perform similar approach on sub-sample level. We divide the JMA into three sub-samples (Jakarta, City Suburbs, and Other Suburbs), as similarly performed in Yudhistira et al. (2018). Table 5 presents the sub-sample results for urban expansion. We use distance to Anyer – Panarukan road as instrument for Jakarta, whereas for city suburbs and other suburbs, we select distance to the old railway station and the 1924 secondary roads. All of our instruments are considered not weak due to high K-P-F statistics. Our estimated coefficients for Jakarta and other suburbs are not statistically different from zero, as such it denies the existence of urban expansion caused by highway expansion. Our estimates for city suburbs, however, show a negative effect that was statistically different from zero. One kilometer improvement in distance to highway ramp induces the expansion of urban areas by 1.6%. It confirms the existence of transport-led urban expansion within the city suburbs. To complement the analysis, we also add sub-sample results for the sprawl index in Appendix 5.

5.3 Robustness Check

To check the consistency of our estimation, we perform similar estimation using a different spatial unit, samples, and dataset. Table 6 reports our robustness check for sprawl index. Column (1) and (2) show the estimated coefficient for the sprawl index using a different unit of analysis. We use 2 km spatial unit for column (1) and 3 km spatial unit – thus, fewer observations – for column (2). Our estimated coefficient on column (2) is consistent with our main TSLS results of which indicating a negative relationship between improvement in highway access and the sprawl index. The magnitude of the coefficient is lower than our main result in column (1), and only statistically significant on 10% level.

In the estimation for column (3) to (7) we add some observations with JMA's adjacent districts, such as Sukabumi, Purwakarta, Karawang, Lebak, and Serang. For the first additional samples, we employ similar historical instruments (the 1924 collector road) with our main estimation from column (2). For additional Serang district samples, however, we use the distance to Anyer-Panarukan road as instrument considering Serang's location in the middle of Tangerang (eastern part of the JMA) and Anyer, Cilegon and also due to its influence to Serang as the first major road network crossed the district. The estimated coefficients for sub-sample JMA and its surrounding districts produce a consistent result, except for Serang. All of our estimations also produces a high value of K-P F-Statistics, indicating that the instruments used are not weak. The magnitude for sub-sample JMA and its surrounding districts varies from 8–

Table 1. OLS Estimation – Jakarta Metropolitan Area

Dependent variable	Δ ln (sprawl index 1990–2014)			Δ ln (urban settlement 1990–2014)		
Method:	OLS (1)	OLS (2)	OLS (3)	OLS (4)	OLS (5)	OLS (6)
Δ distance to nearest highway ramp	-0.048***	-0.046***	-0.038***	0.054***	0.026***	0.016***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
ln (Initial development - 1990)	N	Y	Y	N	Y	Y
Distance	N	Y	Y	N	Y	Y
Geography	N	N	Y	N	N	Y
Observations	1421	1421	1421	1421	1421	1421
Mean	-0.282	-0.282	-0.282	0.342	0.342	0.342
Adjusted R-sq	0.048	0.309	0.332	0.041	0.495	0.510

Note: robust standard-error in parentheses. *, **, *** indicate statistical significance at 10%, 5%, and 1% level. Distance variables include distance to nearest railway station, distance to central Jakarta, distance to central district, and distance to coastal line. Geography variables include elevation and terrain ruggedness index.

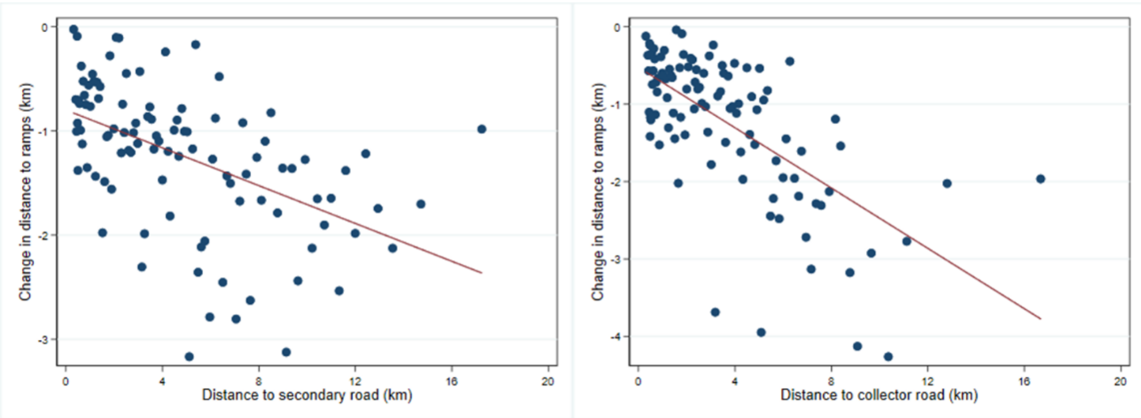

Figure 3. Distance to historical roads on improvement in access to highway ramp

Table 2. First stage estimation - Sprawl Index

Dependent variable:	First-stage estimates Δ distance to nearest highway ramp				
	(1)	(2)	(3)	(4)	(5)
distance to Anyer - Panarukan road	-0.000				0.019*
	(0.010)				(0.010)
distance to historical railway station		0.016			-0.026
		(0.021)			(0.020)
distance to 1924 secondary road			-0.149***		-0.070*
			(0.024)		(0.024)
distance to 1924 collector road				-0.196***	-0.149***
				(0.032)	(0.035)
Initial ln (sprawl index - 1990)	Y	Y	Y	Y	Y
Distance	Y	Y	Y	Y	Y
Geography	Y	Y	Y	Y	Y
Observations	1421	1421	1421	1421	1421
Mean of dependent variables	-1.239	-1.239	-1.239	-1.239	-1.239
Adjusted R-sq	0.208	0.208	0.236	0.243	0.247

Note: robust standard-error in parentheses. *, **, *** indicate statistical significance at 10%, 5%, and 1% level. Distance variables include distance to nearest railway station, distance to central Jakarta, distance to central district, and distance to coastal line. Geography variables include elevation and terrain ruggedness index.

12%, implying a slightly higher effect than our main result in column (2).

Column (8) to (10) show our estimated coefficients when we limit our JMA sample within 30 km, 40 km, and 50 km from Central Jakarta. Our results indicate that the effect only does not exist within 30 km radius, but it exists within 40 km (4.7%) and 50 km (10.2%). The magnitude of the effect is higher as it further away from the center of Jakarta. Lastly, we perform similar approach using a different dataset provided by the European Space Agency – Climate Change Initiatives (ESACCI). Our results using 2 km and 3 km spatial units are consistent with our main result, however, the magnitude is way higher than our preferred estimation. The overestimated coefficient is caused by the different resolution of the data. Our main estimation uses the GHSL data of 38 m spatial resolution, where the ESACCI data is provided at 300 m spatial resolution.

Table 7 reports our robustness check for urban expansion using similar approach. Similar with our results using 2 km spatial unit of observation, we found no statistical

Table 3. First-stage estimation – Urban Expansion

Dependent variable:	First-stage estimates Δ distance to nearest highway ramp				
	(1)	(2)	(3)	(4)	(5)
distance to Anyer - Panarukan road	-0.01				0.016*
	(0.010)				(0.010)
distance to historical railway station		-0.004			-0.020
		(0.020)			(0.020)
distance to 1924 secondary road			-0.178***		-0.085***
			(0.024)		(0.024)
distance to 1924 collector road				-0.213***	-0.154***
				(0.029)	(0.032)
Initial ln (urban settlement - 1990)	Y	Y	Y	Y	Y
Distance	Y	Y	Y	Y	Y
Geography	Y	Y	Y	Y	Y
Observations	1421	1421	1421	1421	1421
Mean of dependent variables	-1.239	-1.239	-1.239	-1.239	-1.239
Adjusted R-sq	0.2	0.199	0.243	0.249	0.253

Note: robust standard-error in parentheses. *, **, *** indicate statistical significance at 10%, 5%, and 1% level. Distance variables include distance to nearest railway station, distance to central Jakarta, distance to central district, and distance to coastal line. Geography variables include elevation and terrain ruggedness index.

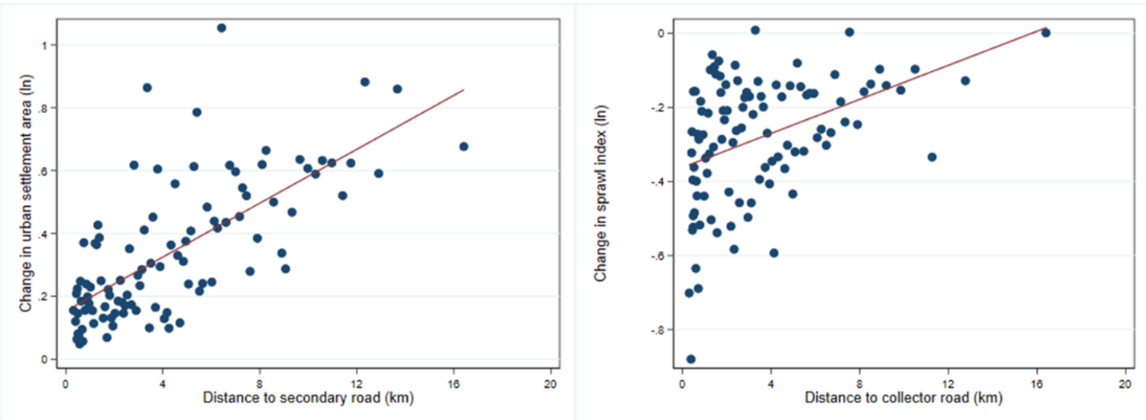

Figure 4. Changes in urban sprawl indicators and distance to historical roads

Table 4. TSLS Regression – Jakarta Metropolitan Area

Dependent variable	Δ ln (sprawl index 1990–2014)		Δ ln (urban settlement 1990–2014)	
Method:	TSLS (1)	TSLS (2)	TSLS (3)	TSLS (4)
Δ distance to nearest highway ramp	-0.066**	-0.096***	-0.032	-0.009
	(0.029)	(0.032)	(0.024)	(0.020)
Initial Development (1990)	Y	Y	Y	Y
Distance	Y	Y	Y	Y
Geography	Y	Y	Y	Y
Observations	1421	1421	1421	1421
Mean	-0.282	-0.282	0.342	0.342
Kleibergen-Paap F-statistic	38.83	38.55	56.02	53.99
Instruments:				
distance to 1924 secondary road	✓		✓	
distance to 1924 collector road		✓		✓

Note: robust standard-error in parentheses. *, **, *** indicate statistical significance at 10%, 5%, and 1% level. Distance variables include distance to nearest railway station, distance to central Jakarta, distance to central district, and distance to coastal line. Geography variables include elevation and terrain ruggedness index.

evidence of transport-led urban expansion in the JMA, using the 3 km spatial unit sample (column 2). Adding adjacent districts in the sample, only Lebak (9.9%) and Serang (6.8%), which produce significant results. The coefficient for JMA plus Sukabumi, Purwakarta, and Karawang all resulted are not statistically different from zero. Column (8) to (10) show our estimated coefficient for observations within 30 km, 40 km, and 50 km radius from Central Jakarta. The estimated coefficient for samples within 30 km radius is consistent with our findings for urban land expansion subsample in Table 5. Our estimated coefficient in column (8) indicates that improvement in highway access causes urban land to expand by 4.1%, slightly higher than our estimated coefficient for city suburbs (1.6%). Column (11) and (12)

Table 5. Urban Expansion – Sub sample results

Dependent variable:	Δ ln (urban settlement 1990–2014)					
Sample:	Jakarta		City Suburbs		Other Suburbs	
Method:	OLS (1)	TSLS (2)	OLS (3)	TSLS (4)	OLS (5)	TSLS (6)
Δ distance to nearest highway ramp	0.005	0.011	0.002	-0.016***	0.027***	0.037
	(0.004)	(0.010)	(0.002)	(0.005)	(0.006)	(0.040)
Initial ln (urban settlement - 1990)	Y	Y	Y	Y	Y	Y
Distance	Y	Y	Y	Y	Y	Y
Geography	Y	Y	Y	Y	Y	Y
Observations	155	155	215	215	1051	1051
Mean	0.066	0.066	0.106	0.106	0.431	0.431
Adjusted R-sq	0.883		0.842		0.503	
Kleibergen-Paap F-statistic		19.43		30.08		29.55
Instruments:						
distance to Anyer - Panarukan road		✓				
distance to old railway station				✓		
distance to 1924 secondary road						✓

Note: robust standard-error in parentheses. *, **, *** indicate statistical significance at 10%, 5%, and 1% level. Distance variables include distance to nearest railway station, distance to central Jakarta, distance to central district, and distance to coastal line. Geography variables include elevation and terrain ruggedness index.

reports the resulted coefficient using ESACCI dataset under 2 km and 3 km spatial unit of observations. Similar to our estimation for sprawl index, we find consistent results with a higher magnitude due to different spatial resolution of the data.

5.4 Falsification Test

We use a falsification test to further confirm that our results do not come from a random process. This test is performed by randomizing each observation of our instrumented variables, as such, each observation is now attributed to different instruments' observations in our TSLS estimation. A statistically significant result in falsification test would indicate that our previous estimation is suffered from placebo effects and reject our interpretation in the previous section. Table 8 presents our falsification test results both for the sprawl index and urban land expansion. The results show that all of our estimates are not statistically different from zero, denying the possibility of placebo effects in the estimation.

6. Conclusions

Recent studies in urban sprawl have found that transport development, whether in the forms of lower commuting costs or more highway rays, plays a major role in explaining urban sprawl (Garcia-Lopez, 2019). By employing the GHSL spatial data from EC-JRC, we investigate whether a transport induced urban sprawl is evident in the JMA. Using two measurements of urban sprawl – sprawl index and urban land expansion – introduced by (Burchfield et al., 2006; Garcia-López, 2019), and employing historical transport infrastructures as instruments, we find that improvement in highway access shapes urban forms of the JMA during 1990–2014.

Our analysis confirms that improvement in highway access hampers the convergence of urban land area in the JMA. From 1990 to 2014, despite the decreasing rate of sprawling development, the scattered development of urban land area is influenced by transport development. Our estimations show that one kilometer improvement in highway access slows the convergence of urban land area by 6.6–9.6%. The effect is lower (4.7%) in the area within 40 km from the city center of Jakarta, and the magnitude varies when we add several districts adjacent to the JMA (8–12%). It implies that the magnitude grows stronger in larger samples. Our results are the first to provide empirical evidence of transport induced urban sprawl within cities. It adds to the body of urban economic literature that transport development does not always results in an increase in urban sprawl as it visible in between-cities cases. Within cities, transport development may not induce urban sprawl, but it hampers the convergence of urban land areas in the metropolitan area.

Our second result confirms the presence of transport-led urban expansion in several areas within the JMA. The effect of improvement in highway access on urban land expansion area evident in the city suburbs and the area within radius 30 km from Central Jakarta. The magnitude is smaller for city suburbs (1.6%), than areas within 30 km radius from the center of Jakarta (4.1%). Our results imply that one kilometer improvement in highway access causes urban land to expand by 1.6% in city suburbs and 4.1% the area within 30 km of Jakarta center. Nevertheless, the results confirm similar results as other studies for inter-cities that transport development causes urban land expansion (Deng et al., 2008; Garcia-López, 2019).

The presence of unmitigated development of urban areas, like urban sprawl, attract the interest of researchers since it potentially brings various consequences for urban areas. A seminal work from Newman & Kenworthy (1989) points out a case of two cities – Barcelona and Atlanta – and how the latter emits carbon ten times higher from commuting due to larger urbanized area despite having a roughly similar number of populations. Several studies have also suggested that higher urban densities and the presence of mixed land-use reduce commuting trip length and the number of motorized trips, thus reducing carbon emission from the transportation sector (Gordon et al., 1989; Levinson & Kumar, 1994), while a sprawling development induces more energy consumption from heating and electricity (Glaeser

Table 6. Robustness Check – Sprawl Index

Dependent variable:	Δ ln (sprawl index 1990–2014)											
Category	Spatial unit		Adjacent districts					Central Jakarta radius			Spatial Data	
Sample:	2 km	3 km	JMA + Sukabumi	JMA + Purwakarta	JMA + Karawang	JMA + Lebak	JMA + Serang	30 km	40 km	50 km	ESACCI 2 km	ESACCI 3 km
Method:	TSLS (1)	TSLS (2)	TSLS (3)	TSLS (4)	TSLS (5)	TSLS (6)	TSLS (7)	TSLS (8)	TSLS (9)	TSLS (10)	TSLS (11)	TSLS (12)
Δ distance to nearest highway ramp	-0.096***	-0.066*	-0.126***	-0.095***	-0.081***	-0.098**	-0.002	-0.002	-0.047**	-0.102***	-0.348***	-0.295***
	(0.032)	(0.037)	(0.031)	(0.034)	(0.027)	(0.049)	(0.010)	(0.029)	(0.022)	(0.028)	(0.084)	(0.097)
Initial Development (1990)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Distance	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Geography	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Observations	1421	635	1477	1430	1587	1498	1523	504	866	1241	703	367
Mean	-0.282	-0.236	-0.272	-0.28	-0.281	-0.268	-0.267	-0.531	-0.399	-0.321	-1.055	-1.117
Kleibergen-Paap F-statistic	38.55	18.41	46.51	34.53	52.65	13.76	186.41	57.93	84.94	48.22	37.84	24.6
Instruments:												
distance to Anyer - Panarukan road							✓					
distance to 1924 collector road	✓	✓	✓	✓	✓	✓		✓	✓	✓	✓	✓

Note: robust standard-error in parentheses. *, **, *** indicate statistical significance at 10%, 5%, and 1% level. Distance variables include distance to nearest railway station, distance to central Jakarta, distance to central district, and distance to coastal line. Geography variables include elevation and terrain ruggedness index.

Table 7. Robustness Check – Urban Expansion

Dependent variable:	Δ ln (urban settlement 1990–2014)											
Category	Spatial unit		Adjacent districts					Central Jakarta radius			Spatial Data	
Sample:	2 km	3 km	JMA + Sukabumi	JMA + Purwakarta	JMA + Karawang	JMA + Lebak	JMA + Serang	30 km	40 km	50 km	ESACCI 2 km	ESACCI 3 km
Method:	TSLS (1)	TSLS (2)	TSLS (3)	TSLS (4)	TSLS (5)	TSLS (6)	TSLS (7)	TSLS (8)	TSLS (9)	TSLS (10)	TSLS (11)	TSLS (12)
Δ distance to nearest highway ramp	-0.032	-0.037	-0.024	-0.012	0.016	-0.099**	-0.068***	-0.041***	0.007	0.001	-0.161***	-0.177***
	(0.024)	(0.038)	(0.018)	(0.026)	(0.019)	(0.039)	(0.011)	(0.011)	(0.011)	(0.018)	(0.044)	(0.053)
Initial Development (1990)	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Distance	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Geography	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Observations	1421	635	1477	1430	1587	1498	1523	504	866	1241	1027	476
Mean	0.342	0.361	0.352	0.347	0.372	0.351	0.331	0.117	0.183	0.293	0.432	0.531
Kleibergen-Paap F-statistic	56.02	23.72	108.87	52.33	103.22	33.85	164.26	73.37	136.03	86.78	41.76	25.57
Instruments:												
distance to Anyer - Panarukan road							✓					
distance to old railway station								✓				
distance to 1924 secondary road	✓	✓	✓	✓	✓	✓			✓	✓	✓	✓

Note: robust standard-error in parentheses. *, **, *** indicate statistical significance at 10%, 5%, and 1% level. Distance variables include distance to nearest railway station, distance to central Jakarta, distance to central district, and distance to coastal line. Geography variables include elevation and terrain ruggedness index.

Table 8. Falsification Test

Dependent variable:	Δ ln (sprawl index 1990–2014)				Δ ln (urban settlement 1990 - 2014)			
Sample:	JMA	Jakarta	City Suburbs	Other Suburbs	JMA	Jakarta	City Suburbs	Other Suburbs
Method:	TSLS (1)	TSLS (2)	TSLS (3)	TSLS (4)	TSLS (1)	TSLS (2)	TSLS (3)	TSLS (4)
Δ distance to nearest highway ramp	1.113	-26.492	0.681	-0.182	-0.514	-0.206	0.151	0.277
	(1.790)	(1197.621)	(2.083)	(0.227)	(1.076)	(1.229)	(0.209)	(0.463)
Initial Development (1990)	Y	Y	Y	Y	Y	Y	Y	Y
Distance	Y	Y	Y	Y	Y	Y	Y	Y
Geography	Y	Y	Y	Y	Y	Y	Y	Y
Observations	1524	155	215	1154	1421	155	215	1051
Mean	-0.296	-0.828	-0.419	-0.202	0.342	0.066	0.106	0.431
Kleibergen-Paap F-statistic	0.387	0	0.107	0.789	0.265	0.027	0.534	0.558
Instruments:								
distance to Anyer - Panarukan road		✓				✓		
distance to old railway station							✓	
distance to 1924 secondary road			✓	✓	✓			✓
distance to 1924 collector road	✓							

Note: robust standard-error in parentheses. *, **, *** indicate statistical significance at 10%, 5%, and 1% level. Distance variables include distance to nearest railway station, distance to central Jakarta, distance to central district, and distance to coastal line. Geography variables include elevation and terrain ruggedness index.

& Kahn, 2010), and higher gasoline consumption (Newman & Kenworthy, 1989).

The impact of urban sprawl is not limited to the environment. It decreases productivity due to loss of agglomeration benefits (Fallah et al., 2011), generates higher crime rates in the low-income neighborhood (Solé-Ollé & Rico, 2008), reduces upward mobility (Ewing et al., 2016), and increases inequality (Lee et al., 2018). Urban sprawl also increases social costs in the provision of public infrastructures by undermining the scale economies of infrastructure provision (Solé-Ollé & Rico, 2008).

Our study brings an indication that the expansion of highways in the JMA during 1990–2014 causes urban development to be more dispersed and less compact to some extent. It indicates that, aside from many benefits that gained from highway expansion, the construction of new highway rays may bring an unmitigated urban development that can potentially lead to an increase in social costs for living in urban areas. We suggest that the unmitigated urban development generated by highway expansion should be considered by policy makers when performing costs and benefits analysis of constructing new highways in the future.

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Appendix

Appendix 1. Variable definition

Urban settlement: Total area of which considered as urban settlement in Global Human Layer Settlement (GHSL) maps.

Sprawl Index: The average percentage of undeveloped land surrounding an urban settlement cell of an area.

Changes in distance to ramps: The straight-line changes in distance to nearest highways ramps of an area in kilometers.

Distance to railway stations: The straight-line (Euclidean) distance to the nearest railway stations in kilometers.

Distance to coast: The straight-line (Euclidean) distance to the nearest coastline in kilometers

Distance to central Jakarta: The straight-line (Euclidean) distance to the nearest national monument in the center of Jakarta in kilometers

Distance to central district: The straight-line (Euclidean) distance to the nearest centroid of each district in kilometers

Elevation: The average elevation of each area in meters above sea level.

Terrain ruggedness index: The standard deviation of difference between the center cell and its surrounding cells.

Distance to old railway stations: The straight-line (Euclidean) distance to the nearest historical railway stations built during NISM era in kilometers

Distance to 1810 Anyer-Panarukan road: The straight-line (Euclidean) distance to the nearest Anyer – Panarukan road built in 1810 by the Dutch colonial era in kilometers

Distance to 1924 secondary road: The straight-line (Euclidean) distance to the nearest secondary road network built in 1924 in kilometers.

Distance to 1924 collector road: The straight-line (Euclidean) distance to the nearest collector road network built in 1924 in kilometers.

Appendix 2. Descriptive statistics

	JMA		Jakarta		City suburbs		Other suburbs	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
Change in								
urban settlement (square kilometers)	0.23	0.39	0.20	0.37	0.25	0.39	0.24	0.40
sprawl index	-6.11	9.34	-4.85	8.02	-6.17	9.25	-6.26	9.52
distance to nearest highway ramp (kilometers)	-1.24	2.32	-1.04	1.81	-2.10	3.17	-1.11	2.16
Urban settlement area in 1990 (square kilometers)	1.66	1.50	3.63	0.54	3.24	0.80	1.13	1.25
Sprawl index in 1990	56.66	36.63	9.40	12.59	19.18	19.41	69.99	30.67
Distance to railway station	15.65	10.00	3.27	2.40	4.82	2.80	19.12	8.72
Distance to central Jakarta (kilometers)	37.71	15.41	10.79	4.65	24.89	9.32	43.38	11.77
Distance to central districts (kilometers)	12.41	7.59	4.75	2.12	5.34	2.16	14.62	7.25
Distance to coastal line (kilometers)	27.77	16.87	9.22	5.67	18.36	10.88	31.78	16.45
Elevation (meters)	100.13	99.17	17.34	16.56	63.78	65.52	117.01	103.15
Terrain ruggedness index	0.45	0.30	0.70	0.11	0.55	0.16	0.40	0.31
Distance to old railway station (kilometers)	14.76	9.51	3.40	2.03	5.43	2.70	17.84	8.65
Distance to 1810 Anyer-Panarukan road (kilometers)	15.46	11.04	4.70	3.37	7.84	5.40	18.16	10.96
Distance to 1924 secondary road (kilometers)	4.85	3.82	1.79	1.51	3.19	2.37	5.53	3.95
Distance to 1924 collector road (kilometers)	3.66	3.04	1.79	1.51	3.18	2.37	3.99	3.19

Appendix 3. First stage estimation, subsamples

Table A1. First stage estimation – Urban Expansion (JMA regions)

Dependent variable:	First-stage estimates Δ distance to nearest highway ramp		
Sample:	Jakarta	City Suburbs	Other Suburbs
	(1)	(2)	(3)
distance to Anyer - Panarukan road	-0.241***		
	(0.0546)		
distance to historical railway station		-0.939***	
		(0.1710)	
distance to 1924 secondary road			-0.137***
			(0.0252)
Initial ln (urban settlement - 1990)	Y	Y	Y
Distance	Y	Y	Y
Geography	Y	Y	Y
Observations	155	215	1051
Adjusted R-sq	0.581	0.353	0.276

Note: robust standard-error in parentheses. *, **, *** indicate statistical significance at 10%, 5%, and 1% level. Distance variables include distance to nearest railway station, distance to central Jakarta, distance to central district, and distance to coastal line. Geography variables include elevation and terrain ruggedness index.

Table A2. First stage estimation – Urban Sprawl (JMA regions)

Dependent variable:	First-stage estimates Δ distance to nearest highway ramp		
Sample:	Jakarta	City Suburbs	Other Suburbs
	(1)	(2)	(3)
distance to Anyer - Panarukan road	-0.236***		
	(0.0529)		
distance to 1924 secondary road		-0.672***	-0.073***
		(0.1000)	(0.0222)
Initial ln (sprawl index - 1990)	Y	Y	Y
Distance	Y	Y	Y
Geography	Y	Y	Y
Observations	155	215	1154
Adjusted R-sq	0.582	0.512	0.296

Note: robust standard-error in parentheses. *, **, *** indicate statistical significance at 10%, 5%, and 1% level. Distance variables include distance to nearest railway station, distance to central Jakarta, distance to central district, and distance to coastal line. Geography variables include elevation and terrain ruggedness index.

Appendix 4. Reduced Form estimation, subsamples

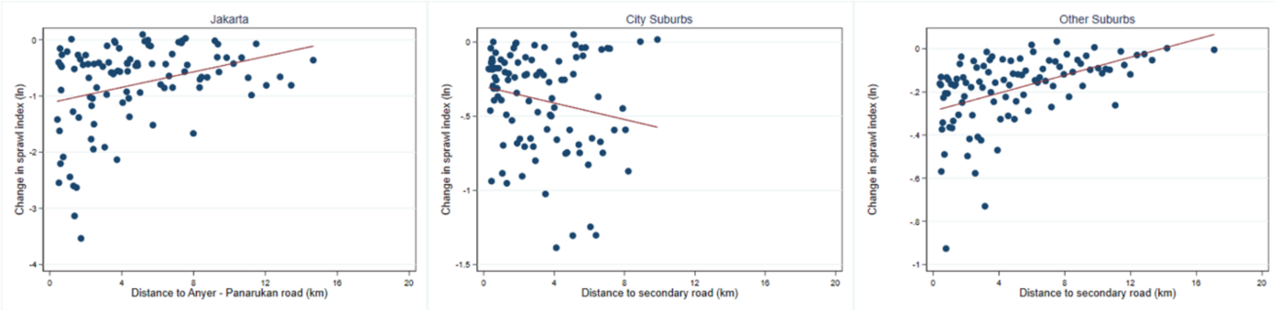

Figure A1. Reduced-form – Sprawl Index (sub-sample)

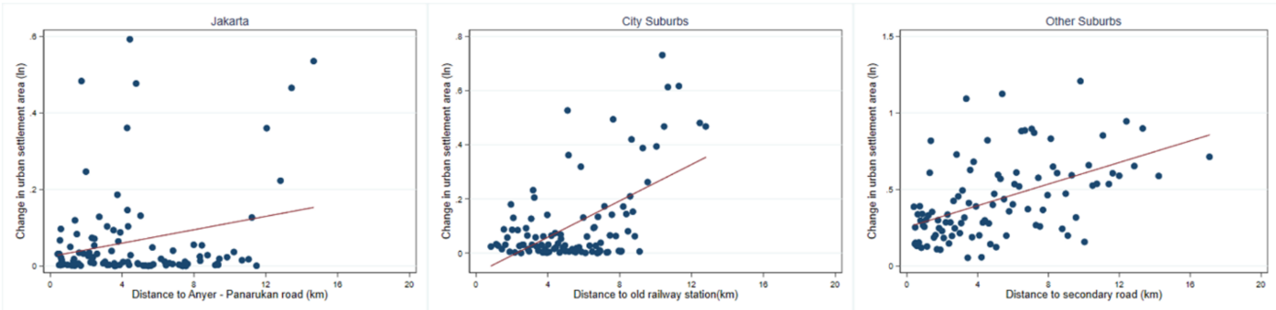

Figure A2. Reduced-form - Urban Expansion (sub-sample)

Appendix 5. Sub-sample results – Sprawl Index

Dependent variable	Δ ln (sprawl index 1990 - 2014)					
Sample:	Jakarta		City Suburbs		Other Suburbs	
Method:	OLS (1)	TSLS (2)	OLS (3)	TSLS (4)	OLS (5)	TSLS (6)
Δ distance to nearest highway ramp	-0.046* (0.028)	-0.176* (0.105)	0.003 (0.008)	0.035* (0.019)	-0.016*** (0.003)	-0.034 (0.028)
Initial ln (urban settlement - 1990)	Y	Y	Y	Y	Y	Y
Distance	Y	Y	Y	Y	Y	Y
Geography	Y	Y	Y	Y	Y	Y
Observations	155	155	215	215	1051	1051
Mean	-0.799	-0.799	-0.389	-0.389	-0.184	-0.184
Adjusted R-sq	0.398		0.487		0.297	
Kleibergen-Paap F-statistic		19.96		44.3		15.03
Instruments:						
distance to Anyer - Panarukan road		✓				
distance to 1924 secondary road				✓		✓

Note: robust standard-error in parentheses. *, **, *** indicate statistical significance at 10%, 5%, and 1% level. Distance variables include distance to nearest railway station, distance to central Jakarta, distance to central district, and distance to coastal line. Geography variables include elevation and terrain ruggedness index.

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