Modeling the Relationship between Population and Land Development under Changing Land Use Policies

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Abstract

This paper discusses a model developed to assess the effects of land-use changes on traffic congestion and air quality. The inputs are characteristics of development and the outputs are time in traffic per capita, and tons of carbon monoxide from vehicles. As previously developed urban dynamics models have done, the model includes a relationship between the output variables and the attractiveness of the area as a place to live. Particular attention is paid in this paper to challenges associated with modeling the relationship between population and land development in urban areas where alternative land-uses are being contemplated. The evolution of an approach to overcoming the challenges is presented.

Introduction

Las Vegas Nevada has been one of the fastest growing metropolitan areas in the United States for over a decade, and the problems that accompany rapid growth are increasingly being felt by residents. While there are many aspects to urban quality of life, two have come to the forefront of the political agenda in Las Vegas as a result of the growth (UNLV CBER 2005, p.52).

The first is traffic congestion (UNLV CBER 2005, p.24).. Not surprisingly for an area where the population doubled in the past 10 years, the rate of increasing transportation infrastructure is lagging behind the increasing rate of demand. Just as Sterman (2000, p. 178) noted about other cities, the attractiveness of Las Vegas as a place to live is decreasing as the gap between the "acceptable" and the "actual" time spent in traffic increases. The costs are both social and economic: decreased individual discretionary time in the case of the former and lower productivity in the case of the latter.

Air quality is another issue of concern related to growth in Las Vegas (UNLV CBER 2005, p.25). As the population increases, more pollutants are emitted into the air from vehicles, construction, and other sources. In Las Vegas, the pollutants of concern are carbon monoxide, dust, and ozone. In a causal loop similar to the one described above, as the gap between the carrying capacity of the air shed to 'process' pollution and the quantity of emissions decreases, the attractiveness of the city as a place to live decreases. In addition to the social costs of increased rates of respiratory illness, the economic casts can be significant at the points where the federal air quality standards are exceeded, and federal highway funding is forfeited as a result.

Stave (2002) discusses a model developed to examine ways to reduce transportation-related air quality degradation in Las Vegas. As congestion increases, average speed of traffic decreases. As average trip time increases, so do emissions. Further, the lower the speed, the less efficiently internal combustion engines burn fuel. Thus, more carbon monoxide is emitted at lower speeds than at higher speeds. Therefore as congestion increases, so does the quantity of pollutants in the air.

While there are many potential policy options for obtaining a more favorable outcome, the policy-makers are looking for solutions that will not cause a reversal of the growth trend and/or will not impose draconian regulations or financial burdens on their constituents. Altering development requirements to achieve a better balance of land-uses and to better incorporate alternative modes of transportation for both new development and redevelopment has relatively little economic or social cost to residents. Perhaps for these reasons, the potential for mitigating the adverse impacts of growth on traffic congestion and air quality via altering land-use has become an attractive approach to policy-makers. But as prior research asserts, it is beneficial to have the ability to simulate the outcomes of various policy alternatives (Forrester 1971 and Sterman 2000). Thus, what was needed in Las Vegas was a model to test how different combinations of a set of land use characteristics might affect traffic congestion, air quality and the growth rate.

The model presented here was developed for this purpose by a group of land-use planners, zoning specialists, and economic development specialists, facilitated by systems dynamics modelers from the University of Nevada Las Vegas using a group model building approach. The model has come to be known as the Land Use, Transportation and Air Quality (LUTAQ) model. The group model building experience is described in a companion paper (Stave and Dwyer) in these proceedings.

The LUTAQ Model

The LUTAQ model tests how the following set of land use characteristics --

- Average distance per trip
- Average number of trips per person per day
- Quantity and quality of mass transit infrastructure
- Quantity and quality of alternative modes of transportation (bike and pedestrian routes)

-- affect the following specific aspects of the quality of life:

- Time in traffic per person per day
- Air quality (represented by the quantity of carbon monoxide emitted by vehicles)
- Economic and other costs per household

and the rate of growth as measured by population.

Basic Causal Relationships

At its most basic level, the model builds on the logic of the urban dynamics models that have come before it (e.g., Forrester 1971, Schroeder. et. al 1975). Focusing on the balancing loop found in previous urban dynamics models, an increasing population produces adverse impacts that affect the relative attractiveness of a particular city as a place to live. In this case, the adverse impacts of interest (output variables) are traffic congestion, air quality, and associated costs. The relationship between population and the output variables is shown in Figure 1.

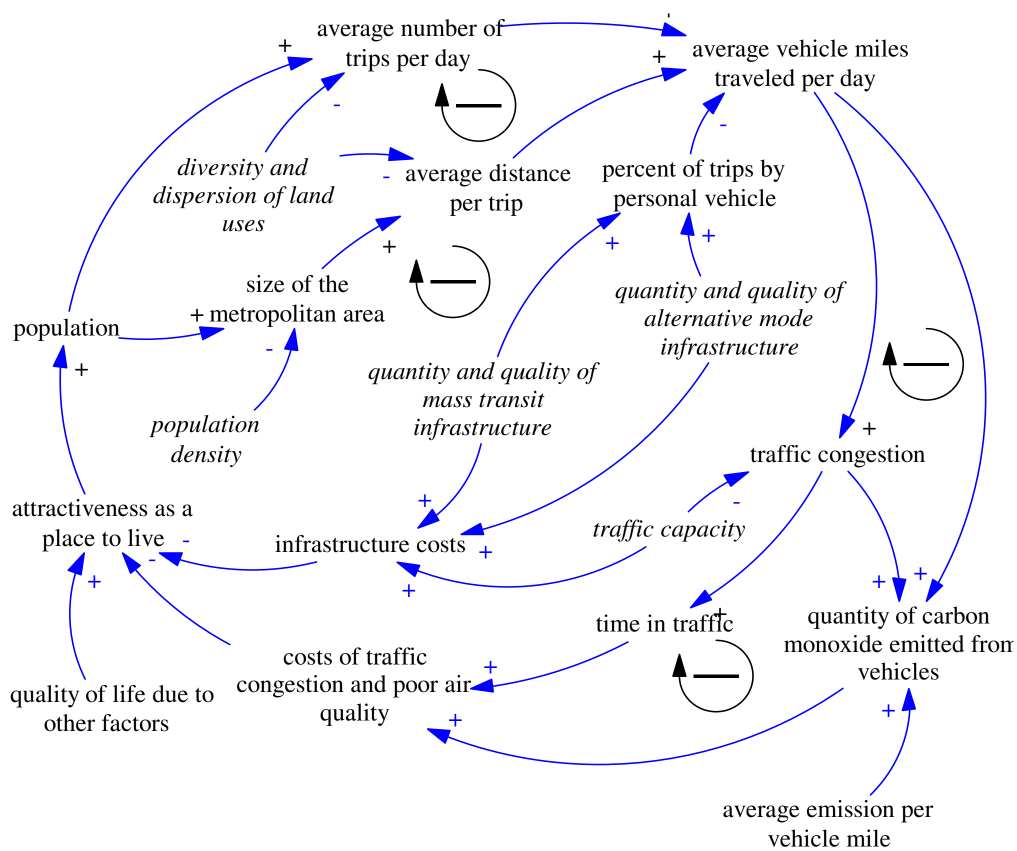

Figure 1. Causal Loop Diagram: Population, area of development, traffic, air quality and attractiveness as a place to live.

As illustrated in the causal loop diagram, population growth degrades the quality of life as it is affected by traffic congestion and air quality when all auxiliary variables are constant. These impacts can however, be mitigated by the variables labeled in italics. These variables are land-use and transportation related policy levers that taken together could be said to describe the character of development. There are two sets of associated costs: one set represents costs of increasing the quantity and/or quality of public infrastructure; the other set are those economic, social, and environmental costs associated with time in traffic and air quality. For example, as time in traffic increases, business productivity and personal leisure time both decrease. As air quality decreases, the social and economic costs of a greater rate of respiratory ailments increase. In addition, where air quality exceeds federal air quality standards, federal highway funding can be forfeited. Policy makers are interested in understanding the costs and benefits of manipulating the land-use and transportation policy levers for the eventual goal of establishing certain development standards in policy that help to mitigate adverse impacts while avoiding unacceptable economic consequences.

Sector Diagram

Figure 2 shows the high-level diagram that organizes input and output variables into sectors. The model contains six sectors and four sub-sectors. The stock and flow representations were then created for each sector.

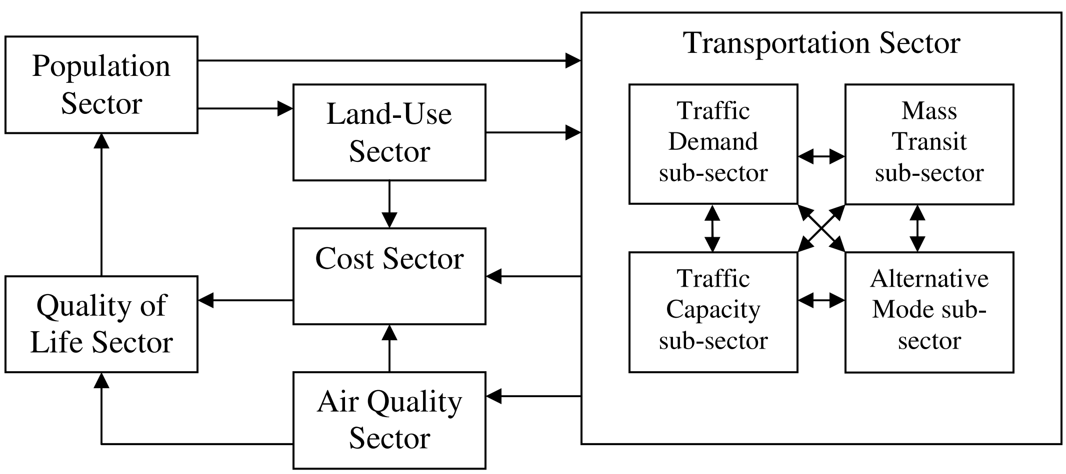

Figure 2: LUTAQ Sector Diagram

Land Use and Population

As the causal loop diagram and the sector diagram show, the quantity and quality of land development in this model affect the amount of traffic demand, amount of traffic capacity, and the percentage of transport satisfied by mass transit and alternative modes of transportation. In short, for the purposes of this model, land-use is the critical intermediate variable between the size of the population and the degree of impact felt in the output variables. The logic here is that varying characteristics of development will produce varying impacts on traffic congestion and air quality. The hypothesis is that manipulating land-use and transportation system characteristics will produce different behavior on the part of the residents. For example, the average trip distance and the average number of trips per day may be higher in areas developed under older ‘auto oriented’ land-use policy than it is in areas with a more efficient mix of land uses (purposely designed to incorporate commercial and retail with residential development). Thus, to assess the relative impacts of two different land-use policies, one needs to understand the difference in individual behavior for each and apply it to the number of people living under it.

In implementing new land-use policy, one must account for both the behavior of the persons living in areas developed under the prior policy (P1), and the behavior of those living within the areas developed and redeveloped under the new policy (P2). Assuming the relevant ‘behavior’ for each policy area is established by the input variables, the necessary quantity is the number of persons living within each policy area. Assuming a new policy (P2) applies to all development that occurs after its implementation, the allocation of the populations as stocks might appear as follows (Figure 3):

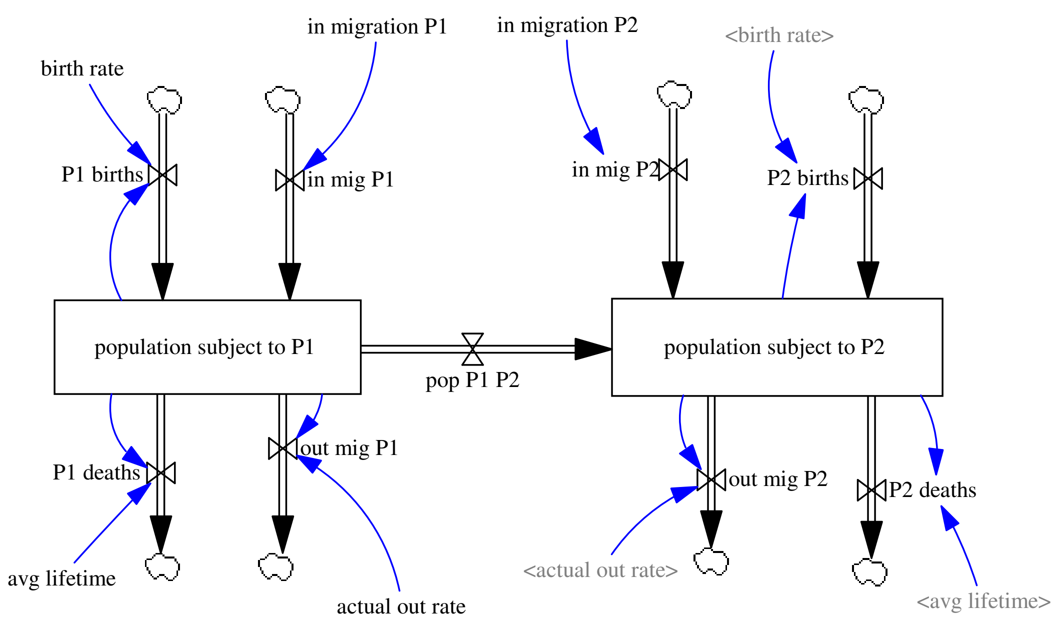

Figure 3: Allocation of Population Under Different Policies

The stock labeled “population subject to P1” represents the number of people living under the prior policy (P1). The initial value of this stock is the population at year0. The stock labeled “population under policy P2” represents the people living under the new policy, and would be equal to zero at year0.

Challenge #1: Allocating in-migration

Figure 3 depicts different in-migration rates for the each of the stocks, but there is a single in-migration for the entire city from which these individual in-migration rates draw. While there are several possibilities for how to allocate the in-migration between the two stocks, for the purpose of this model, it is assumed that the "population subject to P1" will fill to capacity before any in-migration is allocated to "population subject to P2". This is justified by the wide gap between the supply of and demand for housing typical of a rapid growth environment, and for the fact that no additional area is being added under the prior policy (P1) that would allow additional people to move-in (albeit additional capacity could be realized where out migration + deaths > in migration + births). Accepting this assumption, the in-migration rates are connected with a co-flow that then subtracts any in-migration to the P1 stock from the total in-migration to determine the in-migration to the P2 stock (depicted in Figure 4).

Challenge #2: Movement due to redevelopment

The in and out flows from the stocks are the standard flows that one encounters in population model -- births, deaths, in-migration and out-migration – with one exception: a flow from P1 to P2 (pop P1P2). This flow represents the number of people living in an area subject to policy 1 who shift (by redeveloping all or part of the area) to policy 2. A useful way to think of this flow is to consider that these persons are not necessarily moving in a physical sense. If land uses and transportation systems in their neighborhood are retrofit to the new policy, they then become subject to the new policy without a physical move. Thus, the number of people shifting from P1 to P2 each year is a function of the quantity of land subject to P1 being redeveloped so that it becomes subject to P2. This is accomplished by a co-flow that uses the land redevelopment rate and the population density to calculate the rate (depicted in Figure 4).

Challenge #3: Modeling the relationship between land and people

The need to connect the land redevelopment rate calls for the integration of the population model with stocks and flows related to the amount of land subject to each policy. This is also important in the greater LUTAQ model as traffic capacity is a function of the quantity and nature of development under each policy. These stocks and the flow of land redeveloped from P1 to P2 are depicted on Figure 4.

As depicted in figure 4, the population capacity associated with an area-policy combination is a function of the size of the area and the design density. Any "excess" capacity can then be determined by subtracting the population from the population capacity. The "excess population capacity" then drives the quantity of people migrating in after the integration of the births, deaths, and out-migration.

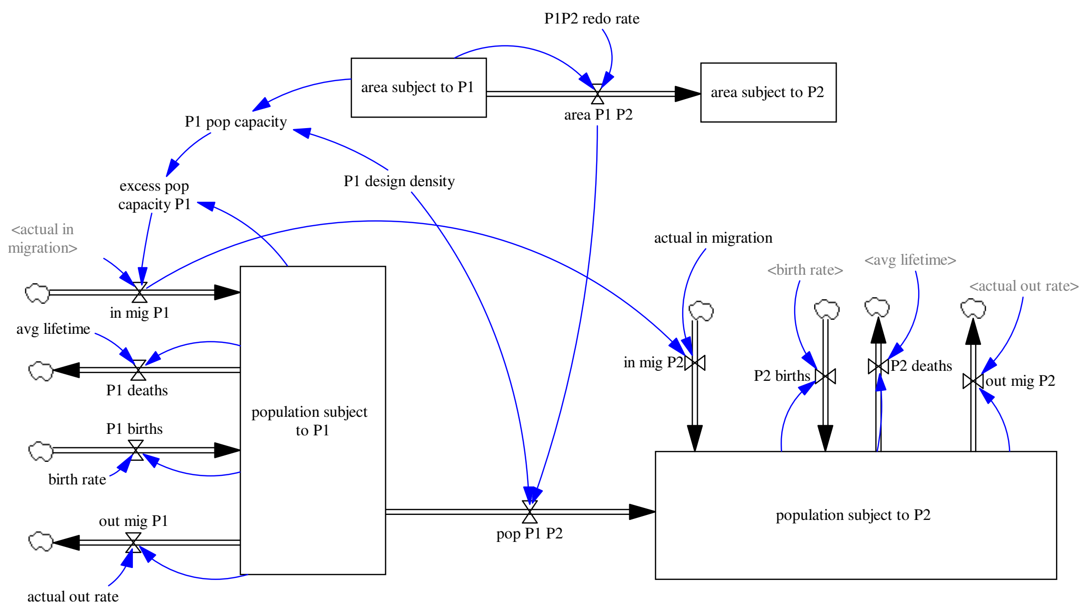

Figure 4: Population and Land Area Under Different Policies (partial)

Challenge #4: Reconciling Significantly Different Urban Form: Downtown versus the Suburbs

Consistent with certain of the earliest criticisms of Forrester's (1969) Urban Dynamics model (Gray, Passel, and Varian 1968) and work to extend the Urban Dynamics Model (Schroeder et. al. 1975) we found it necessary to create two broad categories of development to which different policy scenarios might be applied: the downtown/resort corridor, and everything else, roughly corresponding "city sector" and the surrounding "suburban areas", as they are labeled in certain extensions of the Urban Dynamics model (such as in Schroeder et. al. 1975). This categorization is justified by the disproportionate percentage of employment between the two areas, as well as the difference in nature of their land-use characteristics. The clients wanted the ability to establish new land use policy for each area, allowing them to assess scenarios such as 'going vertical', or increasing the density of housing in the downtown/resort corridor by promoting high-rise residences. This categorization created four combinations of policy and area:

	Policy 1 (existing downtown)	Policy 2 (redeveloped downtown)	Policy 3 (existing suburban)	Policy 4 (new and redeveloped suburban)
Downtown/resort corridor (urban core)	area subject to P1	area subject to P2		
Everything else (surrounding suburban area)			area subject to P3	area subject to P4

Table 1: Possible Scenarios of Area and Policy

The land-use and transportation characteristic of development can then be arrayed for each policy, as depicted in the following example (Table 2):

	Existing downtown (P1)	Redeveloped downtown (P2)	Existing suburb (P3)	New and redeveloped suburb (P4)
Population density (persons/acre)	20	40	8	10
Avgas distance per trip (miles/trip)	2	1	5	4
Average trips per day (trips/person/day)	5	4	6	5
Ratio of travel time bus/personal vehicle	1	.75	2	1
Miles of off-street bike and pedestrian routes per square mile	.25	1	.5	2

Table 2: Example land-use and transportation policy scenarios by development category

As a result, the stock and flow diagram necessarily doubles (Figure 5).

Challenge #5: Allocating in-migration and negative excess capacity

In migration must now be allocated amongst the four population-policy scenarios, and is driven by the same logic of excess capacity. But, when the birth rate exceeds the death rate in a population stock of constant size and density, a negative excess capacity occurs. Since it means that there are more people in the area than can be accommodated by the capacity, the “excess” must physically move somewhere else. For the purpose of the LUTAQ model, an assumption was made regarding the priority of their movement. It was assumed that excess population living downtown would prefer to remain downtown if they could be accommodated by additional capacity created by redevelopment. This potential movement is depicted in Figure 5 as the flow labeled “pop moving P1 P2”. They are then counted as part of the “population subject to P2” in determining the “excess capacity of P2”. Where the “excess capacity of P2” is negative, persons move into the stock of people that must be accommodated by new development. These assumptions and flows are mirrored in the surrounding suburb sector of the model.

Also flowing into “pop in new development” are those in-migrants that cannot be accommodated by the ‘standing inventory’.

Challenge #7: New development

As depicted in figure 5, that part of the population that cannot be accommodated by what might be considered ‘standing capacity’ accumulates in a stock labeled “pop in new development”. But, the relationship between population and area for areas of new development is fundamentally different from that associated with existing and redone areas. In essence the combined quantity of land in stocks P1 and P2 is a fixed quantity, such as was the case with the Urban Dynamics Model (Forrester 1969). This incorporates the assumption that the downtown area (P1) will not grow out into the suburbs (P3). This is justified in the LUTAQ model because the area designated as “downtown” will accommodate the anticipated redevelopment over the time-span of the model. Accepting this assumption, the redevelopment of land subject to P1 reduces the land area subject to P1 and increases the land area subject to P2 by the same amount. The same is true for land subject to P3 redeveloped to P4. The population capacity of the redeveloped land may be different (based on the densities), but the changing land area is equal in size.

This is not the case however with new development occurring at the urban fringe or on vacant infill parcels (new development in the suburban area subject to either P3 or P4). The logic here is that the quantity of new development is a function of the net in-migration (and the number of births exceeding deaths) and the design density. In other words, in the case of new development excess population drives the quantity of new development, as opposed to existing and redeveloped areas where capacity of the area drives the size of the population. Thus the quantity of new development is a function of how many people need to be accommodated each year and the design density of the new area.

If all new suburban development is subject to new policy (P4) then the entire amount of new development and the associated population is transferred into the population and area stocks for P4 each year. However, if some portion of the new development is subject to the prior policy (P3) then the associated quantities of land and people would be added to the P3 stocks each year. This scenario could happen in a setting where suburbs are governed independently (as is the case in Las Vegas) and one entity chooses not to develop according to the new policy.

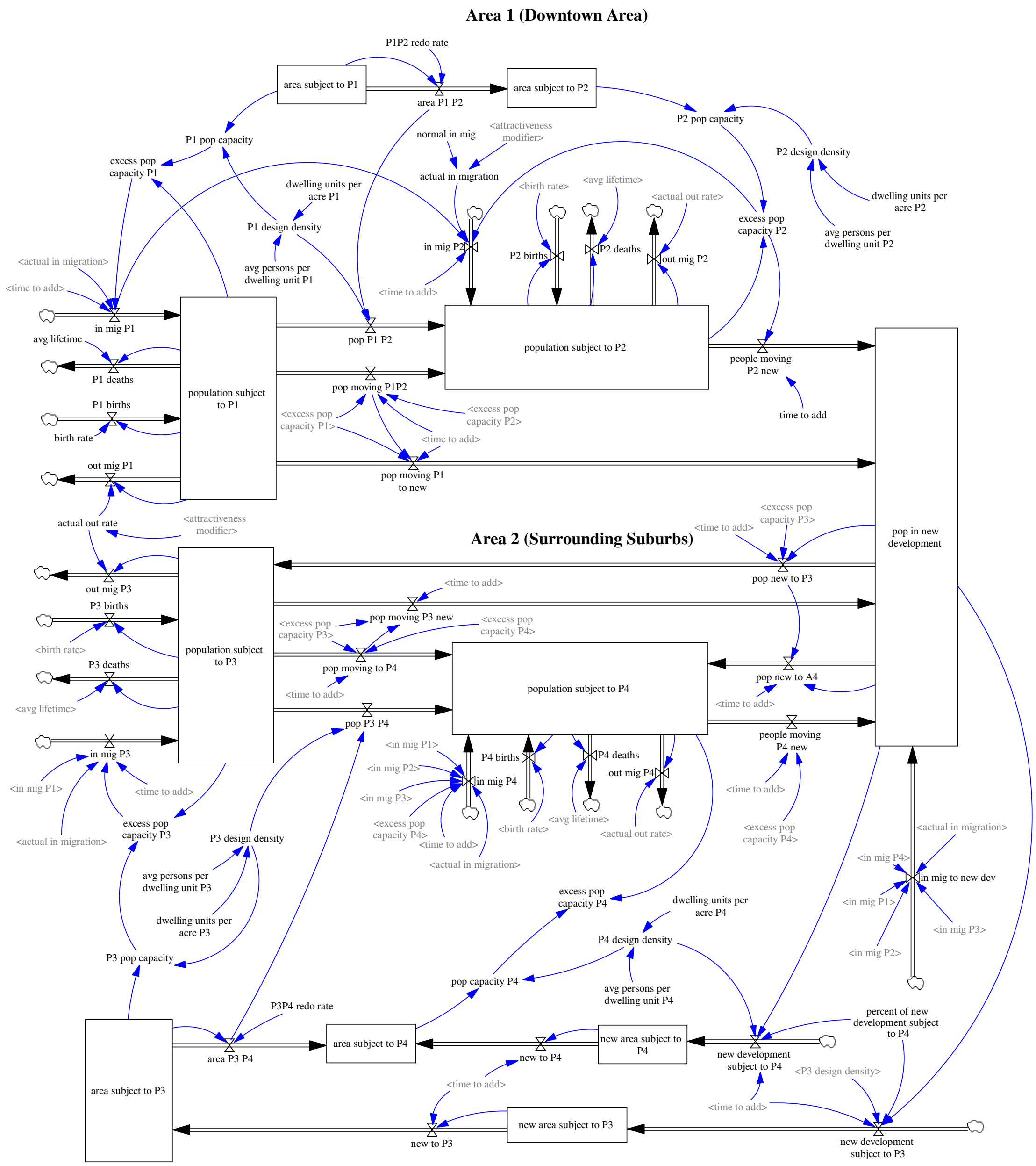

Figure 5: Complete Stock and Flow Diagram for Population and Land Development

Other Notes on the model

The planners working on the LUTAQ team requested that the densities be expressed in "dwelling units", thus dwelling units and "average persons per dwelling unit" are used to compute population density.

One will also note that three variables are used to model in and out migration: the normal rate, the actual rate, and an attractiveness modifier. The attractiveness modifier represents the connecting variable in the model's major feedback loop. As depicted in Figure 1, it modifies in- and out-migration based quality of life. In the case of the LUTAQ model attractiveness is a function of air quality, time in traffic, and a variable accounting for 'everything else'.

Output

Two runs were made to demonstrate output. Eight graphs are presented for each run. The graphs are arranged in four rows and two columns. The four rows represent the policies:

Row 1 = Policy 1 (P1) – The policy under which the urban core area was developed.
Row 2 = Policy 2 (p2) – The new policy applies to redevelopment of the urban core area. This policy does not take affect until next year (2006).
Row 3 = Policy 3 (P3) – The policy under which the existing suburban area was developed.
Row 4 = Policy 4 (P4) – The new policy that applies to new suburban development as well as existing suburban development that is retrofitted to meet the new policy.

The graphs depicting the population subject to each policy are arranged in column 1, and the quantity of land developed under each policy in column 2.

No Action Alternative

The graphs in Figure 6 depict model output for the population and land area of the Las Vegas Nevada metropolitan area for the years 1990 – 2035 should policies applicable prior to the year 2005 be continued through 2035. In other words – no action is taken to alter the outcome.

As one would expect, the population and land area in the urban core remains static at their initial values. No people or land are added to P2, as no policy changes are made from P1 (P1 P2 redo rate = 0). Population growth is entirely absorbed by developing new land at the urban fringe, thus adding people and land to areas subject to historical development policy. No people or land is added to areas subject to new suburban policy since no change is made from the historical development policy (P3 P4 redo rate = 0).

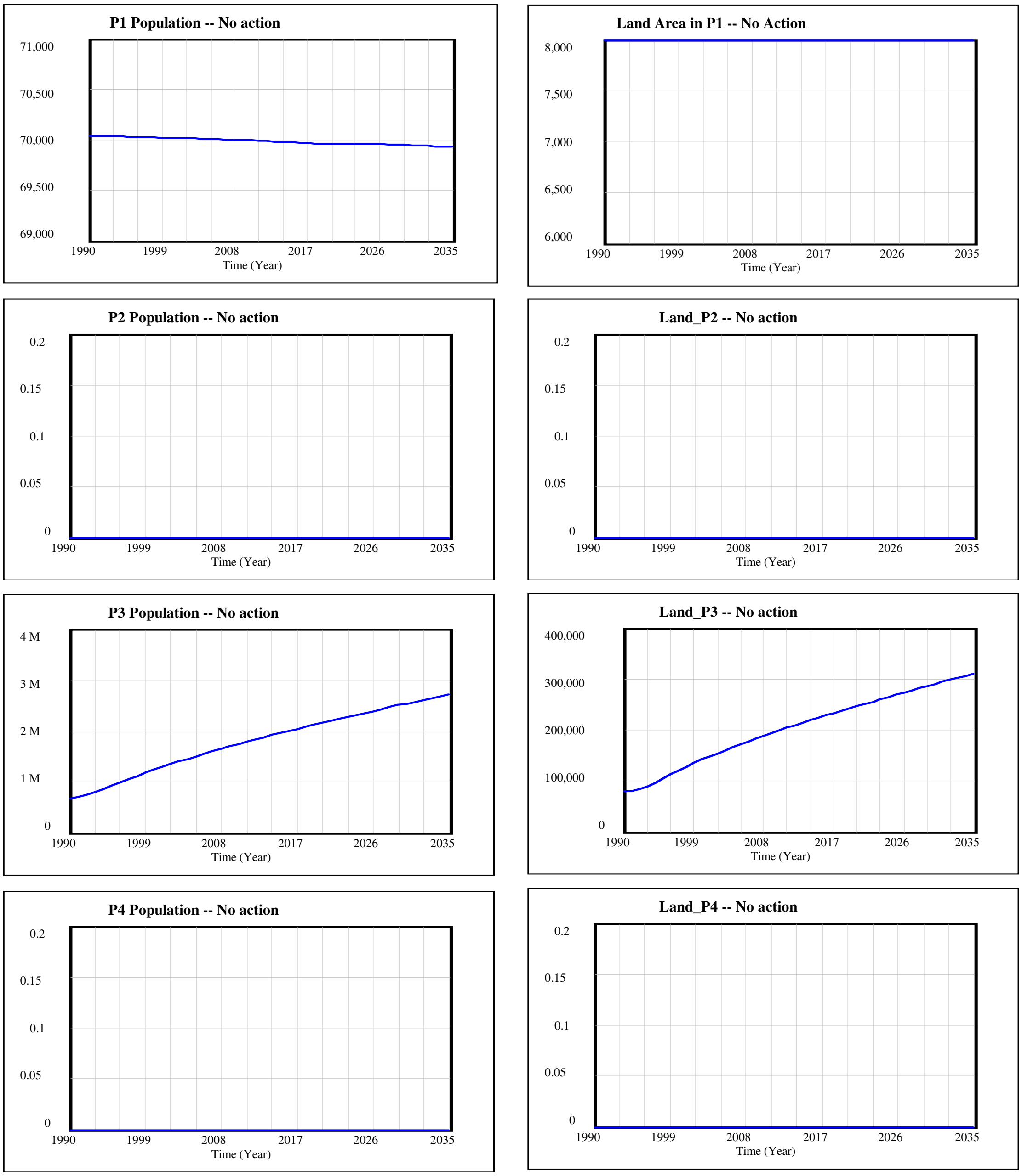

Figure 6. Results of the “no action” alternative run.

Increasing population density alternative

Within the past two years, several residential buildings have been constructed in the urban core of Las Vegas and dozens more are planned. The average price of land in the Las Vegas area is generally thought to be the primary cause of what Las Vegan's refer to as "Manhattanization". At the same time, increasing traffic congestion and worsening air quality have local governments looking for ways to mitigate the adverse impacts of growth. One alternative being examined is to decrease the average distance traveled per trip by increasing the mix of compatible land uses, such as residential, retail, and commercial. Another complementary strategy is to increase the percent of travel by mass transit and alternative modes. This can involve both disincentives to driving and incentives for using mass transit and alternative transportation.

The model run depicted by the output graphs in Figure 7 is reflective of the strategies that are occurring to a limited extent due to market forces, but are under consideration as mandates by policy-makers for both areas of new construction in the suburban area and areas that are redeveloped in both the urban core and the suburban area. The graphs depict the results of redeveloping 8% of the urban core each year at an average density of 25 dwelling units per acre, and adding new development to the suburban area at a density of 5 dwelling units per acre (up from an average of 3.5 dwelling units per acre prior to 2005).

The output graphs depict a decrease in the population and land area of the urban core subject to the old policy (P1) and reciprocal increases in the population and land area of the urban core subject to the new policy (P2) both beginning in the year the new policy takes effect (2006). Thee output graphs also depict a leveling off population growth in and land area of suburbs built under old policy (P3) and an increases in the population and land area of the urban core subject to the new policy (P4).

For the purpose of the LUTAQ model, the quantities in these stocks are used, together with other policy levers, to estimate the traffic capacity, vehicle miles traveled, and carbon monoxide emissions.

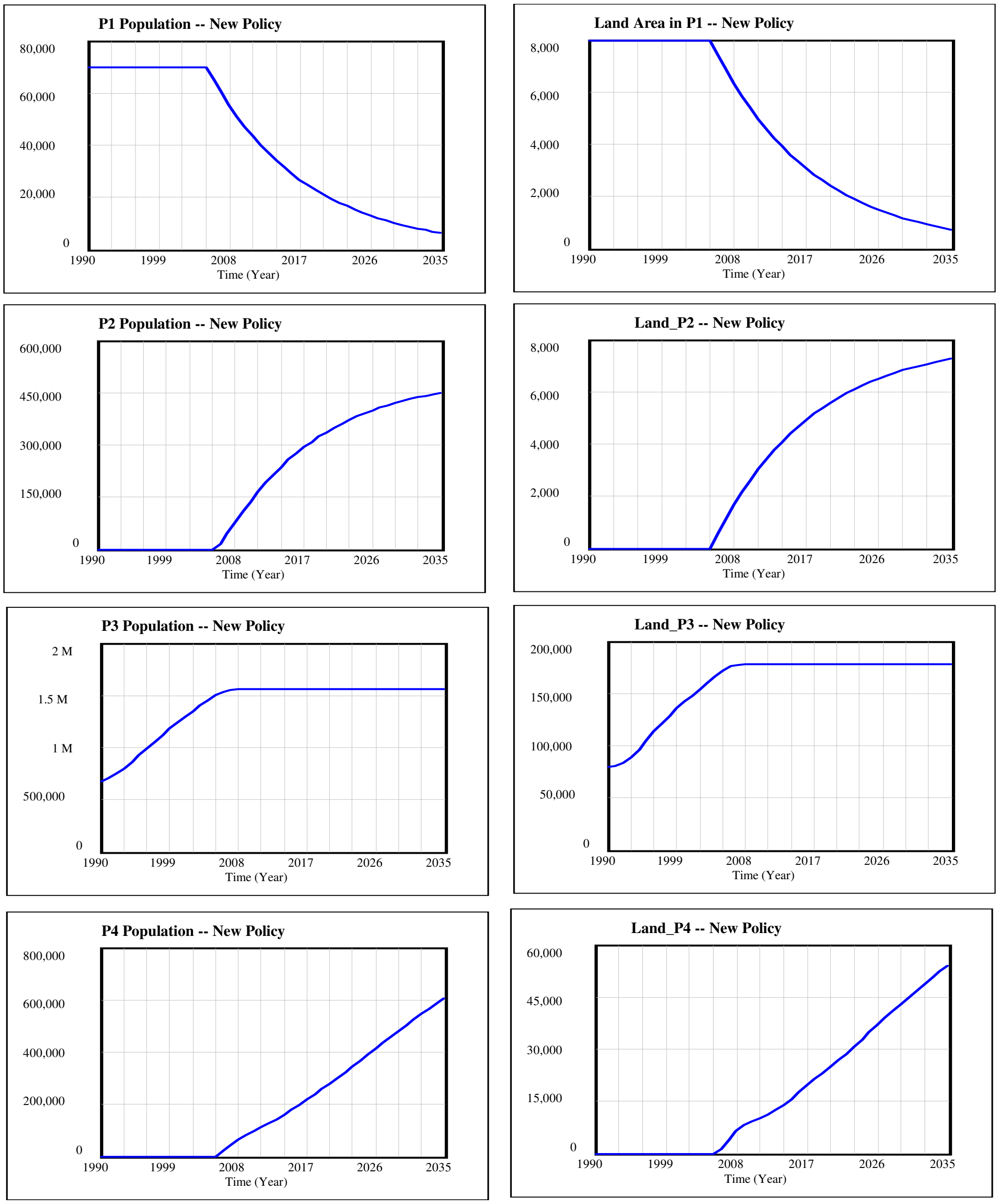

Figure 7. Population and Land Area Under a New Policy Scenario

Final Comments and Future Direction

There are several opportunities to enhance and extend this model. One might be to revisit the assumptions related to the sequence of stocks filling-up. Variables might be and feedback loops related to attractiveness might be added to model the allocation of the population when not at capacity. Another might be to allow lengthen the time-span and incorporate the opportunity for the area of the urban core to expand into the suburbs. Enhancements to the LUTAQ model might include going to the next level of detail in the policy inputs with regard to specific land-use options, and expanding the 'quality of life' sector to incorporate factors beyond time in traffic and air quality.

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