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An Agent based Model to Study the Barrier Effect on an Urban Neighborhood

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Modeling the Barrier-Effect of Roadways:

A Cellular-Automata Neighborhood

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science

at Virginia Commonwealth University.

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Abstract

AN AGENT-BASED MODEL TO STUDY THE

BARRIER EFFECT ON AN URBAN NEIGHBORGOOD

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A Thesis submitted in partial fulfillment of the requirement for the degree of Master of Science in Mathematics at Virginia Commonwealth University

Virginia Commonwealth University, 2012

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Questions on how did we get from there to here, and what dynamics created a particular outcome are common queries. In some cases the answers to such questions can be empirically measured, sometimes surveys can be sent or experiments performed. However, in many cases there are constraints such as time, money and ethics which hinder our pursuit for answers. This

study asks the question: If we take a small neighborhood and introduce a barrier, how will the neighborhood change? Will it be better protected and flourish, or will it decay and die or perhaps will there be no change at all? What determines the outcome? This work tries to answer these questions by creating an Agent-Based Model (ABM) to test different scenarios and observe the results. Urban environments, both natural and built, are complex systems, containing a multitude of people, landscapes and buildings. Simple changes in street-lighting and sidewalks, the addition of trees and green scapes or the enforcement of "broken-window" policies impact local neighborhoods [1]. Measuring behavior changes on a neighborhood level are difficult to quantify, but by using ABM methods we can build our neighborhood, populate it with a variety of actors and watch their interaction with each other, and with introduced stimuli.

Our simulation introduces a barrier (highway) with varying permeability into a mixed use neighborhood loosely based on Richmond's Jackson Ward. Several metrics (such as property value, crime rates, etc.) were used to determine if the neighborhood was under duress, or thriving. In real-world terms we built a roadway though the neighborhood and observed the "severance effect" as our actors' adapted to reduced mobility and remained within their accessible range. The results were complex with so many actors; however the results showed that the neighborhood was negatively impacted by a high volume roadway. The potential usefulness of such a model can be easily adapted for use by urban planners, police departments or transportation engineers.

Chapter 1 - Introduction

1.1 Motivation

Modeling an urban environment is a great challenge. The number of variables and the unexpected behavior of people to stimuli are often difficult to encapsulate in a single coefficient. Behavior changes as perceptions and surroundings change, but is it completely unpredictable? Many incidents in our day to day routines are just that, routines. When an off-handed comment was made within-earshot about how a particular community was deliberately isolated through roadway development and had suffered serious blight as a result, I had thought of other instances where this had occurred. In many cases the road was directly attributed to the neighborhoods' decline, but there was no method to prove that the roadway was the cause. In further research, the issue of food deserts and public health decline were also attributed to community isolation. Ideally, understanding roadway-induced barrier effects upon public health is our goal. An agent based model is a "laboratory" to see how small adjustments to specific criteria can result in changes to a community's status. Models that are realistic and manageable are useful as decision and support tools for better community planning and policies. After all, making our environment more livable and improving public health is a worthwhile endeavor.

1.2 Urban Planning

Controlling the natural urban environment is beyond the capability of most residents, but built urban environments, at their best, thoughtfully created by engaged local residents, developers and planners, can promote healthy and stable communities. At their worst, built environments can negatively affect public health, contribute to crime, and degrade surrounding neighborhoods. In the meta analysis, "New Roads and Human Health: A Systematic Review", by Egan et al., 32 urban studies were reviewed [2]. Although there was informative public health evidence garnered about roadway impact on air quality and traffic deaths, the authors stated that minimal information was found regarding, "road construction associated with community severance (i.e., reduced access to local amenities and disruption of social networks caused by a physical barrier running through the community) (Egan, 2003)". The study of such an important urban health issue is the focus of this thesis - to gain deeper understanding of roadway structures' impact on urban neighborhoods. Specifically we want to simulate the "barrier effect" also known as the "community severance effect" defined as the roadway's impact on human settlements. We created an Agent Based Model (ABM) of a neighborhood, populate it, and observe how the agents respond to the introduction of a roadway barrier.

Understanding the dynamics of such a system with many variables is ideally suited to ABM techniques where agents respond to current dynamic conditions and in turn change their environment by providing constant feedback. As with any good model, agent based models allow us to test "what-if" scenarios and observe long term behavior. ABM techniques augment qualitative measurements, which may or may not exist, and when they match long term behavior to empirical evidence, we feel greater confidence that our model reflects the dynamics of the system.

It has been observed that the building of a road, as well as having roads expanded or even bypassed, can influence a community's traffic flow, commerce, and overall vibrancy. Indeed, there are many elements that affect a community's welfare, and concern has been expressed by both the World Health Organization (WHO) and the Center for Disease Control (CDC) over the urbanization of populations and the impact of transportation policies and structures. Recently the CDC promoted “Natural and Built Environment and Health Research” to encourage researchers to examine relationships among land-use policy, the built environment and human health, and how other critical infrastructure systems function to impede or improve public health [3].

Without accurate and complete information urban planners cannot always anticipate the full impact of proposed transportation policies and structures, and after-the-fact (band-aid) solutions are not the ideal method to resolve urban issues. Furthermore, unaddressed or mishandled urban issues can foster stagnant, degraded neighborhoods within an aftermath of finger-pointing local politics. Ideally, increasing our understanding of roadway-induced repercussions, can aid local decision-makers, engineers, and citizens in understanding the impact of built environments.

1.3: A History of the Study Area

Because of its unique background, similarity to our scenario, and relative availability of data, our study area is loosely based on the Richmond neighborhood of Jackson Ward.

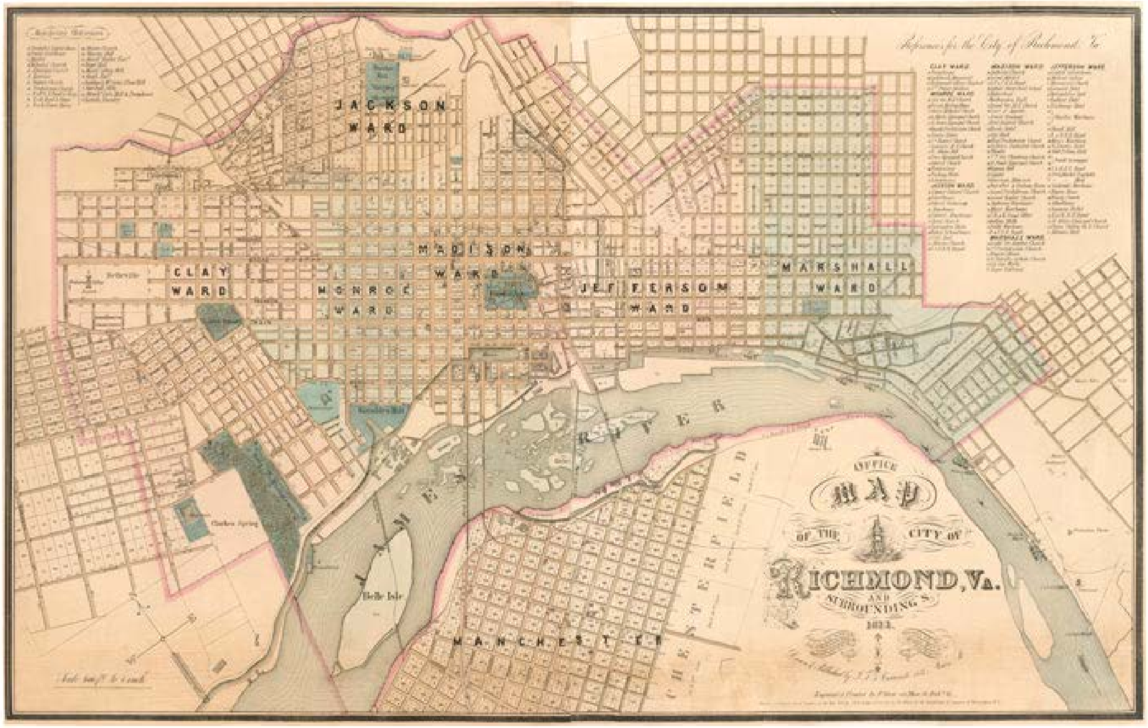

Figure 1.3.1 Map of Richmond 1873 [4]

Jackson Ward was known as one of the most successful African-American communities in the south. It was self-contained, with its own banking-system, social networks and educational systems, a result of the politics of the time creating a culture of "separate but equal." When the municipality identified a requirement for an efficient thoroughfare from north Richmond to Petersburg, several plans were presented. The Richmond-Petersburg Turnpike toll road plan that was contentiously adopted, "lacerated" Jackson Ward into two sections. Eventually this road was absorbed by the interstate I-95, widened, and connected to another interstate freeway and now encompasses an additional downtown expressway.

A description from the City of Richmond's Master Plan of pre-construction Jackson Ward is characterized as a densely populated area with substandard housing [5]. Written in 1946, after the depression and World War II, the Master Plan reported that overcrowding, coupled with aging buildings with limited water and sewer systems was impacting most Jackson

Ward residents' health prior to the construction of the Richmond Petersburg Turnpike (Richmond, 1946). These claims in the Master Plan are somewhat denounced in Silver and Moeser's book, "The Separate City," who felt that the planning consultant Harland Bartholomew used these as excuses to begin a radical program of slum clearance, rebuilding and relocation of the entrenched population [6]. No other anecdotal accounts of Jackson Ward were found that mention substandard housing, lack of sanitation and population density related illnesses such as tuberculosis. Local newspapers describe Jackson Ward as a thriving center of commerce, a "Harlem" of the south, with a dynamic robust social network. In contrast, according to the 1940 census, most of the households in Jackson Ward were not owner-occupied, the Master Plan describes these as rental properties built by predatory slum lords who packed tenants densely and did not provide basic water or sewer systems (Richmond, 1946).

In the days before the automobile, workers necessarily lived closer to central business areas and during the reconstruction era, a high proportion of Jackson Ward residents were African American. This concentration allowed the African-American community to have some political representation. However, in 1902 the Virginia Constitution eliminated many residents from the voter rolls and Jackson Ward was gerrymandered into the surrounding wards of Jefferson, Madison, Clay and the newly created Lee Ward (see Figure 1.3.2). Consequently, the old Jackson Ward residents were easily outnumbered by registered white voters as reported in the July 23, 1903 Times-Dispatch Richmond [7]. The political situation can be seen in the census tract data where Jackson Ward appears in the 1900 census, but is absorbed into other wards or census tracts thereafter.

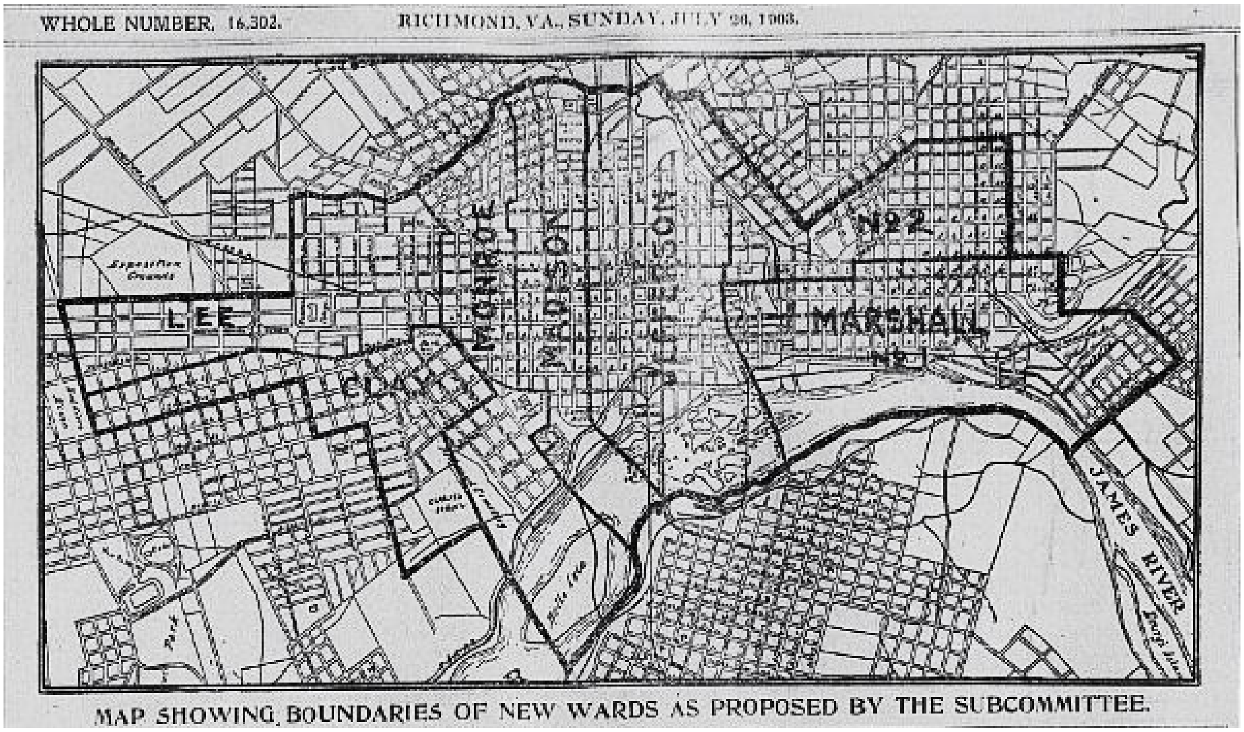

Figure 1.3.2 Proposed New Ward Boundaries [7]

Public policies, some well-meaning, others not, led to the decision to take advantage of federal monies for a thoroughfare from north of Richmond to Petersburg that cut through the middle of Jackson Ward [8]. Since most homes were rental properties owned by slum lords, according to the 1940 Master Plan, these needed to be removed and residents relocated. Despite the reports of poor living conditions, residents took up the fight against the toll road and voted it down twice. Afterwards the Virginia General Assembly created a new state authority on the recommendation of Wilbur and Associates (1953) since such state authorities have “relative freedom from pressure groups” and provide “results in high operational efficiency [9].” Thus, the Richmond-Petersburg Turnpike Authority was established to oversee the construction of the new toll road and by July 1958, the first part of the roadway, was opened to a delighted public, and to a despaired Jackson Ward neighborhood.

Passing through the Jackson Ward area in the downtown core, one can see there are two dramatically different neighborhoods on either side of the roadway. North Jackson Ward has many derelict buildings covered with graffiti and vacant lots. By close inspection of Figure 1.3.3 produced using the geographical mapping tool ArcGIS, we see most of the south side of I-95 is well developed with large commercial, industrial, business and recreational complexes, North Jackson Ward remains largely undeveloped [10] .

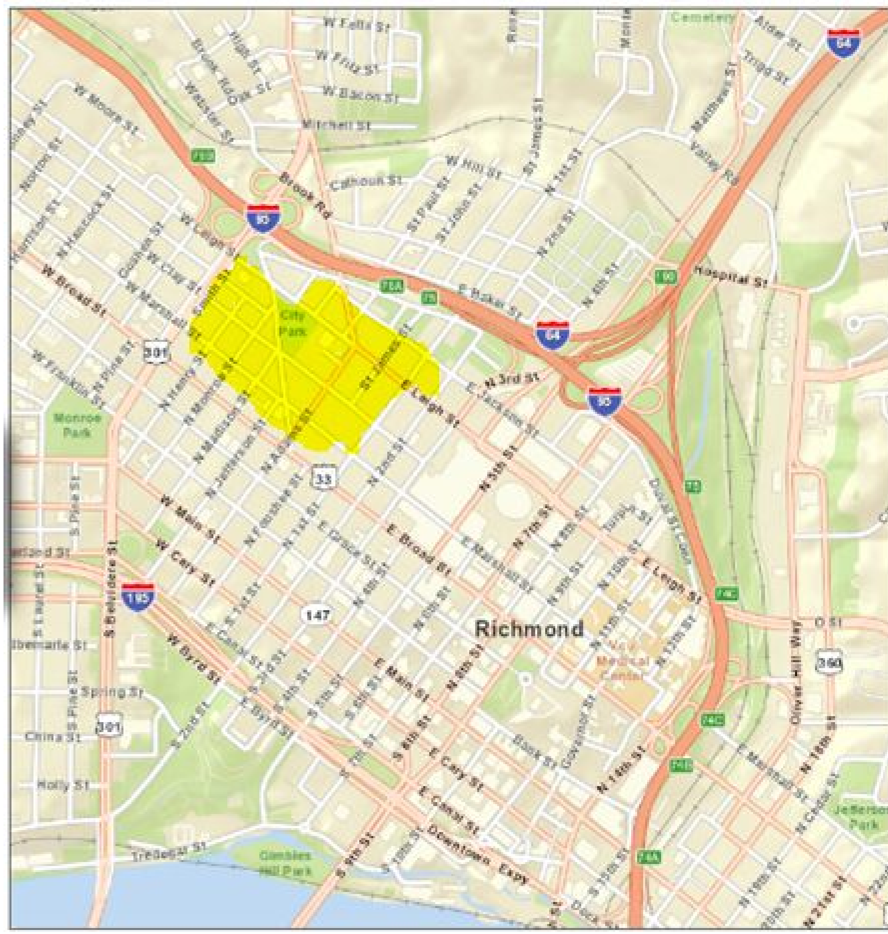

Figure 1.3.3 Map of Richmond Showing Buildings 2012 [10]

Strikingly, the southern side of Jackson Ward has seen large swaths of residential property turned into a new convention center, a coliseum, and commercial biotech research buildings. A diminished historic Jackson Ward is currently under several reconstruction initiatives to restore its neighborhood and is becoming increasingly gentrified. Our ABM simulations will attempt to replicate the effect that road construction had on both sides of Jackson Ward.

Chapter 2 - Data

The creation of a model requires the quantification of many parameters. Because we require relevant historical data, impediments to accurate, useful data arose throughout the research phase of this work. Information regarding population, boundaries, crime reports and property values were often impossible to find. In many cases specific local information had not been kept, records had been destroyed, or had been archived to unknown sites. Furthermore, the municipal authorities who generated the data did not know if or where historical information was archived, leading to a scavenger hunt through private, municipal, state and federal repositories. Although there is anecdotal historical evidence through newspaper articles and historical reference books, it was difficult to prove quantitatively that there was neighborhood degeneration taking place from roadway construction since pre-construction data was sparse and zones were redefined. In these cases, we drew upon analysis from a meta analysis study of other US cities undergoing similar roadway construction through mixed residential and commercial areas, and used it to quantify parameters throughout our neighborhood's transformation.

2.1 The Geographic Jackson Ward Region:

Jackson Ward was defined in an 1888 map with a western boundary of Lombardy Street, north running alongside Bacon's Quarter Branch waterway, jogging northeast outside of the Chesapeake – Ohio Railroad, southeast up Shockhoe Creek and along one of its lower tributaries, up Fifth Street, and finally west through Jackson and Leigh Streets back towards Lombardy

Street (Figure 1.3.1) (Caracristi, 1873). Jackson Ward's upper boundary follows the Bacon's Branch and Shockhoe Creek waterways which created a barrier zone not suitable for residential development; however the topography was ideal for railroad lines being close to both business and shipping areas. This natural barrier was addressed when the railroad lines provided several pedestrian and vehicular traffic corridors for local access.

Richmond maps created after 1888 expanded the boundaries of Jackson Ward when the city appropriated new land such as Coutt's, Price's and Jackson's Addition. However, later maps, such as the 1903 "Boundaries of New Wards" eliminated Jackson Ward entirely and annexed it to Lee, Monroe, Madison and Jefferson Wards (Figure 1.3.2) (Times, 1903).

These alterations became problematic since the study area became nebulous and undefined. Although Jackson Ward is present in the 1900 federal census, by 1910 Jackson Ward disappears, and for the 1930 and 1940 census, populations for our study region are absorbed into Madison, Clay, Jefferson and Monroe Wards [11, 12, 13, 14]. The issue of Jackson Ward's boundaries became even more ambiguous after the construction of Richmond-Petersburg Turnpike in the late 1950's when northern Jackson Ward was renamed Giplin [15].

Currently, boundaries of Historic Jackson Ward are still being altered with new parcels being considered for historic status, while others, those closest to the roadway, are in the process of being re-designated as commercial areas. North Jackson Ward (Gilpin) is presently considered a high crime area, with many vacant lots, and decrepit buildings. For the purposes of this study, we wish to consider both sides of Jackson Ward to observe the impact of the Richmond – Petersburg Turnpike.

As illustrated in Figure 2.1.1, the northern section of Jackson Ward (Gilpin), currently has no historical designation and is slated for redevelopment as mixed commercial and condominium properties as detailed in Richmond's Department of Community Development final report on North Jackson Ward dated August 2007 [15].

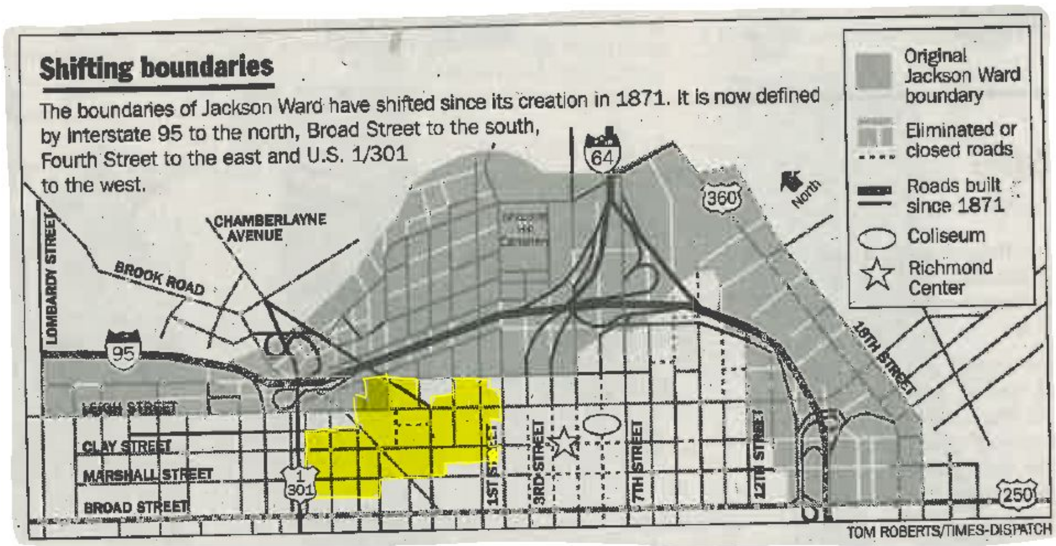

Figure 2.1.1: 2007 City of Richmond Historic Designation Status yellow [16]

2.2 The Population of the Jackson Ward Area from 1930 – 1970:

Along with the 10 year census data, this study drew upon the Federal Bureau of Investigation's (FBI) annual Uniform Crime Reports (UCR) to find Richmond City populations for some interim years [17]. The total population of Richmond had significant leaps due to annexation of outlying areas. However, when all annual data was graphed, we found the population growth is quadratic between the years 1900 to 2009, with an r^2 value of 0.9154, and illustrates a gradual increase in Richmond's population peaking in 1970 and declining thereafter (Figure 2.2.1).

Although Jackson Ward disappears from census data in 1910, the earlier 1900 Census listed Jackson Ward as having a population of 18,713. In comparison, Richmond's total population at that time was 85,050, revealing Jackson Ward housed 22% of Richmond's total population in 1910 (Census, 1910).

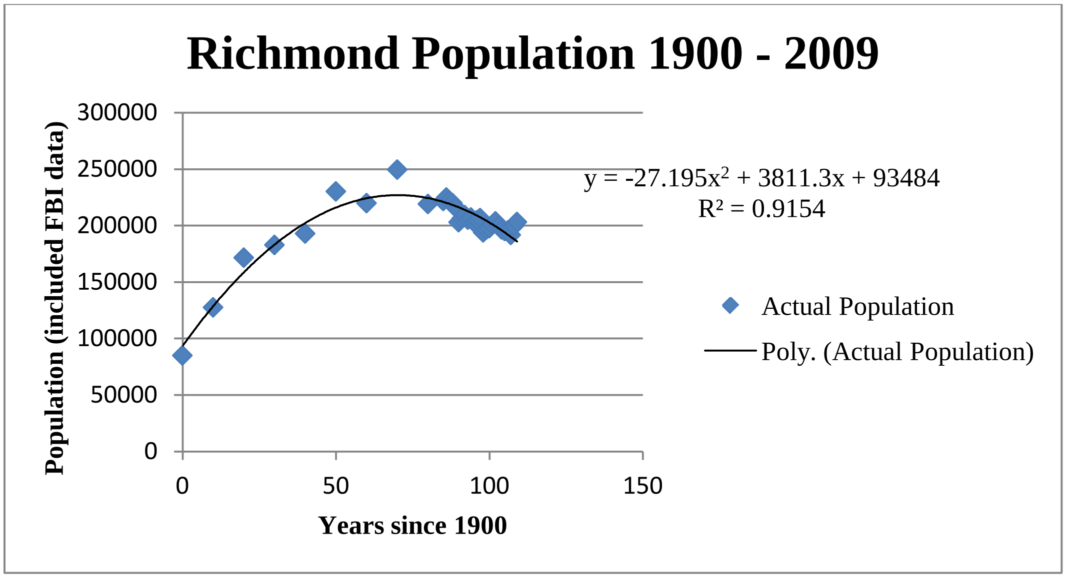

Figure 2.2.1 Richmond Population 1900 to 2009

In a later 1935 census map we discover that Jackson Ward had been absorbed by Madison, Monroe, Lee and Jefferson Wards similar to the proposed New Ward Map of 1903 shown in Figure 1.3.2. Nevertheless, the 1946 Richmond Planning Commission's (RPC) "A Master Plan for the Physical Development for the City" (1946) contains a breakdown of population by census tract in addition to several informative demographic maps. By studying the 1940 Census tract map it was found that tracts N-1, N-2, N-3, N-6 and N-7 appear to be contained within the original Jackson Ward region with a combined population of 23,538, which given that Richmond's population was 193,042 at the time, implies that Jackson Ward housed 12.2% of the 1940 population [18]. From 1900 to 1940 Richmond saw a population increase of 127%, Jackson Ward, over the same time period saw an increase of 25%. In 1941, after the census, Jackson Ward was further reduced when the City relocated 301 families to Gilpin Court (Richmond, 1946). Since the maps were compared visually, we cannot be certain that all of Jackson Ward was contained within these five census tracts, however it provides a good approximation.

Population of Richmond City from Census and FBI Reports 1900 – 2009

Year	**1900**	**1910**	**1920**	**1930**	**1940**	**1950**	**1960**	**1970**	**1980**
Population	85050	127628	171667	182929	193042	230310	219958	249621	219214

Year	**1985**	**1986**	**1987**	**1988**	**1989**	**1990**	**1991**	**1992**
Population	221857	224943	222113	219979	216229	203056	206292	209279

Year	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Population	205331	207261	203133	204881	206692	194024	196505	197790

Year	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**
Population	200842	203799	199968	196667	195271	195708	191785	199674	203233

Table 2.2.1 Population Data Table

The population of Richmond appears to be growing based on the quadratic function fitted to the data so we can enhance our population statistics to include intercensal years.

The Population of Richmond can be predicted according to Equation 1:

$$\textit{Population} \qquad P(x) = -27.195x^2 + 3811.3x + 93484 \qquad (1)$$

Where x represents the years after 1900

2.3 Richmond Crime Statistics from 1930 – 1970:

Crime statistics submitted to FBI were voluntary starting in August of 1930. Throughout the initial years of data collection in 1930 and 1931, the UCR's were detailed monthly reports broken down by general geographic region and type of crime. For the years 1932, 1933, 1938, 1939, and 1961, no Richmond crime statistics were reported in the UCR's. Moreover, the UCRs only record the most serious crime for any incident producing a large quantity of underreported crimes. For example, if a murder was committed during a robbery, only the murder would be reported, producing a large quantity of underreported crimes. Additionally, several crime categories were combined by the FBI throughout the study period, such as rape and assault, and negligent and non-negligent homicide; in these cases we also combined the categories.

Crimes for the whole Richmond metropolitan area are only recorded in the UCRs. Local neighborhood crime statistics were not available from the City of Richmond Police Department, Richmond City Hall, the Virginia State Police, or the Virginia State Library Archives. Additionally, crime statistics are not available from court records since "Courts of no Record" were used to charge and fine criminals for lower level offenses that make up the bulk of criminal activity in Richmond [19]. However, a general picture of criminal activity is given in Table 2.3.1 [20].

FBI Uniform Crime Reports 1931 - 1970 Total Reported Crimes for Richmond City Virginia

Year	**1930**	**1931**	**1932**	**1933**	**1934**	**1935**	**1936**	**1937**	**1938**	**1939**
Crimes	N/A	6402	N/A	N/A	6335	8101	7718	7274	N/A	N/A
Year	**1940**	**1941**	**1942**	**1943**	**1944**	**1945**	**1946**	**1947**	**1948**	**1949**
Crimes	6063	1818	5507	5846	5264	5400	5774	6098	6683	6647
Year	**1950**	**1951**	**1952**	**1953**	**1954**	**1955**	**1956**	**1957**	**1958**	**1959**
Crimes	6413	6163	3139	6140	7409	7722	8841	7881	6903	7446
Year	**1960**	**1962**	**1963**	**1964**	**1965**	**1966**	**1967**	**1968**	**1969**	**1970**
Crimes	6688	7005	7530	9619	9498	10793	11933	11838	16797	21278

Table 2.3.1 Total Reported Crimes

In 1960 we find that incidents of burglaries surpass the incidents of theft/larceny as shown in Figure 2.3.1. After 1959 the FBI no longer recorded "larcenies under $50", and we see the number of total larcenies fell from 3,601 to 1380 in 1960 at the same time burglaries rose from 1780 to 3,601 which may imply that many larcenies were redefined as burglaries. Another anomaly in the data appears in 1969 and 1970 where there are two consecutive increases of 4,481 and 4,959 reported crimes.

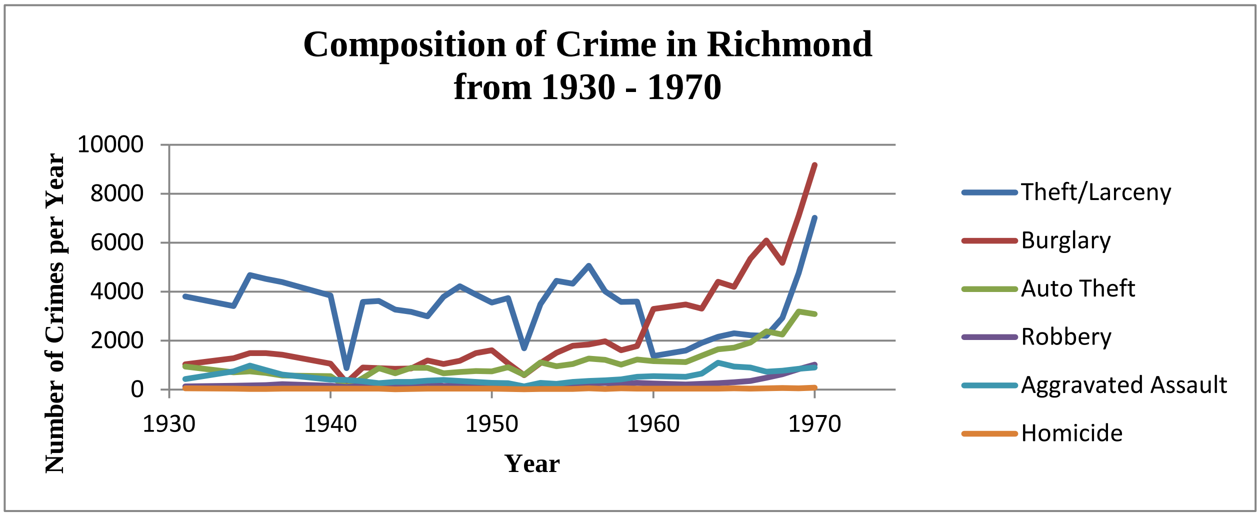

Figure 2.3.1 Composition of Crime

Using data from FBI Reports we find the composition of crime to be fairly consistent throughout the forty year interval shown in Figure 3.3.1 with non-violent crimes such as larceny and burglary, making-up 75% of the total number of crimes as shown in Figure 2.3.2.

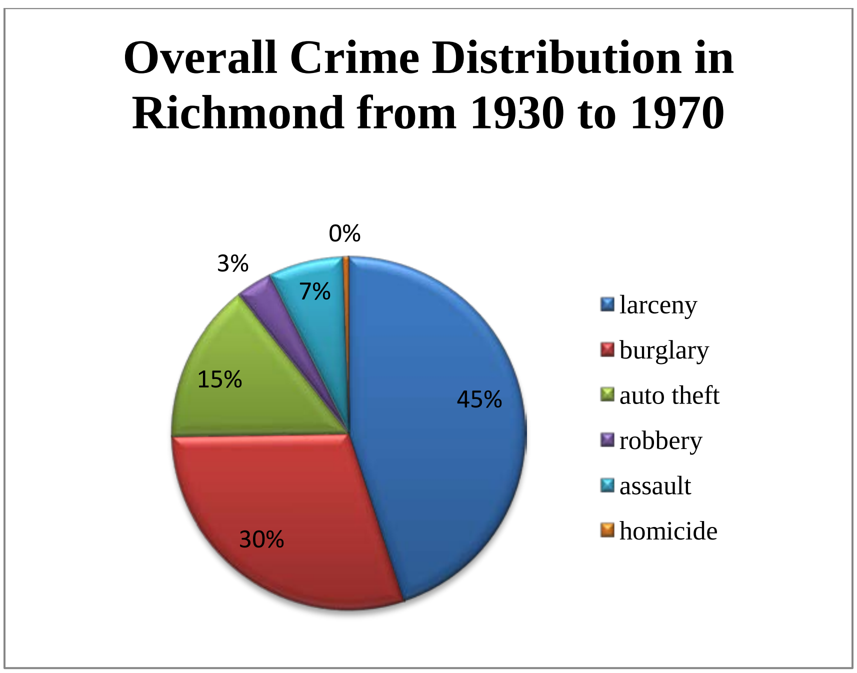

Figure 2.3.2 Composition of Richmond Criminal Activity

Underreporting of crimes and attempted criminal activity became an important issue for our model since we wish to include *all* criminal activity. Attempted larceny would only be reported if there where physical signs or proof of an attempt, and the FBI reports provided no statistics on the success rate for larceny, burglary, or car theft. Although most homicides are reported, there was very little data from which to draw a larger conclusion regarding criminal attempts versus criminal successes. Similarly assaults, specifically domestic assaults, are also underreported, therefore the most useful data and most likely crime reported, *including* its attempt, is robbery. The Virginia State Police Department of Criminal Statistics was asked to generate a report comparing attempted and completed robberies using their most recent and accurate statistics. The Virginia State Police found that of the 5680 robberies reported in 2010, 794 were unsuccessful attempts, indicating an 86% criminal success rate for robbery [21]. Under the assumption that criminal failure or success is fairly constant, we used this result to estimate that 85% of all criminal activities were successful in our neighborhood model.

Using the population estimates from FBI crime and Census reports in Table 2.3.2 and Figure 2.3.3 we observe an increase in the number of crimes per 100,000 people from 1930 – 1970. There are significant decreases in 1941 and 1952 in the number of reported crimes. Furthermore, in 1952, the total numbers of crimes are half the previous and following years.

FBI Uniform Crime Reports 1931 - 1970 Crimes per 100,000 people Richmond

Year	**1930**	**1931**	**1932**	**1933**	**1934**	**1935**	**1936**	**1937**	**1938**	**1939**
Crimes	N/A	3451	N/A	3949	3306	4185	3949	3687	N/A	N/A
Year	**1940**	**1941**	**1942**	**1943**	**1944**	**1945**	**1946**	**1947**	**1948**	**1949**
Crimes	3141	891	2679	2823	2524	2572	2733	2869	3126	3092
Year	**1950**	**1951**	**1952**	**1953**	**1954**	**1955**	**1956**	**1957**	**1958**	**1959**
Crimes	2785	2838	1439	2802	3368	3497	3989	3544	3095	3329
Year	**1960**	**1962**	**1963**	**1964**	**1965**	**1966**	**1967**	**1968**	**1969**	**1970**
Crimes	3041	3110	3337	4256	4197	4764	5262	5217	7400	8524

Table 2.3.2

It is possible that this anomaly may be attributed to a change in how crimes were recorded, rather than a decrease in actual crimes committed. We may also consider that the events of those years impacted crime rates. Perhaps the lower number of crimes reported in the 1941 UCR may partially be attributed to the conscription of military aged males in October 1940 and the subsequent entrance of the United States into the Second World War after the December 1941 attack on Pearl Harbor. Similarly, the Korean War may account for a decrease in reported crimes from 1950 to 1953 [22].

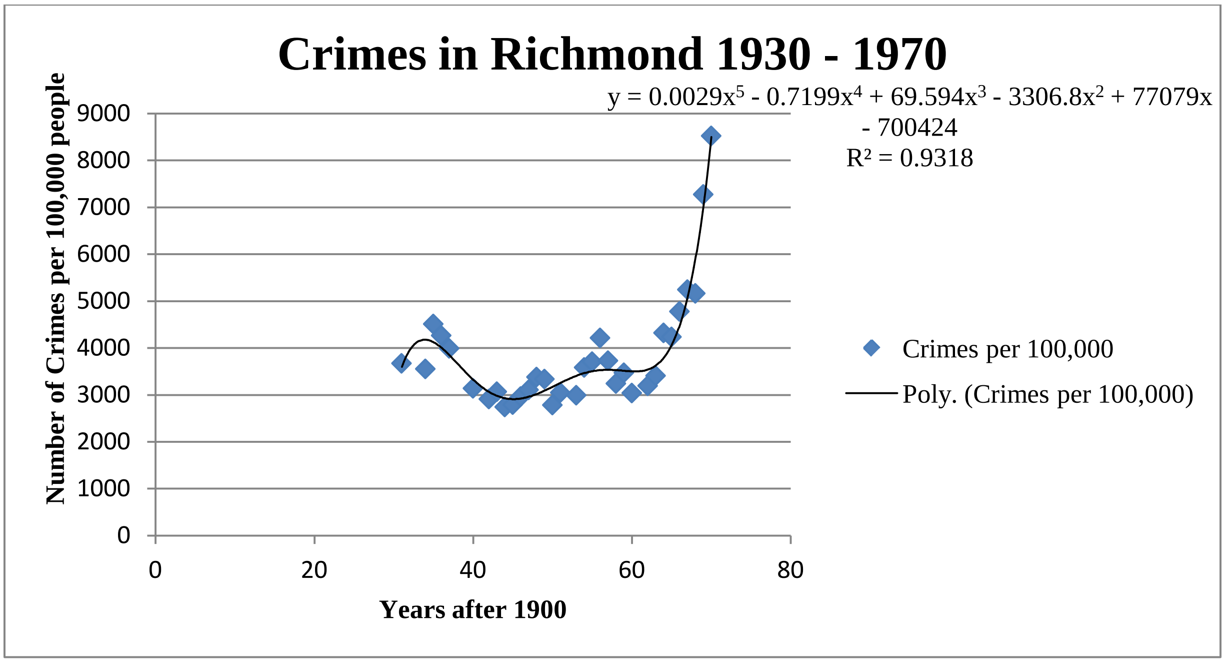

Figure 2.3.3 Crime in Richmond per 100,000 people

2.4 Jackson Ward Property Values from 1930 – 1970:

Estimating pre-roadway-construction property values was found using tables presented in the 1946 Richmond Planning Commission's "A Master Plan for the Physical Development for the City". Jackson Ward census data, as previously stated, can be reasonably estimated by census tracts N-1, N-2, N-3, N-6 and N-7 (N-4 is the Gilpin area). Plate 22 of the Master Plan records that the five census tracts only had a home ownership from 5% to 25%, with a staggering 90% to 100% of the units occupied. Moreover, the three decennial maps in 1920, 1930, and 1940 reported a range from 51.3 to 93.0 persons per acre in Jackson Ward with no available space for neighborhood residential development (Richmond, 1946). Using the median monthly rent from the 1940 census and by using the conversion from Table 39 which calculates property value based on monthly rent, we estimate 1940 property values were between $800 and $1600 per lot in tracts N-1, N-2, N-3, N-6 and N-7 Figure 2.4.1 (Richmond, 1946).

TABLE No. 39

RENTALS AND HOME VALUES—RICHMOND, VIRGINIA

*Monthly Rentals of Rented Units**

RENTAL RATE	Approximate Value (80 Times Monthly Rental)	Number	Per Cent
Under $10	Less than $800	6,321	17.5
$10 to $15	$800 to $1,200	7,834	21.7
$15 to $20	$1,200 to $1,600	5,455	15.1
$20 to $30	$1,600 to $2,400	6,253	17.3
$30 to $50	$2,400 to $4,000	7,157	19.8
$50 to $75	$4,000 to $6,000	2,446	6.8
$75 and over	$6,000 and over	499	1.4
Unreported		138	.4
		36,103	100.0

Value of Owner-Occupied Homes (One-Family)

VALUE	Equivalent Rental (Value Divided by 80)	Number	Per Cent
Under $1,000	Less than $12.50	525	4.6
$1,000 to $1,500	$12.50 to $18.75	625	5.6
$1,500 to $2,000	$18.75 to $25.00	773	6.8
$2,000 to $3,000	$25.00 to $37.50	1,447	12.8
$3,000 to $5,000	$37.50 to $62.50	2,773	24.5
$5,000 to $7,500	$62.50 to $93.75	2,919	25.8
$7,500 and over	$93.75 and over	2,191	19.4
Unreported		56	.5
(Median Value $4,617)		11,309	100.0

*The rents are for shelter only, and do not include amounts for heat, light, etc.

Data: U. S. Census, 1940: Housing, Volume III. Characteristics by Monthly Rent or Value—I.

Figure 2.4.1 Rental and Home Values from 1940 Census Housing

Using the same methodology, the 1970 census shows property in the same location valued from $4000 to $5600 [23, 24]. For comparison purposes, Table 2.4.2 below adjusts for inflation.

Year and Property Value	**1940**	**1970**	**% change**
Property Value based on median monthly rent	$800 – $1600	$4000 - $5600	26.4% to 80.5% Increase from 1940 to 1970
Adjusted to 1940 Dollars	$800 – $1600	$1444 - $2022	
Adjusted to 1970 Dollars	$2216 - $4431	$4000 - $5600	

Table 2.4.2 Average Property Values 1940 and 1970 Conversion

The inherent difficulty with comparing property values is that property value is not only a function of square footage, but location, building size and facilities, state of repair and age, and its environs. If we further complicate the assessment with mixed use areas that include industry and commercial uses, using median property values is an oversimplified representation of neighborhood transformation. In Carey's paper "Impact of Highways on Property Values: Case Study of the Superstition Freeway Corridor", he states that the "overall effects of such development difficult to quantify" when evaluating property [25]. After performing meta-analysis of other works, and conducting his own surveys, Carey concluded that there was a negative impact on property values due to freeway construction for single family units; on the other hand, construction had a positive impact on multi-family units and some commercial properties. Using Carey's (2001) methodology and results to adjust our property values we will divide the roadway impact area. There are three zones on either side of the road: Zone "A" contains properties considered adjacent to the roadway up to to ⅛ mile away; Zone "B" covers the region from ⅛ mile to ½ mile from the road and the furthest zone "C" considered the control zone runs ½ mile outwards. The control zone is where the impact of the roadway's noise and pollution are considered negligible and won't impact the property value.

Based on one regression model and adjusting for property characteristics in detached single family homes, he found that zone “A” had an average loss of $6,299.45 or 2.577% in property value, whereas zone “B” lost $3.245.93 or 1.963% of its property value, given zone “C” was the control area, it had no adjustment (Carey, 2001). Furthermore, the single family homes appreciated at different rates according to their distance from the roadway, zone “A” appreciated at 2.81%, zone “B” at 2.89% and zone “C” appreciated at 4.32%. Detached single-family homes in zone “A” appreciated 35% more slowly while zone “B” was slightly less affected with a 33% lower appreciation rate from the control area “C” (Carey, 2001). When Carey examined the roadway impact on multi-family dwellings there was an appreciation of property values in zones “A” and “B” over the control zone. However it was zone “B” which fared best from the freeway’s construction with an appreciated value of 18.79% increase over the control and zone “A” with a much smaller 5.621% increase (Carey, 2001). When considering the impact on a business, we must consider both its proximity to exit ramps and its visibility from the roadway. Carey quotes one Washington report that estimated the appreciation of commercial properties as high as 17% in the impact area over the control zone “C” (Carey, 2001). For simplification purposes our model will only consider a business and multi-family property’s proximity to the roadway and not to exit ramps.

Carey’s study also showed property values were a function of the property’s distance from the roadway and the traffic volume. For the purposes of our model we will use a combination of these two effects. By Carey’s calculations there was a $0.052 drop in detached single property values per vehicle in zone “A”, whereas zone “B”, saw a decrease of $0.027 per vehicle on the roadway (Carey, 2001).

Vacant buildings also have an effect on local neighborhoods, especially if the properties are adjacent to a large roadway and become less desirable due to noise and pollution. Vacant buildings become a magnet for criminal activity. Vacancy levels over 5% are considered detrimental to surrounding properties owing to increased health and safety threats to the local neighborhood [26]. As described in "a Vacant Building Management Plan for the City of Richmond," in 2007, George states, there were 736 crimes committed in 348 occupied parcels (buildings), by comparison there were 174 crimes committed on 66 vacant parcels (buildings). This difference of crimes shows vacant buildings had a 25% increase in criminal activity over occupied buildings (George, 2008).

2.5 Richmond-Petersburg Turnpike Volume

The Richmond-Petersburg Turnpike was a toll road intended to alleviate vehicular congestion running north-south connecting the City of Richmond and the City of Petersburg. Since it was a toll road using public monies, reports to the Virginia General Assembly were required annually. These reports provided great detail about Turnpike toll transactions until its absorption in the interstate system after 1973. As we can see in Table 2.5.1 and the accompanying Figure 2.5.1, the traffic volume grew exponentially over the toll road's life-time [28, 29, 30].

Richmond-Petersburg Turnpike
Toll Transactions from 1958 – 1973

	1958	**1959**	**1960**	**1961**	**1962**	**1963**	**1964**	**1965**
Vehicles	8100215	16758382	18725746	19692354	20927147	22941646	25642517	29445477
% Change			11.74	5.16	6.27	9.63	11.77	14.83

	1966	**1967**	**1968**	**1969**	**1970**	**1971**	**1972**	**1973**
Vehicles	33378981	37009133	41400830	50717723	56420463	61442469	69157600	76516064
% Change	13.36	10.88	11.87	22.50	11.24	8.90	12.56	10.64

Table 2.5.1 Annual Turnpike Toll Transactions

The Richmond Petersburg Turnpike was partially opened on June 30, 1958 and only fully operational on August 12, 1958. The data for 1958 will not be used in calculating a regression but is presented in the annual traffic volume table. [27].

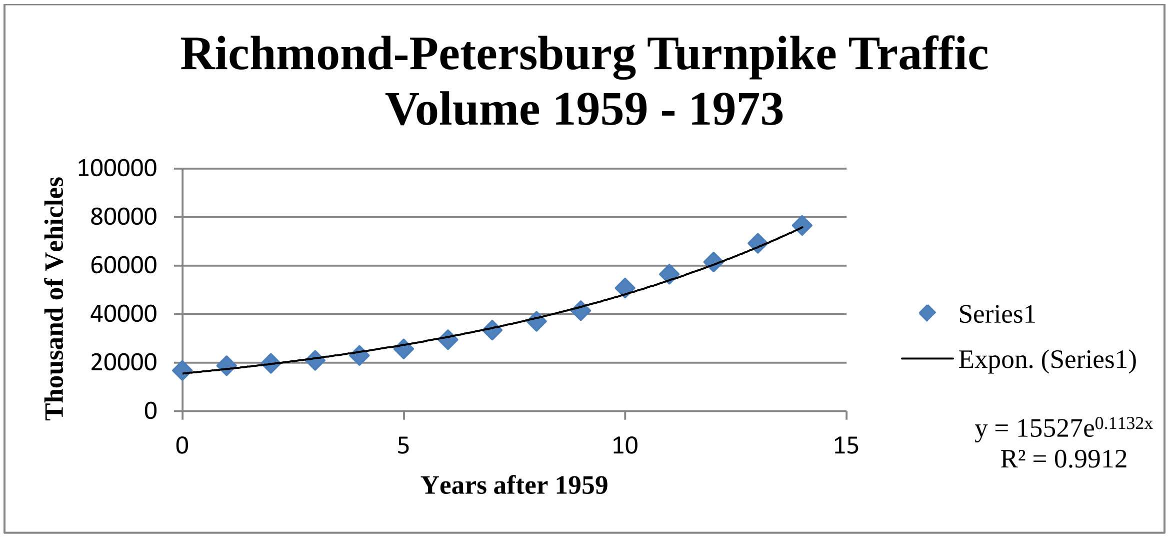

Figure 2.5.1 Turnpike Toll Transaction from 1958 – 1973

The turnpike was so popular it was eventually widened in 1973 to accommodate the traffic increase shown in Figure 2.5.1. The turnpike's permeability would be partially determined by access to the roadway through roadway exits; however we will simplify the idea of permeability to consider any surface area road with open access through side roads and driveways. With open access, if a car or person is simply trying to cross from one side to another, permeability would be a function of vehicle speed, number of lanes and number of vehicles. Permeability calculated using these three variables would be heavily influenced by the high volumes of traffic seen on the Richmond-Petersburg Turnpike. However further study into the sensitivity of exit proximity upon permeability could be studied at a later time.

Chapter 3 – Agent Based Model

3.1 The Agent Based Model

Agent based modeling is a modeling paradigm that can be used to understand environment and agent interactions based on a set of rules. The rules may vary for each agent, for the environment and may change over time. It is the collective behavior that is of interest given any variety of rules. Agent based models are created in layers with the smallest behaviors contained within a larger construction. Often behavior is defined stochastically rather than with static parameters. It is the addition of probabilities that provide ABMs flexibility and reveal behaviors not obvious in a deterministic system of equations. Furthermore, ABMs can be programmed to learn or adapt their rules to current circumstances. To quote Bonabeau, "ABM has the ability to observe emergent behaviors that are not possible to see in the separate "decoupled" entities. The overall is greater than the sum of its parts" [31].

ABM evolved from cellular automata models developed by John von Neumann in 1952 (Bonabeau, 2002). These initial models were limited since number of possible outcomes to a set of agents and rules can become unmanageable when calculating using paper and pen. ABM is especially effective when implemented on a computer so that they can describe complex social behaviors that are difficult to quantify.

3.2 Our Neighborhood Model

At the onset, we must understand that communities are dynamic, and transform due to a multitude of factors. We track several measures we considered indicative of a healthy community; those being the number of residents, the number of criminals, the number of abandoned buildings and the median property value. The long term effect of isolation through reduced access and transience of existing population is of particular interest when observing the long term health of the neighborhood.

Highway construction has been shown to change the composition of local neighborhoods and populations. By creating a direct link to distant areas, many workers can affordably live further from their worksite, while taking advantage of improved access to commercial or retail outlets close to the roadway. Businesses may relocate closer to the roadway, and the reduction of shipping costs can be beneficial to industries. This migration of residential, commercial and industrial uses changes the demographics of the impact region (Carey, 2001). Established residents may not be beneficiaries from the new roadway, and its impact on their community may be acute.

Traffic based businesses such as fast food restaurants, gas stations and convenience stores may benefit from the increased traffic provided they are within convenient access points since these types of businesses rely on quick customer access and service. Most drivers would be unwilling to backtrack for a small value item, which in essence, transfers revenues from an inconvenient business, to a business with better access (Carey, 2001). In Mazey's study "The Effect of a Physio-Political Barrier Upon Urban Activity Space", the roadway is a barrier which impacts local residents' personal action spaces. Residents "exhibit directional biases" along the roadway which tends to foster a greater degree of interaction with neighbors and a lesser interaction with areas across the roadway [32]. This does not imply that the residents will not cross the barrier, since as Mazey's study suggests, people "were willing to cross the barrier in order to obtain higher-order goods or services, but less likely to cross the barrier for lower-order ones indicating that the barrier's effect was not consistent through all personal activities (Mazey, 1981). In terms of our model, the road becomes a porous barrier, and depending on the road's volume and size, the neighborhood residents will cross the boundary to get the services they require.

The data generated from Jackson Ward before, during, and after it underwent a major roadway construction project in the late 1950's was compiled in Chapter 2. The information includes the road's volume; the neighborhood population, local property values, and per capita incidences of certain crimes. Using these data sets, we hope to extrapolate some understanding of the relationship between roadways and the state of the community's health. The software program, *NetLogo*, was used to create our ABM, and produce simulations to generate data which we can compare to our empirical models [33].

3.3 The Agents

There are three types of agents, which represent the three types of people which exist in a neighborhood: residents, criminals and policemen. All agents have values for health, income, employment, address, mobility and type. The type is identified by color, a resident (yellow), a police officer (blue) or a criminal (red).

Set-up:

Residents are created based on a random value less than or equal to the maximum allowable people per household, police presence is controlled by the user to observe the impact of increased patrols, and criminals are generated based on both the crime rate per capita and the average number of crimes per criminal. Specifically, the number of criminals is determined by the crimes per capita divided by the number of crimes per criminal.

Resident agents can be employed or unemployed, depending on the unemployment rate set by the user. If unemployed, individuals had an income of $8,000 based on unemployment payments, otherwise employed residents were given a randomized average annual income set by the user. Criminals were considered unemployed and assigned a base income of $8,000. Mobility is set by the user separately for residents and criminals. The higher the mobility, the more likely the agent is to cross the road. If we equate this to the availability of transportation then we see that a resident with no mobility would be far more isolated than one with a car or other convenient form of public transportation. Mobility is not given for police officers since they are confined to their designated neighborhood. Each resident has a home address which is the x-coordinate and y-coordinate of the patch from where he was sprouted.

Agent Characteristics	
Status	Resident (R), Criminal (C), Policeman (P)
Health	Random 0 - 100
Address	x-coordinate, y-coordinate
Mobility	1 - 10
Number of times moved	0 - 3
Employed	True, False
Income	$8000 up to a random user setting

Table 3.3.1 Agent Characteristics

3.4 The Model Environment (Patches)

The neighborhood itself has been bisected by a barrier road with a permeability which can be set from 0% to 100% - a setting of 100% permeability will effectively remove the barrier, whereas a setting of 0% making the road impossible to cross. Further studies that examine the relationship between road volume, speed, and lanes and their influence on permeability would be a natural extension of this study.

Non-road patches are color coded; lime green represents single-family homes, dark green represents multi-family homes (apartment buildings) and brown represents businesses. Patches that do not house any agents are considered abandoned and colored white (Figure 3.4.1). Businesses are restricted a maximum of ten employees; multi-family homes (apartment buildings) can house up to thirty people, single-family homes house a maximum of eight individuals. Each patch is also given a property value that is closely associated to its proximity to the road; the values are adjusted based on Carey's results for road proximity and property values (Carey, 2001).

Patch Characteristics	
Color	Black, Lime, Dark Green, Brown, White
Permeability	0% – 100% (all non-road patches have 100%)
Maximum employees	0 – 10
Number of employees	0 – 10
Maximum residents	8 or 30 (depending on single or multi family)
Number of residents	0 – 30
Occupied?	True, false
Distance from Road	Absolute value of y-coordinate
Property Value	Randomized from user setting and road dist
Revenue	For businesses 5% of property value

Table 3.4.1 Patch Characteristics

Each patch is considered the size of one lot, approximately the size of a single family home, a small business, or a small apartment block. When a property becomes abandoned it is devalued by 10% and in turn devalues each of its neighbors' property values by 5%. Businesses will be estimated to have annually generated revenue of 5% of their property value.

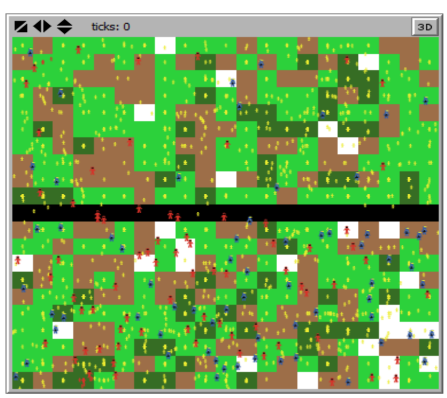

Figure 3.4.1 Neighborhood and Agents

3.5: Movement

Each tick of the model simulation represents one day. Residents are sprouted from their homes during the set-up phase of the model, and user input determines the number of criminals. The criminals are distributed in an 80% // 20% split between the “bad” (upper) neighborhood and the “good” (lower) neighborhood. As we see in Figure 3.4.1 the red criminals are concentrated in the upper neighborhood, with the police officers allocated equally to both sides of the barrier.

The model is set to have non-wrapping top and bottom boundaries, so when all agents begin to move they first check to see if they can move forward. If an agent is next to a closed edge, he will randomly change direction and move forward a space. If the agent encounters the road he then generates a random value to see if he can cross the barrier. If his random value divided by his mobility is less than the permeability of the road, he can cross the barrier; otherwise he will change direction and move away from the road. With this method the agent has a better chance of crossing the road when he has a high mobility.

As residents move, they may share a patch with another agent. No action is specified if a resident meets another resident or a police officer. If a resident’s patch is burgled, the resident will lose a maximum of $1000 as well as 10% health. If a resident is unhealthy (health less than 50%) he will try to move to a new higher property-value patch within the standard 8 patch neighborhood. Once every 60 ticks, if a resident is healthy, (85% health), he will try to sprout a new resident at his home address (birth). If there is no room at his home patch, he will invite a friend to move into an opening within the neighborhood.

While patrolling, a police officer will interact with a criminal within a 1 unit cone of vision. The criminal will be warned and then flee 85% of the time and the remaining 15% of the time the criminal is jailed and removed from the neighborhood. The police officer remains in the neighborhood and continues his patrol.

Criminals interact with all agents and patches. At each time step a criminal has a 30% chance of trying to commit a crime. If a criminal is on the prowl to commit a crime then based on a random percentage, the criminal will perform one of the following activities: killing, robbing, assaulting, burgling, thieving or car theft. The distribution of criminal activities uses the crime composition in Richmond from 1940 to 1970. Once a criminal begins a crime, he has an 85% chance of success. This in accordance with statistics provided by the Virginia State Police, see data in Chapter 2. If a crime fails, the criminal flees the scene.

3.6 Crime Details

Since criminals are the main actors n this model, they interact with both agents and patches (Table 3.6.1).

Criminal Activities (random number generated between 0 – 100)			
$0 \leq x < 0.5296904$	KILL	Resident	dies
$0.5296905 \leq x < 3.8433928$	ROB	Resident	Loses health and income
$3.8433928 \leq x < 10.6492194$	ASSAULT	Resident	Loses health
$10.6492194 \leq x < 25.2536939$	CAR THEFT	Resident	Loses income
$25.2536939 \leq x < 55.0592417$	BURGLE	Patch and Resident	Loses health and income
$55.0592417 \leq x \leq 97$	THEFT	Resident	Loses health and income
$x > 97$	RECRUIT	Resident	

Table 3.6.1 Criminal Activities

A criminal can kill residents; if he is successful he receives a 5% gain in health and a maximum of $1000 and the resident dies. If the criminal is unsuccessful, he loses 50% of his health.

A successful robbery results in a 20% loss to the victim's health and a maximum loss of $300, whereas the criminal will gain a maximum of $300 and 25% health. If the crime fails, it means the victim fought the criminal and the criminal loses 25% health. When a criminal robs a business, the business will also lose an employee, and 1% of its property value.

When a criminal decides to assault a resident, the victim will lose 60% of their health and the criminal gains 15% health. No income is exchanged during an assault. If the victim successfully resists, the criminal loses 25% of his health.

Car theft is between the criminal and the resident and has a maximum loss of $10,000. The victim loses 10% health whereas the criminal gains 15% health. If the criminal is unsuccessful he loses 5% of his health. Simple thefts cause the victim to lose only 3% of his health with a maximum loss of $300, while the criminal gains 5% health and a maximum of $300. If the criminal is unsuccessful, he loses 20% of his health.

Burglary is when a criminal interacts with the patches. If he happens upon a vacant lot he sets up residence at that location and gains 25% health. It is of great advantage for a criminal to have a protected hide out and he will seek one out whenever he is unhealthy, this is explained in further detail later. When the criminal burglarizes a single or multi-family residence, he gains a maximum of $1000 worth of goods and an additional 10% health. The resident who lives at the patch loses a maximum of $1000 and 10% health. When a criminal burglarizes any business, the patch loses 2% of its property value, the criminal gains 5% health and 5% of the revenue or .1% of the property if the business has no revenue.

One of the interesting features of criminal activity is its ability to reproduce through recruitment. If a criminal interacts with a resident under "duress", defined as having an income under $8000, there is a 10% chance he will be successfully recruited to the criminal class. The resident now becomes a criminal with the general characteristics of a criminal and moves out of his residence in search of a more desirable location for his new activities (a hide-out).

During any of the criminal's actions, if he attempts a crime on a police officer he is immediately arrested. If he attempts a crime upon a resident and fails, he flees the area, represented by a movement of 2.

Crime	**Criminal**		**Resident**	**Patch**
	Successful crime	Failed crime	Successful crime	Successful crime
Kill	+ 5% health, + max $1,000	-50% health	die	lose 1% to 2 % Property value
Robbery	+ 5% health, + max $300	-25% health	- 20% health, max -$300	lose 1% Property value and 1 employee if patch is a business
Assault	+ 5% health	-25% health	- 60% health	N/A
Car Theft	+15% health, + max $3000	-5% health	- 10% health, max -$10,000	N/A
Burglary	+ 10 % health, + max $1000 or 5% Revenue	-20% health	- 10% health, max -$1000	lose 1 to 2 % Property value or 5% Revenue
Theft	+ 5% health, + max $300	-20% health	- 3% health, max -$300	N/A
Recruit	N/A	N/A	N/A	N/A

Table 3.6.2 Crime Details

3.7 Update Details

In addition to resident movement, there is a regular update of resident and patch values. A resident gains 3% of his health for every 15 ticks, and a criminal loses 3% for every 15 ticks. Once a resident or criminal reaches a threshold of 5% health, he leaves the neighborhood and dies. If the criminal or resident is under 50% health he will seek out a better habitat. Residents will look to their immediate surroundings for a better property value, while a criminal will look for a vacant or a nearly vacant lot. In the criminal's case, if he finds a vacant lot he will gain 25% health. Both criminals and residents can only move a maximum of three times, if they still are unhealthy and want to move, they leave the neighborhood and die.

As previously mentioned the number of police officers remains constant at a level set by the user. Criminals have a 15% chance of reproducing once every 60 ticks if they are healthy (health 95%) and have a hide-out. Residents can also reproduce every 60 ticks if they have a health of 85% but will lose 25% health while giving "birth". This last constraint was placed upon residents so they would not be continually reproducing. If there is no available space on the resident's patch they will try to reproduce a new resident at another location with vacant space.

Property is updated according to two time scales; the first is the identification of occupied versus unoccupied buildings which is performed every 60 ticks. The simulation looks for vacant buildings and changes their color to white if they no longer house any residents or employees. Every 200 ticks, businesses that have lost 70% of their property value will close, their employees will leave the neighborhood, and the patch will turn white. Since criminals are not official residents, their hideouts are never considered occupied.

Property depreciates and appreciates according to roadway proximity is evaluated every 365 ticks; see zones "A", "B", "C" in section 2.3 as per Carey's property value study (Carey 2001). Zone "A" contains properties considered adjacent to the roadway 3 patches wide; Zone "B" covers the region from patch three to patch 5; the furthest zone is "C" which is considered the control zone which runs from patch 6 to the edge of our neighborhood at patch 10. Since properties update periodically, the graphs show jumps from one value to another after reassessment.

Populations are tracked for each neighborhood. Aggregate patch characteristics (property value and number of abandoned properties) are also recorded at each time step (tick).

Property Value Updates - Rates Attributed to Barrier Road				
Property	Action	Zone A	Zone B	Zone C
Single Family	Selling	2.577% Decrease	1.963% Decrease	Control Zone
Multi-Family	Selling	5.621% Increase	18.79% Increase	Control Zone
Business	Selling	17% Increase	6% Increase	Control Zone
Vacant	Selling	40% Decrease	40% Decrease	40% Decrease
Single Family	Depreciation	0.00004% Decrease	0.00002% Decrease	Control Zone
Multi-Family	Depreciation	N/A	N/A	Control Zone
Business	Depreciation	N/A	N/A	Control Zone
Single Family	Appreciation	2.81% Increase	2.89 % Increase	4.32% Increase
Multi-Family	Appreciation	5.621% Increase	18.79% Increase	9% Increase
Business	Appreciation	5% Increase	3% increase	2% Increase
Next to a vacant property	Selling	5% Decrease	5% Decrease	5% Decrease

Table 3.7.1 Property Update Details

Chapter 4 – Results

The ABM has many variables, but we will narrow our focus to just three (Permeability "*P*", Resident mobility "*R*" and Criminal mobility "*C*") in order to determine if the barrier road has an impact on residents, criminals and vacant properties. Other variables, such as police presence and reproduction will mostly be held static unless noted otherwise. Starting values for the residential population is randomly generated by each patch; the number of criminals in the neighborhood is defined by the user.

To observe the impact of the road, we will adjust the mobility of the resident, the mobility of the criminal, the number of police officers, and the permeability of the road. Movement across the barrier road will be determined according to equation (2) below.

$$\textit{movement across barrier} \qquad \frac{\textit{random}(100)}{\textit{mobility}} < \textit{permeability} \qquad (2)$$

The possibility of crossing the barrier is determined by a randomly generated value between 0 and 100 (inclusive) which is then divided by the agent's mobility. This value must be strictly less than the permeability of the road in order for the agent to cross.

4.1: The Impact of Mobility

In this section we initially examine the impact of mobility on the criminal and residential populations as well as on the number of abandoned properties when there is a low road permeability of 5%. If an agent has increased mobility, indicating availability of transportation, he will be more likely to cross the barrier. Simulations using low permeability and different levels of mobility for residents and criminals did not appear to impact our neighborhoods.

The road has a fixed permeability of 5%, indicating a heavily used road; the top neighborhood is preset to having 80% of the criminal population, whereas the bottom neighborhood has 20% of the criminals. These simulations do not include any police presence or reproduction and show criminal population increase as a result of the recruitment process.

Figure 4.1.1 shows that when residents have a high mobility and criminals have a low mobility, the criminal population initially increases since there is no police presence and the residential population decreases. We can also see how property values decrease as homes are vacated and abandoned properties increase. Moreover, once the residential population is removed, the criminal population decreases since it has no prey from which to gain health or income.

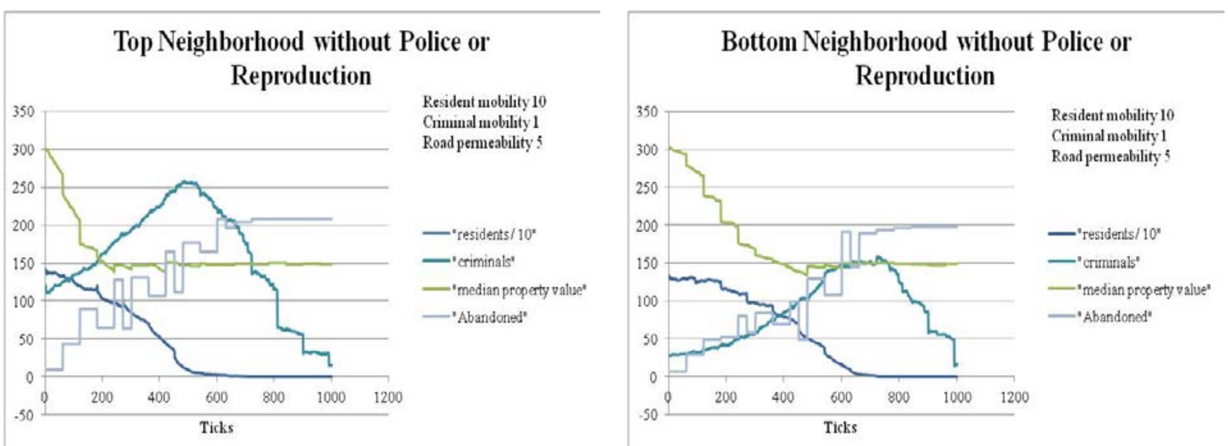

Figure 4.1.1: Permeability 5%, Resident Mobility 10, Criminal Mobility 1

In Figure 4.1.1 we see that the two neighborhoods had nearly the same criminal growth and residential decline with the top neighborhood losing its residential population around 500 ticks and the bottom neighborhood losing its residential population after 600 ticks.

Figure 4.1.2 has the same permeability of 5% as Figure 4.1.1 but both criminals and residents have a moderately good mobility. We observe that the two neighborhoods are nearly identical.

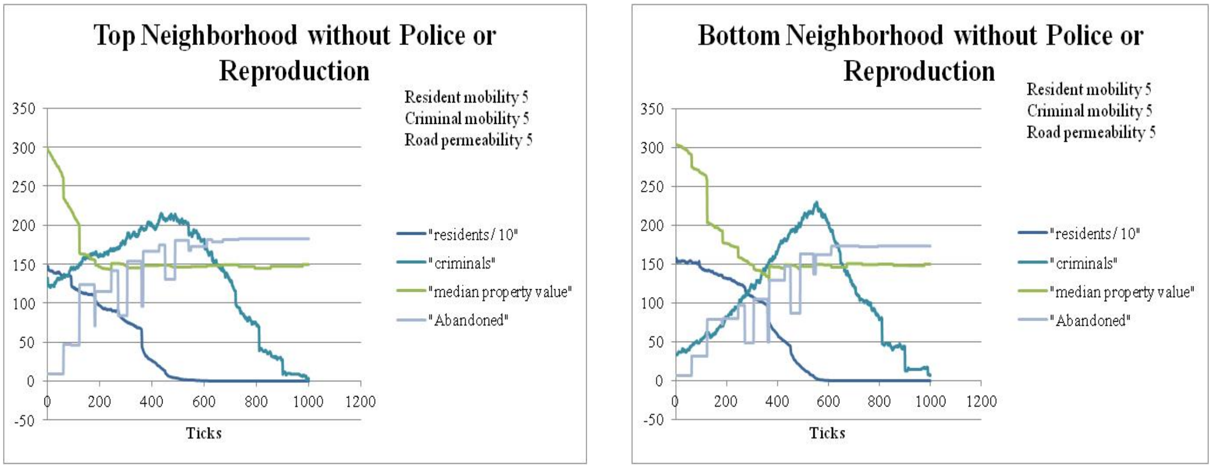

Figure 4.1.2: Permeability 5%, Resident Mobility 5, Criminal Mobility 5

In both neighborhoods the criminal population reaches a maximum value and thereafter since most residents have left the neighborhood, the criminals lose health, decline, and leave the neighborhood. If the criminals did not lose health at each tick, they would be self sustaining and we would see a steady state of criminals at the maximum level.

Road permeability prevents most migrations but without policing, both neighborhoods experience increases in crime and abandoned properties, which decreases population and property values, the only difference between the top and bottom neighborhoods, is that the top neighborhood experiences changes at a slightly earlier time.

4.2 The Impact of Policing

In this section we examine the effect on the criminal and residential populations when road permeability is fixed and the police presence varies within the neighborhood. Due to the unpredictable nature of policing it was necessary to estimate the type and number of interactions a police officer would have with a criminal. In section 3.5 we determined that 85% of the time, a police officer will warn visible criminals against illegal activities causing the criminals in our

ABM to flee and lose a small amount of health. When the police officer decides to make an arrest, a single criminal will be targeted and will be removed from the neighborhood.

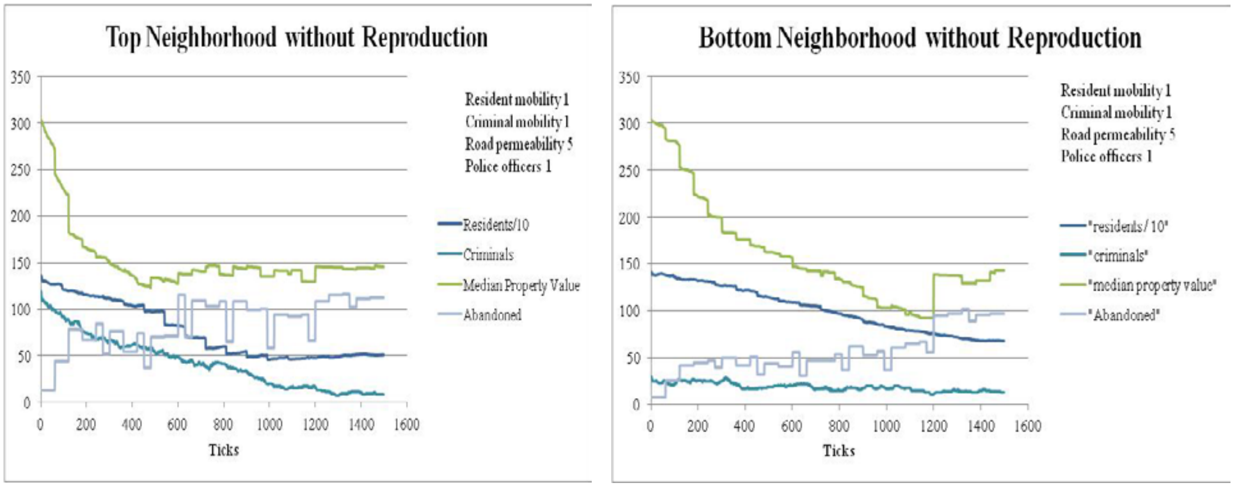

Figure 4.2.1 Permeability 5%, Police 1, Resident mobility 1, Criminal mobility 1

The introduction of police officers dramatically changed the neighborhood outcome we observed in section 4.1 as seen in Figure 4.2.1. Since the ABM police officers are always on patrol and interacted with the criminals constantly it results in a dramatic drop in criminals and a faster stabilization of the residential population. The residential population initially declined slightly due to some criminal interaction, and an absence of resident reproduction.

Simulations with different number of police officers yielded similar results. When we increased the number of police officers, the number of criminals dropped more rapidly; this is a trivial result for the simulation and provided little information on roadway impact since both neighborhoods were similarly affected. Refining the interaction of police officers and criminals should be studied in the future since the model is highly sensitive to police presence. Figure 4.2.2 verifies that the impact of the police officers profoundly affects the two populations. As criminals decline quickly with each added officer, the residential population stabilizes more quickly.

4.3: The Impact of Permeability

In this section we examine the effect on the criminal and residential populations when there is change to road permeability. Police presence throughout this section will be fixed at 1 officer in each neighborhood, property value updates and health value updates are activated but reproduction of criminals and residents will only occur when specified.

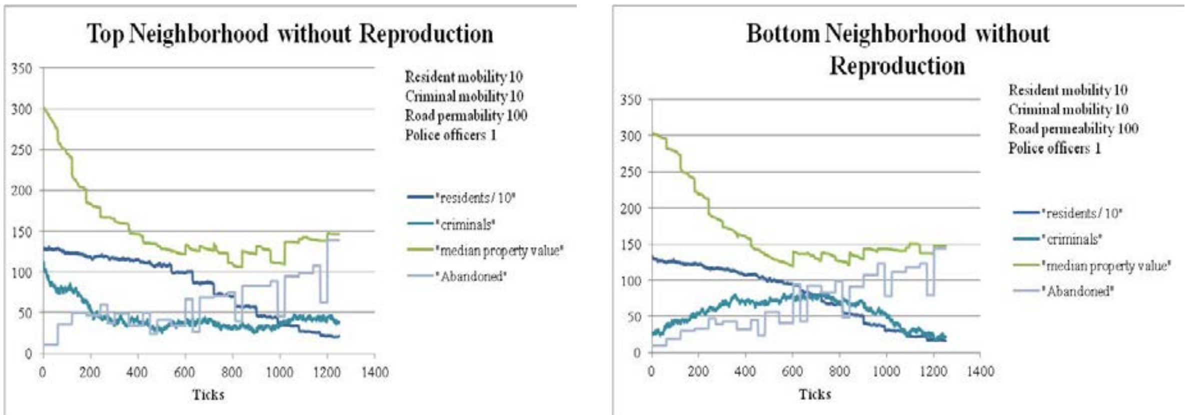

Figure 4.3.1 Road Permeability 100%, Police 1, Resident Mobility 10, Criminal Mobility 10

Figure 4.3.1 is set with an easily negotiable roadway with residents and criminals having accessible transportation, and one police officer in each neighborhood. Both top and bottom neighborhoods show residential and criminal population decline. As the residential population declines, the criminal population declines in the bottom neighborhood since it has no method to reproduce other than recruitment.

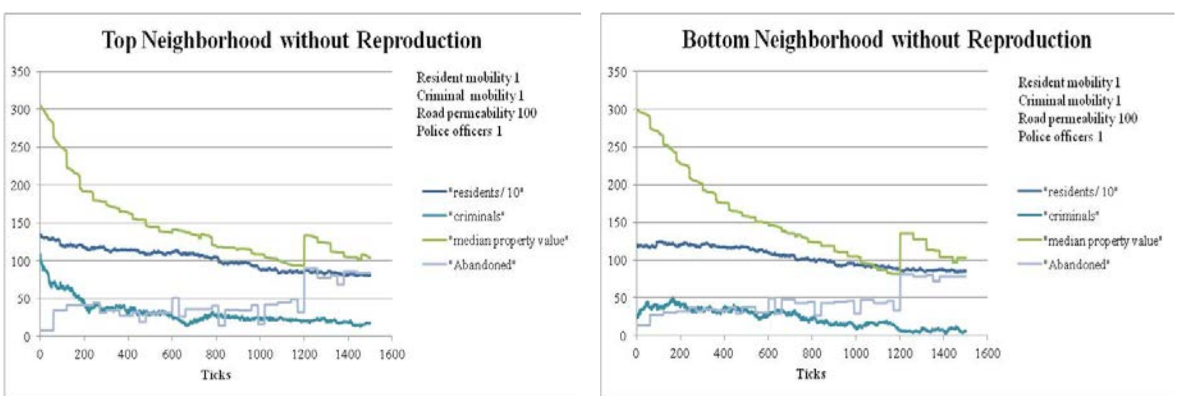

Figure 4.3.2 Road Permeability 100%, Police 1, Resident Mobility 1, Criminal Mobility 1

Both residents and criminals have limited mobility however since the road does not impede movement, we see both neighborhoods change similarly with gradual declines in population. A 100% permeable road provides a high likelihood of migration across the barrier, allowing for free flow of commerce and social networking as shown by the similar growth rates between the bottom and top neighborhoods (Figure 4.3.2). When the simulation was run with a 50% permeable barrier we observed the same result. Simulations confirm that the more permeable the barrier, the less impediment to movement for both criminals and residents as shown by similar growth and decay patterns.

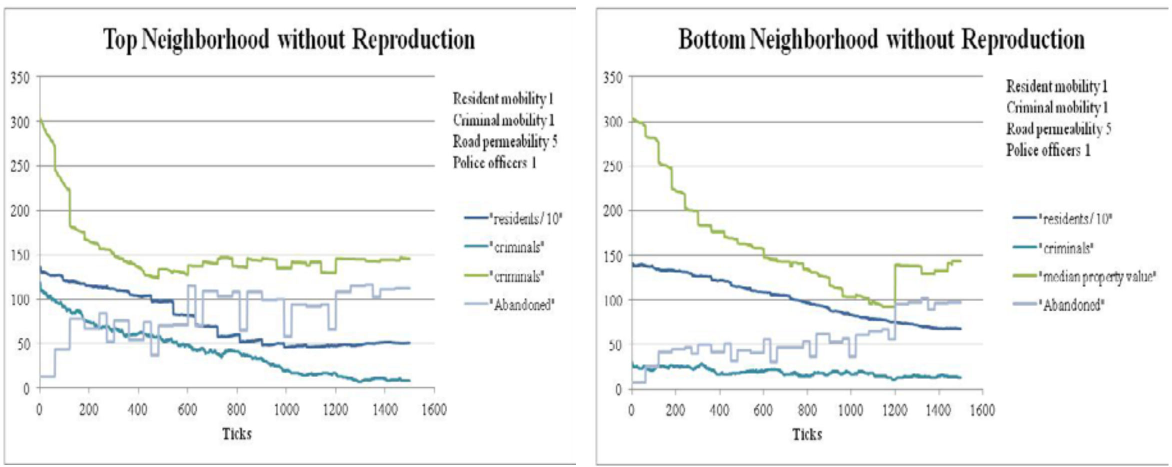

Figure 4.3.3 Road Permeability 5%, Police 1, Resident Mobility 1, Criminal Mobility 1

The effect of reduced mobility for the residential and criminal populations when there is a barrier road with 5% permeability still shows a similar change over time for both neighborhoods. There is an initial drop in criminal and residential populations in the top neighborhood but the bottom neighborhood populations appear to be stabilizing. The effect of the barrier road with a 0% permeability allows the residential population in the bottom neighborhood to stabilize, and there is a small reduction in the criminal population. In contrast, the top neighborhood experiences a steep decline in both criminal and residential populations and an increase in abandoned properties.

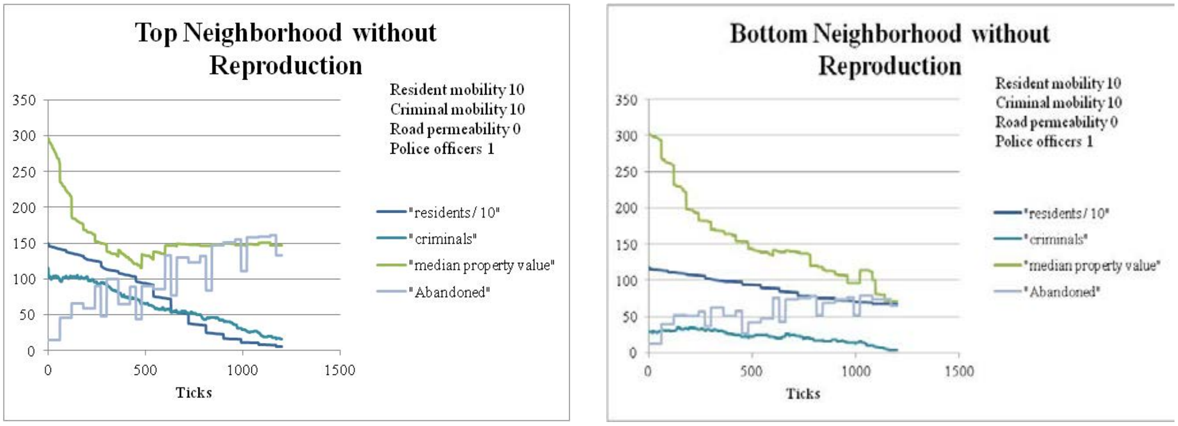

Figure 4.3.4 Road Permeability 0%, Police 1, Resident Mobility 10, Criminal Mobility 10

Figure 4.3.4 shows that the impact of mobility is negligible when the road has a permeability of 0%. The non-permeable barrier severs the two neighborhoods and allows them to develop separately. The isolated bottom neighborhood stabilizes quickly as the criminal population goes to zero, whereas the top neighborhood sees a steep decline in residential and criminal populations and a large increase in abandoned properties over the same period.

Now when we add the reproduction function to our simulations, we find that instead of stabilization of the populations we have population growth.

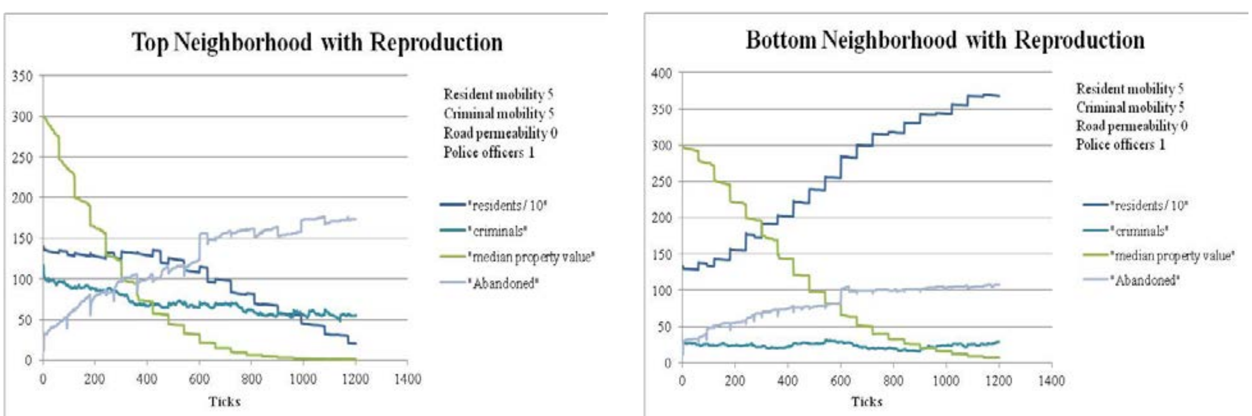

Figure 4.3.5 Road Permeability 0%, Police 1, Resident Mobility 5, Criminal Mobility 5

In Figure 4.3.5 we see decay of the residential population in the high crime area, but growth in the residential population in the bottom neighborhood. The criminal population in the top neighborhood is stable in both neighborhoods. Abandoned properties are quite high in the top neighborhood and slightly increasing in the bottom neighborhood.

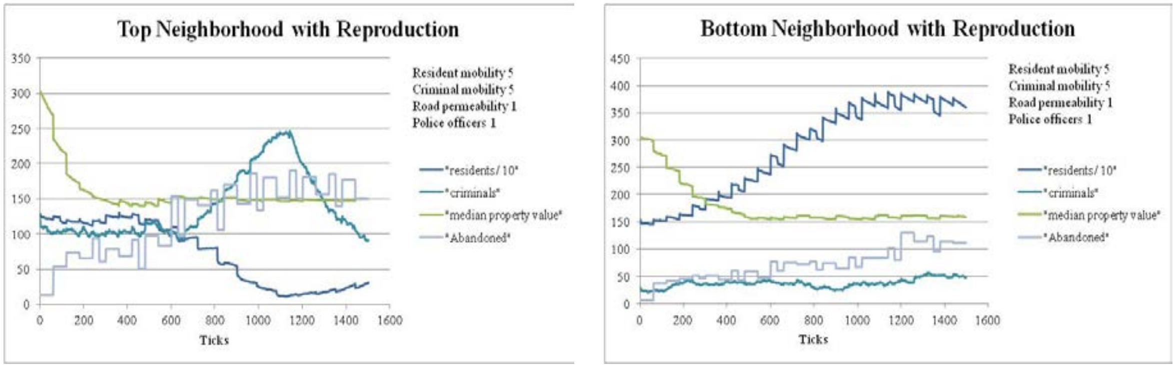

Figure 4.3.6 Road Permeability 1%, Police 1, Resident Mobility 5, Criminal Mobility 5

Figure 4.3.6 provides an almost completely isolated environment with a moderate amount of mobility and very low permeability. The top neighborhood experiences a criminal explosion which drives out the residents, resulting in a criminal population plunge. The bottom neighborhood experiences population growth and stabilizes along with a small stable criminal population. The number of abandoned properties in the top neighborhood is much higher than the bottom neighborhood. Although the median property value stabilizes in the top neighborhood since abandoned properties are not being devalued after being unoccupied, we do not find higher median property values or as much stabilization occurring with the larger bottom population as expected. This is discussed further in our extensions to our model in Chapter 5.

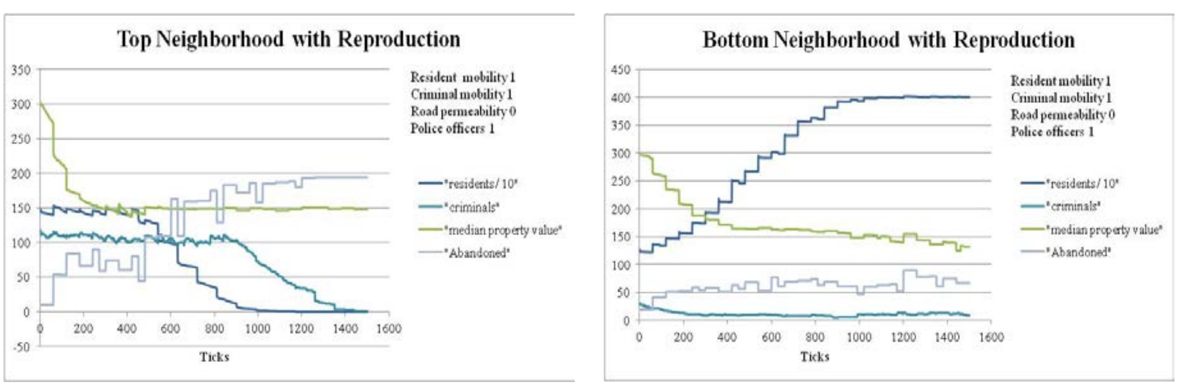

Figure 4.3.7 Road Permeability 0%, Police 1, Resident mobility 1, Criminal mobility 1

In this extreme case where we have almost no mobility and an impermeable road we see the two neighborhoods developing quite differently. The top neighborhood experiences an initial loss of residents, followed by a loss of criminals and the resultant abandoned properties. However in the bottom neighborhood, the abandoned properties are stabilizing through revitalization rather than abandonment. The population grows and maximizes while the criminal population remains low. Revitalization in our ABM model was created as a part of the reproduction function for residents who were healthy but did not have room in their own homes for another resident.

4.4 ABM Comparison to Jackson Ward

A pie graph representing the composition of crimes during simulation in Figure 4.4.1 below compares favorably with the composition of crimes in Richmond from 1930 to 1970. Our model reflects the breakdown of criminal activities except for recruitment activities, for which we had no actual data to compare.

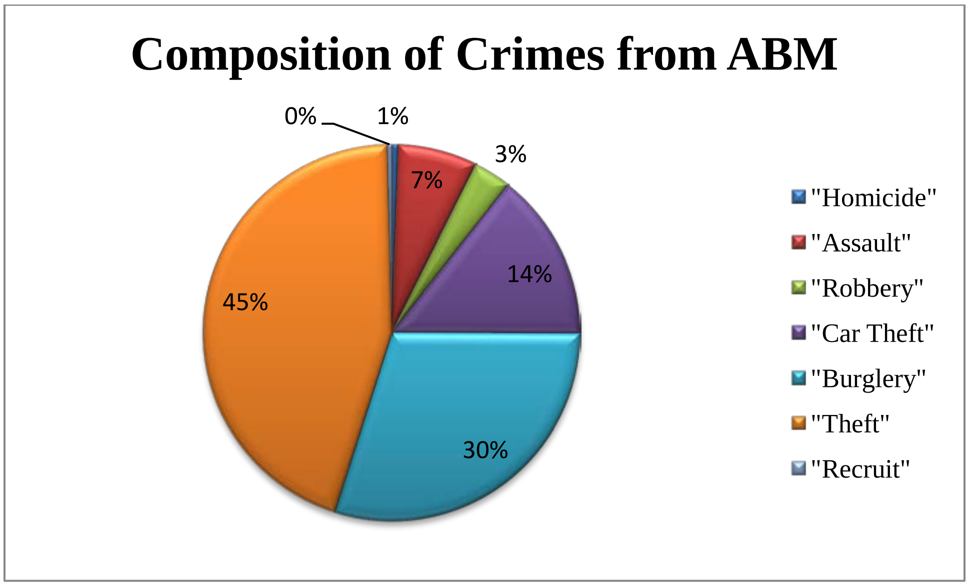

Figure 4.4.1 ABM Crime Composition

In most simulations, although the population decayed in the neighborhoods, the rates were different than Richmond's population changes. Most graphs indicated a linear or exponential decay, whereas Richmond's actual population change was quadratic. The one simulation that did give a quadratic residential population occurred where both criminals and residents had a moderate mobility of 5, a road permeability of 1%, one police officer, and the ability to reproduce was activated see Figure 4.3.6.

Summary of Outcomes

Resident mobility	Criminal mobility	Police presence	Road permeability	Reproduction	Outcome
1, 5, 10	1, 5 10	0	5	no	Bottom and top neighborhoods grew similarly - residential populations decayed and criminals populations peaked then decayed (time delay)
1	1	1, 3, 5	5	no	Bottom and top neighborhoods grew similarly - residential populations stabilized while criminal populations decayed (added police gave faster results)
10, 1	10, 1	1	100	no	Resident population decayed in both neighborhoods, criminal population stabilized in top neighborhood, peaked then decayed in bottom neighborhood
5	5	1	50, 5	no	Both neighborhoods experience residential and criminal decline
1, 5, 10	1, 5, 10	1	5, 0	no	Top neighborhood experiences residential and criminal decline, bottom neighborhood experiences initial decline then stabilization
1	1	1	100	yes	Top and bottom neighborhoods experience similar growth patterns
5	5	1	1	yes	Top neighborhood experiences residential decline, and criminal growth then decline. Bottom neighborhood residential population experiences growth and stabilizes while criminal population stabilizes
1	1	1	0	yes	Top neighborhood experiences residential and criminal decline. Bottom neighborhood residential population experiences growth and stabilizes while criminal population stabilizes at a low level

Table 4.4.1 Summary of Outcomes

The criminal population increased in section 4.1 when there was no policing present and when reproduction was available in Figure 4.3.6. During simulation, these criminal population increases lasted for short durations, since after criminals had decimated their residential population prey, the criminal population had no other source of income. Long term projections from our simulations predict a criminal population of zero, which is unrealistic in real world applications, and shows that the simulation in its present form does not reflect long term behavior. Criminal on criminal interactions are mentioned in Chapter 5 extensions, since their inclusion would provide a more realistic model.

The simulation most closely matching our crimes per capita increase from in Chapter 2, would be figure 4.3.6, where the road permeability was 1%, police presence was 1, and resident and criminal mobility were 1, and reproduction was permitted. In this simulation the population grows quadratically and the criminals grow rapidly which would mean that the crimes per capita would have a very large increase similar to our Crimes in Richmond Figure 2.3.3.

Chapter 5 – Conclusions and Extensions of the Model

We have seen from the simulations in section 4.1 that mobility of the criminal and the residents had little effect if the road had a low permeability. When the road was 50% permeable and the criminals and residents had similar access to transportation, the neighborhoods changed in unison. Mobility only delayed similar growth and decay patterns from one neighborhood to the other. The model's high sensitivity to police presence leads us to ask the question why and lends itself to further investigation. If the police presence was set at a higher value than one per neighborhood, then our criminals could not reproduce quickly enough to maintain a non-zero population. As we saw in section 4.3, if permeability is very low, the two neighborhoods experience different growth and decay rates depending on the preset criminal distribution. The residents and the criminals become trapped within their neighborhood and if a resident is weakened by too many attacks he will move and leave the neighborhood. When permeability is fixed at 0%, mobility is a non-issue.

Refining a complex system into a manageable study came with compromises. There were many other dynamics which could be included in this model. They include: the inclusion of bicycle paths and green spaces; street lighting; transience of the neighborhood (owner occupied); sidewalks and pedestrian traffic; proximity to on and off ramps; criminal on criminal activity; and resident upon criminal interactions. Each of these variables will affect criminal activity, resident's health and property values.

Throughout the development of the model there were many assumptions that had to be made, an obvious extension would be to research the nature of police and criminal interactions (criminal patrolling) and incorporate these into the ABM. Presetting our top and bottom neighborhoods to have different property dynamics would have impacted the results as well, and could be studied in future work. Another area for further research would be the rates at which properties are valued in response to businesses proximity. Additionally, we could also include a function which models health consequences in relation to the proximity of the road due to exposure to pollution. Other types of property development, such as office buildings, hospitals, arenas, and other non-residential uses were not included in this model. Since these other property uses develop along highway corridors, they are also worthy of future research since abandoned properties are often converted to new uses that benefit from road proximity. This model also could be extended for studying "food deserts" and rates of diabetes within inner cities by testing the inclusion of grocery stores. Implementing a human behavior module as it pertains to crossing a barrier to attain goods, or because the property value is higher, or because business traffic is higher, would make our model more realistic. Modifications to directed movement for criminals and residents with a concentration on criminal activities near the roadway should be considered for future work.

The model could be applied to other scenarios and could be used to model a river as the barrier and bridges as access points would provide further information on the influence of access points on permeability. Also research on how permeable barriers are breached should be examined closely since it not only impacts microscopic cellular functions, but other types of physical barriers like roads, walls, and dams etc. The inclusion of a calculation for permeability based on the characteristics of the barrier, and the characteristics of the outside elements was beyond the scope of this paper but would be an interesting study as well.

In summary using the ABM method is ideal for modeling a variety of urban issues, and provides a richness of outcomes that can be difficult to duplicate using other methods. As previously mentioned, further research into agent interactions are a natural extension to this model which would have added interesting dynamics and a more realistic model. However, it was shown that the introduction of a permeable barrier can change the outcome of a neighborhood simply by its ability to isolate a population, and prevent social and commercial interactions across the barrier.

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Appendix A

NetLogo Program:

```
;; our population is divided into three categories (status), residents (R) and criminals (C) and policemen (P) are
breeds of turtle
globals[GOOD  MODERATE  LOW R C P KL RB AS TH C_T BR RC];; global variables for permeability of
barrier road GOOD = 80, MODERATE = 65, LOW = 20
breed [population person]
turtles-own [status chance health employed? income addressx addressy mobility moved]      ;; both criminals
residents and police have health income
patches-own [pchance permeability
occupied? dist_from_road property_value revenue max_employees num_employees max_residents num_residents]

;; patches can be roads, businesses or homes
;; procedures: setup, build-road s, build-neighborhood, build-population, build-criminals, build-police


to setup

  clear-all
  build-neighborhood      ;; patch procedure
  build-crime             ;; turtle procedure
  UPDATE-PLOT

end



to build-neighborhood

ask patches
[
  set pchance random 100                                                  ;; assigns a random
number to each neighborhood patch
  set occupied?  false                                                    ;; since we will be
sprouting a percent population from each patch we will not have any unoccupied
  if pchance > (percent-residential + percent-multi-family-dwelling) and pycor != 0
  [
    set pcolor brown                                                      ;; businesses are
indicated by brown patches
    set permeability 100
    set max_employees 10                                                  ;; maximum
number of employees at business
    set num_employees .8 * max_employees                                  ;;
randomized number of employees
    set max_residents 0
    set num_residents 0
    set occupied? true
    set dist_from_road abs(pycor)
    assign-property-value
    set revenue .005 * property_value                                     ;; increase in
revenue should come from number of turtles that frequent the patch
   ]
  if pchance < percent-multi-family-dwelling and pycor != 0
  [
```

```
   set pcolor 53                                                                    ;; single family homes
are indicated by lime green patches
   set permeability 100
   set max_employees 0
   set num_employees 0
   set max_residents 30                                                                ;; maximum number
of residents at apartment
   set num_residents random max_residents + 1                                                  ;;
randomized number of residents living at apartment
   sprout-population num_residents                                                       ;; apartment
patches sprout number of residents
   [
     set shape "person"                                                              ;; set shape to be a
person
     set status R                                                                  ;; set the status as resident
     set health random-normal 75 20                                                         ;; set the health
as a random number 0 - 100
     set color yellow                                                                ;; set the colour to
yellow
     set size .25                                                                  ;; set resident size to .25
     set addressx xcor                                                               ;; gives x coordinate of
home address of turtle
     set addressy ycor                                                               ;; gives y coordinate of
home address of turtle
     set mobility res-mobility
     set moved 0
     set chance random 100                                                               ;; set each turtle to
have a random chance
     ifelse (chance < unemployment-rate)                                                      ;; chance of
being employed or unemployed based on user input
      [set employed? false set income 8000]                                                   ;;
unemployment income is 8000
      [set employed? true set income random avg-personal-income]                                         ;;
randomized average personal income
    ]
   if num_residents = 0 [set pcolor white set occupied? false]
   if num_residents != 0 [set occupied? true]
   set dist_from_road abs(pycor)
   assign-property-value
  ]
 if (pchance >= percent-multi-family-dwelling and pchance <= (percent-multi-family-dwelling + percent-
residential) and pycor != 0)
 [
   set pcolor lime                                                                  ;; single family homes
are indicated by lime green patches
   set permeability 100
   set max_employees 0
   set num_employees 0
   set max_residents 8                                                                 ;; maximum number
of residents at house
   set num_residents random max_residents + 1                                                  ;;
randomized number of residents living at house
   sprout-population num_residents                                                       ;; house patches
sprout number of residents
   [
```

```
      set shape "person"                                          ;; set shape to be a
person
      set status R                                                ;; set the status as resident
      set health random-normal 75 20                                      ;; set the health
as a random number 0 - 100
      set color yellow                                            ;; set the colour to
yellow
      set size .25                                                ;; set resident size to .25
      set addressx xcor                                             ;; gives x coordinate of
home address of turtle
      set addressy ycor                                             ;; gives y coordinate of
home address of turtle
      set mobility res-mobility
      set moved 0
      set chance random 100                                         ;; set each turtle to
have a random chance
      ifelse (chance < unemployment-rate)                                 ;; chance of
being employed or unemployed based on user input
       [set employed? false set income 8000]                              ;;
unemployment income is 8000
       [set employed? true set income random avg-personal-income]                 ;;
randomized average personal income
     ]
    set dist_from_road abs(pycor)
    if num_residents = 0 [set pcolor white set occupied? false]
    if num_residents != 0 [set occupied? true]
    assign-property-value
   ]
  if pycor = 0                                                    ;; creates top barrier road
  [
    set pcolor black                                              ;; sets colour to black
    set permeability road-permeability                                    ;; permeability
set by slider
    set pchance 0
    set num_employees 0
    set max_employees 0
    set max_residents 0
    set num_residents 0
    set occupied? false
    set property_value 0
   ]
  if pchance >= 95                                                ;; creates top barrier
road
  [
    set pcolor white                                              ;; sets colour to black
    set permeability 100
    set num_employees 0
    set max_employees 0
    set max_residents 0
    set num_residents 0
    set occupied? false
    set dist_from_road abs(pycor)
    assign-property-value
   ]
]
```

```
end


to build-crime  ;;
   set KL 0
   set RB 0
   set TH 0
   set AS 0
   set C_T 0
   set BR 0
   set RC 0

  create-population  ceiling (.2 * ((count population) * crime-rate) / crimes-per-criminal)
;; creates criminals
  [
    setxy random-xcor -1 + random-float -9                                    ;; random
location for people on grid
    set status C                                                              ;; set the status as
criminal
    set health random-normal 60 35                                            ;; set the health
as a random number 0 - 100
    set color red                                                             ;; set the colour to red
    set size .5                                                               ;; set turtle size to .5
    set employed? false                                                       ;; assume that the
criminal is not employed and all income comes from crime
    set income 8000                                                           ;; minimal poverty
level income
    set shape "criminal"                                                      ;; turtle will be shaped
like a criminal
    set mobility crime-mobility
    set moved 0
   ]
  create-population  ceiling (.8 * ((count population) * crime-rate) / crimes-per-criminal)
;; creates criminals
  [
    setxy random-xcor 1 + random-float 9                                      ;; random
location for people on grid
    set status C                                                              ;; set the status as
criminal
    set health random-normal 60 35                                            ;; set the health
as a random number 0 - 100
    set color red                                                             ;; set the colour to red
    set size .5                                                               ;; set turtle size to .5
    set employed? false                                                       ;; assume that the
criminal is not employed and all income comes from crime
    set income 8000                                                           ;; minimal poverty
level income
    set shape "criminal"                                                      ;; turtle will be shaped
like a criminal
    set mobility crime-mobility
    set moved 0
   ]
```

```
   create-population .5 * police-presence                                                    ;; creates
policemen
  [
    set shape  "policeman"                                                               ;; set shape to be a
policeman
    setxy random-xcor -1 + random-float -9                                                  ;; random
location for people on grid
    set status P                                                                   ;; set the status as
policeman
    set health 100                                                                  ;; set the health as 100
    set color blue                                                                  ;; set the colour to blue
    set size .5                                                                    ;; set turtle size to 2
    set income 35000                                                                  ;; assumes that
average parolman's salary is 35,000 dollars
    set employed? true                                                                ;; assume that
policeman is employed
   ]
 create-population .5 * police-presence                                                    ;; creates
policemen
  [
    set shape  "policeman"                                                               ;; set shape to be a
policeman
    setxy random-xcor 1 + random-float 9                                                    ;; random
location for people on grid
    set status P                                                                   ;; set the status as
policeman
    set health 100                                                                  ;; set the health as 100
    set color blue                                                                  ;; set the colour to blue
    set size .5                                                                    ;; set turtle size to 2
    set income 35000                                                                  ;; assumes that
average parolman's salary is 35,000 dollars
    set employed? true                                                                ;; assume that
policeman is employed
   ]


end



to assign-property-value

  if pcolor != black [set property_value (random-normal avg-property-value 20)]
;; assigns a property value around the average from the slider to all patches that are occupied
  if pcolor = white
  [
   set property_value property_value * .6
   ask neighbors [set property_value property_value * .95]
  ]
  if pcolor = lime
  [
   if dist_from_road < 3 [set property_value (.97423 * property_value)]                          ;;
zone "A"
   if dist_from_road >= 3 and dist_from_road < 6 [set property_value (.98037 * property_value)]
;; zone "B"
   ]
```

```
 if pcolor = 53
 [
   if dist_from_road < 3 [set property_value (1.05621 * property_value)]                                    ;;
zone "A"
   if dist_from_road >= 3 and dist_from_road < 6 [set property_value (1.1879 * property_value)]
;; zone "B"
  ]
 if pcolor = brown
 [
   if dist_from_road < 3 [set property_value (1.17 * property_value)]                                    ;;
zone "A"
   if dist_from_road >= 3 and dist_from_road < 6 [set property_value (1.06 * property_value)]
;; zone "B"
  ]

end



to go

  WALK
  UPDATE-PLOT
  UPDATE-HEALTH
  UPDATE-PROPERTY
 ;;  REPRODUCE
  tick

end



to WALK
ask turtles
 [ set heading random 360
   if ( can-move? 1)
   [
     if color = yellow and [(random 100 + .001) / res-mobility < permeability] of patch-ahead 1 [ fd 1 ]
     if color = red and [(random 100 + .001  ) / crime-mobility  < permeability] of patch-ahead 1 [ fd 1 ]
     if color = blue and [random 100 + .001 < permeability] of patch-ahead 1 [ fd 1 ]
    ]
   if (color = red and random 100 >= 30) [PROWL]
   if (color = blue) [PATROL]
;;    if (color = yellow and random 100 < 3) [ACTIVITY]  ;;this proceedure takes up too much computing power
 ]
 display

end



to PROWL   ;; turtle (Criminal) proceedure

set chance random-float 100
if chance < .5296905 [KILL]
if (chance >= .5296905 and chance < (.5296905 + 3.3137023)) [ROB]
```

```
if (chance >= (.5296905 + 3.3137023) and chance < (.5296905 + 3.3137023 + 6.8058266)) [ASSAULT]
if (chance >= (.5296905 + 3.3137023 + 6.8058266) and chance < (.5296905 + 3.3137023 + 6.8058266 +
14.6044745)) [CAR_THEFT]
if (chance >= (.5296905 + 3.3137023 + 6.8058266 + 14.6044745) and chance < (.5296905 + 3.3137023 +
6.8058266 + 14.6044745 + 29.8055478))[BURGLE]
if chance >= (.5296905 + 3.3137023 + 6.8058266 + 14.6044745 + 29.8055478) and chance <= 97 [THEFT]
if chance > 97  [RECRUIT]
;; from 1931 to 1970 in Richmond type of crime breaks down to
;; homicide .05296905%, robbery 3.3137023%, assault 6.8058266%, car theft 14.6044745%, burglary 29.8055478%
and theft 44.94075829%
;; in 2010 Virgina State Police records that 85 % of attempted robberies are sucessful.  We will use that 85% success
rate for all crimes

end



to KILL    ;; turtle (Criminal) proceedure

ifelse any? turtles-here with [color = blue] [ARREST]                                          ;; if
criminal attempts a crime upon an officer he is immediately arrested
[ifelse (random 100 >= 85) [ask turtles-here with [color = red] [set health (.5 * health) FLEE]]
;; unsuccessful attempt
 [                                                                                          ;; successful crime
   if any? turtles-here with [color = yellow]
   [ask one-of turtles-here with [color = yellow]
     [
      setxy addressx addressy
      set KL KL + 1
      ask patch-here
      [
        if pcolor = brown
        [ set property_value .99 * property_value
          if num_employees > 0  [set num_employees num_employees - 1 ]
          if num_employees <= 0 [set num_employees 0 set occupied? false]
          ]
        if pcolor = lime or pcolor = 53
        [set property_value .99 * property_value
          if num_residents > 0 [set num_residents num_residents - 1]
          if num_residents <= 0 [set num_residents 0 set occupied? false]
          ]
         if pcolor = white   ;; this is if someone just moved into a white patch and it hasn't been updated yet
        [ set property_value .99 * property_value
          if num_employees > 0 [set num_employees num_employees - 1]
          if num_employees <= 0 [set num_employees 0 set occupied? false]
          if num_residents > 0 [set num_residents num_residents - 1]
          if num_residents <= 0 [set num_residents 0 set occupied? false]
          ]
      set property_value .98 * property_value
      ]
      die  ;; Ask Resident here to die
     ]
   ask one-of turtles-here with [color = red] [set health (5 + health) set income (income + random 1000)]
;; Criminal gains 5% health and random $1000 from homicide
   ]
 ]
```

```
]
end


to ROB    ;; turtle (Criminal) proceedure

ifelse any? turtles-here with [color = blue] [ARREST]                                              ;; if
criminal attempts a crime upon an officer her is immediately arrested
[ifelse (random 100 >= 85) [ask turtles-here with [color = red] [set health (.75 * health) FLEE]]
;; unsuccessful attempt
 [                                                                                   ;; successful crime
   if any? turtles-here with [color = yellow]
   [ask one-of turtles-here with [color = yellow]
     [
       set RB RB + 1
       set health (.80 * health)                                                          ;; trauma to victim's
health down 20% from robbery
       set income (income - random 300)                                                      ;; victim loses
random $300 in income from robbery
       ask patch-here
       [
         if pcolor = brown
         [ set property_value .99 * property_value
           if num_employees > 0  [set num_employees num_employees - 1 ]
           if num_employees <= 0 [set num_employees 0 set occupied? false]
          ]
        ]
     ]
     ask one-of turtles-here with [color = red] [set health (5 + health) set income (income + random 300)]
    ]
  ]
]

end


to ASSAULT  ;; turtle (criminal) proceedure

ifelse any? turtles-here with [color = blue] [ARREST]                                              ;; if
criminal attempts a crime upon an officer her is immediately arrested
[ifelse (random 100 >= 85) [ask turtles-here with [color = red] [set health (.75 * health) FLEE]]
;; unsuccessful attempt
  [                                                                                  ;; successful crime
   if any? turtles-here with [color = yellow]
   [ask one-of turtles-here with [color = yellow]
     [
       set AS AS + 1
       set health (.40 * health);; trauma to victim's health down 60% from assault
     ]
   ask one-of turtles-here with [color = red] [set health (5 + health)]
    ]
   ]
 ]                                                                                   ;; successful crime
```

```
end


to CAR_THEFT    ;; turtle (Criminal) proceedure

ifelse any? turtles-here with [color = blue][ARREST]                                              ;; if
criminal attempts a crime upon an officer her is immediately arrested
[ifelse (random 100 >= 85) [ask turtles-here with [color = red] [set health (.95 * health) FLEE]]
;; unsuccessful attempt
 [                                                                          ;; Successful crime
   if any? turtles-here with [color = yellow]
   [ask one-of turtles-here with [color = yellow]                     ;; Loses 10% health from car theft
     [
       set C_T C_T + 1
       set health (.90 * health)
       set income (income - random 10000)];; Resident loses random $10000 in income from car theft
    ask one-of turtles-here with [color = red]  [ set health (15 + health)  set income (income + random 3000)]
   ]                                          ;; Criminal gains 15% health and max $3000 income from car theft
 ]
]

end


to BURGLE    ;; turtle (Criminal) proceedure

ifelse any? turtles-here with [color = blue] [ARREST]                                             ;; if
criminal attempts a crime upon an officer her is immediately arrested
[
 ifelse random 100 >= 85 [ask turtles-here with [color = red] [set health (.80 * health) FLEE]]    ;; unsuccessful
attempt
 [
   ask patch-here
   [
     if (pcolor = white)
     [
       ask one-of turtles-here with [color = red]
       [ set addressx xcor set addressy ycor
         set health (3 + health)]
      ]                                                                       ;; Successful Crime
     if (pcolor = lime or pcolor = 53)                                                ;; If a home is
burglarized
     [
       ask one-of turtles-here with [color = red]
       [set health (10 + health)  set income (income + random 1000)]               ;; 10% increase to criminal's
health and increase to criminals income up to $1000 from burglary
       ask turtles with [color = yellow and addressx = xcor and addressy = ycor]                          ;;
Ask residents who live here to ...
       [
         set health (.90 * health)                                                    ;; 15% decrease to
victim's health from burglary
         set income (income - random 1000)                                                ;; maximum
$1000 decrease to victims income from burglary
```

```
        ]
       set property_value (.98 * property_value)                              ;; Property value
decreases by the above value because it is targeted by criminals
      ]
     if (pcolor = brown and revenue > 0)                                        ;; Rob an open
business
     [
       ask one-of turtles-here with [color = red]
       [set income (income + .05 * revenue)  set health (5 + health)]          ;; criminal receives a random 5%
of patch revenue and 5% health from burglary
       set revenue (.95 * revenue) set property_value .98 * property_value
      ]
     if (pcolor = brown and revenue <= 0)
     [
       ask one-of turtles-here with [color = red]
       [ set income (income + .001 * property_value) set health (5 + health) ]          ;; criminal receives
maximum of .1% of property value and 5% health from burglary
        set property_value .98 * property_value                                 ;; Property value
decreases by 2% from criminal targeting
      ]
    set BR BR + 1
   ]
  ]
]

end



to THEFT    ;; turtle (Criminal) proceedure

ifelse any? turtles-here with [color = blue] [ARREST]                                  ;; if
criminal attempts a crime upon an officer her is immediately arrested
[ifelse (random 100 >= 85) [ask one-of turtles-here with [color = red] [set health (.8 * health) FLEE]]
;; unsuccessful attempt
  [                                                                    ;; Successful crime
   if any? turtles-here with [color = yellow]
   [ask one-of turtles-here with [color = yellow]                                ;; Ask
the Resident here to ...
     [
       set TH TH + 1
       set health (.97 * health)                                            ;; Resident loses 3%
health
       set income (income - random 300)                                        ;; Resident
loses random $300 in income
      ]
   ask one-of turtles-here with [color = red]
   [set health (5 + health)  set income (income + random 300)]             ;; Criminal gains 5% health and
$300 from theft
   ]
  ]
]

end
```

```
to RECRUIT  ;; turtle (criminal) proceedure

ifelse any? turtles-here with [color = blue]  [ARREST]                                                ;; if
criminal attempts a crime upon an officer her is immediately arrested
[                                                                                          ;; Criminal sees if person is
poor and successfully asks him to join gang
  if any? turtles-here with [color = yellow] and random 100 >= 90                                       ;;
chance of successfulrecruitment 10%
    [
      ask one-of turtles-here with [color = yellow and income < 8000]
      [
        set RC RC + 1
        set status C
        set color red
        set employed? false
        set mobility crime-mobility
        set moved 0                                                                          ;; reset turtle status to
criminal and color red
        ask patch addressx addressy
        [
          if num_employees > 0 [set num_employees num_employees - 1]
          if num_employees <= 0 [set num_employees 0 set occupied? false]
          if num_residents > 0 [set num_residents num_residents - 1]
          if num_residents <= 0 [set num_residents 0 set occupied? false]
        ]
      ]
   ]
]

end



to FLEE     ;; turtle (Criminal) proceedure

ask turtles-here with [color = red]
[
   set heading random 360
   if (can-move? 1 and turtles with [color = blue] = nobody)
   [
     ifelse [pcolor = black and (random 100 + .001) / crime-mobility < permeability] of patch-ahead 1
     [fd 1]
     [ if [pcolor != black] of patch-ahead 1 [fd 1]]                                            ;; they turn
around and walk away at a random heading within field of vision
   ]                                                                                       ;; Move forward at twice the
speed.
 ]

end



to PATROL  ;; turtle (Criminal) proceedure
```

```
ifelse any? turtles-here with [color = red and random 100 < 85] in-cone 1 150  [WARN]  [ARREST]
;; There is a 25% chance of a simple warning from police
                                                    ;; Police will arrest the criminal 85% of the time

end



to WARN ;; turtle (Criminal) proceedure

ask turtles-here with [color = red] [set health (.85 * health) FLEE]                                          ;;
Criminal is warned by police officer loses 15% health

end



to ARREST ;; turtle (Criminal) proceedure

if any? turtles-here with [color = red]
[
  ask one-of turtles-here with [color = red]
  [die]
 ]                                                                                     ;; Criminal here goes to Jail
(removed from neighborhood)...

end



;;to ACTIVITY ;; turtle (Criminal) proceedure

;;set chance random 100
;;if chance < 34 [ROB]
;;ifelse chance > 95 [RECRUIT][ASSAULT]


;;end



to UPDATE-HEALTH  ;; turtle procedure

ask turtles
 [
  if (color = red) [ if (ticks mod 15 = 0) [ set health (health - 3) ] ]
;; If Criminal
   if (color = yellow) [ if (ticks mod 15 = 0) [ set health (health + 3) ] ]
;; lose 1 health point every 15 ticks
    ;; If Resident gain 1 health point every 15 ticks

  if (color = red and health <= 5) [ die  ]
```

```
  if (color = yellow and health <= 5)                                                          ;; if health falls
to 5% of below
  [
    setxy addressx addressy
    ask patch addressx addressy
    [
;;       if num_residents > max_residents [set pcolor blue]     ; this becomes true - bug
;;       if num_employees > max_employees [set pcolor yellow]   ; this becomes true - bug

      if num_residents > 0  [set num_residents (num_residents - 1)]
      if (num_residents <= 0 and pycor != 0) [set num_residents 0 set occupied? false]
      if num_employees > 0 [set num_employees (num_employees - 1)]
      if (num_employees <= 0 and pycor != 0) [set num_employees 0 set occupied? false]
     ]
    die
   ]                                                               ;; if health falls to 5% of below
  if (color = yellow and health <= 50 and ticks mod 90 = 89)
   [
;;     if num_residents > max_residents [set pcolor blue]     ; this becomes true - bug
;;     if num_employees > max_employees [set pcolor yellow]   ; this becomes true - bug

     MOVE-RESIDENT
     if moved > 3
     [
       ask patch addressx addressy
       [
         if num_residents > 0  [set num_residents (num_residents - 1)]
         if (num_residents <= 0 and pycor != 0) [set num_residents 0 set occupied? false]
         if num_employees > 0 [set num_employees (num_employees - 1)]
         if (num_employees <= 0 and pycor != 0) [set num_employees 0 set occupied? false]
       ]
     die
    ]
   ]
  if (color = red and health <= 50 and ticks mod 90 = 89)
   [MOVE-CRIMINAL if moved > 3 [die]]
 ]



end





to MOVE-RESIDENT

if ( can-move? 3)  [ if [ pcolor = black and (random 100 + .001) / res-mobility < permeability] of patch-ahead 1 [ fd
3 ]]
move-to max-one-of neighbors [property_value]
if pycor != 0
[

 ;; if patch-here (num_residents < max_residents or num_employees < max_employees)
 if (num_residents < max_residents or num_employees < max_employees)
```

```
 [

    let g pxcor let h pycor
    if((pcolor = 53 or pcolor = lime) and num_residents < max_residents)
      [
        if pcolor = 53 [set occupied? true set num_residents (num_residents + 1) ]
        if pcolor = lime [set occupied? true set num_residents (num_residents + 1) ]

      ]
      if (pcolor = brown and num_employees < max_employees) [set num_employees (num_employees + 1) set
occupied? true ]
      if (pcolor = white)
      [
        if pchance < percent-multi-family-dwelling
          [set pcolor 53 set occupied? true set num_residents 1 ]
        if (pchance >= percent-multi-family-dwelling and pchance < (percent-multi-family-dwelling + percent-
residential))
          [set pcolor lime set occupied? true set num_residents 1]
        if pchance > (percent-multi-family-dwelling + percent-residential)
          [set pcolor brown set occupied? true set num_employees 1]
      ]

  ;; ask myself   ;?? - to test
    if (num_residents < max_residents or num_employees < max_employees)
   [
       set moved moved + 1
       ask patch addressx addressy
       [
         if pcolor = lime or pcolor = 53
         [
           if num_residents > 0  [set num_residents (num_residents - 1)]
           if num_residents <= 0 [set num_residents 0 set occupied? false]
         ]
         if pcolor = brown
         [
           if num_employees > 0  [set num_employees (num_employees - 1)]
           if num_employees <= 0 [set num_employees 0 set occupied? false]
          ]
        ]
       set addressx g set addressy h
      ]
   ]
 setxy addressx addressy
 ]


end



to MOVE-CRIMINAL

if ( can-move? 3)  [ if [ pcolor = black and (random 100 + .001) / crime-mobility < permeability] of patch-ahead 1 [
fd 3 ]]
```

```
 move-to min-one-of neighbors [property_value]
 let j pxcor let k pycor
 if (num_residents <= 0 and num_employees <= 0 and ycor != 0)
   [set health (health + 25) set addressx j set addressy k set moved moved + 1 ]
 if (num_residents > 0 or num_employees > 0) and pycor != 0
   [ set addressx j set addressy k set moved moved + 1]


end




to REPRODUCE ;; turtle procedure

ask turtles
[
 if (color = yellow and health >= 85 and ticks mod 60 = 59) [REPRODUCE-RESIDENTS set health health - 25]

 if (color = red and health >= 95 and pcolor = white and random 100 > 85 and ticks mod 60 = 59) [REPRODUCE-
CRIMINALS set health health + 25]
]

end



to REPRODUCE-RESIDENTS

if count turtles with [color = yellow] < Max-Res
[
  setxy addressx addressy
  let a addressx let b addressy
  ask patch addressx addressy
  [
;;    if num_residents > max_residents [set pcolor blue]
;;    if num_employees > max_employees [set pcolor yellow]
    if ( num_residents < max_residents or num_employees < max_employees )
     [
       sprout 1
       [
         set shape "person"                                    ;; set shape to be a
person
         set status R                                         ;; set the status as resident
         set health random 100                                  ;; set the health as a
random number 0 - 100
         set color yellow                                       ;; set the colour to yellow
         set size .25                                          ;; set resident size to .25
         set mobility res-mobility
         set moved 0
         set addressx pxcor set addressy pycor
         set employed? false set income 8000                          ;; baby
       ]
       if pcolor = lime or pcolor = 53
        [if num_residents <= 0
```

```
        [
          set num_residents (count turtles with [color = yellow and addressx = a and addressy = b])  ;; bug fix
          set num_residents (num_residents + 1) set occupied? true
          ]
        ]
      if pcolor = brown
       [
        if num_employees <= 0 [set num_residents 0]
        set num_employees (num_employees + 1) set occupied? true
        ]
     ]
    if (num_residents >= max_residents or num_employees >= max_employees)
    [
      ask one-of turtles-here with [color = yellow]
      [
      if ( can-move? 3)  [ if [ pcolor = black and (random 100 + .001) / res-mobility < permeability] of patch-ahead 1
[ fd 3 ]]
        move-to max-one-of neighbors [property_value]
      if((pcolor = 53 or pcolor = lime) and num_residents < max_residents)
      [
        hatch 1
        [
          set shape "person"                                        ;; set shape to be a
person
          set status R                                              ;; set the status as resident
          set health random 100                                     ;; set the health as a
random number 0 - 100
          set color yellow                                          ;; set the colour to
yellow
          set size .25                                              ;; set resident size to .25
          set mobility res-mobility
          set moved 0
          set addressx pxcor set addressy pycor
          set employed? true
          set income random avg-personal-income
                                          ;; randomized average personal income
         ]
         if pcolor = 53
         [
           set occupied? true
           show count turtles with [color = yellow and addressx = a and addressy = b]
           if num_residents <= 0 [set num_residents 0]
           set num_residents (num_residents + 1)
          ]
         if pcolor = lime
         [
           set occupied? true
           show count turtles with [color = yellow and addressx = a and addressy = b]
           if num_residents <= 0 [set num_residents 0]
           set num_residents (num_residents + 1)
          ]
        ]
       if (pcolor = brown and num_employees < max_employees)
       [
         hatch 1
         [
```

```
          set shape "person"                                                          ;; set shape to be a
person
          set status R                                                                ;; set the status as
resident
          set health random 100                                                       ;; set the health as a
random number 0 - 100
          set color yellow                                                            ;; set the colour to
yellow
          set size .25                                                                ;; set resident size to .25
          set mobility res-mobility
          set moved 0
          set addressx pxcor set addressy pycor
          set employed? true
          set income random avg-personal-income                                       ;; randomized average
personal income
         ]
        if num_employees <= 0 [set num_employees 0]
        set num_employees (num_employees + 1)
        set occupied? true
      ]
      if (pcolor = white and (num_employees < max_employees or num_residents <
max_residents))[REVITALIZE]
     ]

    ]
    ]
    setxy a b
    ]


end



to REPRODUCE-CRIMINALS

  hatch 1
  [
    set shape "criminal"                                                        ;; set shape to be a person
    set status C                                                                ;; set the status as resident
    set health random 100                                                       ;; set the health as a
random number 0 - 100
    set color red                                                               ;; set the colour to yellow
    set size .25                                                                ;; set resident size to .25
    set mobility crime-mobility
    set moved 0
    set employed? false set income 8000
    set addressx xcor set addressy ycor                                         ;; randomized
average personal income
   ]


end
```

```
to REVITALIZE

ask patch-here
[
  set occupied? true
  ask neighbors [set property_value property_value * 1.053]
  set pchance random 100
  if abs(pycor)> 0 and abs(pycor)< 3 [set pchance (pchance +  (100 - road-permeability) * 35)]
;; increased chance of business in zone "A"
  if abs(pycor)>= 3 and abs(pycor)<= 6 [set pchance (pchance - (100 - road-permeability) * 35)]
;; increased chance of business in zone "B"
  if abs(pycor)>= 6 [set pchance  random-normal 40 20]  ;; doesn't make sense to adjust a random number that is
between the two extremes                          ;; increased chance of business in zone "C"
  if pchance < percent-multi-family-dwelling
  [
    set pcolor 53
    set max_residents 30
    set num_employees 0
    set num_residents 1
    sprout num_residents
    [
      set shape "person"                                                          ;; set shape to be a
person
      set status R                                                                ;; set the status as resident
      set health random 100                                                          ;; set the health as a
random number 0 - 100
      set color yellow                                                              ;; set the colour to yellow
      set size .25                                                                  ;; set resident size to .25
      set mobility res-mobility
      set moved 0
      set addressx pxcor set addressy pycor
      set employed? true
      set income random avg-personal-income                                         ;; randomized average
personal income
     ]
    if dist_from_road < 3 [set property_value (1.05621 * random-normal avg-property-value 20)]
;; zone "A"
    if dist_from_road >= 3 and dist_from_road < 6 [set property_value (1.1879 * random-normal avg-property-value
20)]            ;; zone "B"
    if dist_from_road >= 6 [set property_value random-normal avg-property-value 20]
   ]
  if (pchance >= percent-multi-family-dwelling  and pchance <= ( percent-residential + percent-multi-family-
dwelling))
  [
    set pcolor lime
    set max_residents 8
    set num_employees 0
    set num_residents 1
    sprout num_residents
    [
      set shape "person"                                                          ;; set shape to be a
person
      set status R                                                                ;; set the status as resident
```

```
        set health random 100                                          ;; set the health as a
random number 0 - 100
        set color yellow                                               ;; set the colour to yellow
        set size .25                                                   ;; set resident size to .25
        set mobility res-mobility
        set moved 0
        set addressx pxcor set addressy pycor
        set employed? true
        set income random avg-personal-income                          ;; randomized average
personal income
       ]
     if dist_from_road < 3 [set property_value (.97423 * random-normal avg-property-value 20)]
;; zone "A"
     if dist_from_road >= 3 and dist_from_road < 6 [set property_value (.98037 * random-normal avg-property-value
20)]              ;; zone "B"
     if dist_from_road >= 6 [set property_value random-normal avg-property-value 20]
;; zone "C"
    ]
   if (pchance > percent-multi-family-dwelling + percent-residential)
   [
     set pcolor brown
     set max_employees 10
     set num_residents 0
     set num_employees max_employees                                   ;; reopened
business at max employees
     if dist_from_road < 3 [set property_value (1.17 * random-normal avg-property-value 20)]
;; zone "A"
     if dist_from_road >= 3 and dist_from_road < 6 [ set property_value (1.06 * random-normal avg-property-value
20)]              ;; zone "B"
     if dist_from_road >= 6 [set property_value random-normal avg-property-value 20]
     sprout max_employees
     [
        set shape "person"                                             ;; set shape to be a
person
        set status R                                                   ;; set the status as resident
        set health random 100                                          ;; set the health as a
random number 0 - 100
        set color yellow                                               ;; set the colour to yellow
        set size .25                                                   ;; set resident size to .25
        set mobility res-mobility
        set moved 0
        set addressx pxcor set addressy pycor
        set employed? true
        set income random avg-personal-income                          ;; randomized average
personal income
       ]
     ]
   ]

end
```

```
to UPDATE-PROPERTY  ;; patch proceedure add in distance from road

ask patches

  [

;;    if pcolor = lime or pcolor = 53 [set num_residents count turtles with [addressx = pxcor and addressy = pycor]]
;;    if pcolor = brown [set num_employees count turtles with [addressx = pxcor and addressy = pycor]]
    BLIGHT
    DEPRECIATE
    APPRECIATE
   ]

end




to BLIGHT

  if pycor = 0                                                                    ;; creates top barrier road
  [
    set pcolor black                                                               ;; sets colour to black
    set permeability road-permeability                                                   ;; permeability
set by slider
    set pchance 0
    set num_employees 0
    set max_employees 0
    set max_residents 0
    set num_residents 0
    set occupied? false
    set property_value 0
   ]
if ticks mod 60 = 59 and pycor != 0
  [
  if (pcolor = brown and num_employees <= 0 )[set num_employees 0 set occupied? false]
  if (pcolor = 53 and num_residents <= 0)[set num_residents 0 set occupied? false]
  if (pcolor = lime and num_residents <= 0) [set num_residents 0 set occupied? false]
  if ((occupied? = false or pcolor = white )and pycor != 0)
    [
      set pcolor white
      set num_employees 0
      set num_residents 0
      set occupied? false
      set property_value .6 * random-normal avg-property-value 20
      ask neighbors [set property_value property_value * .95]
     ]
  if (pcolor = brown and property_value < .3 * avg-property-value  and ticks mod 200 = 199) ;; closing business
    [
      set pcolor white
      set num_employees 0
      ask turtles-here
        [
        if (addressx = pxcor and addressy = pycor)[ die]
        ]  ;;test
      set num_residents 0
```

```
      set occupied? false
      set property_value .6 * random-normal avg-property-value 20
      set revenue 0
      ask neighbors [ set property_value property_value * .95]
    ]
  ]

end



to DEPRECIATE

  if (ticks mod 365 = 364)   ;; depreciation of single family homes from traffic annually for zone A and B
   [
    if pcolor = lime
    [
      if dist_from_road < 3
      [
        set property_value
        (1 - (.00000040975 * .01 * (100 - road-permeability)) * property_value)
       ]                                          ;; zone "A"
      if dist_from_road >= 3 and dist_from_road < 6
      [
        set property_value
        (1 - (.00000021351975 * .01 * (100 - road-permeability)) * property_value)
       ]                             ;; zone "B"
    ]
  ]

end



to APPRECIATE

    if (ticks mod 365 = 364 and occupied?)   ;; appreciation of property over time
   [
    if pcolor = lime
    [
      if dist_from_road < 3 [set property_value (1.0281 * property_value)]                                    ;;
zone "A"
      if dist_from_road >= 3 and dist_from_road < 6 [set property_value (1.0289 * property_value)]
;; zone "B"
      if dist_from_road >= 6 [set property_value (1.0432 * property_value)]                                    ;;
zone "C"
     ]
    if pcolor = 53
    [
      if dist_from_road < 3 [set property_value (1.05621 * property_value)]                                    ;;
zone "A"
      if dist_from_road >= 3 and dist_from_road < 6 [set property_value (1.1879 * property_value)]
;; zone "B"
```

```
      if dist_from_road >= 6 [set property_value (1.09 * property_value)]                               ;;
zone "C"
      ]
     if pcolor = brown
     [
      if dist_from_road < 3 [set property_value (1.05 * property_value)]                               ;;
zone "A"
      if dist_from_road >= 3 and dist_from_road < 6 [set property_value (1.03 * property_value)]
;; zone "B"
      if dist_from_road >= 6 [set property_value (1.02 * property_value)]                               ;;
zone "C"
      ]
    ]

end



to UPDATE-PLOT

  set-current-plot "Crime Report"
  set-current-plot-pen "assault"
  plot AS / 3
  set-current-plot-pen "theft"
  plot TH / 15
  set-current-plot-pen "car theft"
  plot C_T / 5
  set-current-plot-pen "burglery"
  plot BR / 15
  set-current-plot-pen "Homicide"
  plot KL
  set-current-plot-pen "robbery"
  plot RB / 2
  set-current-plot-pen "recruit"
  plot RC
  set-plot-y-range  0 5000
  if ticks > 800                                                              ;; don't change the range
until we've plotted all
                                                                              ;; the way across once
   [
     set-plot-x-range (ticks - 800) ticks                                     ;; scroll the range
of the plot only the last 200 ticks are visible
   ]


  set-current-plot "Top Neighborhood"
  set-current-plot-pen "residents / 10"
  plot count turtles with [ycor > 0 and color = yellow] / 10
  set-current-plot-pen "criminals"
  plot count turtles with [ycor > 0 and color = red]
  set-current-plot-pen "abandoned"
  plot count patches with [pycor > 0 and pcolor = white]
  set-current-plot-pen "median property value"
  plot median [ property_value ] of patches with [pycor > 0]
  set-plot-y-range  0 500
```

```
  if ticks > 800                                          ;; don't change the range
until we've plotted all
                                                          ;; the way across once
   [
     set-plot-x-range (ticks - 800) ticks                 ;; scroll the range
of the plot only the last 200 ticks are visible
   ]

  set-current-plot "Bottom Neighborhood"
  set-current-plot-pen "residents / 10"
  plot count turtles with [ycor < 0 and color = yellow] / 10
  set-current-plot-pen "criminals"
  plot count turtles with [ycor < 0 and color = red]
  set-current-plot-pen "abandoned"
  plot count patches with [pycor < 0 and pcolor = white]
  set-current-plot-pen "median property value"
  plot median [ property_value ] of patches with [pycor < 0]
  set-plot-y-range  0 500
  if ticks > 800                                          ;; don't change the range
until we've plotted all
                                                          ;; the way across once
   [
     set-plot-x-range (ticks - 800) ticks                 ;; scroll the range
of the plot only the last 200 ticks are visible
   ]

End
NetLogo Program
```

APPENDIX B

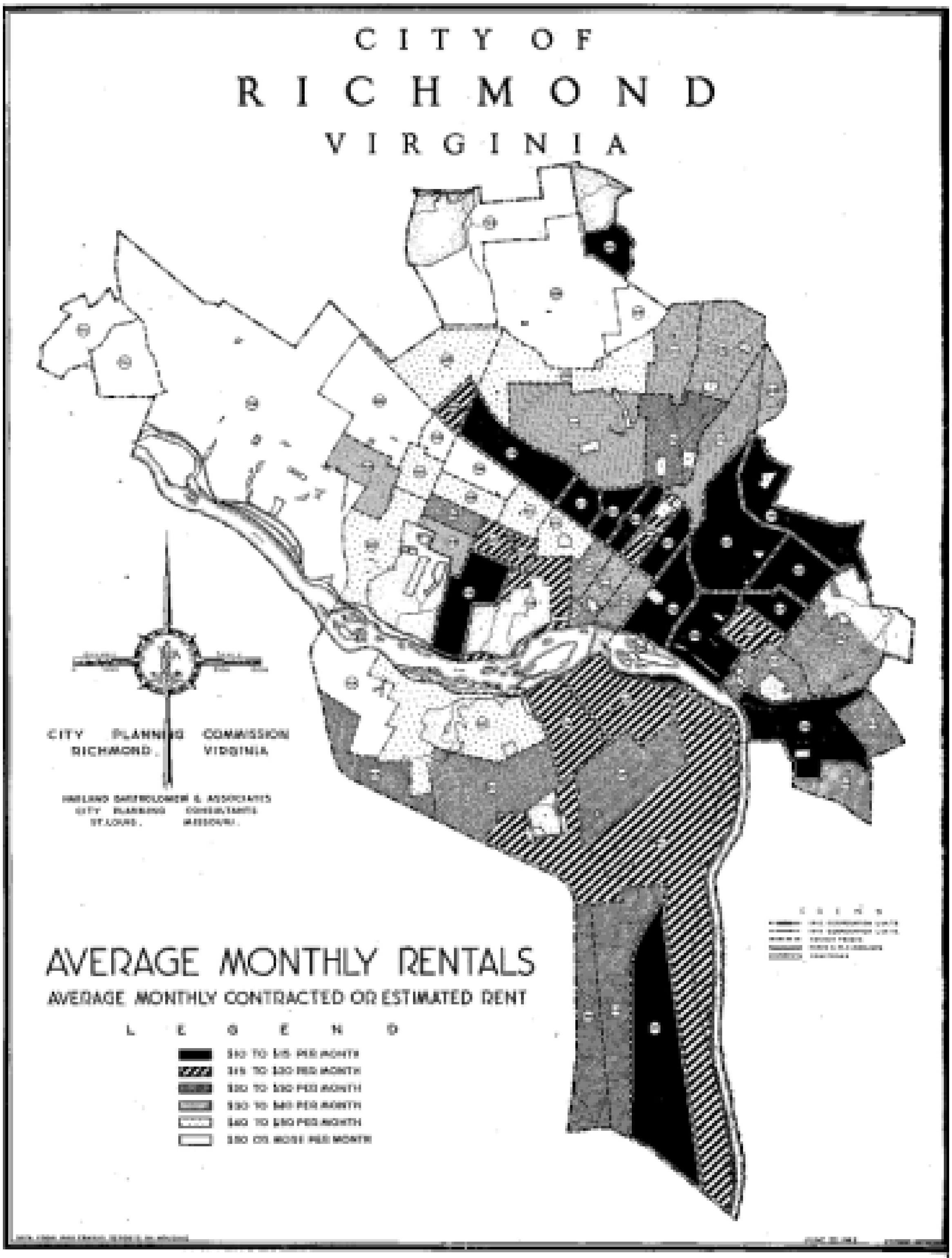

PLATE NUMBER 28