Table of Contents

Go Back

Coupled Human–Biologic Systems in Urban Areas: Towards an Analytical Framework Using Dynamic Simulation

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Abstract
This paper hypothesizes a newly understood, autonomous third force that shapes urban expansion even without demographic or economic pressures. It is a self-reinforcing feedback relationship driving urban sprawl. It is represented as a multi-causal feedback loop whereby roads beget roads through a process of ever declining developmental densities. The loop's dynamic structure is central to a framework for analyzing human-biologic systems in urban areas. The hypothesis is articulated as a system dynamics model calibrated on the Salt Lake City-Ogden metropolitan area, closely validated against recent observations, and used to explore the urban system performance implications of various policy options through to the year 2030. Other relevant dynamics are then outlined peripheral to this core. Thus this paper is about the dynamics of sprawl and how it serves as a dynamic organizing principle around which to conceptualize further explorations of human-biologic systems in urban area.

Key words: urban sprawl, system dynamics, travel demand, policy simulation

1. Urban metabolics and coupled human-biologic systems

Urbanization is increasingly salient to inquiry concerning atmospheric futures and global climate change. Historically humans have disproportionately favored a rural and agriculturally based settlement pattern. By the middle of the 20th Century, thirty percent of our species lived in urban areas. Mankind is about to cross a cultural threshold when in 2007 we become a predominantly urban species. By 2030, sixty percent of the world's population will be urban. Ninety-four percent of a projected increase of 2.1 billion inhabitants will be urban (United Nations, 2002).

Urban areas presently occupy 3 percent of the earth's habitable surface area. With expected increases in urban populations, continued urban density declines and continued loss of habitable landscapes, urban areas could occupy 8-to-9 percent of the earth's habitable surface area by 2030. Declining urban densities are linked to increased energy consumption levels. Urban-to-rural per capita energy consumption ratios are about four-to-one and increasing. These trends suggest that urban land use and metabolic patterns merit closer scrutiny.

This is particularly the case when considering biospheric–atmospheric exchange, the human dimensions of global climate change and the local determinants of human health.

Figure 1 identifies key relationships between urbanization and biospheric-atmospheric exchange. Demographic and economic drivers of urbanization precipitate a pattern of urban land development to accommodate a variety of urban activities – working, residing, traveling - and entail a variety of landscape ecologic changes – paving, planting, irrigating. These are mediated through an iterative process of urban developmental decision-making and collaborative learning.

Human activities and urban biota emit and absorb a variety of trace gases and suspended particulates. Most significant are water vapor, volatile organic compounds (VOC), and the oxides of carbon, nitrogen and sulphur (CO, CO_2, NOx and SOx). Trace gases play important roles in the global accumulation of greenhouse gases, the local formation of tropospheric ozone, plant metabolics and the exacerbation of cardiopulmonary health conditions.

The dynamics of urbanization and biospheric-atmospheric exchange are not understood in an integrated or systemic way. They are related to the metabolic rates of cities. Figure 2 shows one aspect of this – the relationship between urban population density and per capita energy consumption for selected urban agglomerations. Note the marked change observed in energy consumption rates when comparing Vienna, Toronto and Phoenix. The suggestion for the moment is that as densities decline, energy consumption rates increase thus driving upward rates of trace gas emissions.

But the matter is not quite so simple. Other relevant processes include the dynamics of urban demo-economics, the dynamics of urban sprawl, the prospects for CO_2 sequestration via urban forest expansion, and the modulation of ozone formation via alternative urban biotic regimes.

The purpose of this paper is to delineate an analytical framework for addressing these issues. The effort begins with the recognition that all urban processes affecting bio-atmospheric exchange are initially land-based. The strategy is to focus on urban densities, urban land use and the processes that affect the appropriation of rural land into the urban sphere.

Demographic growth and economic change have long been recognized as key in determining the pace of urban land development. But a newly understood, autonomous third force causes urban land development to expand even in the absence of demo-economic pressures. It is the self-reinforcing feedback relationship underlying the well-known phenomenon of urban sprawl. Urban sprawl is grounded in a multi-causal feedback loop whereby roads beget roads through a process of ever declining developmental densities. The dynamic organization of this loop is given a central role in the framework for analyzing coupled human-biologic systems in urban areas. Other relevant dynamics are then elaborated peripheral to this core. Thus the main thrust of this paper is about the dynamics of sprawl.

In the section immediately below, we outline the basics with respect to America's consumption of urban land and urban road-building as preliminaries to the articulation of a self-reinforcing feedback loop of congestion, road-building, sprawl, more congestion and even more road-building. The third section focuses on the feedback loop itself and the evidence supporting its veracity. The fourth section articulates the structure of this dynamic as set forth in a model validated against data drawn from the Salt Lake City-Ogden, Utah, metropolitan area. The fifth section outlines findings from simulation of policy alternatives, and the sixth section suggests how elaborations might be added to enhance the fullness of our analysis.

2. Urban land development, travel demand and road building in the U.S.A.

Between 1950 and 1990, urbanized lands in America quintupled while urban populations doubled. This brought on a two and one-half-fold decline in urban land use densities. Metropolitan rates of change in per capita urban land use consumption appear to be accelerating. A recent map interpretation of urban land use change for the Chicago-Milwaukee region shows urban growth between 1955 and 1975 covering a spatial extent equivalent to all pre-1955 growth, while urban growth between 1975 and 1995 covers a spatial extent equivalent to all pre-

1975 growth. In a region with moderate population growth, urban land appears to be doubling every twenty years (Acevedo, 1999).

In both rapidly growing and slowly growing metropolitan regions, urban land development consistently outpaces population growth. In the New York, Chicago and San Francisco, growth in urban land between 1950 and 1990 outpaced population growth by factors of between 2.5 and 5. Yet during the same period, the Cleveland area expanded by 33 percent even as the population declined by 11 percent (Diamond and Noonan, 1996). Fulton (2001) presents data from which one can compute the change in urban land relative to the change in population by major U.S. Census region for the period 1982 – 1997. There we learn that this ratio in the fast-growing West is 1.6:1 while in the slow-growing Northeast it is 5.7:1.

Contrary to expectations, rates of urban land development appear to be poorly correlated with rate of urban population or job growth.

Figure 3 shows an image of urban land development in the continental United States. It is based on a 1993 to 2001 comparison of U.S. Air Force Defense Meteorological Satellite data on night-lights (Mitchell, 2001). The gray and blue tones show development before 1993 while the yellow and red tones show development from 1993 to 2001. The raw acreage developed during the latter period closely matches the acreage developed during the earlier and much longer period.

Figure 4 show how this process is evolving before and after 1993 in the rapidly growing Southern Appalachian Piedmont region. The satellite image is placed along side data from metropolitan areas in the region from the Fulton report to show results in both graphic and numeric forms. The populations of the cities shown there grew during the 1982 – 1997 period from between 9 and 61 percent while their urban land areas grew from between 29 and 139 percent. The median rate of growth in urban land was 3.3 times the median rate of population growth.

Figure 5 show how this process is evolving in the declining region of Ohio, western Pennsylvania and northern West Virginia. The populations of the cities show there changed during the 1982–1997 period from between 2 and –15 percent while their urban land areas grew from between 25 and 53 percent. The median rate of growth in urban land was 7.6 times the median rate of population *decline*.

Since 1980, suburban populations have grown ten-times faster than central-city populations. Four-fifths of the country's urban growth is located in dispersed suburban settings. In contrast, European urban regions have three to four times the density. Notably, the comparison holds for the newly developed suburban areas of European cities as well (Newman and Kenworthy, 1989).

From 1950-90 urban land grew at an average annual rate of 9.0 percent. For the nation's urban road network to keep up, it would have had to grow at about 4 percent per year (approximately a square root relationship: $1.04 = (1.09)^{1/2}$). A nearly comparable statistic on substantially paved urban roads indicates a 3.8 percent growth rate over a similar time period (Bureau of Transportation Statistics, 2000). Data from 1990-99 on urban lane miles shows a 4.1 percent annual average growth. Urban land and urban road lane miles appear to grow in an appropriate relation to one another.

As urban road lane mile grew, national passenger vehicle miles increased by an average of 4.2 percent per year during the period 1950 – 1990 (Benfield, 1999). During the 1980's growth in vehicle miles traveled (VMT) was more than four times the growth in driving-age population. By 1995 VMT per capita was over 2.3 times the rate for 1965 and roughly double that of Europe's more prosperous countries (Bureau of Transportation Statistics, 2000). In North

American metropolitan regions, growth in urban land use, urban road lane miles and VMTs have consistently outpaced growth in population, earnings or jobs.

The disassociation between urban land development and population growth prompts one to ask what other factors might be driving urban land consumption.

A few comparisons with European practice prompts one to consider whether rapid rates of urban land development might not be related to land use and surface transportation policies. Focusing briefly on the U.S in comparison to Great Britain and France, one notes first that a higher percentage of surface transportation expenditures in the U.S. go to roadway construction (86%) than in Britain (70%) or France (57%). Correspondingly a lower percentage goes to transit facilities in the U.S. that typically require higher-density, European-style neighborhoods to provide service efficiently. Gasoline is 3 times more costly in Great Britain and 3.6 times more costly in France than in the U.S. due predominantly to different fuel tax policies. Personal vehicle miles traveled per capita are 47% lower in Great Britain and 45% lower in France than in the U.S. Transit trips per capita are 3.7 times higher in London and 4.2 time higher in Paris than in Philadelphia. The density of new urban land developments in the U.S. is typically 3-to-4 times lower than in Europe. There appears to be something about the relationship between urban land development and U.S. policy and practice regarding surface transportation and urban land use.

3. The dynamic organizing principle governing human-biologic systems in urban areas

Against the backdrop of these patterns, one needs also to note a changing urban environmental context. Ours is no longer a manufacturing society. We can no longer point to smoke stacks and industrial pollution as principal determinants of urban environmental conditions. Urban land development, vehicle trip generation and roadway capacity expansion now drive urban environmental dynamics. The transport sector uses two-thirds of U.S. oil supplies. It produces a third of U.S. carbon emissions, 90 percent of urban CO emissions and 50 percent of tropospheric ozone precursors (Benfield, 1999). Urban land use and land development patterns affect long-term trends in municipal and industrial demand for water, water supply systems and stream quality. Newman and Kenworthy (1989) find that low-density suburbs requires four to five times more water than do medium-density suburbs. Yet without remediation measures, stream degradation can be a more serious issue in medium-density cities where impervious materials predominate (Arnold and Gibbons, 1996). Urban land development, vehicle trip generation and roadway capacity expansion now mediate between urban demo-economics forces and the environmental dimensions of urban system performance – between people and jobs on the one hand and fuel use, trace gas emissions, stream quality, wildlife habitat and solid waste on the other.

Expansion of an urban road network induces a reduction in developmental densities and stimulates even further travel demand and further roadway capacity expansion. Anthony Downs's (2001) congressional testimony is based on his insights into the implication of this process. He comes to very pessimistic conclusions.

Newman and Kenworthy (1999: 140) describe this nexus with particular cogency:

> Most major cities that built extensive freeways then found that this process spread out land use and generated more and more traffic, until very soon after completion the freeways were already badly congested. The obvious response to the failure of freeways to cope with traffic congestion is to suggest that still more roads are urgently needed.

> The new roads are then justified again on technical grounds in terms of time, fuel, and other perceived savings to the community from eliminating congestion. This sets in motion a vicious circle of self-fulfilling prophecy of congestion, road building, sprawl, congestion and more road building. Automobile dependence is inevitable in such traffic engineering. Awareness of this phenomenon, called induced or generated traffic, is now much more common in the literature. In fact, traffic is now being referred to not as a liquid that flows where it is directed, but as a gas that expands to fill all available space.

Recognizing and modulating the strength of this feedback relationship is strategic to the long-term management of human–biologic systems in urban areas.

Figure 6 shows the cover from the industry bulletin, Asphalt, dated April 1966. It shows clearly the industry's view of Newman and Kenworthy's feedback loop. From the industry's point of view, this loop guaranteed an increasing schedule of business activity. Do note the special phrases, "roads stimulate travel," "more road-tax revenue means extra paved roads," and "improved roads … develop even more traffic." Today, the industry would quickly disavow these statements: the politics of road building were simpler and more supportive in 1966 than now.

The idea captured by the special phrases in Figure 6 is now referred to as induced traffic or induced travel demand. It is the idea that roadway investments induce longer, further and more numerous trips ('if you build it, they will come"), that induced traffic absorbs roadway capacity intended to ease congestion ("you can't pave your way out of traffic congestion"), and that investments in transit and land use controls should have priority over new roadway construction ("transit first"). As Robert Cervero (2003) notes, "Few issues in the urban transportation field have sparked as much controversy … as claims of 'induced demand.'"

Seeking to quantitatively verify these claims has become a small "industry" in its own right. In 1994, the British Standing Advisory Committee on Trunk Roads and Generation of Traffic (Goodwin, 1996) was the first to assess the effects of additional highway lane miles on induced traffic volumes. They estimated a one percent increase in road lane miles brought on a one percent increase in vehicular traffic. This finding caused the government to abandon its policy of building more roads in response to projected growth in vehicular traffic.

In the U.S., the Transportation Research Board (1995) of the National Academy of Science addressed the subject with reserve but did concede that, "Major highway capacity additions such as a freeway bypass or a major interchange reconstruction are likely to attract further development."

In a California-based study, Hansen and Huang (1997) found that adding lane miles to the state road network did induce substantial new traffic. At the metropolitan level, a one-percent increase in lane miles induced a 0.9% increase in vehicle miles traveled within four years.

Missing from these studies was the description of a mechanism or a behavior that would explain why added roadway capacity yields added traffic. Fishman (1989: 143) had previously suggested it had to do with the relationship between transportation systems investments and urban land speculation. Speaking of developer Henry Howard Houston and the Wissahickon Heights section of Chestnut Hill, Philadelphia, built in the late 1890's, Fishman notes:

> … a basic point which held true not only in the railroad era but also in the highway era that followed it: The ultimate purpose of suburban transportation lines is not to move people; it is to increase the value of the land through which it passes. The best suburban

land developer must also be a rail developer so he can direct his lines through land he already owns and retain the bulk of its increased value for himself.

Transportation system investments do raise land values but not so much so as to discourage developmental density declines. Lower density is, after all, the featured attraction of newly developed lands. Stratham et al. (2000) measured this effect and found that a 1% increase in per capita roadway capacity leads individuals to reside at a 0.25% lower density and work at a 0.22% lower density. In addition to inducing added travel demand, new roadways also induce added land development at consistently lower densities.

Closing the circle, the Urban Transportation Center (1999) showed that in metropolitan Chicago the prior period's population growth induced the present period's roadway capacity expansion. Roads attract populations and populations attract roads.

Cervero (2003) sought to sort out the effects of induced travel demand, induced building growth and induced roadway investment by employing path analytic techniques to a model composed of four simultaneous equations. With these he defined the direct and indirect effects of lane mile growth on roadway speed, travel demand, development activity and back again to lane mile growth.

Cervero's model is useful in sorting out the mechanics of the processes. Added roadway capacity improves average travel speeds and both spur further land development. The improved speeds and the added development both contribute to increased traffic. The increased traffic then spurs even further roadway capacity improvements. Elasticities are provided for each effect as captured over a 2-to-4 year time horizon. But then he hedges his position by noting that these effects "generally accumulate with time."

4. A systems thinking – system dynamics approach

Cervero's last remark gives a clue as to why one might want to expand upon statistical analyses while using a more integrative approach. When effects generally accumulate through long period of time, why would one want to assess roadway capacity expansion impacts with elasticities estimated over a 2-to-4 year time horizon? Cities do not equilibrate in 2-to-4 years. Cities do not equilibrate, period. They are emergent systems. The characteristics of any complex system emerge out of the rich interactions among its elemental parts (Gilbert, 1995). Einstein's remark about problem solving comes to mind: "You can't solve a problem with the same kind of thinking that created the problem." Experimentation with other approaches is required.

Consider instead the following two hypotheses: (1) that the vicious cycle described by Newman and Kenworthy (1999) accounts for increases in urban land consumption, vehicle miles traveled, roadway capacity, and urban environmental degradation at rates disproportionately high relative to the underlying rates of demographic and economic change and (2) that recognizing and regulating (dampening) the strength of this reciprocally reinforcing feedback loop is essential for the successful management of not only urban densities, trip generation, and traffic congestion but also urban economic and environmental indicators such as infrastructure costs, water demand, local governmental fiscal capacity, energy use, and urban trace gas emissions.

To test these hypotheses, consider a system dynamics model that simulates over the 50 years from 1980 to 2030 an approximation of Newman and Kenworthy's dynamic nexus and identifies long-term impacts on urban system performance characteristics.

At this early stage in model development, it is useful to have the model striped to its barest essentials. The model recognizes only three stocks. While implications for other stocks will be inferred, these are less central. Stocks at the core of the model include population, urban land, and urban roadway capacity.

The structure of the model is simple, strategic and telling. Population growth is exogenous and "drives" land development. Newly developed land generates additional trips. Additional trips increase the region's road-building goal: building roads is a goal-attainment process. Pursuing the goal gets roads built, lowers developmental densities, and requires incrementally greater amounts of land per building structure. The greater amounts of land required then generate incrementally more trips per acre and thus increase the road-building goal. The reinforcing feedback effect transforms the impacts of a nearly linear "driver" (population) into exponentially growing land consumption and traffic generation functions. This dynamic structure is formally a goal attainment process nested within a reinforcing feedback loop. Its reference behavior is a pattern of incessantly more fervent activity (road building) in pursuit as an ever-receding goal (traffic congestion relief) with ever diminishing success. It is the simplest way to explain why growth in urban land, traffic and road building so consistently outpaces changes in population, earnings and jobs and why road building so infrequently succeeds in meeting its goals. The model is named SprawlSim I.

The model is initialized with data from the Salt Lake-Ogden metropolitan area for the year 1980. For validation purposes, simulations are run with policy variables in default positions, year 1999 simulation values are noted, and these values are compared with observations from 1999. Validation results are reported below.

Modulating the feedback dynamic during the projected time horizon is a core function of local land use and transportation policies. Elementary policy options include controlling land developmental densities, altering the rates of road construction, diverting traffic to alternative travel modes, and filling the road gap with intelligent transportation systems capacity enhancements instead of building roads. Each policy individually is insufficient to effectively modulate the dynamics of sprawl, but in reasonable combination the process can be substantially managed, densities can be largely maintained, and traffic congestion made bearable.

Figure 7 shows a causal loop diagram for the SprawlSim model. The model and the causal loop diagram were made using High Performance System's STELLA® system dynamic software package. Figure 7 shows the basic structure of the model's dynamic organizing principle. Start with the region's stock of Urban Land, which expands because of population growth. As Urban Land develops, it causes a specific flow of person-trips to be generated each year by people seeking to get where they need to go. These are calculated on the basis of a monotonically increasing function relating person-trips per acre to time. As TripGeneration goes up, the desired roadway capacity increases. This flow is called the TargetLaneMiles. It represents the added highway capacity transportation engineers would want to see built given trends in TripGeneration. TargetLaneMiles are compared to the actual regional roadway system capacity also measured in lane miles and any deficit is defined as the RoadGap. A positive RoadGap drives the building of roads as a goal-attainment process. This increases the region's roadway capacity measured in Lane Miles and in LaneMile\1000Persons. An increase in LaneMile\1000Persons drives new development densities down marginally by an amount suggested by a research provided by Stratham (2000). These now marginally lower densities govern urban land requirements during the next round of developingAcres. These then feeds back into the volume of Urban Land in the region, and the process starts all over again.

Figure 8 shows a system map for the SprawlSim model that corresponds to the causal loop diagram of Figure 7. To navigate through the system map, start with Pop%GrowRate. This defines the population growth called net Growing. It causes new building structures (NetBuildingGrowth) to be built on newly developed urban land (developingAcres). The process is governed by a monotonically increasing function relating buildings per person to time as is appropriate given changing demographic age structures in the region. This adds to the stock of Urban Land. Person-trips are generated as a time-dependent function of Urban Land. These are converted into desired urban road lane miles (TargetLaneMiles), after consideration for (1) the diversion of person-trips to non-automotive modes of travel (NonAuto%*NonAutoTrafficEquiv) and (2) the diminution of the need for added highway capacity by alternatively expanding the existing roadway capacity through intelligent transportation system investments (ITS%CapacityIncr). The rest of the system map follows the logic defined above for the causal loop diagram of Figure 7.

Several policy sliders facilitate experimentation with feedback modulation. These, too, can be seen on the system map in Figure 8. Developmental densities can be increased with a slider that presumes a user-specified percentage increase in new development densities as might be achieved through changes in local land use and land development policies (PctDensityIncrease). For example a 21 percent increase in density could be achieved by following the recommendations developed for Envision Utah by ECONorthwest (1999) as part of their Quality Growth Strategy. These recommendations pertain to a modification of the structure of new housing starts by building structure type so as to match the pattern of structure types needed given the proportions of owner – and rental occupancy in the region.

The percentage of trips made by non-automobile modes of transportation can be increased with a slider that presumes increased investment in and use of buses, regional rapid transit, bicycle lanes and walking (NonAuto%). Considerable investments in these alternatives are recently under way within the Salt Lake-Ogden area and are being responded to with notable user enthusiasm.

Intelligent transportation systems (ITS) refer to a class of road capacity management strategies designed to get more capacity out of existing roads. They include activities like freeway on-ramp metering, traffic signal synchronization and well-enforced peak-hour parking limitations on arterials. An ITS slider allows one to increase the traffic handling capacity of existing roads by a user-specified percent (ITS%CapacityIncr). It uses the presumption that when these policies are implemented demand for newly added roadway capacity is proportionately reduced.

The fraction of the road gap built per year (FrOfGapBtl\Yr) reflects the intensity of the regional road building effort relative to perceived road building need. Changing this slider from its default value lets the user simulate more intense or less intense road building activity relative to perceived needs.

All policy slider take effect in the year 2004. Any change in the FrOfGapBtl\Yr takes effect without delay. All other policies have an average implementation lag time of 3 years. This means most of the policy's effects take 7 years for near-complete implementation.

The model was initialized with data from 1980 for the Salt Lake-Ogden metropolitan area. Initial values were defined for urban population (InitPop) using data on county population from the Governor's Office of Planning and Budget (GOPB, 2001). County population was converted to urban population using a ratio obtained by inspection of Federal Highway Administration data on urbanized areas within the state (FHWA, 1999). Data on Urban Land was obtained from the

Utah office of the USDA's Natural Resources Conservation Service where current and historic records from the Natural Resources Inventory are maintained (Grow, 2002). This provided the input for InitUrbLand. Data on urban roadway lane miles is available for the study area reaching back to 1992 (FHWA, Table HM-71, various dates). Data on roadway lane miles for all urban areas in Utah is available reaching back at least to 1980 (FHWA, Table HM-60, various dates). A variety of interpolation methods were used to estimate the initial value for the region's urban roadway lane miles (InitLaneMi).

A baseline simulation was used to validate the model's performance against recent observations. Initialized with 1980 data, the model was run until 1999 and stopped. Simulation values were noted and compared to observations gleaned from the data sources given above. The comparison is summarized in Table 1 as a set of percentage error terms. These range from a low of 0.3 percent to a high of 2.1 percent for an average absolute error among the five observations of 1.3 percent. Percentage errors of this low magnitude lend credibility to the use of the model as a projection tool especially since it is stripped to the barest essential relationships and does not include several enhancements that would improve its accuracy.

5. Experimental policy simulations: defeating urban sprawl and traffic congestion

The outcomes of baseline simulations to the year 2030 are shown in Figures 9 and 10. Figure 9 shows trajectories from 1980 to 2030 with respect to key indicators of urban system performance – urban land per capita, urban roadway lane miles per 1000 persons and average daily person trips per capita. Land per capita grows from 0.2 gross urban acres per person to 0.4 acres per person or alternatively from 2/10ths of an acre per person to 3/10ths of an acre per person – roughly a 50 percent density decline. Urban roadway lane miles per 1000 grow from 3.5 to 7 for about a 100 percent increase. Person trips per person grow from 1.5 per day to 3.7 for about a 125 percent increase. Note that smaller percentage changes in densities are associated with larger percentage changes in trip-making and road-building. Also note that each of these three measures of urban system performance show distinct signs of exponential growth.

Figure 10 tracks changes as measured by percentage increases from initial values. This helps show relative rates of change among measures of urban system performance. There we track change in urban population, urban land, urban roads and person trips. Urban population has the lowest percentage rate of change. Urban land expands at roughly twice the speed. Urban roadway capacity exceeds the rate of population growth by a factor of three, while trip-making explodes at four times the rate of population growth. The percentage change in the road gap is not shown until Figure 14. It is a rough proxy for roadway congestion. Under the baseline simulation, it grows eight times faster than population.

Given the untoward nature of baseline results, one can safely assume that community leaders will not permit historic patterns and practices to be expended unmodified into the future. But what combination of system modification will be effective in managing the untoward results of an undampened feedback loop?

To explore this question, two experiments were designed and run in comparison with the baseline simulation (trajectory 1). These are tracked in Figures 11 – 14 with the comparative graph trajectories labeled 1, 2 and 3. Remember the simple model show above in Figure 8 has been modified so that all policy changes take effect only after 2004 and kick in with an average three-year implementation delay (STELLA® function [SMTH1, 3]).

In the first experiment, aggressive changes were made in all policy sliders. The fraction of the road gap built per year was cut in half. A set of land use policies sufficient to increase densities by 22 percent was assumed. The percent of non-automobile traffic was presumed to change from a default value of three percent to a value of 22 percent. And ITS improvements were presumed to substitute for 14 percent of needed roadway capacity. This tough combination of policies is called “shock-and-awe.”

The second experiment was made identical to the first except that the intensity of road building was increased by 50 percent instead of being cut by 50 percent. Because this scenario seeks to accommodate society’s road-building impulse, it is call “cake-and-eat-it-too.”

Figure 11 shows the outcomes of the baseline simulation and the two experimental runs on population densities measured in people per gross urban acre. The baseline shows strong decline in densities. Both experimental runs show some control over continued density declines. Densities in 2004, when policy changes are initiated, stand at 4.2 persons per acre. Without policy change, they would decline to 3.2 persons per acre by 2030. Both experimental runs limit further declines to the 3.8 – 3.9 persons per acre range. Figure 11 shows that some effective control over sprawl is possible and that both experimental policy sets have roughly the same general level of impact.

Figure 12 shows the outcomes of the baseline simulation and the two experimental runs on trip generation measured by percentage change in trips per capita. The baseline shows a 125 percent increase in trip generation by 2030. Both experimental runs show some control over continued increases in trip generation. Both experimental runs limit further increases to the 80 percent range. Figure 12 shows that some effective control over trip generation is possible and that both experimental policy sets have roughly the same general level of impact.

Figure 13 shows the outcomes of the baseline simulation and the two experimental runs on roadway capacity as measured by the percentage change in roadway lane miles. The baseline shows a 125 percent increase in per capita roadway capacity by 2030. The shock-and-awe strategy shows a meager 10 percent increase in per capita roadway capacity, while the cake-and-eat-it-too strategy shows only a 25 percent increase. Both experimental runs show a tempering of road building to rates well in proportion to population growth. Figure 13 shows that need to build roads can be brought under control and that the difference between the two experimental policy strategies in modest.

Figure 14 shows the outcomes of the baseline simulation and the two experimental runs on roadway congestion as measured by percentage changes in the road gap – the difference between desired and actual roadway capacity. The baseline shows a 1000 percent increase in the road gap by 2030. This implies a seriously growing problem with traffic congestion under the baseline scenario. The shock-and-awe strategy reduces this growth substantially. It reduces congestion substantially and allows 16 years before congestion returns to 2004 levels. But then it continues to increase at an all-too-rapid pace that parallels the baseline case. By 2030, it shows about a 700 percent increase in congestion. The cake-and-eat-it-too strategy shows a different trajectory. It, too, cuts substantially into the road gap. But then it equilibrates at about a 250 percent increase – a level of congestion first encountered in 1997. This outcome is interesting and merits some further explanation.

It appears that seeking to meet desired roadway capacity standards without simultaneously controlling developmental densities, diverting traffic to alternative modes, and improving the capacity of the existing road network is totally ineffective. It also appears that both experimental policy sets are substantially effective at containing sprawl. This is because they both dampen the feedback effects defined by the causal loop diagram in Figure 7.

But the shock-and-awe strategy requires an unnecessary sacrifice. It unnecessarily imposes a continued problem of roadway congestion and travel delay.

The cake-and-eat-it-too strategy provides nearly the same level of sprawl control but also provides substantial traffic congestion relief. There is a simple reason why this happens. The policies on land use densities, alternative travel and existing road capacity sufficiently dampen reinforcing feedback effects and lower the perceived need to build roads so as to permit an appropriately lowered volume of road building to proceed without its counter-productive impacts on induced development and induced traffic.

SprawlSim offers strong evidence for the conclusion that sprawl can be controlled and that roads can be build to meet their intended purpose of congestion relief. But the latter result holds only under very restrictive conditions, namely that an appropriately lower level of road-building be accompanied by vigorous programs promoting developmental density controls, abundant travel by alternative modes and effective enhancements to existing roadway capacity.

6. From SprawlSim to a coupled human-biologic urban system model

The argument advanced in Section 3 is that a sprawl-inducing feedback mechanism is the dynamic organizing principle shaping urban developmental trajectories in North American cities today. This principle constitutes a third driving force, an autonomous element that can take its place along side demographic and economic forces as determinants of urban system trajectories.

Having discerned a way to model this force and to modulate its impacts, the next step is to outline how that model might be enhanced to represent a series of other important urban-based human and biotic processes.

The first task is to improve the basic SprawlSim model. Track both net job formation and the stock of job opportunities. Link jobs to demographic migration. Differentiate between commercial and residential building activity. Simulate change in average trip lengths. Expand the determinant to trip making. Include a calculation of average daily vehicle miles traveled (VMT), and assess desired road capacity based on VMT. Use simulated values for traffic volume (VMT) and capacity to estimate average system-wide travel speeds.

The second task is to extend the basic model to include a sector on state and local fiscal matters. Show how land development requires added regional and local infrastructure, how the amount required varies with developmental densities and how this influences the rate of state and local expenditures. But also show how these same expenditures add to property value and urban activities, how these additions increase property and sales tax revenues without increased tax rates, and how these revenues can, if densities are not too low, provide sufficient revenues to fund required infrastructure expansion. Show how, if land use and transportation policies are used to constructive effects, state and local budgets can be readily balanced and how, if not, easily driven to deficit. Link infrastructure expenditures back to urban developmental densities as they, too, like road building, push population densities down.

The third task is to extend the basic model to include a sector on anthropogenic trace gas emissions. With simulations on jobs and urban commercial and residential land use, calculate point- and area-source trace gas emissions. With simulations on vehicle traffic and speed, simulate linear-source emissions with particular attention to SO_x, VOC and NO_x.

The fourth task is to add a sector on urban flora. While the region was originally treeless, it is now about two-fifths forested. The change was enabled by the introduction of extensive irrigation.

Now water is scarce. Citizens are urged to conserve. Xeriscaping is encouraged. Urban foresters wonder whether they should replace dying trees of which there are many.

In the short run, conservation will reduce the need to expand regional water development systems. It will spare the region a great expense and a significant environmental loss. In the long run, water conservation will permit the economic development of the region to continue.

But there is a second alternative. It relates to water, trees and tropospheric ozone. Ozone formation is very temperature-sensitive once temperatures exceed 90 degrees F. Trees cool the city. They offset an increasingly intense urban heat island effect. They emit water vapor that reacts with O+ thus reducing the formation of ozone (O3). They absorb ozone precursors. But the wrong kind of tree will emit VOC, another O3 precursor. Fortunately we have been planting and could continue to plant tree like maples that are low VOC emitters. If so, an expansion of the urban forest will not only sequester more CO2, it will slow the formation of ozone.

Use the sector on urban flora to explore the tradeoff in the use of water between sustained urban growth and cleaner urban air.

The fifth task is to forge linkages between the sector on anthropogenic trace gas emissions and the sector on urban flora. Show how anthropogenic trace gases affect the long-run health of trees. Show how biogenic trace gases and other biogenic effects interact with anthropogenic trace gases to alter ozone formation and airborne particulates.

Finally link all the above to a human health sector with linkages back to the local fiscal sector and to the propensity to form jobs and to migrate into the region.

For each model sector, organize an interest group with domain experts, stakeholders and policy decision makers. Involve them in the task of group-based model building. Rely on each group to validate the logic of that sector's model structure. Integrate each sector into the model one at a time and, calibrate with local data, and seek to re-validate the model's accuracy at each stage. Explore and document the policy implications gleaned from each interest group's interaction with the process of model building and policy simulation.

With appropriate collaboration underwritten by extensive and extended research support, the prospects are good for elaborating a useful framework for the design and development of a dynamic simulation model of human-biologic systems in urban areas.

7. Summary

In 1950, 30 percent of the world's population was urban. Fifty years later, urban areas take up 3 percent of the earth's habitable surface area. United Nations projects that the world's population will be 60% urban by 2030 by which time nearly all growth will be urban growth. With continued density declines, urban areas could take up 8-to-9 percent of the earth's habitable surface area. This is clearly a period during which the urban dynamics commands our attention. Forging an integrated understanding of the dynamics of urbanization and its relationship to biospheric-atmospheric exchange is one of the most pressing aspects of the urban challenge.

To press forward with the challenge, I hypothesize an autonomous third force that causes urban expansion in the absence of demographic and economic pressures. This force strongly shapes the trajectories of urban system performance. This force is characterized as a self-reinforcing feedback loop whereby roads beget roads through a process of ever-declining developmental densities. Urban sprawl and traffic congestion are emergent properties of an urban system impelled undiminished by the logic of its structure.

Earlier efforts have offered partial characterizations of this force. These appear as research on induced traffic, induced travel demand, induced land development and induced road building. We have come to understand that urban roads attract urban populations and urban populations attract urban roads.

To integrate these ideas and test the feedback hypothesis, I present a system dynamics model designed to simulate urban sprawl and traffic congestion. Its logic is simple. Newly developed land generates additional trips. Additional trips increase the region's road-building goal. Pursuing the goal gets roads built, lowers new development densities, and requires incrementally more land per building structure. This then generates incrementally more trips per acre and thus increases the road-building goal. The logic of sprawl-inducing feedback transforms the impacts of a nearly linear "driver" (population) into exponentially growing land consumption and traffic generation.

Formally, the dynamic structure of this process is a goal attainment process nested within a reinforcing feedback loop. Its reference behavior is a pattern of incessantly more fervent activity (road building) in pursuit as an ever-receding goal (traffic congestion relief) with ever diminishing success. It is the simplest way to explain why growth in urban land so consistently outpaces changes in population and why road building so seldom succeeds in meeting its goals. The model is named SprawlSim I.

Mathematically the model is a complex set of simultaneous differential equations. It is initialized with 1980 data from the Salt Lake City-Ogden metropolitan area. The model's nominal time horizon extends to the year 2030. It contains user-adjustable policy variables that simulate policy initiatives launched in the year 2004 with 90% implementation by 2011. These simulate the effects of four land use and transportation policy options that collectively have the potential to dampen the model's sprawl-inducing feedback mechanism.

To validate the model, simulations were stopped during the year 1999, five simulation values were noted and then compared to observations for the same year. Simulation errors range from 0.3% to 2.1% with an average error of 1.3%. Percentage errors of this low magnitude lend credibility to the use of the model as a projection tool.

A baseline and two experimental policy simulations were run to test the prospects for defeating urban sprawl and traffic congestion. Given the untoward nature of baseline results, one can safely assume that community leaders will not permit historic patterns and practices to be expended unmodified into the future. The "shock-and-awe" experimental policy scenario effectively dampens the reinforcing feedback loop but exacts an unnecessary sacrifice. It imposes a level of traffic congestion that need not be endured. The "cake-and-eat-it-too" scenario constrains developmental densities, meets travel demand with both demand and supply management strategies and addresses remaining travel demand in an even shorter period than now. The experiments show what combination of policies can be used to both control sprawl and relieve traffic congestion.

Having modeled America's sprawl-inducing feedback mechanism, the next step is to outline how that model might be enhanced to represent a series of other important urban-based human and biotic processes. Nine measures are recommended. (1) Enhance the existing SprawlSim model to account for jobs, land use types, trip lengths, vehicle miles traveled and average vehicle speeds. (2) Add a sector to the model on state and local fiscal practices with a density-dependent infrastructure expenditure function showing the conditions under which expenditures add to land value, draw upon fiscal resources, and induce further developmental density declines. (3) Add a sector on anthropogenic trace gas emissions. (4) Add a sector on urban forests to explore the tradeoff in water use between sustained urban growth and cleaner urban air. (5) Link trace gas emissions to urban forest health. (6) Link all the above to human health, local fiscal effects and demo-economic responses. (7) For each sector, involve domain experts, stakeholders and policy decision makers in group based model building. (8) Document the impacts of these activities on participants' comprehension of policy complexity and (9) define the implications for elaborating a more comprehensive understanding of human-biologic interactions in urban areas.

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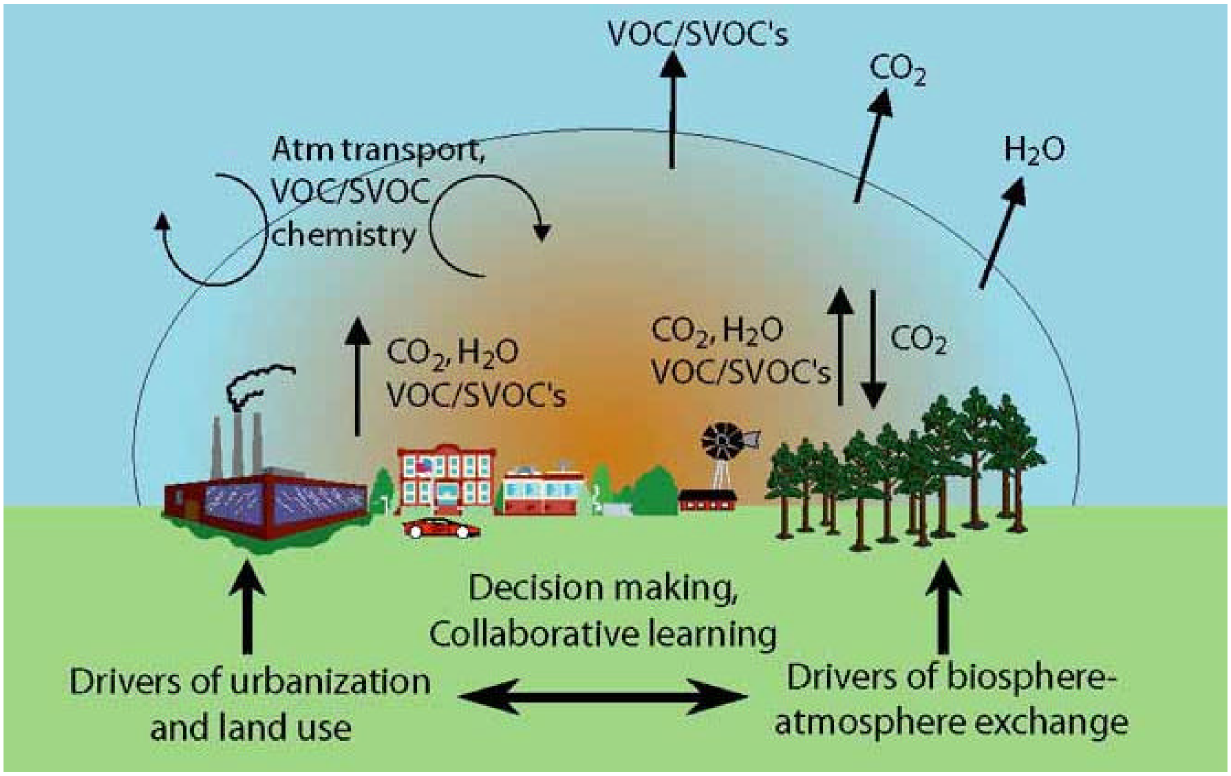

Figure 1. Key relationships between urbanization and biospheric-atmospheric exchange.

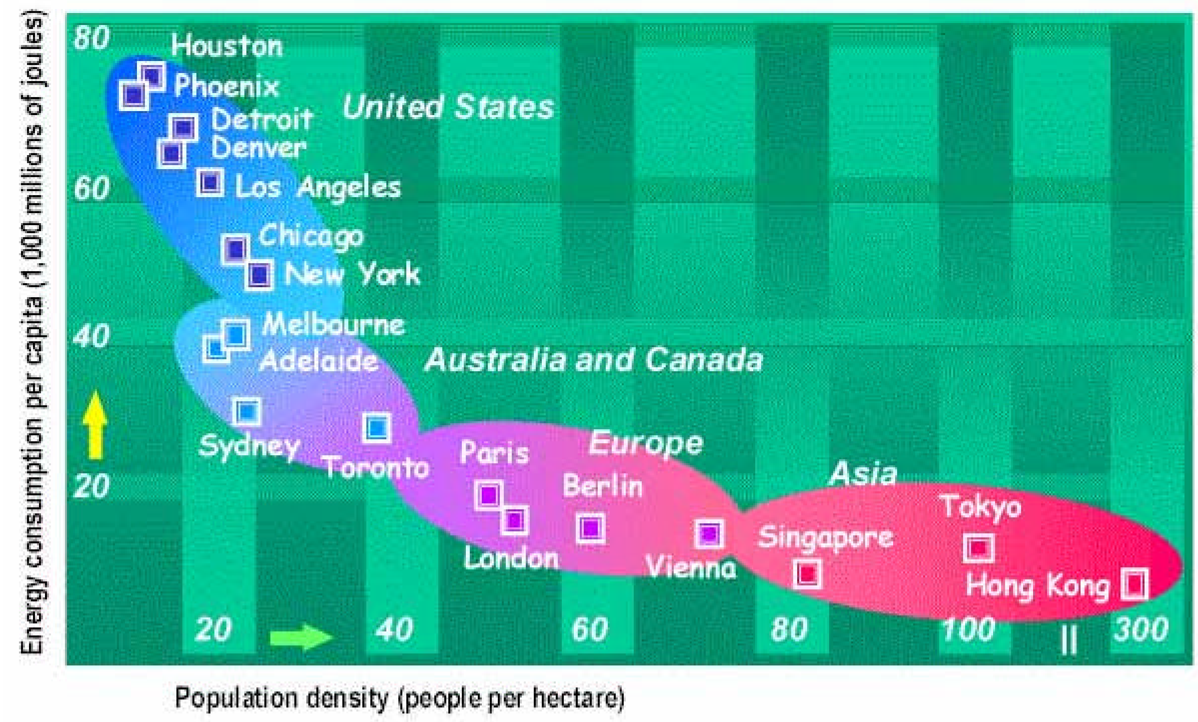

Figure 2. The relationship between population density and energy consumption in cities.

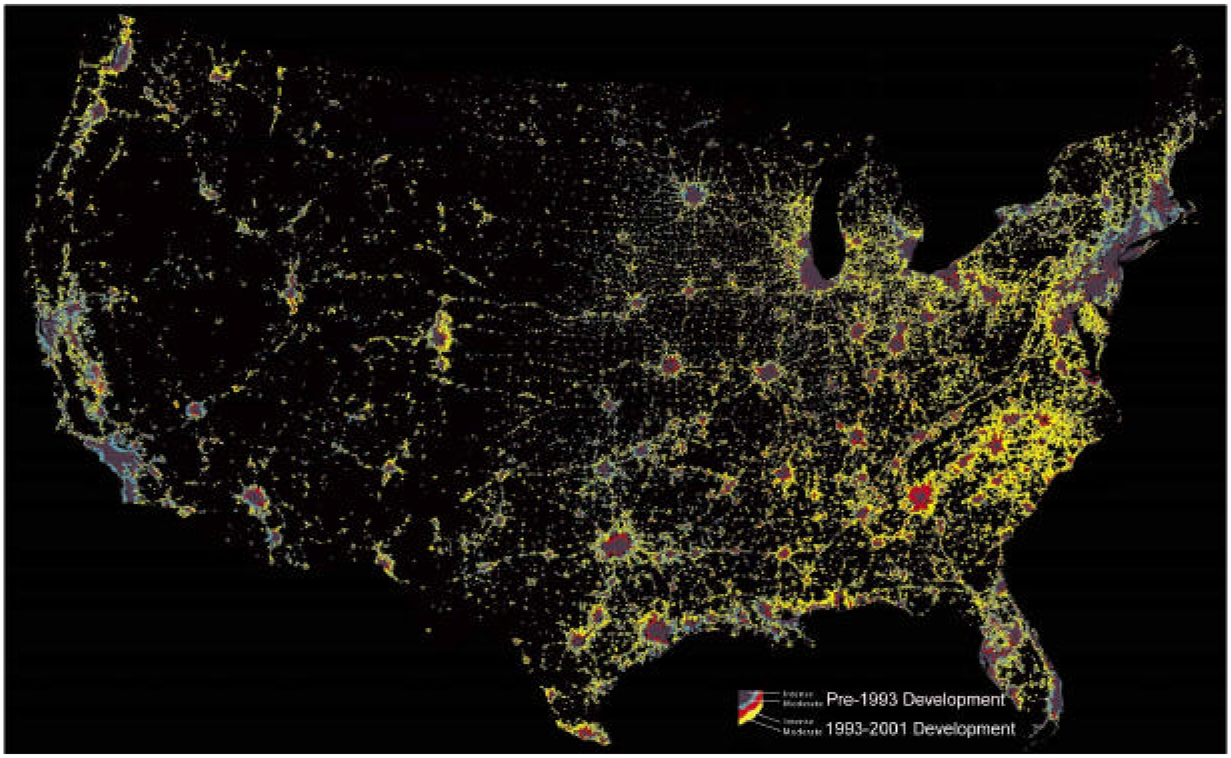

Figure 3. Continental U.S. urban land development pre- and post 1993.

Sprawl in a Growing Region

(land)=3.3* (pop)

Range of Change in Population and Urbanized Land, 1982-97

Maximum	61%	139%
Minimum	9%	29%
Median	22%	72%

The Piedmont of the Southern Appalachian Mountains

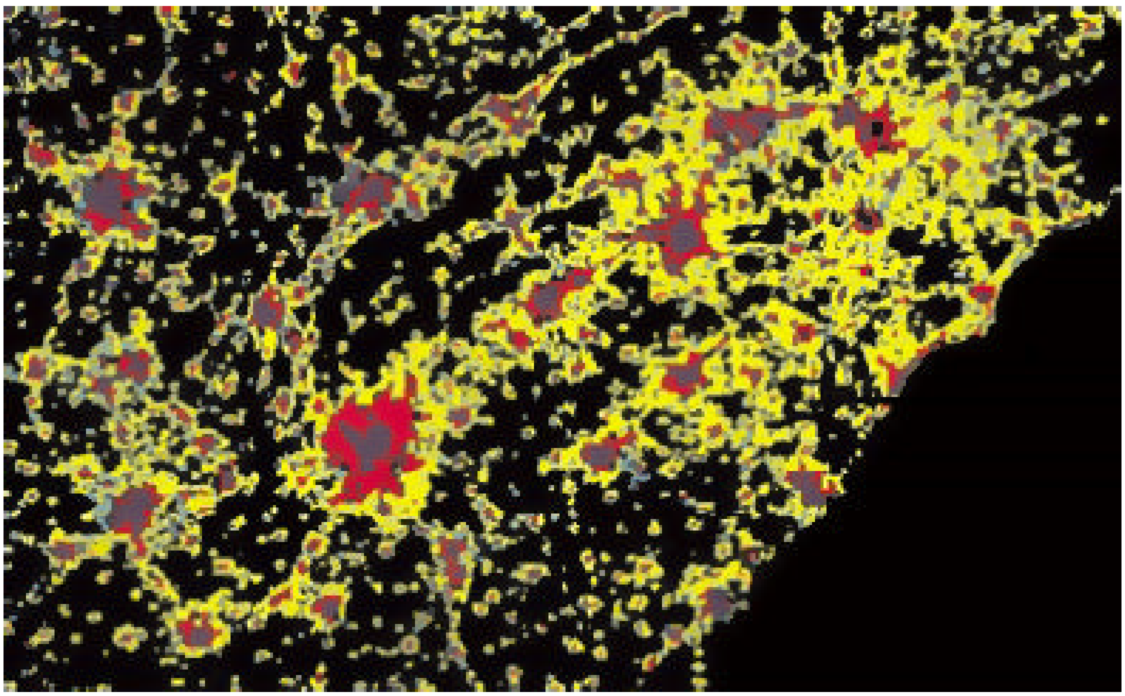

Figure 4. Sprawl in a growing region represented graphically and numerically.

Sprawl in a Declining Region

(land) = -7.6* (pop)

Range of Change in Population and Urbanized Land, 1982-1997

Maximum	2.3%	53%
Minimum	-15%	25%
Median	-5%	38%

Ohio, Western Pennsylvania and West Virginia (Columbus, Cleveland, Youngstown, Pittsburgh and Wheeling)

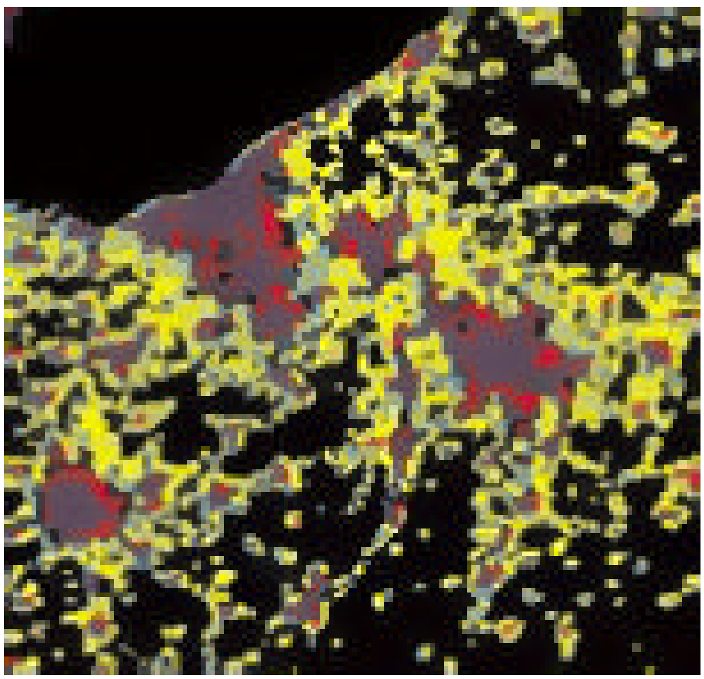

Figure 5. Sprawl in a declining region represented graphically and numerically.

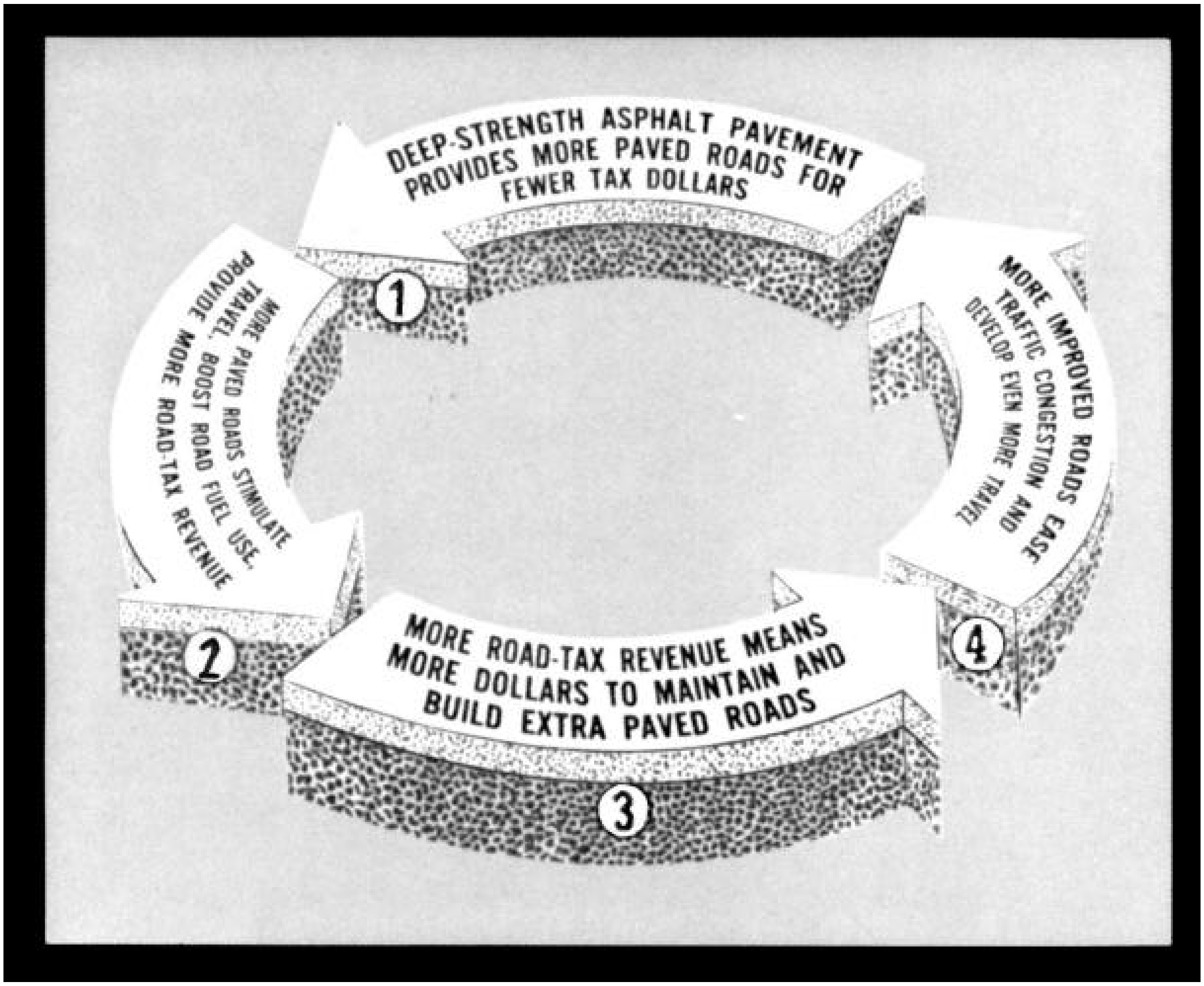

Figure 6. Roads beget roads: From the cover of *Asphalt Bulletin,* April 1966.

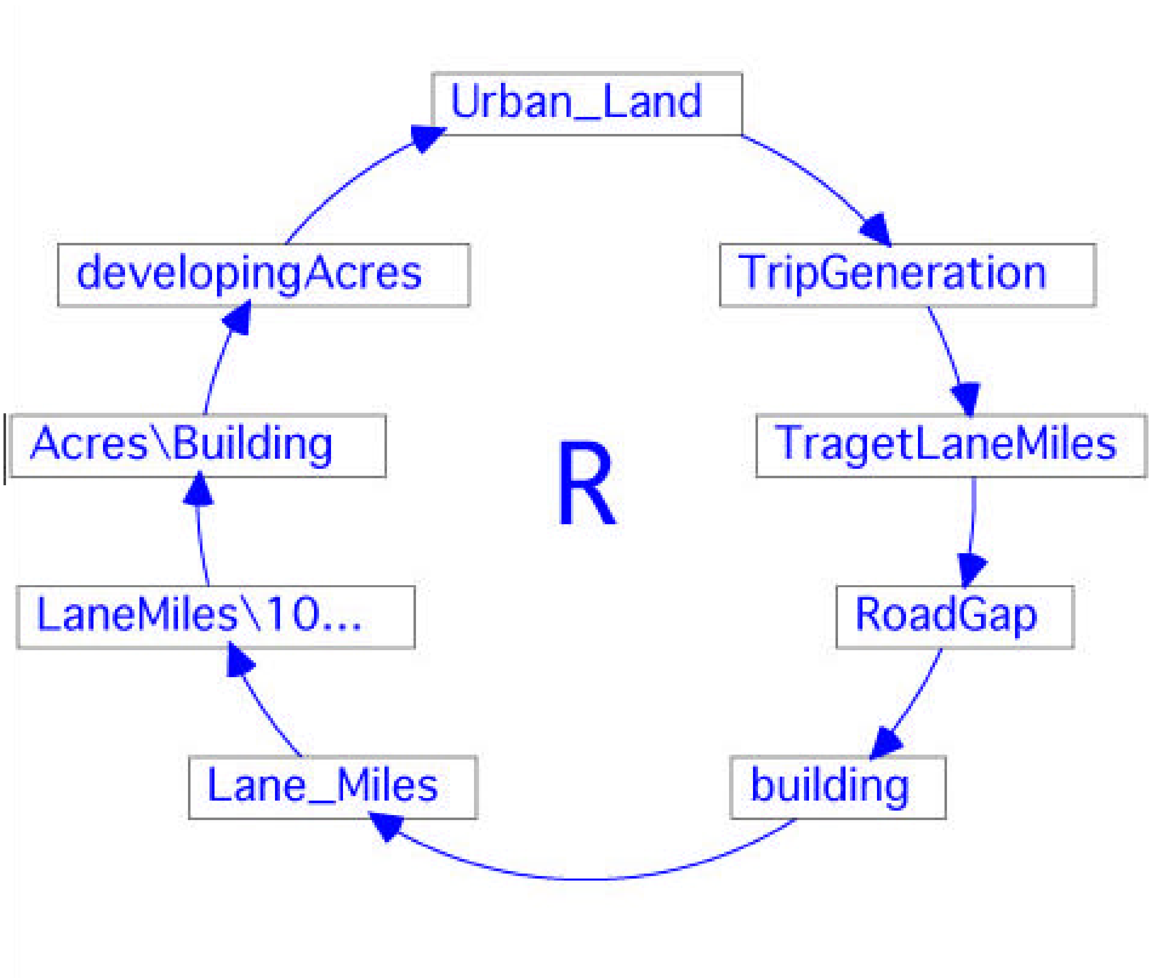

Figure 7. A causal loop diagram of a sprawl-inducing feedback mechanism.

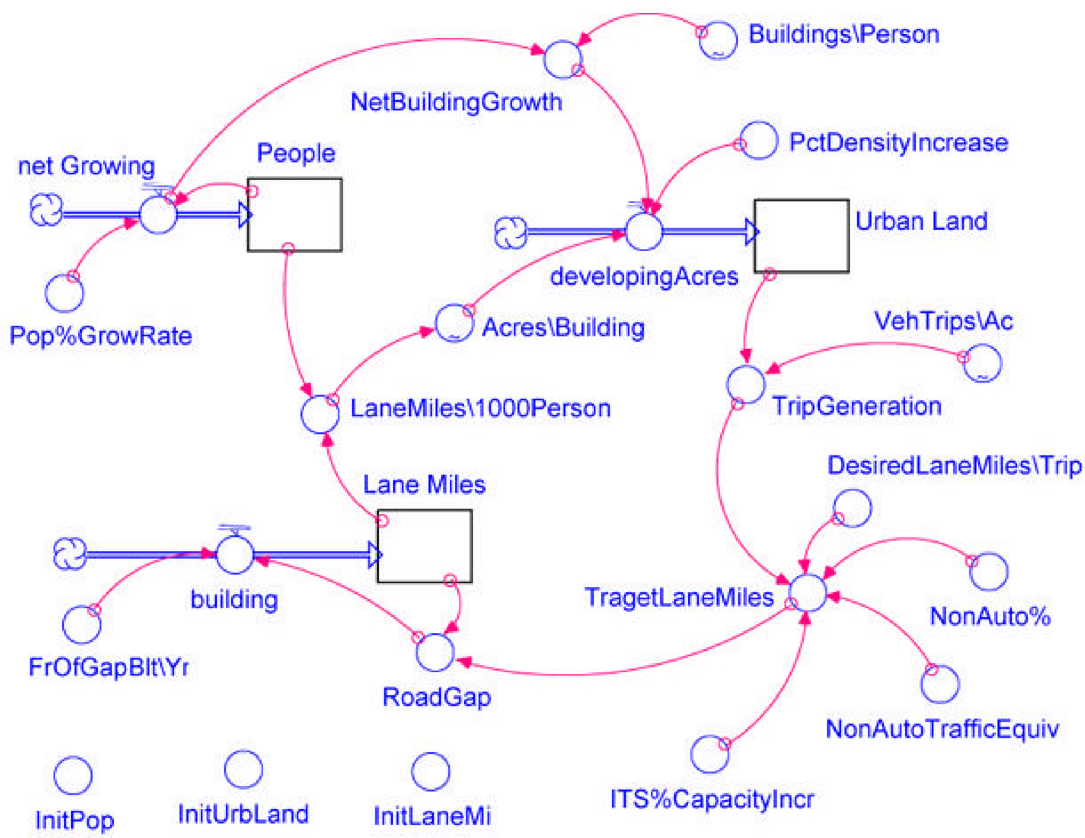

Figure 8. A system map of the SprawlSim system dynamics model.

Table 1. Validation Statistics for SprawlSim from the Salt Lake City-Ogden Area.

ITEM	1980	1999	Simulation	Error
Urban Population	827,000	1,184,000	1,187,780	+ 0.3%
Urban Land (acres)	166,000	272,000	267,694	- 1.6%
People/Acre	4.98	4.35	4.44	+ 2.1%
Road Lane Miles	2,821	4,636	4,610	+ 1.1%
Lane Miles/1000 people	3.41	3.92	3.87	- 1.3%

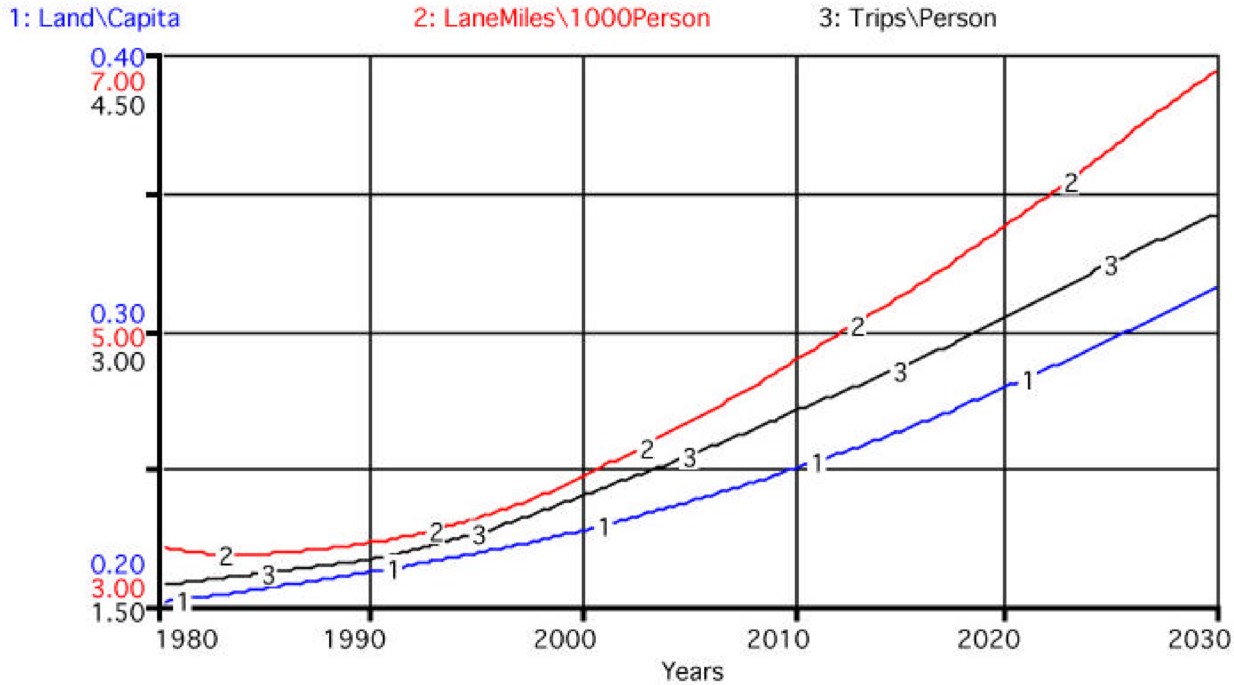

Figure 9. Key ratios: density, road capacity and travel behavior, baseline simulation.

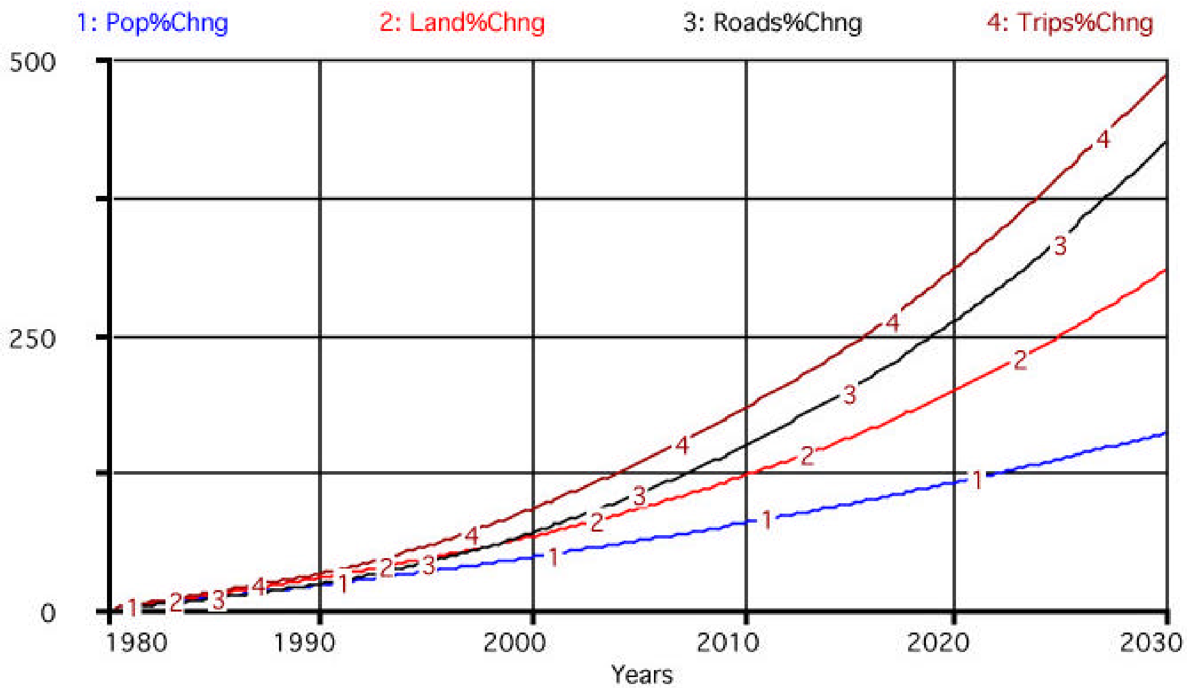

Figure 10. Percentage change in urban activities, baseline simulation.

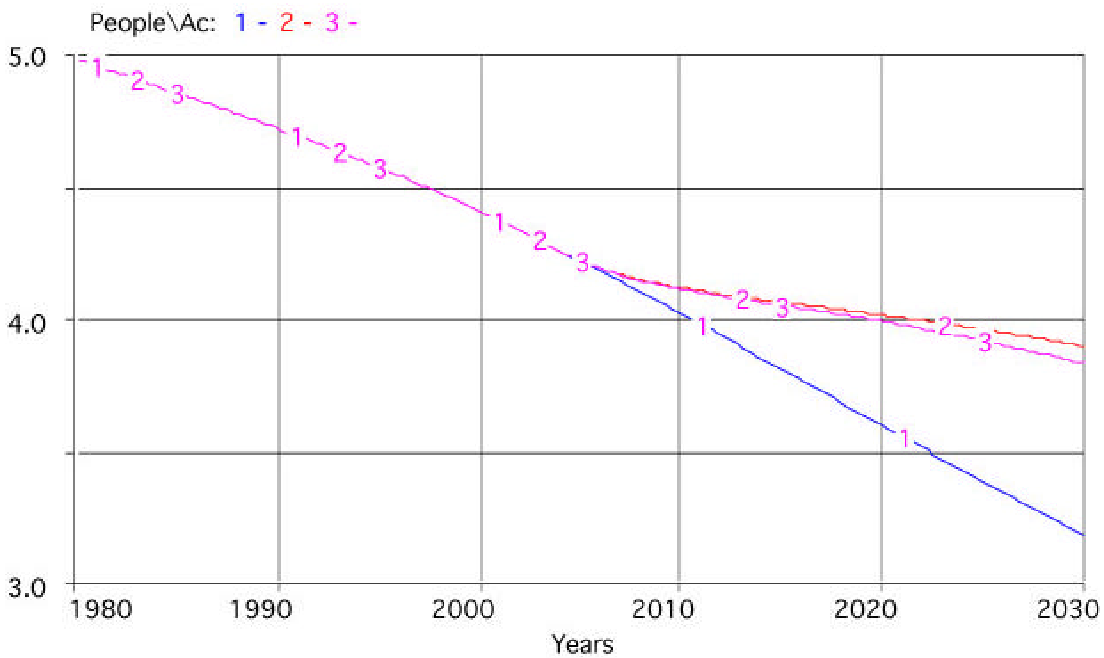

Figure 11. Population density as people per acre - three scenarios: (1) baseline, (2) shock-and-awe, (3) cake-and-eat-it-too.

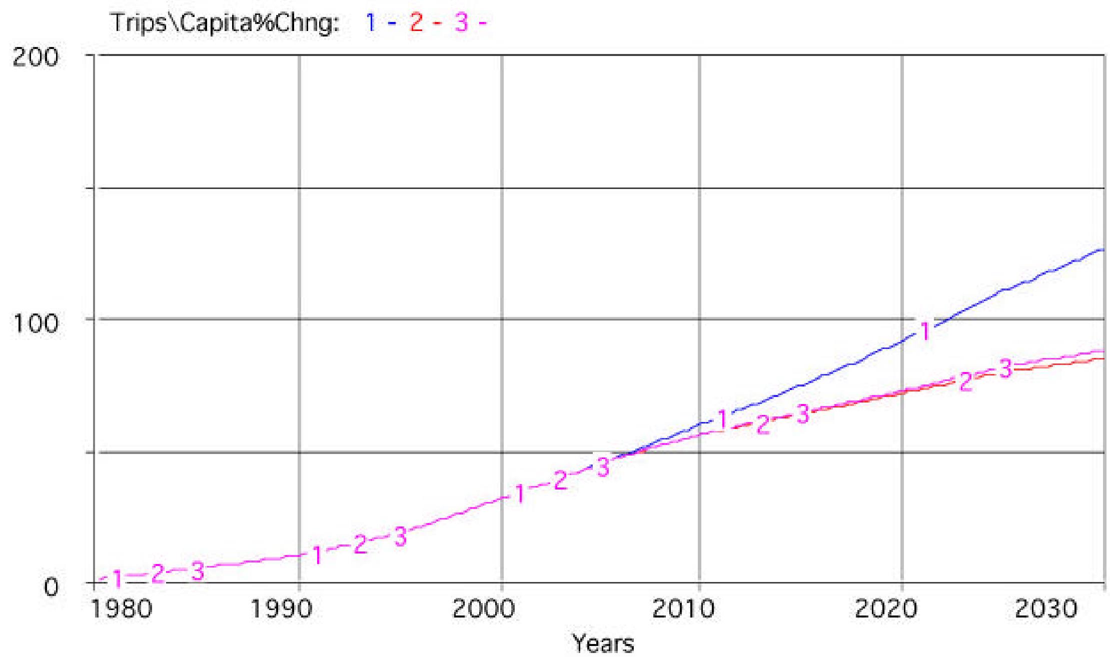

Figure 12. Travel behavior as percentage change in trips per capita - three scenarios: (1) baseline, (2) shock-and-awe, (3) cake-and-eat-it-too.

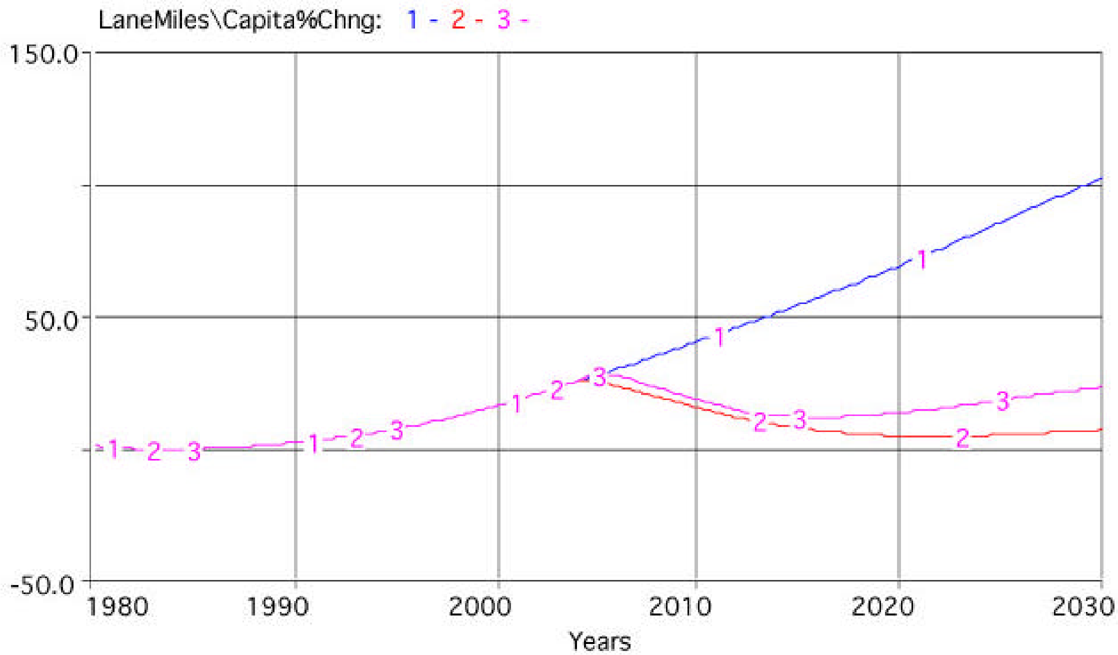

Figure 13. Roadway capacity as percentage change in lane miles per capita - three scenarios: (1) baseline, (2) shock-and-awe, (3) cake-and-eat-it-too.

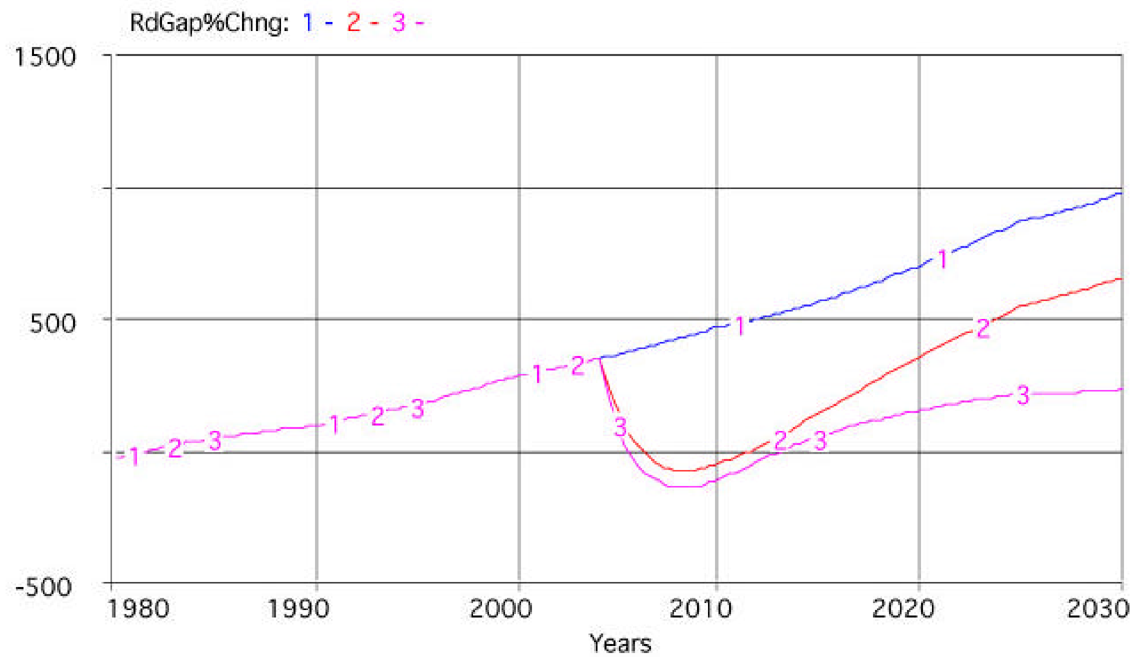

Figure 14. Traffic congestion as percentage change in the road gap - three scenarios: (1) baseline, (2) shock-and-awe, (3) cake-and-eat-it-too.

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Back to the Top