Simulating Dispersed Employers, Highways, and Traffic's Effect on Urban Form

Erick Jones

Introduction / Problem description

Cities are shaped by a variety of factors, but with the Interstate Highway Act; the presence of highways might affect a city's shape more than any other factor. This has led to the idea of urban sprawl. The original monocentric city model takes into account income, travel cost, utility, and a few other parameters to estimate the urban form of a city assuming that everyone commutes to the city center.

The monocentric model has also been modified to consider amenities and varying incomes, but do not typically consider different travel times based on proximity to higher speed limit roads (i.e. highways); models generally calculate travel cost as a function of distance from the city center. So, if the travel time for a commuter further away from work is shorter than for a commuter who is technically closer due to location of a highway the typical model would not capture that.

Furthermore, the monocentric city model assumes everyone commutes to the center of the city and while some modifications have multiple city centers, very few take into account that commuters can work anywhere in the city. Therefore, the calculus for a resident choosing to live in a certain area could change.

Lastly, traffic's effects on a city's form are not captured at all by the monocentric model as there isn't a time-based component. Therefore, a resident might choose an area expecting a certain travel time but would find their actual travel time to be substantially higher, lowering the value of their location choice. While it can be debated if residents consider travel times during rush hour when deciding where to live, almost no urban form models consider traffic dynamically.

This paper attempts to address the gap in literature for the effect of roads with varying speed limits on the urban form, the effect of commuters working in numerous different areas of the city, and the effect of traffic (if residents used it as a factor for housing decisions).

Methods

The modeled city is loosely based on Austin. So first, I broke the city into 11 sections as seen in **Figure 1** below. Downtown is broken into two sections and directly south of the city is broken up into two sections as well. This was Then I determined which roads and highways to model and settled on 6; Mopac, I-35, US-183, US-290, Lamar Blvd., and 8th street.

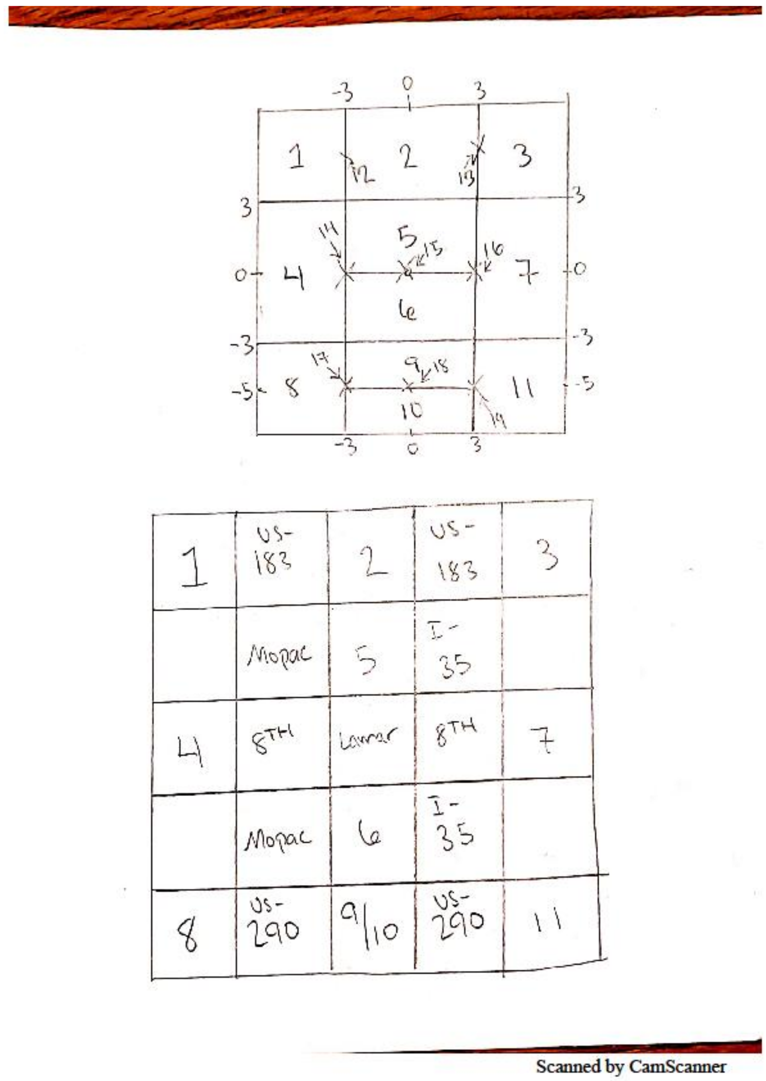


Figure 1 - City Layout and Histogram Legend

Next, I created Poisson arrival rates for each of the sectors and created a custom distribution for destinations. The arrival rates are based on a rough estimation of where the population lives, so both downtown areas have the highest arrival rates, south Lamar, and north Lamar the next highest, and the rest of the areas have lower arrivals. Destinations where weighted towards the city center, its own sector, and its closest neighbors, while sectors that are further away are much less. I generated uniforms and used the cumulative sums of the custom distribution to determine each commuter's location.

Next, I created logic paths for each commuter to get from its arrival to its destination. Instead of modeling all possible paths, I created logic at 19 points based on the final destination. The current point a commuter is on determines the next point to travel to based on the final destination; this is a deterministic process. At the same time the travel time was also calculated based on which road was taken and the distance to the next point. The highways Mopac, I-35, US-290, and US-183 have a speed of 65 mph, while the roads Lamar and 8^{th} only have a speed of 45 mph. Logic points 1-11 correspond to the middle of the respective sectors 1-11. Points 12-19 correspond to points on roads, highways, and highway intersections.

The timescale was important in this simulation and each period was 5 minutes and each simulation was for 36 time periods or 3 hours. For every period arrivals from all 11 sectors where determined, their destinations where determined, their path was calculated, and all commuters, who arrived in previous periods and had not yet reached their destinations, current location was calculated. However, since the path was deterministic all the information about the current time period and any time period before it could be stored as a table; future time periods could simply add to the same table.

The first set of 30 simulations, which do not calculate traffic, took about 130,000 seconds (36 hours) to run. The code wasn't too efficient overall and could have been parallelized but there was a daunting amount of calculations to produce even for such a simple problem on such a short time scale.

From there I used statistical data processing techniques in R to calculate the mean, standard deviation of the number of commuters in a given location and travel time for various city sectors.

For the traffic modifications, I created an exponential function that is 1 at low values of commuters and 3 at high values of commuters, see **Equation** below. However, I wanted the traffic to be stochastic, so I used the calculated base (1.004) of the exponential function as the mean and determined a standard deviation (0.001) that kept when plugged into a normal distribution kept the traffic multiplier reasonable in most cases. The number of commuters on each road or highway was determined by sampling from a normal distribution with the mean and standard deviation calculated from the 30 simulations earlier. Each sector weighted their individual traffic multiplier based on the average percentage of time they took each road. That entire process was one traffic interaction simulation. I repeated these steps 30 times and calculated the mean and standard deviation.

$$Traffic\ Multiplier_{Road\ or\ Highway} = 1.004^{Commuters\ on\ Specific\ Road\ or\ Highway}$$

The urban form was determined using a modification of the monocentric city model [1],[2]. Instead of assuming a travel cost as a function of distance from the city center. I determined the travel cost as a function of the calculated travel time for a given section. I also included an amenity in the city center to make sure the city was weighted at the center. I modeled the original monocentric city model with an travel costs of \$1,000 multiplied by distance (miles) from the city center, an income of \$37,823 (Austin's median per capital income), \$8,000 agriculture rent (the price per acre of agricultural land in the Hill Country), and a utility of 3,750 (iterated to give a population of about 100,000).

I also modeled a special version of this model that assumes that everyone works in the center and follows the best deterministic route to get there. And of course the model that calculates destinations based on a custom distribution, but doesn't include traffic effects and a model with all of those customizations, but does take into account traffic effects. All models data was then processed and the land area and population where calculated.

Results

I calculated the mean and standard deviation for highways at all time periods for all 30 simulations, **see Tables Below.** Also are graphs depicting the flow of time for the "average" system **(Figure 2)**. The first few time periods the traffic is light, but it quickly picks up and reaches an equilibrium for the rest of the time periods. It is almost impossible to distinguish the later periods from each other as shown in **Figure 2.** Furthermore, even though both arrivals and destinations are stochastic there isn't a large standard deviation for almost any time period or scenario. Traffic is pretty constant day in and day out.

Mopac and I-35 are the busiest highways or roads with I-35 slightly edging out Mopac in terms of traffic. The next busiest roads are US-183 and US-290 with 290 having a significantly higher share of commuters than US-183. Lastly, the streets 8th and Lamar Blvd have the least number of commuters, but oddly enough, 8th street has almost 3 times as many commuters as Lamar. The southern areas are more populated in this model so it makes sense that US-290 is busier than US-183, but Lamar goes through the center of 4 sectors while 8th street only goes through 3. However, the 6 of the edge sectors that want to go downtown will typically take 8th street.

Table 1- Mean of Commuters on a Given Road or Highway by time period

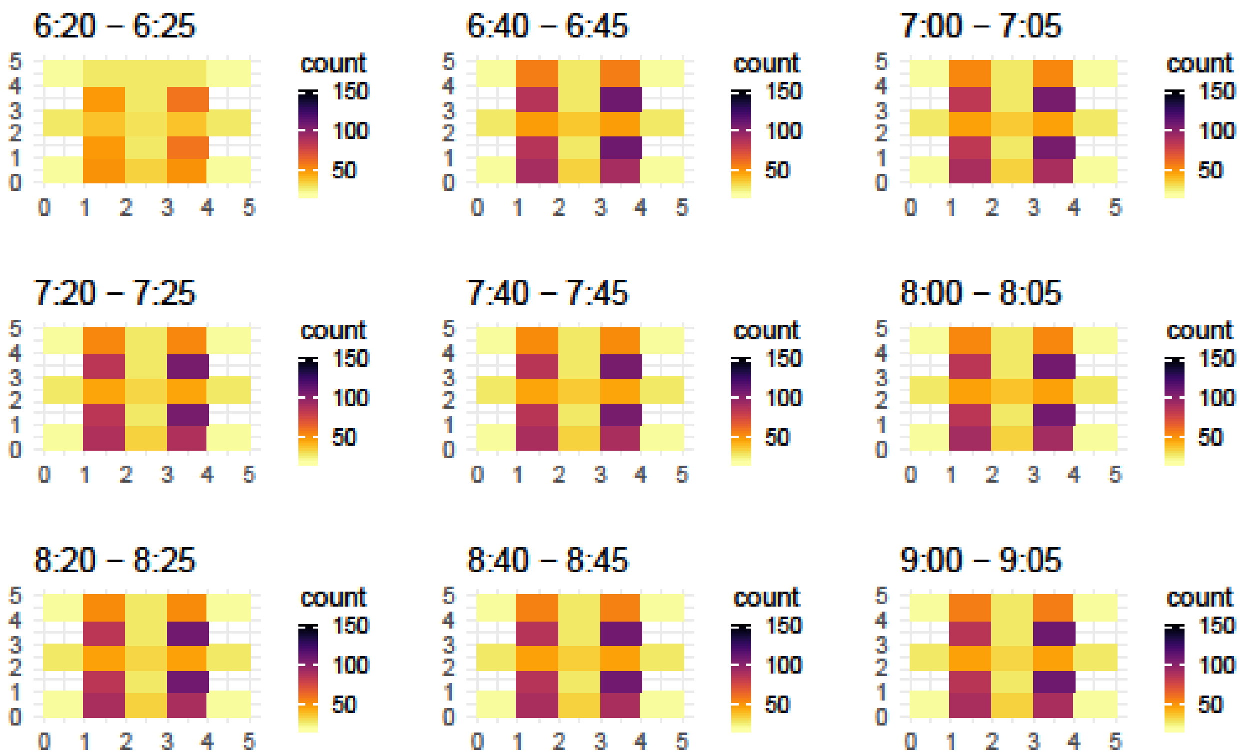
	Time	Mopac	I–35	US–183	Lamar Blvd	8th Street	US–290
1	5	50	61.4	28.6	16	45.9	54.7
2	10	97.5	119	57	30.1	75.7	102.4
3	15	140	168.5	77.9	34.8	96.6	145
4	20	162.2	194.8	96.6	35.5	94	166.4
5	25	171.8	212.8	107.6	35.5	94.8	183.3
6	30	174.2	221	113.9	37.1	95.9	184.9
7	35	174.1	216.8	112.9	37.3	96.5	184.1
8	40	174.6	217.6	112.5	34.8	98.5	182.9
9	45	169.1	217.5	111.2	35.6	96	182.3
10	50	168.6	213.9	107.3	35.5	93.8	181.6
11	55	166.6	218.7	106.3	35.6	95.6	181.1
12	60	168.9	218.5	107.6	33.8	95.6	179
13	65	174	218.9	109.4	34	94.6	179.2
14	70	170.3	214.7	108.2	32.7	92	178.7
15	75	174.6	218.7	109.8	33.7	93.9	182.8
16	80	174	210.5	108.9	34.3	91.5	178.6
17	85	173.3	211.8	104.6	36.5	91.7	183.2
18	90	172.8	214.7	105.3	35.5	92	182
19	95	172.2	216.7	104.7	36.2	93	180.1
20	100	172.7	216.8	105.1	36.7	90.5	181.1
21	105	171.5	219.6	106.5	37.4	94.6	185.5
22	110	169.7	216	107.6	38	94.7	185.3
23	115	168.9	221.9	108.7	36.6	96.7	184
24	120	169.4	220.8	109.6	35.1	95.8	181.2
25	125	171.1	218.9	108.9	34.8	94.5	183.2
26	130	170	218.2	106.6	33.4	94.1	181.7
27	135	172.2	219.5	107.5	33.2	94.7	185.4
28	140	169.5	217.2	108.3	33.3	95.7	181.4
29	145	173.4	219.4	110.5	34.1	96	181.3
30	150	173.6	217.9	111.3	34.6	94.7	182.4
31	155	172.6	218.1	112.7	34.4	94.5	183
32	160	173.3	220	114.1	34.4	94.5	181.3
33	165	171.3	220.7	112.5	35.3	93.6	181.3
34	170	171.7	220.6	113.6	32.9	93.3	181.9
35	175	173.6	220.8	114	33.4	92.9	181.1
36	180	169.2	217.8	109.4	33.4	92.3	180

Table 2 - Standard Deviation of Commuters on a Given Road or Highway

	Time	Mopac	I–35	US–183	Lamar Blvd	8th Street	US–290
1	5	7.5	9	6.9	5	1.2	10
2	10	10.7	15.2	10	7	1.6	8.6
3	15	14.5	19.8	10.2	8.4	1.8	11.4
4	20	15.6	21.3	13.9	5.5	1.8	10.5
5	25	16	17.1	13.9	6	1.7	11.7
6	30	16.5	19.3	16.1	5.7	1.7	11.1
7	35	17.2	20.1	16.2	6.7	1.8	11.3
8	40	16.8	22	16.1	6.6	1.9	10.6
9	45	17	17.8	15.4	6.3	2.1	12.4
10	50	14.6	19.4	10.3	6.1	2.1	13.5
11	55	15.4	19.9	11.2	5.2	2	12.2
12	60	16.6	17.9	11.8	7.2	1.9	9
13	65	17.7	21	15.6	7.7	1.7	8.6
14	70	19.7	19.5	13.1	8.1	1.7	7.4
15	75	17.5	20	12.1	6.2	1.7	11.8
16	80	16.1	18.1	11.9	5.6	1.7	9.8
17	85	15.4	17.7	11.9	5.6	1.6	9.4
18	90	17.5	17.9	13.8	6.1	1.7	10
19	95	15.3	18.8	14.9	6.7	1.7	10.5
20	100	16.1	14.6	13.1	5.6	1.7	10.3
21	105	17.1	17	11.7	6.9	1.6	10.2
22	110	16.4	17.5	11.2	8.3	1.6	10.2
23	115	15.6	21.3	14.1	6.7	1.7	11.2
24	120	15.3	18.1	16	5.6	1.9	10.7
25	125	14.9	18.3	13.5	6.2	2	12.3
26	130	18.2	17.8	14.4	7.2	2	11.4
27	135	16.3	18.5	14.7	6.9	1.8	11.3
28	140	15.2	19.9	15.1	5.1	1.7	11.3
29	145	18.5	20.3	13.5	5.1	1.7	8.6
30	150	17.7	18.4	14.8	7	1.9	8.2
31	155	14.7	17.9	15.8	7.3	1.9	9.2
32	160	14.6	16.7	14.5	5.7	1.9	10.3
33	165	14.4	20	14.6	6.7	1.9	11.8
34	170	16.8	20.1	12.6	5.9	1.7	10.5
35	175	16.9	21.1	12.4	6.8	1.8	10.7
36	180	15.4	21	15.8	5.1	1.8	10.1

As mentioned above the traffic densities in **Figure 2** below, but the first period does show the progression of how the traffic evolves. The legend to the histograms below is the drawing on the bottom of **Figure 1.** These histograms show how Mopac and I-35 are the main carriers of commuters with the remaining highways carrying the bulk of the remaining commuters.

Figure 2 - Traffic Density at a Given Time



Using the largest means and standard deviations I formed a conservative confidence interval for each road and highway, see **Table 3**. As mentioned before the means are pretty constant so the standard deviations are relatively low. Note this is including the first few periods with almost zero traffic (i.e. no truncation) which makes the results even more surprising. Since the standard deviations are so low the 99% confidence interval bounds are relatively tight and once again it seems the traffic is the traffic.

Table 3 - Mean, Standard Deviation, and 99% Confidence Intervals for Traffic by Road or Highway

	Mopac	I–35	US–183	Lamar Blvd	8th Street	US–290
Max Mean	174.6	221.9	114.1	38	98.5	185.5
Max Standard Deviation	19.7	22	16.2	8.4	2.1	13.5
99% Interval Lower Bound	164.7	210.8	105.9	33.8	97.4	178.7
99% Interval Upper Bound	184.5	233	122.3	42.2	99.6	192.3

Using the largest means, I calculated travel costs for each sector by multiplying the travel time by 2 trips a day, 300 days a year, at a cost of 15 cents per min, multiplied by distance traveled. Note those are also the multipliers for the estimated monocentric model. Below is **Table 4** showing the old and new travel costs associated with each sector. The estimated monocentric model generally has higher travel costs than the monocentric model, except for at the city center and a few other sectors. The calculated multicentric model; however, has much cheaper travel costs, due to more people working closer to their sector. However, once you take into account traffic, the story changes. While some sectors particularly those near downtown still have cheaper costs, the sectors on the edges have higher and sometimes much higher travel costs.

Table 4 - Travel Costs for Various Models

	Sector 1	Sector 2	Sector 3	Sector 4	Sector 5	Sector 6	Sector 7	Sector 8	Sector 9	Sector 10	Sector 11
Monocentric	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000	1000
Estimated Monocentric	1440	1005.3	1440	1050.3	405	405	1050.3	1500.3	884.7	1005.3	1500.3
Calculated Multicentric	872.3	520.2	904.6	619.5	297.2	272.9	609	837.6	481.6	625	810.5
Traffic Multicentric	1675.7	998.3	1789.3	1158.5	507.9	508.7	1269.2	1702	976.7	1166.9	1754.7

The main insights from this paper are as it relates to urban form. How does accounting for a city using the distance that are actually traveled on a road or highway affect the monocentric model? How do multiple job locations affect the monocentric model?

Our results show in **Figure 3,** show that when you have to account for Manhattan distances to get to the city center, the city shrinks and it expands on highway or road corridors and contracts from the periphery. On the other hand, when everyone doesn't have to commute to the center and can find jobs closer to where they live, the city explodes. The growth still takes place mostly on the road and highway corridors, but it isn't nearly as restrictive, and the periphery areas see slightly more expansion. For the traffic case, those general patterns are still there, growth along the road and highway corridors, but the city as a whole shrinks because of the high costs of travel from the edge areas.

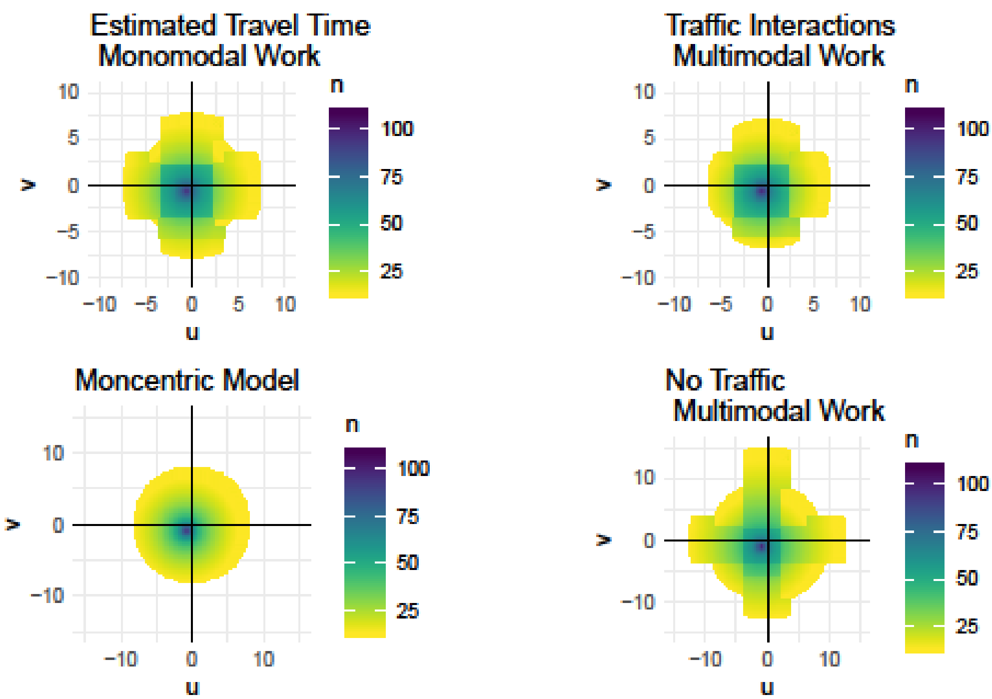


Figure 3- Urban Form of Various Models

The land area of most of the models are pretty similar with the exception of the multimodal city with no traffic. That city not only has a huge amount of area (land area is in square miles) and a huge population but is also denser than the monocentric model. However, the monomodal model and the traffic multimodal model encourage more density for different reasons. For the monomodal model, the closer you are to downtown or a major highway the cheaper your costs. However, for the traffic model the closer you are to where you work, which is still most likely to be downtown and a road or highway with the least amount of traffic the cheaper your costs.

Table 5 - Land Area, Population, and Population Density Across Models

	Land_Area	Population	Population_Density
Monocentric	166.28	105277	633
Estimated Monomodal Work	131.32	100145	763
No Traffic Multimodal	320.52	221410	691
Traffic Multimodal	107.76	84636	785

Discussion

This paper expanded on the monocentric model and examined how a variety of job locations, traffic, and Manhattan distances affect the costs of residents and ultimately urban form. This is becoming more important as cities start to take the lead on climate change and become bigger engines of the economy.

Manhattan distances change the perfect symmetry of the original monocentric model and do have a noticeable effect on population density, but the population and the city size remain roughly the same. Therefore, I can say that the travel cost assumptions of the original model are more or less justified.

However, accounting for the fact that not all work is downtown and people will tend to work near where they live adds a whole new dimension. It dramatically expands the city and its population, but still creates a denser city than the original model, due to the effect of traveling Manhattan distances and wanting to live next to a fast road or highway. Even though the city is much larger, it would be interesting to compare the per capita travel distance and emissions to the monocentric city, because although the city has sprawled so would the jobs.

The traffic multimodal model gives interesting and seemingly conflicting results. Because work locations are spread throughout the city, it would seem as there wouldn't be as much traffic. Also, since people are more likely to live close to their work regardless of where they live, traffic shouldn't have that much of influence on their decisions.

Nonetheless, for my parameterization which might have given slightly aggressive values for the time multipliers of traffic, it shows that traffic still matters with respect to travel cost. And this seems to correlate with reality, even as a city sprawls traffic gets worse everywhere especially in the central city, where even as jobs disperse a large number of people still work. So, housing downtown and along major roads or highways is still at premium. However, the benefits of larger housing further away from the city are muted because of the high travel costs.

Self-driving cars could alter this calculus as the time cost of being in the car wouldn't be as high and they would also reduce the traffic multiplier as they more efficiently drive down the roads. Furthermore, telecommuting or staggered starting hours could shift some of the load off of the roads.

However, even though traffic can dramatically affect travel costs, most cities have evolved closer to my no traffic multimodal model. This might be an effect of resident cost underestimation than anything else. I would wager when deciding on a house in a far off neighborhood, the extra time cost incurred by due to traffic is never taken into account especially for residents new to a city unaccustomed to the traffic flow. Or even more simply the city grew since a resident purchased a home. Also, their utility function could value housing more than other things.

Nonetheless, this paper shows that traffic is an important effect to consider when either choosing where to live in a city or when designing it. The city will expand along major road and highway corridors and become denser as a whole. But once those corridors become clogged with traffic the city struggles to grow and might even contract dramatically.

Limitation and Possible Future Work

Although, the model used different arrival rates in an area to approximate different population densities in different areas, there was no continued updating of these population densities based on the new urban form. The simulations should have been rerun with the newly calculated population densities until the difference was with some error bound. This would have taken possibly days to run but would be more accurate. How much more accurate is unknown.

Furthermore, while various areas had different population densities the work locations were determined mostly by proximity to other areas. The city center was weighted more than other areas, but the proximity method might give excessive weight to corner areas. Normalizing the job location distribution based on real life data or simply lowering the weights on the corner areas might give accurate results and wouldn't require too much more computational effort.

In reality, not only are the destinations varied spatially, but temporally as well, meaning people go to different places at different times in different concentrations. The arrivals and destinations for 6-9 am on a Tuesday would be significantly different than the arrivals and destinations for 12-3pm on a Saturday. While I have argued that rush hour traffic would give the worst case and probably most relevant results for deciding road sizes and residents' decisions, if an extremely attractive amenity was located somewhere that created odd traffic at different times, it could affect the urban form.

Originally, I had planned to give each commuter a small suite of options to get to each destination and then to choose his optimal route based on traffic conditions which could be modeled as an MDP. However, this complexity was excluded for brevity since it could have added significantly more time to the project both computationally and in preprocessing. Nonetheless, depending on the logic method deployed it could possibly be done with relatively small additional computation time and add more interesting stochasticity to the model. As it stands now the only stochasticity in the models are the arrivals, destinations, and traffic effects, the route is determined by a deterministic algorithm (which I argue still gives interesting and semi-accurate results).

Sources

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[2] J. K. Brueckner, "Chapter 20 The structure of urban equilibria: A unified treatment of the muth-mills model," *Handb. Reg. Urban Econ.*, vol. 2, pp. 821–845, 1987.

Appendix

The code used to run these analyses is included in the submission docs.

The actual simulation file that calculated all the tables is called Traffic_Sim it is available as an .R file and a .RMD file. The output from the 30 hour simulation was saved as First_Sim.Rdata

Most of the data analysis was done in the file Traffic_Sim_Data.Rmd with the First_Sim.Rdata file as an input.

The results from the data analysis were then inputted into Modeling_City_Sim.Rmd where the urban form could be evaluated. That file needs the data from Traffic_Sim_Data.Rmd file to run.

So I ran Traffic_Sim.R to produce First_Sim.Rdata whose data I used to run Traffic_Sim_Data.Rmd whose outputs power the Modeling_City_Sim.Rmd.

All these files are in the submission.