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Developing densely

Estimating the effect of subway growth on New York City land uses

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Abstract: In the early twentieth century, New York City's population, developed land area, and subway network size all increased dramatically. The rapid expansion of the transit system and land development present intriguing questions as to whether land development led subway growth or if subway expansion was a precursor to real estate development. The research described in this article uses Granger causality models based on parcel-level data to explore the co-development of the subway system and residential and commercial land uses, and attempts to determine whether subway stations were a leading indicator of residential and commercial development or if subway station expansion followed residential and commercial construction. The results of this study suggest that the subway network developed in an orderly fashion and grew densest in areas where there was growth in commercial development. There is no evidence that subway growth preceded residential development throughout the city. These results suggest that subway stations opened in areas already well-served by the system and that network growth often followed residential and commercial development. The subway network acted as an agent of decentralization away from lower Manhattan as routes and stations were sought in areas with established ridership demand.

Keywords: Subways; land use; density; New York City; Granger causality

1 Introduction

Transportation infrastructure provides access to locations. As infrastructure improves, access improves and land becomes desirable for development or redevelopment. Conversely, the development of urban areas contributes to the value of transportation systems. In this way, transportation infrastructure and land development are dependent on each other. Transportation infrastructure is designed and built to serve economic and social needs, and land development is dependent on access to transportation (and therefore on economic and social opportunities). In order to improve our understanding of the complex interdependence of transportation and land use, this research explores the development of New York City during the era of subway growth.

The New York City subway system developed rapidly in the first half of the twentieth century. Multiple private companies competed for contracts to provide new transit service to the growing metropolis, creating a system of fast, affordable rail transit centered on lower Manhattan and extending into the outer boroughs. This paper uses historical data on subway construction and parcel-level land use to explore the relationships between residential development, commercial development, and subway system expansion. The data are analyzed using Granger causality methods to estimate whether subway growth is a leading indicator of land development or if land development led subway expansion in the boroughs of Manhattan, Brooklyn, Queens, and the Bronx in New York City during the twentieth century.[1]

This research focuses on the interdependent development of the city's subway network with residential and commercial land uses. Unlike many previous studies of urban growth, this research considers subway expansion as part of the land development process. In many cities, such as Los Angeles, streetcar systems were built by land developers who needed to provide access to new residential areas. New York was unique in that the transit systems dating to the early elevated rail lines were built by transit companies with no formal connection to the land development market. The subway system followed this model, under which the city assisted with construction but the costs of operations were recovered through fares.

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[1] Staten Island was omitted from this analysis because of its geographic isolation relative to the other boroughs. The island is not connected to the subway system and only directly accessible from Manhattan by ferry and from Brooklyn by the Verrazano-Narrows Bridge.

In the first decade of the twentieth century, much of New York City's population was crowded into tenement districts, with 80 percent of the population living on 25 percent of the city's land area in 1910 (Jablonski 2006). The largest tenement districts were in lower Manhattan. City leaders sought new subway service to help disperse the extremely high residential densities in lower Manhattan and to separate commercial development from residential areas, goals supported by the zoning code of 1916.[2] However, the subway was built under partially competitive circumstances and much of the growth of the network occurred in areas where the subway already existed rather than in undeveloped areas.

New York offers a valuable lesson in transportation and land use development. Three important factors that affected the spatial development of the city are highlighted in this article. The first is that three transit companies (consolidated by the city in 1940) built the subways privately through public concessions with the aid of public financing. The transit operators were not land developers and relied solely on fares to pay their operating costs. Under these competitive conditions, transit companies sought profitable routes rather than extensive coverage and reach into the outer boroughs. This has implications for the co-development hypothesis, in that companies seeking profitable routes are likely to follow existing development rather than lead new development. The end result is a dense network of transit that can support very high residential and commercial densities.

The second factor is that zoning in New York City was largely unrestricted outside of lower Manhattan between the first zoning code in 1916 and the first comprehensive zoning map in 1961. The 1916 code restricted the height and bulk of buildings throughout the city and restricted uses in some areas. For most of the city, developers and land speculators were able to build structures and uses that held the greatest value, and where zoning controls did prescribe specific uses or densities, such as single-family residential, developers regularly requested and received variances in order to develop more densely (Revell 2002)

The third factor considered here is that the nature of industry in New York was rapidly changing during the period of subway growth. Offices were pushing blue-collar manufacturing out of Manhattan and into the surrounding suburban areas of the outer boroughs (Harris 1993). Transit access supported thischange. Thomas Jablonski (2006, p. 6) explains this process: "In Manhattan, as land became more expensive, new office building developments grew denser and taller to sustain profitability. This necessitated more subways, increasing the land values of commercial development sites adjacent to the new subway stations." Commercial displacement from the core, in which workers and business shifted towards less developed (but not necessarily undeveloped) areas, was made possible by the high quality of transit service provided by the subways. These three factors suggest novel insights into the effects of transit network density on the intensity of land use development.

2 Hypotheses

This research considers two alternative hypotheses. The first hypothesis is based on the conventional view that subway expansion led residential growth. Figure 1 illustrates the common perception that the subway led development and shows the expansion of the subway through an unpopulated section of Queens around the Fortieth Street Station of the No. 7 line during construction; Manhattan skyscrapers are visible in the distance. Figures 2 and 3 are aerial views of the station area from 1921 and 1954, respectively. The No. 7 line enters at the left of the photos and turns slightly north immediately after the Fortieth Street station. During construction, the land was mostly undeveloped. The station opened in 1917, and as shown in Figure 2, much of the surrounding land was plotted but undeveloped in 1921. By 1954, the surrounding area had long been fully developed with large apartment buildings.

Figure 1: Elevated IRT 7 Fortieth Street station under construction, Queens, 1917. Source: New York City Metropolitan Transit Authority.

The Fortieth Street Station, however, is not representative of most of the subway system's growth. As privately operated

[2] Tenement reform was addressed separately from the zoning code and focused on building design, ensuring light and air to reach all units.

Figure 2: Aerial view of IRT 7 Fortieth Street station, Queens, 1921. Source: The City of New York.

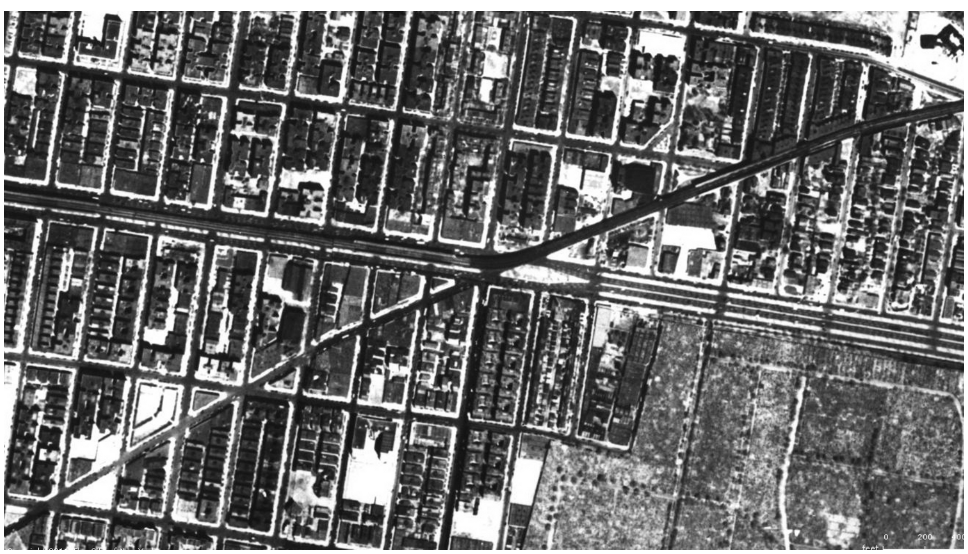

Figure 3: Aerial view of IRT 7 Fortieth Street station, Queens, 1954. Source: The City of New York.

transit providers, the transit companies bid on the rights to develop routes they expected to be profitable. Competing companies sought routes where density was already relatively high, rather than routes in undeveloped areas. A new route that extended far into the boroughs was riskier to develop than a route with an established rider base. These conditions made it less likely that new subway construction always led land development, as transit operators preferred routes that would be immediately profitable upon opening.

The second hypothesis tested is that land development led subway growth, as measured by station openings. New York City already had a large population when the first subway service was launched, and private operation of the transit lines reinforced the importance of building the network in areas where ridership and fare revenue would be high immediately upon opening. Unlike transit systems built by land speculators who invested in transit to provide access to undeveloped land, the New York system was built in an established and growing city.

To test these hypotheses multiple methods are used. Correlation coefficients are calculated to examine the potential connections between subway growth and residential and commercial land development. Parcel-level data is then merged with subway station data and analyzed using Granger causality methods in order to estimate how well the presence of subway stations predicts land development or, alternatively, whether land development is a better predictor of subway growth. These methods and data are described in detail below.

3 Background

Untangling the relationship between transportation and land use is a major concern to planners, officials, and researchers. Historically, many American cities developed streetcar and rail transit systems in the late 1800s and early decades of the 1900s. These systems provided access to early suburbs for the middle class.[3] Most of these systems were operated privately, like the famous Red Line streetcars of Los Angeles. The systems in Los Angeles, Philadelphia, Minneapolis, and Boston, among others, were promoted by real estate interests interested in creating access to new land for residential development. In New York City, however, the subway system was operated as a transit business and there were no real estate holdings to offset capital costs. The new subway system had to generate enough revenues through fare collection to pay for the service.

[3] For additional detail about early suburbanization in Philadelphia and Boston see (Jackson 1985; Warner 1968, 1978).

The primary mechanisms local governments have to control land use are zoning, other regulatory measures, and financial incentives that are used to guide development (Frug and Barron 2008). These are crude tools for integrating transportation and land use development. Looking historically at how cities have developed around privately built transit systems in the absence of strong land use regulations provides real-world examples of how developers value access. In areas with high accessibility and land costs, developers maximize the economic return from their land by building as densely as possible. Such incentives limited the potential for the subway to "suburbanize" New York City as subway technologies dispersed the population. New construction where the transit network is most highly developed is a countervailing force that concentrates residents and businesses, though at a lower intensity than had existed previously.

There are multiple ways to think about how transportation affects the built environment and vice versa. This paper is concerned with the intensity of development at the parcel level near subway stations. A common refrain heard from contemporary transit advocates is that rail investment leads to denser land development than would otherwise be the case (Calthorpe and Fulton 2001; Litman 2005). This is a difficult causal relationship to model for a number of reasons. First, in order to densify, cities must have population and economic growth. If density increases near stations during a period of no growth, then decline will be evident in other areas. Increased residential and commercial densities reflect redistributive efforts, in which people and firms locate in closer proximity to each other than they otherwise would.

Proponents of rapid transit in New York were primarily concerned with maintaining the economic vitality of the city in the face of crushing residential and commercial building densities. Residential densities exceeded 38 000 persons per square kilometer in parts of lower Manhattan during the early years of the century, and Wall Street skyscrapers were placing tremendous strain on the narrow streets below. Sidewalks were shielded from daylight; crowds of peopleand horses, produced severe congestion; and disease was rampant (Derrick and History of New York City Project 2001). To address these concerns, the city enacted tenement reform legislation and the landmark 1916 zoning code that limited building bulk, and use. In these conditions, rapid transit was seen as a decentralizing force that would lower densities and promote development elsewhere (New York Times 1922).

The role of transit in suburbanizing New York is quite different than the expected urban transformations led by transit development in the twenty-first century. By the time the boroughs consolidated into one city in 1898, it was clear that the existing transit system of elevated trains, horse-drawn street cars, and electric trolleys was inadequate for dispersing the population of lower Manhattan. These early transit technologies had encouraged some land speculation and development on the island as far north as Harlem, but business interests and politicians were adamant that the city needed faster transit service in order to shift the pattern of development (Cheape 1980).

By the late 1910s, public transit was competing with automobiles for personal travel (Schrag 2000). Streetcar lines in the city were losing ridership to subways and automobiles. Automobile registrations in New York City jumped from just over 39 000 in 1915 to more than 610 000 in 1927 (Schrag 2000). Although the subway system was expanding quickly during this period, the meteoric rise in auto registrations suggests that New York was not destined for a transit-oriented future and that there was potential for the outer boroughs to grow around the automobile. This future came to pass in many areas, such as eastern Queens and Brooklyn, and certainly, Staten Island. But the subways and their nickel fares were viable competitors with the private automobile so long as development in the city supported transit use.

4 Subway history

In 1900, New York City had a large central business district in lower Manhattan and a smaller business district in downtown Brooklyn. These districts were served by a network of elevated trains and surface rail built in the decades following the Civil War, and most of the lines and services of these transit systems were in Manhattan. Three elevated lines ran north from South Ferry at the southern tip of the Manhattan, and one ran north from City Hall at the foot of the Brooklyn Bridge. In some cases, these elevated lines were simply replaced by subway lines decades later: the line that ran north into the Bronx and terminated at Bronx Park (now home to the Bronx Zoo) was replaced by the No. 6 subway line. There were very few east-west lines crossing Manhattan, and much of the island remained underserved by transit. There was no service in Manhattan north of 155th Street in Harlem (Derrick and History of New York City Project 2001). After a few decades of operation, the elevated lines declined in popularity and ridership and were increasingly criticized for ruining neighborhoods through noise, blocked sunlight, and other problems (Divall and Bond 2003). At the same time, most of the outer boroughs (Queens, Staten Island, and the Bronx) were largely semi-rural and underdeveloped, though Brooklyn did have an established employment center and shipping related industries.[4] Civic leaders were eager to develop a mass transit system that promoted decentralization and encouraged development of the outer boroughs. In 1894, the New York state legislature authorized a new Rapid Transit Commission (RTC) charged with administering a new rail system for New York City (Hood 1995).

In 1903, the elevated rail system was transferred via a 99-year lease to the Interborough Rapid Transit Company (IRT), which was contracted to build the first subways in the city (Divall and Bond 2003). The New York subway officially opened in 1904 and grew rapidly in the years thereafter. The initial concessions were difficult to sell, though subway operations were highly profitable once the systems opened (Lavis 1915). According to a contemporary account, "the new lines will be built underground in the more thickly populated sections of Manhattan and Brooklyn and elevated in the outlying districts," (Lavis 1915, p. 3). Figure 4 shows the number of stations opened per year and the cumulative number of stations. Stations that have been closed are not included in these data, though very few stations have been closed without being replaced or consolidated with other nearby stations. The current system has approximately 470 stations. The number of stations does not grow consistently over time, in part because stations along individual subway lines tend to open all at once rather than sequentially. The rapid growth of the system was over by 1940, though quite a few stations have opened in the years since. The last new station (in terms of new service, rather than serving as a replacement for a previously existing station) opened in 1989. Currently, the T Line is under construction on the east side of Manhattan along Second Avenue between 125th Street to the north and Thirteenth Street to the south; it is expected to open in 2017, but the project has been plagued by cost and time overruns.

5 Zoning controls

Between the first zoning code in 1916 and zoning reform in 1961, the outer boroughs had limited zoning regulations. The zoning code regulated building bulk but did not restrict uses in most areas of the city outside of Manhattan and parts of Brooklyn. In some ways, the New York zoning code was created in order to help disperse the concentrated development in lower Manhattan (Fischler 1998). Tenement housing on

[4] The Brooklyn Bridge opened in 1883 and greatly improved access to lower Manhattan. The Brooklyn waterfront was also busy with shipbuilding. However, the eastern and northern sections of the borough were largely undeveloped or agricultural.

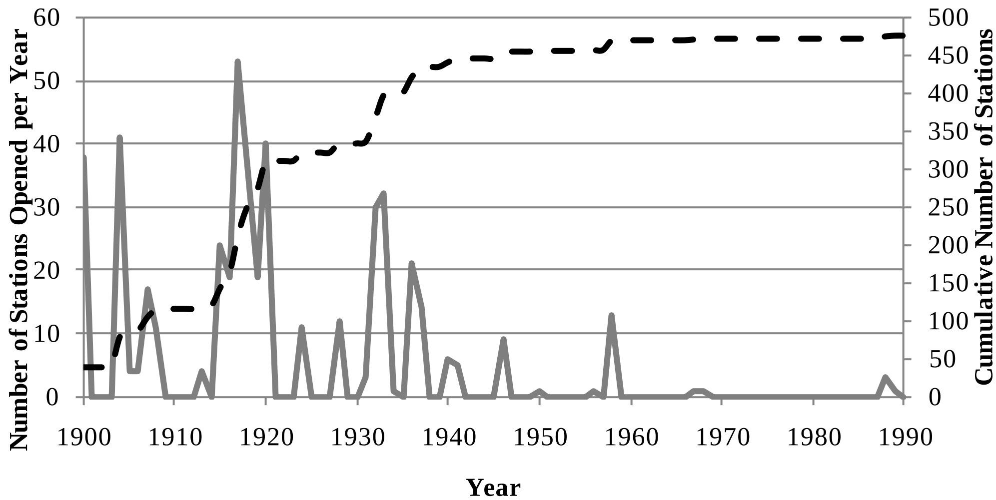

Figure 4: Number of New York City subway stations by year opened and cumulative totals, 1900–1990 (excluding Staten Island).

the Lower East Side produced unsafe and undesirable densities as high as 167 000 persons per square kilometer in 1900 (Cox 2010). Population dispersion was not the only impetus for zoning, as many businesses and landlords advocated for restrictions on building heights ("skyscraper zoning") and the separation of commercial and industrial uses (Weiss 1992). As Weiss notes, at the time of the first zoning code Manhattan had more buildings taller than 21 stories than the rest of the country combined, and these enormous buildings were blocking light and views on the street.

The new zoning ordinance did not stop skyscrapers from being developed, as evidenced by the preponderance of tall building that comprise the Manhattan skyline. Rather, the intent of the zoning code was to minimize congestion, crowding, blockage of light, and negative economic effects by limiting the size and shape of buildings, especially in the central business district. The Manhattan grid system, developed in 1811, created many small parcels of land that were difficult to assemble into large tracts, so developers in the core pushed their buildings upwards (Willis 1995). These skyscrapers used the entire area of the parcels, generally prevented sunlight from reaching the street, and crowded out non-commercial uses.

Even though the new zoning code restricted some types of buildings and industries in parts of the city, land developers were reluctant to build new residential structures in un- or under-developed areas due to the risk of problematic neighboring land uses (Revell 2002). Without zoning controls in place there was no certainty that a future factory would not impinge on a residential or manufacturing development, thus reducing the desirability of the area. Turner (1922) notes that many land owners had little interest in developing the land around subway stations far from the city center because of uncertainty about neighboring land uses,

The 1916 zoning code did regulate building height and bulk, but famously had the city been built out to full extent allowed by the code, it would house over 55 million people today (New York City Department of City Planning 2009). While the new ordinance designated residential districts, much of Queens, Brooklyn, and the Bronx remained "unrestricted" land, meaning developers were largely free to build what they wanted and thought they could successfully market. Where restrictions did exist, variances were relatively easy to obtain, though most of the variances granted were for building more densely than the code allowed (Revell 2002). In many cases, developers sought to build multifamily housing near transit even if the land was zoned for less intensive development.

In 1961, the city introduced a major revision of the zoning code including more prescribed uses and restrictions than had previously existed. The 1961 code is the basis for the current zoning throughout the city. New York City Department of City Planning (2009) describes the change:

> New theories were capturing the imaginations of planners. Le Corbusier's "towers in the park" were influencing urban designers of the time and the concept of incentive zoning—trading additional floor area for public amenities—began to take hold. The last, still vacant areas on the city's edges needed to be developed at densities that recognized the new, automobile-oriented preferences.

> And demands to make zoning approvals simpler, swifter and more comprehensible were a constant.

The new zoning code was the end of the line for transit supporting densities as a guiding factor for subway expansion.

6 Data and Methodology

The analysis presented here uses New York City Primary Land Use Tax Output (PLUTO) data for Manhattan, Queens, Brooklyn, and the Bronx, combined with datasets of subway stations and lines. Staten Island was omitted from the analysis due to geographic isolation from the transit system. PLUTO provides parcel-level data that includes the square footage of each parcel, size of building area, year constructed, and square footage devoted to each use, among other information. The dataset was developed by the New York City Department of City Planning. The subway dataset includes data on each station in the existing New York system in the four boroughs studied. The year each station opened was determined, making it possible to estimate line effects and station effects.

The data presented organizational challenges. The parcel-level nature of the PLUTO dataset results in hundreds of thousands of individual data points. While this level of disaggregation provides a wealth of detail, it is impractical and undesirable to estimate the co-development of transportation and land use at such a small scale. In this analysis, the data were aggregated to 2.6 km2 (one square mile) cells. Hawth's Tools in ArcGIS 9.3 were used to create a new shapefile of grids to join the parcel data and subway data. Even though each grid potential is larger than the 800-meter (roughly one-half-mile) radius around stations that is conventionally used for planning transit-oriented land use, the grids allow for more robust statistical analysis. The cells that did not have any subway stations when the system had reached its greatest extent were omitted from the analysis.

Lot densities were calculated using PLUTO data and aggregated by decade. In most of the study area, the original structures are still in place, though a great number of them have been modified. The median age of buildings in the city is 70 years. While these newer and larger buildings may introduce some bias into the data, they represent a very small component of the total density calculation, and it is only the marginal increase in density that may have a distorting effect. This diminishes the potential bias in the results.

7 Subway Growth

In 1910, commercial densities were highest in lower Manhattan (Figure 5); residential densities were spread more evenly throughout the city (Figure 6), but the spatial pattern of residential density clearly conforms to the area served by subway stations. Many parts of the city had very low commercial densities or a complete absence of commercial uses, but did have subway stations. The grid cells displayed in Figures 5 and 6 are used to aggregate the land development and station data for the analysis presented later in this paper. Parcel-level data was used to calculate average parcel-level density for each use. This calculation accounts for parcels containing multiple uses; for example, storefronts with apartments above are counted for both residential and commercial densities. The scale of commercial densities extends to ten square units of commercial area per unit of lot space; the residential scale extends to two residential units per unit of lot space.

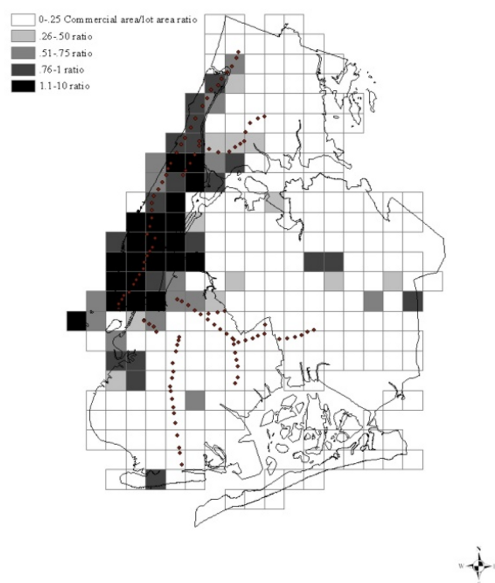

Figure 5: New York City net commercial density, 1910.

Figure 7 shows the growth of the subway system for the period 1910–1950. Most of the station growth occurred near areas already served by transit. The red circles denoting stations opened between 1910 and 1920 show that some areas of Queens had service by 1920 (refer to Figures 1– 3), and service was also extended to some southern areas of Brooklyn during this decade. In the following two decades, however, most of the growth in the subway system was near areas already served, shown by green and blue circles. The city consolidated the privately operated BMT and IRT systems in 1940, and in the following decade invested in the Independent

Figure 6: New York City net residential density, 1910.

lines, which are represented by black circles. As with earlier system growth, some new stations opened in areas previously not served by transit, but most of the new stations reinforced the existing network (Jablonski 2006). Much of the privately driven growth in the subway system appears to be at least partially tied to densities from 1910; the least densely populated areas in 1910 have the lowest subway station densities in 1950.

8 Correlation Tests

The relationship between transportation systems and land development can take three forms. First, transportation investment can lead land development. This occurs where real estate interests invest in transportation in order to increase the value of their land holdings; this model was followed in many North American cities, including Los Angeles and Minneapolis. A second form is when joint development occurs and transportation is built concurrently with new buildings. As transit connections are made based on population growth in new areas, the transport system will grow in an orderly fashion following predictable routes. Levinson (2008b) described this as the "orderliness hypothesis." Lastly, new transit systems may be built to serve areas of the city that are already developed. In New York City, transit systems relied on farebox revenues to pay for operating costs. This suggests that the early operators of New York's subways would not have been speculative with regard to line expansion. Unlike their counterparts in Los Angeles or Minneapolis, New York transit operators were not land developers. This last form, transit investment follows land use, is hypothesized to predominate in New York, though potentially with some mutual causality and joint development. However, residential and commercial land development may exhibit different growth characteristics than commercial activities. Like transit operations, commercial uses depend upon residents to supply both a market and a labor force. In some cases, commercial activities may crowd out residential activities as the transit network improves and increases land values.

In order to determine whether subway growth occurred before or after residential and commercial development, Spearman's rank correlation tests are calculated. Analysis cells, shown in Figures 5 and 6, with missing values were deleted. Figure 8 shows the rank correlations between subway station density and land use densities. In the early decades of subway growth, the correlations were weak among the relationships tested, but over time the correlations strengthened. The residential rank correlations are consistently higher than the commercial correlations for the entire period. By 1930, both commercial (0.58) and residential (0.63) rank densities strongly correlated with station densities, and the residential rank densities continued to strengthen until reaching a peak in 1950 (0.69). The system was largely complete at this point, and the city's population growth had stabilized at approximately 7.8 million, where it remained for the next few decades.[5] Since these peaks, the correlations have remained largely stable with a slight decline, and are still strong today (> 0.55 for commercial and > 0.64 for residential ranks).

Given that the subway was intended to suburbanize the city away from lower Manhattan, these correlations conform to expectations. It is noteworthy that the correlations started to weaken somewhat when subway construction slowed. The city did not continue to densify once the system was mature, but this is not surprising under the circumstances, namely that the population of the city stopped growing. Two factors that certainly had smaller effects but are not tested here were the turn towards automobility in the city, perhaps best embodied by the parkways and other roads built by Robert Moses,[6] and the more restrictive zoning code for the whole city introduced in 1961. The new zoning code limited potential densities through height, bulk and use restrictions and introduced parking requirements throughout the outer boroughs and northern Manhattan in order to better serve automobile-

[5] The city's population remained around 7.8 million until the 1970s when the population declined substantially. By 2000 the population recovered and now stands around 8.3 million.

[6] See Caro (1974) for full details of Moses' road building.

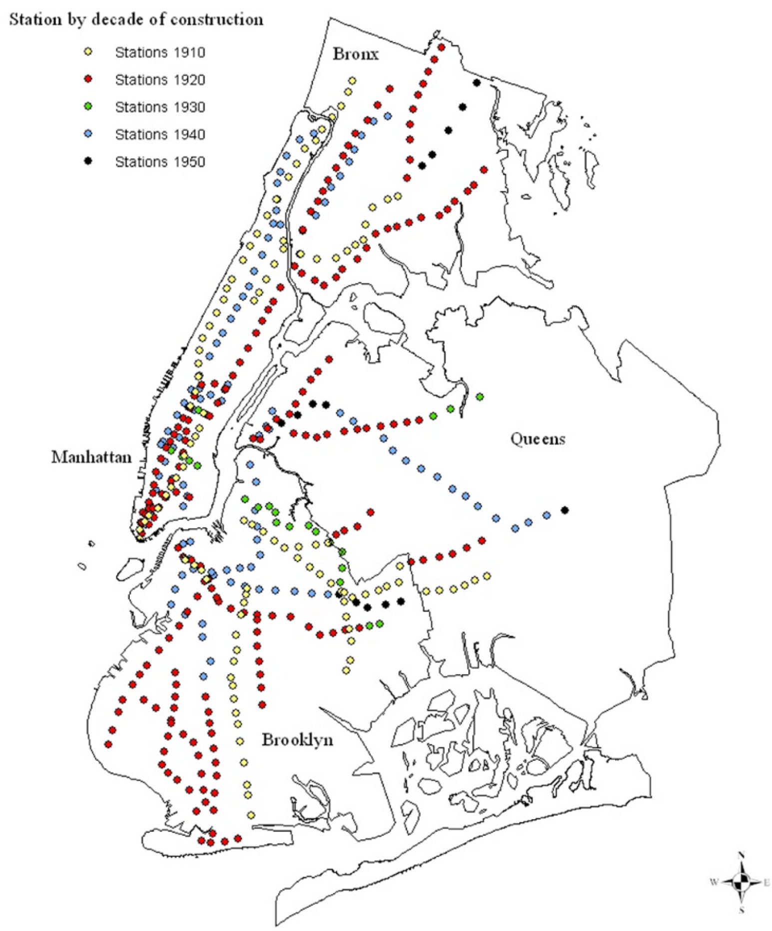

Figure 7: Subway stations by decade of construction. Data: New York City PLUTO, New York City Transit.

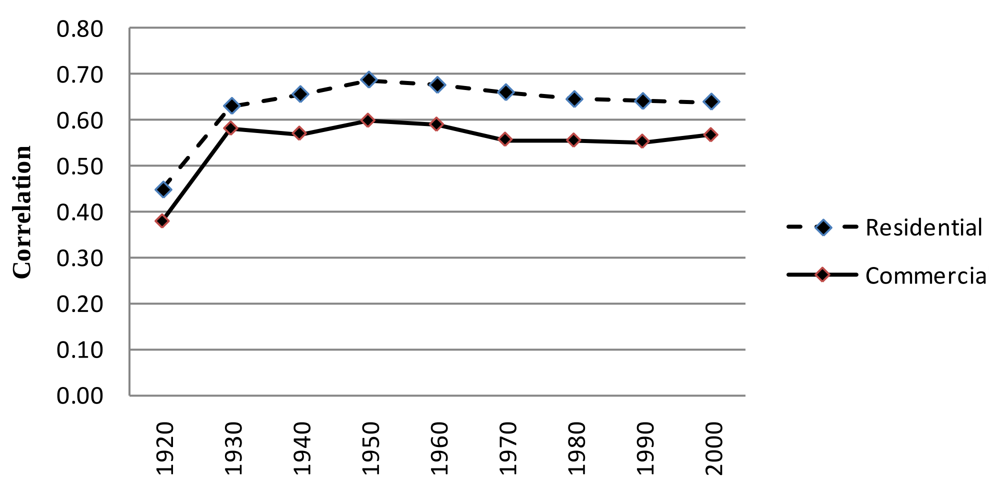

Figure 8: Spearman rank correlation of residential and commecial density ranks by station density.

oriented development. Parking requirements often reduce the buildable size of lots to levels below what is allowed (Shoup 2005), and reduce the likelihood of achieving densities that support transit.

The strong correlations between land use densities and stations partially reflect the durability of the built environment. While subway stations are moved occasionally, there have been few closures since the 1940s when redundant stations were shut down. There are few areas of the city where subway service has declined since it was introduced, at least as measured by access to the system.[7] However, it should be noted that these correlations are limited to the intensity of development and do not reflect actual population or employment. This caveat does not diminish the usefulness of the data, but does limit the generalizable lessons.

9 Models

Granger causality models are used to estimate leading indicators of subway and land use development. Sets of time-series data are compared to see if one set of variables Granger causes a change in another set, suggesting that one lagged variable at least partially predicts the present value of another. These models are based on the work of Clive Granger, who developed these techniques for econometric modeling in order to determine the direction of causality among related variables (Granger 1969). A limitation of these methods is that causality is not explicitly tested; rather, the estimated coefficients describe the strength of the relationship between variables across time and help predict if certain phenomena are leading indicators of the dependent variable. The models do not test for causality in the conventional sense, and the results should not be interpreted as a statement of conventional causality. It is more accurate to describe Granger causality as estimating the strength of a relationship between the presence of one phenomenon and the subsequent measurement of another phenomenon.

In the case of this research, I compare the estimated Granger causality of land use types and development densities on subway development, and of subway development on changes in land development. The data series are compared to see if land development preceded subway development, or if subway development preceded land development. Other transportation researchers have used similar methods to estimate the effect of road expansion on vehicle-miles traveled (Cervero and Hansen 2002; Fulton *et al.* 2000). Others have looked at municipal competition (Binet 2003). More recently, scholars have applied these techniques to the coevolution of transit and land development in Minneapolis-Saint Paul (Xie and Levinson 2009) and London (Levinson 2008a).

The Granger causality models presented here are not intended to be fully predictive of development for New York City. Intentionally left out of the models are factors that influence urban growth including population changes, employment, and industrial shifts; other transportation technologies such as cars and buses; and zoning regulations. While these factors are certainly important to a full understanding of New York City's development during the twentieth century, it is assumed that exogenous aspatial factors are also in play. This means that growth and change occur across the region, and there is no reason to expect that one area will have an advantage over others. Since transit development does improve accessibility and increase the value of land, growth is to be expected in areas where accessibility is high.

Three models were estimated conventionally using the "correlated panels corrected time series" (xtpcse) command in Stata 11 with subway station density, residential net density and commercial net density for the period 1910–1950 as the dependent variables. The explanatory variables in the models included lagged variables representing the changes in density for building uses and subway stations across the previous period. These models estimate to what extent the change in subway growth and/or land development affect the dependent variable. For instance, residential densities in 1930 may have a larger impact on residential densities in 1940 than new subway construction between 1930 and 1940. Conversely, if the subway was built in response to residential demand, new subway construction (and increased station densities) will be more dependent on residential densities from the previous period than on the presence (or absence) of stations in the previous period. The relationships tested here are used to determine which came first—land use densities or subway construction.

The distance (in kilometers) from City Hall of each grid cell centroid is included as an explanatory variable under the assumption that the subway continued to grow outward to serve population growth.[8] City Hall sits at the base of the Brooklyn Bridge and was the site of the first subway station, making it a suitable proxy for the center of the city during subway expan-

[7] The most tragic loss of subway access is at the site of the World Trade Center, which has not had a subway station since the terrorist attacks in 2001. There is a new transit complex slated to open in 2015 at the site. Other nearby subway stations on different lines serve the area.

[8] The grid cells are shown in Figures 5 and 6.

sion.[9] The subway system developed radially outwards from lower and mid-Manhattan, and even today it is difficult to use the subway to travel between the outer boroughs. The radial network features extremely high station density in many areas of Manhattan and downtown Brooklyn, and other lines that offer the only rail transit service in areas of Brooklyn, Queens and the Bronx. There is no correlation between the distance from downtown and the year the stations opened.

Station effects are estimated using the change in density of stations in a cell. As station density increases, the overall accessibility of the area rises, which should result in more intense development. More simply, a neighborhood with multiple stations is likely to have greater residential and commercial density than a neighborhood with a single station; thus, station effects should be larger than distance effects.

10 Results

Summary statistics for some variables included as explanatory factors are presented in Table 1. The mean of the net densities are reported, calculated as the ratio of residential or commercial area to lot area for each cell used for aggregation. The residential and commercial density variables are calculated as the ratios of the total built space for residential or commercial purposes to the total parcel area for each grid cell. These ratios represent a measure of net density, exclusive of streets and other unbuildable areas. Station density is calculated as the number of subway stations per square mile. The time period analyzed includes the decades of 1910-1950, which was a period of rapid population growth, built-environment development, and subway system expansion. The descriptive statistics in Table 1 show that although net residential densities are far higher than net commercial densities in station areas, commercial densities increased slightly over time while residential densities decreased slightly The standard deviations of these means suggest that the changes were not uniformly distributed across the city, however.

The results from three estimated models are shown in Table 2. All estimates are calculated using data aggregated to cells, as described earlier. Changes in densities, net densities in previous periods, distances from City Hall, and changes in New York City population are included as explanatory factors. The first column (1) shows the results for influences on station

Table 1: Summary statistics for key variables, 1910–1950.

Variable	Mean	Standard deviation
Station density	2.6177	2.5217
Residential lot density	1.0798	0.7092
Commercial lot density	0.6035	1.2916
Change in Commercial ($t_0 - t_1$)	0.052 59	0.3869
Change in Residential ($t_0 - t_1$)	−0.0166	0.243 67

densities. The results show a positive and statistically significant relationship ($P = 0.038$) between changes in net commercial density and subway station density, whereas changes in residential densities have no effect. The distance from City Hall also has a significant relationship ($P = 0.030$) where station densities decline as distance increases. Together these estimates suggest that growth of commercial development and proximity to City Hall help predict the density of subway stations. These results partially affirm the hypothesis that land development precedes the growth of the transit network.

The results for residential densities, shown in column (2), have a significant ($P = 0.015$) and positive correlation with changes in the city's overall population. These results fail to confirm the hypothesis that subway growth was a major driver of land development. The change in station densities has no measureable effect on net residential densities in this model. These results challenge the conventional view that subway growth ushered in suburban development, but conform to the historical development of the transit system. Early route proposals that sought to encourage the construction of lines in undeveloped areas were often opposed by real estate investors who preferred improvements to the existing transit system, and were rejected by the New York State Public Service Commission (Cunningham and Hart 1993).

Net commercial density is positively correlated with changes in station densities ($P = 0.025$), partially confirming the first hypothesis, though in this case commercial uses rather than residential space responds to new transit service. Interestingly, changes in residential density also have a positive and significant ($P = 0.084$) effect on commercial density. Change in New York's population is also highly significant ($P = 0.000$) and positive. These results suggest that commercial activities favored areas with high levels of subway accessibility and rising residential populations. The models presented suggest that population growth was highly correlated with residential and commercial growth, but the growth of the

[9] The City Hall subway station was originally opened to demonstrate the use of pneumatic power to propel underground trains. The area near City Hall featured many elevated transit lines and other technologies that existed before the subway was built. The first line opened was the 1, which runs along Broadway and the west side of Central Park north into the Bronx.

Table 2: Lagged estimators on station, residential and commercial densities, New York City 1910–1950 (std. errors in parentheses).

	Dependent Variable					
	Station Density m, t (1)		Residential Density m, t (2)		Commercial Density m, t (3)	
Change in station density $(t_0 - t_1)$			−0.0012	(−0.0129)	0.0594**	(−0.0265)
Change in net commercial density $(t_0 - t_1)$	0.5981*	(−0.2876)	0.0372	(−0.0304)		
Change in net residential density $(t_0 - t_1)$	−0.0643	(−0.2952)			0.0743*	(−0.0429)
Station density (t_1)	0.9062***	(−0.1583)				
Residential density (t_1)			0.9586***	(−0.0739)		
Commercial density (t_1)					1.0326***	(−0.1076)
Distance from City Hall (km)	−0.0369*	(−0.017)	0.0006	(−0.0048)	−0.0045	(−0.0046)
Change in city population $(t_0 - t_1)$	−0.0543	(−3.345)	0.7120**	(−0.2932)	0.6889***	(−0.1803)
Constant	1.3129*	(−0.7759)	−0.0814	(−0.1387)	−0.0336	(−0.1217)
r^2	0.76		0.87		0.91	
n	496		496		496	

* significant at 10 percent level
**significant at 5 percent level
***significant at 1 percent level

subway system was not significantly correlated with the city's growth.

11 Conclusion

Two hypotheses about the development of New York City's transit system along with residential and commercial densities were tested. The first hypothesis is that subway development preceded residential development throughout the city. While it is certain that subway construction preceded residential development in some areas (Figure 1), analysis performed in this research does not confirm any correlation between subway growth and residential densities, suggesting that places where the subway system was built first were uncommon.

The second hypothesis tested is the converse of the first, namely that land development was a leading indicator of subway growth. The analysis in this research suggests that this hypothesis is partially confirmed, but rather than residential growth, it is commercial land use that is correlated with the density of subway stations. The conventional narrative of transit development often assumes that transit growth preceded land development. This paper argues that the conventional narrative is incomplete in the context of New York City, and that the growth of the subway system was partially dependent on land uses, and in particular that transit network growth largely followed land development. This is especially true for commercial land uses, the growth of which is associated with the increasing density of subway stations. While residential densities were not found to be significantly correlated with subway growth, they were found to be positively associated with commercial densities.

Two additional issues may have affected subway network growth and land development. First, the subway system was largely completed in the absence of substantial competition from automobiles. In fact, because of the underground and elevated characteristics of the New York system, the trains did not compete for road space with automobiles, as was the case in Los Angeles and in most other streetcar cities. Private automobile ownership did flourish in New York, but not at the expense of rapid rail transit. Second, land development was loosely regulated through the zoning code in most parts of the city. Developers were largely able to pursue speculative activities and could relatively easily receive variances to build more densely or more intensively than allowed under law in areas where they saw demand. This allowed developers to pursue commercial activities in areas where they perceived demand.

One generalizable implication from this research is that transportation networks are influenced by developed land. While transportation improvements increase the value of land by enhancing accessibility, under the right circumstances existing land development enhances the value of transportation investments. In New York, the subway was built partly as a response to existing demand, and the result is a dense subway network that continues to be a symbol of the city.

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