

1974

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Gordon W. Davies

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Citation of this paper:

Davies, Gordon W.. "The Effect of a Subway on the Spatial Distribution of Population." Department of Economics Research Reports, 7404. London, ON: Department of Economics, University of Western Ontario (1974).

20262

Research Report 7404

THE EFFECT OF A SUBWAY ON THE
SPATIAL DISTRIBUTION OF POPULATION

Gordon W. Davies

March, 1974

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ABSTRACT

In this paper we assess the effect of the original Yonge Street subway on the spatial distribution of population in Metropolitan Toronto. We find that the subway was originally constructed through a low density corridor and that it resulted in relatively larger increases in gross residential density for Census tracts which were closer to the line. This result has important implications for transportation planning which normally assumes a fixed spatial distribution of population and it is of interest to those who believe that there are non-trivial externalities associated with high urban population densities.

THE EFFECT OF A SUBWAY ON THE
SPATIAL DISTRIBUTION OF POPULATION*

Introduction

The objective of the research described in this paper is to determine the effect of the original Yonge Street subway line on the spatial distribution of population in Metropolitan Toronto. The conventional view is that the effect of a subway on residential density is substantial, based on the observation that large apartment blocks are often located near the terminals of a subway line.¹ This view may be incorrect, however, because increased space near the subway line is often allocated to commercial uses, parking and other terminal facilities for transit riders, and maintenance and storage yards for the subway system itself.²

It is important to examine this relationship in order to forecast demand for subway trips. In calculating expected future mass transit ridership, urban transportation plans typically project the spatial distribution of population and employment on the basis of past trends or the desired form of the area as reflected in other planning documents. These spatial patterns are then used to calculate mass transit use, given some assumptions about modal split.³ If, however, residence and employment densities adjust to the location of the subway line, future mass transit use may be very different from that predicted in the original plan.⁴

The effect of a subway on the spatial distribution of population is also of interest to those who believe that there are important externalities associated with the form of urban development.⁵ The popular view is that expressway or road-oriented urban areas are spatially less concentrated

than mass transit-oriented areas. The implicit comparison we make in this research is between the effects of a mass transit system and a road, rather than expressway, system.

A proposal for a subway in Toronto was originally formulated in 1910 and recommended again in 1912 and 1942. The present Yonge Street subway was proposed in 1945 and approved by a general municipal vote in January, 1946. Construction on the line began in September, 1949 and was completed in March, 1954. This original line ran from Front Street at Union Station 1200 feet east to Yonge Street and then north to Eglinton, for a total length of 4.6 miles.⁶ (See Figure 1.) No other subway lines were opened prior to the 1961 Census. The only expressway in place at the time of the 1961 Census was an east-west section of approximately 2.5 miles, opened in August, 1958. Censuses of 1951, 1956, and 1961 give a substantial number of observations on the distribution of population by Census tracts.⁷ We can therefore infer the effect of the subway by comparing the distribution of population in 1956 and 1961, after the line was opened, with the distribution of population in 1951, before the line was opened.

We find that the subway line was originally constructed through a low density corridor, i.e., that density increased with distance from the corridor through which the line was constructed, ceteris paribus. The same relationship between density and distance from the corridor is found to exist after the subway was constructed but the effect is less pronounced in later years implying that construction of the subway altered the spatial form of the area. In addition, we find that tracts closer to the subway line experienced larger relative increases in their populations over time than tracts further out, ceteris paribus, which is consistent with the result described above. This last relationship is found for the periods 1951-56 and 1951-61 but is

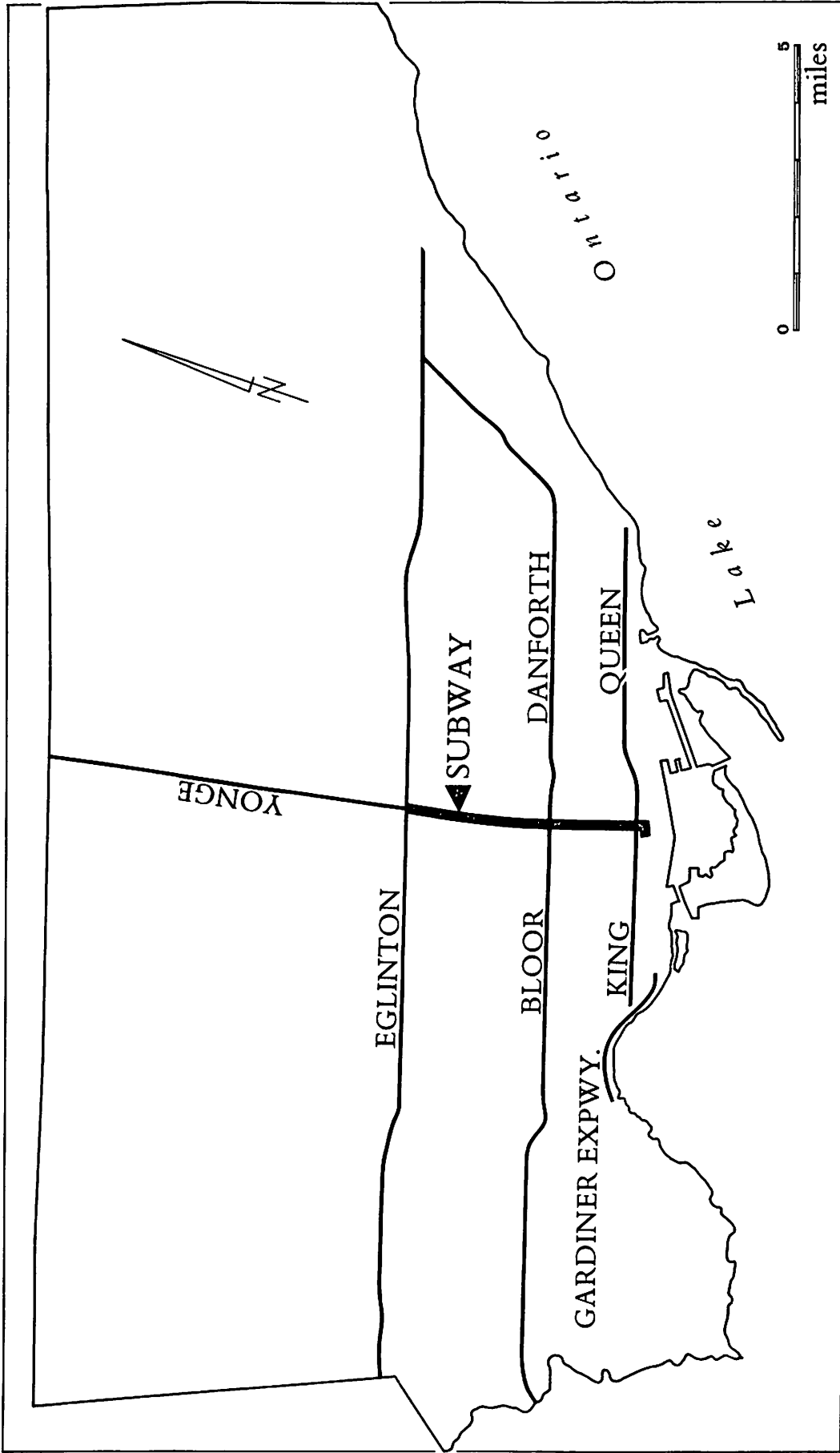


Figure 1. Location of subway in Metropolitan Toronto, 1961.

statistically significant only for the period 1951-61, likely because some time is required for urban development or redevelopment to occur.

In the next section of the paper we specify two models to test the effect of the subway and formulate a number of hypotheses. The following two sections give the sources of data and results, respectively, and the paper concludes with a summary statement of the findings.

Hypotheses

We make two sets of tests of the effect of the subway line. For the first set of tests we formulate a model of residential densities and estimate it with cross-section data for 1951, 1956, and 1961. The objective of this set of tests is to investigate the relationship between the location of the subway and population density at the time the line was originally constructed. This is important because the relationship between density and proximity to the subway in any subsequent year will be affected by the relationship in the year in which the subway was constructed. By examining the differences in the relationship between density and proximity to the subway in different years we can also infer the effect that the subway had on densities. For the second set of tests, we formulate a model which explains the relative change in density (or population) by Census tract for 1951-56 and 1951-61 and infer the effect of the subway line directly.

The relationship between the amount of space (the inverse of density) which a household consumes and distance from the CBD can be derived from the journey-to-work model of residential location if the city is assumed to be topographically uniform and monocentric.⁸ In this model, a household with a given income trades off commuting costs represented by distance from the CBD with the amount of space consumed. Households with higher incomes

consume more land at lower rents the further from the CBD they locate.

That is, $\partial(L/P)/\partial d > 0$ where L is the amount of land at a given distance from the CBD, P is population and d is distance from the CBD. Since density is defined as P/L , this implies $\partial(P/L)/\partial d < 0$, i.e., density declines with distance from the CBD.

The spatial distribution of population therefore depends partly on the size distribution of income. Specifically, it has been shown that, under other assumptions, density is a convex function of distance, i.e.,

$$D = f(d) \quad (1)$$

where $f' < 0$ and $|f'|' < 0$.⁹ This function was first estimated by Colin Clark [4] for a number of cities and has since been used extensively by others.¹⁰ Actual density along any given corridor may be uniformly above or below the density implied by this function. To determine whether density at a given distance from the CBD varied systematically with distance from the corridor through which the subway was constructed, we estimate three forms of the function

$$D = g(d, ds) \quad (2)$$

where ds is distance from the subway line. If $\partial D/\partial ds > 0$, density increases with distance from the subway line, which implies that the line was constructed through a low density corridor. The opposite is implied if $\partial D/\partial ds < 0$.

The reason we experiment with a variety of functional forms is because there are no theoretical reasons to select one form in preference to another and because the effect of the subway may be sensitive to the particular functional form chosen. One possibility is

$$D = D_0 e^{\alpha d + \beta ds} + \epsilon \quad (3)$$

Given ds , however, this function implies that the slope of the gradient

decreases at a constant rate as distance increases. If actual density is plotted against distance for Toronto, the data reveal a gradient which is, in fact, flatter closer to the center of the city than at moderate distances. One functional form which gives a density gradient which is flatter near the center of the city is

$$D = D_0 e^{\alpha d^2 + \beta ds + \epsilon} \quad (4)$$

which is the equation for a half bell curve when $\alpha < 0$. In natural logs, this is

$$\ln D = \ln D_0 + \alpha d^2 + \beta ds + \epsilon \quad (5)$$

which is the first functional form we fit to the data.

The data also reveal a mild "cratering" of the density gradient near the CBD; that is, density first rising with distance and then decreasing. One functional which gives this cratering for appropriate values of the coefficients is

$$D = D_0 e^{\alpha d + \beta d^2 + \gamma ds + \epsilon} \quad (6)$$

For $\alpha, \beta < 0$, this function gives monotonically decreasing densities and for $\alpha > 0$ and $\beta < 0$, rising and then decreasing densities.¹¹ Taking natural logs we have

$$\ln D = \ln D_0 + \alpha d + \beta d^2 + \gamma ds + \epsilon \quad (7)$$

which is the second functional form we fit to the data.

A third possibility is

$$D = D_0 e^{\alpha d} \beta d e^{\gamma ds} e^{\epsilon} \quad (8)$$

This function constrains density at the exact center of the city to be zero whereas the previous two do not. The natural log transformation of this is

$$\ln D = \ln D_0 + \alpha d + \beta \ln d + \gamma ds + \epsilon \quad (9)$$

which is the final functional form we test.

In the second set of experiments we examine the effect of the subway line on the change in the spatial distribution of population over time. We explain the relative change in population by Census tract by distance from the CBD, tract density in 1951, and distance from the subway line. That is,

$$T = h(d, D_{51}, ds) \quad (10)$$

where T is the relative change in the population of the Census tract from the base year, and D_{51} is Census tract density in 1951.

Given tract densities in the base year and distance from the subway line, the change in population by tract will normally increase with distance from the CBD because, as incomes rise over time, households will choose to locate further from the CBD if we assume, as is normally done, that accessibility behaves as an inferior good. There are no a priori or theoretical reasons to expect that the relationship between the change in density and distance from the CBD to have any particular functional form but it is reasonable to expect that the second derivative of the change in population with respect to distance will be negative because there will be some limit to the distance from the center of the city at which households will chose to locate.

Given distance from the CBD and from the subway line, tracts with higher densities in the base year will experience lower relative increases in their populations, for two reasons. First, tracts with higher densities will have a lower potential for residential development. Second, as incomes rise over time, assuming that space is a normal good, there will be a shift in demand from high density use to low density use. Again, it is reasonable to expect that the inhibiting effect of density on residential development is nonlinear, specifically, that the second derivative of the change in

population with respect to density is positive.

Our final hypothesis is that, given distance from the CBD and base-year densities, tracts closer to the subway line will experience a higher relative increase in their populations because of the savings in travel time resulting from proximity to the subway.

Summarizing, for the second set of tests, we estimate the following functional form for 1951-56 and 1951-61:

$$T = \alpha + \beta d^2 + \gamma d^3 + \rho D_{51} + \lambda D_{51}^2 + \delta ds + \epsilon. \quad (11)$$

Our hypotheses are $\beta > 0$, $\gamma < 0$, $\rho < 0$, $\lambda > 0$, and $\delta < 0$.

Data

The population by Census tract for the Toronto Census Metropolitan area is given in 1951, 1956, and 1961 and unpublished data on the land areas of the 1966 Census tracts are available from Statistics Canada. Since the boundaries of a large number of tracts are the same in 1951, 1956, 1961, and 1966, we can derive the land area in square miles for most tracts in 1951, 1956, and 1961. A few observations for each of these years are lost because the boundaries of some tracts have changed from Census to Census: most of these tracts are at the periphery of the area. Also, a few other tracts were deleted from the sample in each year. These include the Toronto Island Census tract and tracts in which most or all of the land use was atypical and institutionally determined. For example, tracts containing mainly government buildings, campuses, airports, and golf courses were deleted from the sample. We calculate Census tract gross residential density as total tract population divided by the total land area of the tract in square miles.¹² There are 205 such observations in 1951, 285 in 1956, and 270 in 1961.

We calculate distance from the CBD as the straight-line distance from the (approximate) center of the tract to a central point in the downtown area which is taken to be the intersection of Yonge and King Streets. This variable was calculated in miles from scale maps of the Metropolitan area. Distance from the subway line was calculated as the minimum distance between the subway line and the (approximate) center of the Census tract. This variable is also expressed in miles.¹³

In the second set of tests, we use the relative change in gross residential density between 1951 and 1956 and between 1951 and 1961, distance from the CBD, and distance from the subway line. The relative change in density by Census tract is

$$\frac{\frac{P_{t+1,i}}{A_i} - \frac{P_{t,i}}{A_i}}{\frac{P_{t,i}}{A_i}} \quad (12)$$

where $P_{t,i}$ is the population of tract i in period t and A_i is the total land area in square miles of tract i . This reduces to

$$T = \frac{P_{t+1,i} - P_{t,i}}{P_{t,i}} \quad (13)$$

which is the relative change in population by Census tract. There are 208 of these observations common to 1951, 1956, and 1961.¹⁴ The distance variables for this set of tests are the same as for the first set.

In the next section we consider the results for the two sets of tests.

Results

The three functional forms estimated for each of 1951, 1956, and 1961 are:

$$\ln D = \ln D_0 + \alpha d^2 + \beta ds + \epsilon \quad (5)$$

$$\ln D = \ln D_0 + \alpha d + \beta d^2 + \gamma ds + \epsilon \quad (7)$$

and
$$\ln D = \ln D_0 + \alpha d + \beta \ln d + \gamma ds + \epsilon . \quad (9)$$

The results for the regression for 1951 using the first functional form are given in line 1 of Table I. All of the coefficients are significant at least at the 2.5 per cent significance level, the coefficient on d^2 is of the hypothesized sign, and the coefficient on ds is positive, indicating that the subway was constructed through a relatively low density corridor. Comparable regressions for 1956 and 1961 are shown in lines 4 and 7, respectively, of Table I. Again, all of the coefficients are highly significant, the coefficient on d^2 is of the hypothesized sign, and the coefficient on ds is positive.

Results of regressions using the second functional form are shown for 1951, 1956, and 1961 in lines 2, 5, and 8, respectively, of Table I. All of the coefficients in these regressions are significant at least at the one per cent level, except for the coefficient on d^2 for 1951 which is insignificant. The coefficients on d and d^2 are all negative, which implies a monotonically decreasing gradient. The coefficients on ds are again positive and are significant at the .005 level.

The results for the third functional form are shown in lines 3, 6, and 9 of Table I. In this case, all of the coefficients are significant at least at the .005 level. The coefficients on d and the log of d imply that density first rises with distance and then falls. This result is imposed by

TABLE I

Natural Log of Population Density by Census Tract: 1951, 1956, and 1961

Line	Year	Functional Form	Constant	d	d ²	ln d	ds	Number of Observations	R ²
1	1951	1	9.954 (95.864)		-.0318 (-8.087)		.107 (2.306)	205	.403
2	1951	2	10.698 (55.498)	-.360 (-4.503)	-.00756 (-1.151)		.181 (3.830)	205	.458
3	1951	3	10.624 (83.057)	-.699 (-9.770)		1.003 (4.649)	.201 (4.480)	205	.507
4	1956	1	9.850 (79.350)		-.0342 (-9.340)		.125 (2.478)	285	.467
5	1956	2	10.285 (46.131)	-.197 (-2.338)	-.0230 (-3.822)		.176 (3.215)	285	.478
6	1956	3	10.513 (68.166)	-.771 (-10.510)		1.309 (5.843)	.186 (3.535)	285	.510
7	1961	1	10.104 (152.471)		-.0237 (-12.445)		.0583 (2.193)	270	.663
8	1961	2	10.538 (87.544)	-.189 (-4.260)	-.0129 (-4.104)		.103 (3.707)	270	.685
9	1961	3	10.617 (111.724)	-.508 (-11.924)		.755 (5.044)	.107 (3.894)	270	.694

(t - values in parentheses)

the functional form which, as noted, constrains density to be zero at the city center. The coefficients on ds are all positive.

The R^2 's for these equations range from .403 to .694, indicating quite a close fit to the data, particularly in view of the fact that we are using cross-section data with gross residential density as the dependent variable.

Based on the above results for 1951 we can conclude that the original subway line was constructed through a relatively low residential density corridor. For the second two functional forms, the coefficient on ds declines in the two subsequent years; for the first functional form it rises slightly from .107 in 1951 to .125 in 1956 and decreases to .0583 in 1956. The implication is that, although the subway was originally constructed through a low density corridor, the effect of the line was to increase densities for tracts near to the line in subsequent years, even though the relationship between density and distance from the line remained positive up to seven years after its construction. The results are discussed in more detail in the final section of the paper.

An alternative specification of the subway variable was estimated with the data. The existence of the subway line may cause lower densities for census tracts near to it but higher densities further out, i.e., $\partial D / \partial ds > 0$ for $d \leq \bar{d}$ and $\partial D / \partial ds < 0$ for $d > \bar{d}$. These hypotheses are formulated to take account of the possibility of increased land near the subway being used for commercial purposes, with a net positive effect on density for distances beyond this region. The test was made by introducing ds and ds^2 together in the equations. The combined hypotheses are not supported by the results for any of the functional forms and the results of these tests do not contradict those given in Table I.

For the next set of tests we regress the relative change in density on a constant, d^2 , d^3 , D_{51} , D_{51}^2 and ds . The results for this regression for 1951-56 and 1951-61 are shown in Table II. The R^2 's of these equations are reasonable for cross-section data and all of the coefficients are of the hypothesized signs and significant at a variety of levels, except for the coefficient on ds which is insignificant in the first regression. The second regression in Table II shows that tracts nearer to the subway line experienced higher relative changes in their populations, ceteris paribus.

The results for the two sets of tests are therefore consistent and imply that the subway was originally constructed through a low density corridor and that construction of the line in 1954 resulted in higher densities closer to the location of the line, although this effect was significant after seven years but not after two, most likely because it requires some time for development or redevelopment to occur.

Summary

In this section we consolidate the results of the tests described above and consider their implications. Table III gives the elasticities of density with respect to distance from the subway for each of 1951, 1956, and 1961 for the three functional forms and the elasticity of the relative change in population with respect to distance from the subway for 1951-56 and 1951-61.¹⁵

Considering the first set of elasticities, we note that density uniformly increases with distance from the subway. This implies that the subway was located in a corridor which had lower densities than other corridors. This finding is not necessarily in any way criticism of the choice of location for the subway. Residential land use which is of lower than average density

TABLE II

Relative Change in Population by Census Tract:

1951-56 and 1951-61

Period	Constant	d^2	d^3	$D_{51} \cdot 10^3$	$D_{51} \cdot 10^3$	ds	Number of Observations	R^2
1951-56	.289 (2.368)	.0178 (3.119)	- .00115 (-2.988)	- .0376 (-4.790)	.000679 (4.590)	-.00378 (-.157)	208	.360
1951-61	.430 (1.433)	.0459 (3.261)	- .00181 (-1.915)	- .0600 (-3.101)	.00118 (3.245)	- .122 (-2.072)	208	.329

(t - values in parentheses)

TABLE III
 Elasticities of Density and Change in Population
 With Respect to Distance from Subway

Year	Functional Form	Elasticity
Density		
1951	1	.107
1956	1	.125
1961	1	.0583
1951	2	.181
1956	2	.176
1961	2	.103
1951	3	.201
1956	3	.186
1961	3	.107
Relative Change in Population		
1951-56	-	-.113
1951-61	-	-3.66

may imply commercial land use which is of higher than average density.

With subsequent adjustments in the spatial distribution of population and employment, eventual transit ridership may justify locating the subway through a corridor which is initially predominantly commercial.

Although these elasticities are all positive they are, with one exception, smaller in later years. For the first functional form the elasticity increases from .107 in 1951 to .125 in 1956 and decreases to .0583 in 1961. For the second and third functional forms the elasticities decrease by approximately the same relative amount between 1951 and 1956 and between 1956 and 1961. Since the positive relationship between density and distance from the subway is smaller in later years, we can infer, as noted, that the subway exerted a net positive influence on residential location decisions, i.e., that the increased use of land near the subway for commercial purposes, parking and other terminal facilities for transit riders, and maintenance and storage yards for the transit system was more than offset by an increased use of land for residential purposes, or a higher density in residential land use, or both. (An increased use of land both for commercial and for residential purposes would be possible if there is undeveloped land available before the subway was constructed.)

Although our estimates of the elasticities vary from .107 to .201, it is true in all cases that they decline by about fifty per cent between 1951 and 1961. In other words, the results show that construction of the subway line resulted in a per cent increase in density for a one per cent decrease in distance from the subway which was fifty per cent smaller in 1961 than in 1951.

The second set of elasticities allows a better assessment of the magnitude of the effect of the subway on the spatial distribution of population.

The elasticity with respect to distance from the subway is $-.113$ for the relative change in population between 1951 and 1956 and -3.66 between 1951 and 1961. These results are consistent with the previous ones since they mean that tracts closer to the subway line experienced relatively larger increases in their populations than tracts further out. Between 1951 and 1956, the absolute size of the effect (which is not statistically significant) is small but between 1951 and 1961 it is fairly large. The interpretation is that construction of the line in 1954 resulted in a relative increase in the population of a Census tract which was larger by about 3.7 per cent for each decrease of one per cent in the distance of the tract to the subway line. The fact that the relationship is significant after seven years but not after two is explained by the observation that development or redevelopment of urban land is a protracted process which involves land assembly, possibly rezoning, construction, and the relocation of households and individuals.

A suggested extension of the research described in this paper would be to evaluate the effects of subsequent increases in subway mileage, construction of extensive expressway facilities, and introduction of the Government of Ontario commuter railway. All of these changes in transportation infrastructure were introduced in Metropolitan Toronto between 1961 and 1971 and likely exerted important influences on the spatial form of the area.

FOOTNOTES

*The author wishes to thank R. A. L. Carter, E. F. Haites, J. R. Melvin, R. S. Woodward, and, especially, Mark Frankena for helpful comments on earlier versions of this paper. The Research Division of the Metropolitan Toronto Planning Board provided exact completion dates of all expressway and subway projects and the Census Division of Statistics Canada (formerly Dominion Bureau of Statistics) supplied unpublished land areas of all Census tracts in Metropolitan Toronto in 1966. The author acknowledges sole responsibility for the content of this paper.

¹A useful source of facts about the Toronto subway system is Toronto Transit Commission [16]. This booklet includes photographs of substantial residential development near four different subway terminals [16: 30, 40, 61].

²The Davisville and Greenwood maintenance yards and shops occupy 9.7 and 31.48 acres of land, respectively [16: 30, 43].

³For an example of this procedure, see Kates, Peat, Marwick [11; 12].

⁴See M. Frankena [8: 1-5], for this and other criticisms of urban transportation plans.

⁵For a discussion of the potential for using transportation infrastructure as an instrument of urban development, see D. N. Nowlan and N. Nowlan [15: 52-57].

⁶See Toronto Transit Commission [16: 21-56] for a brief history of the subway in Toronto.

⁷Dominion Bureau of Statistics [5; 6; 7].

⁸Two versions of the journey-to-work model are Wm. Alonso [1] and J. F. Kain [10].

⁹See M. J. Beckman [2] and A. Montesano [13].

¹⁰For a survey of the literature on density gradients, see B. J. L. Berry, J. W. Simmons, and R. J. Tennant [3]. Two recent applications are D. Harrison, Jr. and J. F. Kain [9] and J. Yellin [17].

¹¹This form is suggested by B. E. Newling [14].

¹²The denominator in gross residential density is total tract land area. New residential density is defined as tract population divided by the area of land in the tract zoned for residential use.

¹³We use distance from the subway line rather than distance from the nearest subway terminal for convenience. Subway terminals, in any case, are very close together so that little distortion is introduced by this simplification.

¹⁴The sample size for this set of tests is 208, as opposed to 205 for 1951 in the first set of tests, because we do not need tract land areas for the second set. There are fewer tracts which have land areas common to 1951 and 1966 (the only year for which land areas are available) than there are tracts which have common boundaries in 1951, 1956, and 1961.

¹⁵The elasticity of density with respect to distance from the subway is the same as the coefficient on ds . The elasticity of the relative change in population is calculated at a distance of three miles from the center of the city and a relative change in population of .10, which is typical for tracts between 1.5 and 2.5 miles from the subway.

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