Is Vehicular Pollution A Pending Crisis?

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Introduction

"In 1997…most of Southeast Asia was shrouded for weeks in a poisonous smog so dense that in some cities visibility was reduced to a few feet." -Allen Hammond*, Which World?*

Approximately three million people die each year from air pollution, as opposed to one million from traffic fatalities, according to the World Health Organization. Vehicle emissions provide the pollution that causes about half of those deaths (Fischlowitz-Roberts, 2002). These emissions, including carbon monoxide, nitrogen dioxide, hydrocarbons, sulfur dioxide, lead, and suspended particulate matter, can be highly toxic, as evidenced by the increasing number of deaths caused by them. And yet, all over the world, vehicle fleets continue to grow, making urban areas frighteningly congested, consuming more fuel, and adding more and more pollution to the environment.

This continuous growth in pollution is very undesirable, in global terms. Already there are signs of economic and environmental stress, such as the rising prices of oil and concerns about its future availability; deaths from pollution exceeding those from fairly common disasters such as vehicle crashes; smog and acid rain in densely populated urban areas; and the increasing extinction of species through conspicuous consumption. Not all of the earth's resources are renewable, and if this trend of vehicle and pollution growth continues, it may lead to what systems dynamics guru Jay Forrester calls a pollution crisis (Figure 1c, next page). An increasing demand for products that pollute the environment, which follows population growth, creates a very high concentration of pollution. This causes a sharp drop in the population because of its toxicity and abundance, and it may result in economic and social chaos. Such a scenario is not unlikely at the rate that the world is developing.

There is no easy way to slow down or halt the advance of this crisis. On an individual level, one can use one's resources as efficiently as possible and attempt to raise awareness of the importance of the environment. On a macroscopic scale, the most efficient way to attempt a change could be to make pollution very unprofitable for industry and other businesses, rather than attempting to change people's minds about the environment. Changing minds, however, can be a powerful thing; in order to gain understanding of the situation for myself, before trying to help other people do the same, I built a Stella model of the relationship between population, vehicles, and carbon monoxide pollution. The model was not ultimately successful in answering the question put above, that is, whether vehicular pollution is ultimately sustainable in terms of population, but in the process of model building I gained an invaluable understanding of what it means to build a model and of the dynamic relationship between pollution and population.

In computer models of a population, the population will generally show one of four behaviors (Figure 1): continuous growth, sigmoidal growth, overshoot, or oscillation, as set out by Donella Meadows in *Limits to Growth*. A population that grows continuously (a) has no built-in limits such as a fixed amount of resources, or its limits are far off; limits to growth come into action in sigmoidal growth (b) to act as a carrying capacity. In overshoot (c), on the other hand, the limits are there and they cannot be delayed or eased. An overshoot will happen because the signals that warn of the coming crisis are delayed until there is nothing anyone can do. Signals are also delayed in oscillation (d), but the limits can be recovered, i.e., the population can grow after its collapse until it gets too large and collapses once more.

With the prior knowledge I had of the behavior of pollution and population, I expected the final version of the model to either oscillate or overshoot in a pollution crisis. The final graph (see Figure 10), however, showed sigmoidal growth. This is only a function of the model structure, since no one can tell what will really happen in a century or two, if there will be overshoot or continuous growth. What this model shows, though, is that limits to pollution do exist, and do have an effect on the generic population being studied. If we want to live in a healthy environment with the danger from a pollution crisis minimized, we must keep our limits in mind.

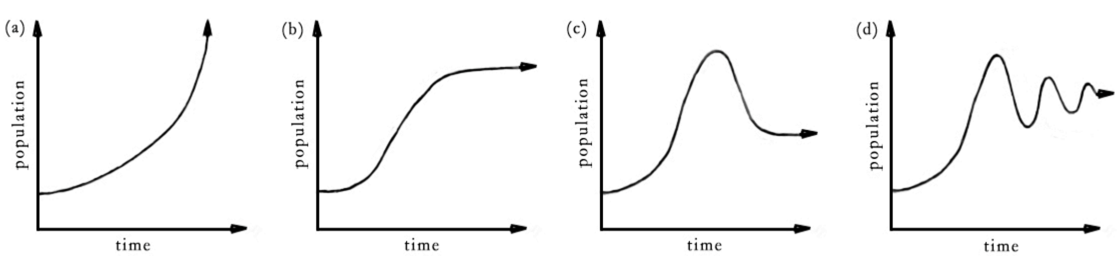

Figure 1. Behavior over time graphs: (a) continuous growth; (b) sigmoid; (c) overshoot; (d) oscillation.

The Model-Building Process

At first, I didn't know enough about the subject of pollution in computer models to have a clear idea of what I would be doing. Inspired by a World Watch booklet called "Subsidies, Politics, and the Environment," I wanted to model the effect of land-use subsidies on urban air pollution, using population, pollution, and the economy. Never having done an economic model before, I had a vague idea of price and inventory stocks: this proved too complicated, however, and the inventory stock gradually metamorphosed into a motor vehicle stock.

I only realized the fact later, after several research-intensive days, that subsidies would be too difficult and what I was really interested in was urban sprawl. Living in Portland, Oregon, a city with strictly controlled sprawl and numerous land-use laws, led to wanting to model the way land-use policy affected air pollution from motor vehicles. This meant scrapping the economy part of the model, and adding in vehicle density and population density, and their effects on the increase in pollution and demand for motor vehicles. Vehicle density versus population density, i.e., the ratio of people who used

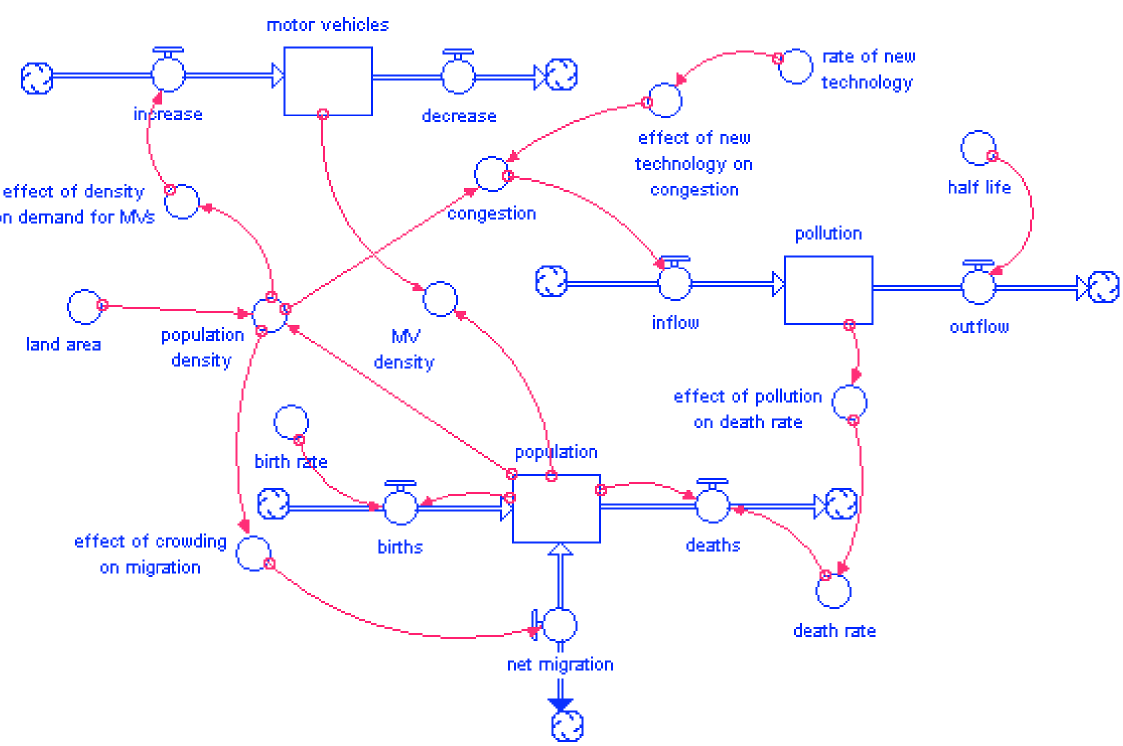

Figure 2. The first model, which incorporates stocks of population, pollution, and motor vehicles.

public transport rather than their own vehicles, would also play a part in my thinking. What I then needed to find out was how to measure pollution with population and motor vehicles; how population affects the demand for motor vehicles; how new technology, such as catalytic converters that reduce emissions by a great deal, would reduce congestion; and how to measure congestion in terms of land, population, and motor vehicles.

The first model, in Figure 2, was built in map mode, since at that time I had no numbers or equations to make the model work. Population density (people per square kilometer) affects the population through a migration multiplier, and congestion and demand for motor vehicles in some vague way that I didn't yet understand. Pollution, of course, affected the death rate. I didn't yet know what to do with motor vehicle density, however, and it was left hanging in the middle of the model with nothing to do.

More research provided some answers, but not all of them. While I gained a greater understanding of how the model would be constructed (since Figure 1 was simply the idea put into Stella, for reference), I still had little idea of how to actually go about creating such a complicated model. I decided to build the three stocks separately and connect them after I was sure that they worked. To that end, I started with population, using Delhi, India as the city, since there was a great deal of information about pollution there from motor vehicles. Using actual figures from the Indian Census gave exponential population growth, so I moved on to motor vehicles.

Trying to figure out how to measure an increase in vehicles had me stuck. Vehicle aging gave an average dwell time, but an increase was difficult to model. At first I tried creating a trendline using Excel and the number of vehicles in various years; this, however, was not the best way to go about increasing the vehicle stock. This method measured a trend, not an actual increase that could be affected by various converters.

With Mrs. Fisher, I connected population and vehicles (Figure 3, next page), since vehicles actually depended on population. The increase in motor vehicles would be determined by the percentage of adults who are able to drive, taken from migration and the maturation flow from children to adults (with driving age in Delhi acting as a dwell time). Not all adults who are able to drive *do* drive, however, so the new vehicles for new drivers converter estimated the percent of adults who drive who buy new vehicles: this determined the increase in vehicles, rather than a trendline. In addition to the vehicle dwell time, I added cars removed from driver deaths.

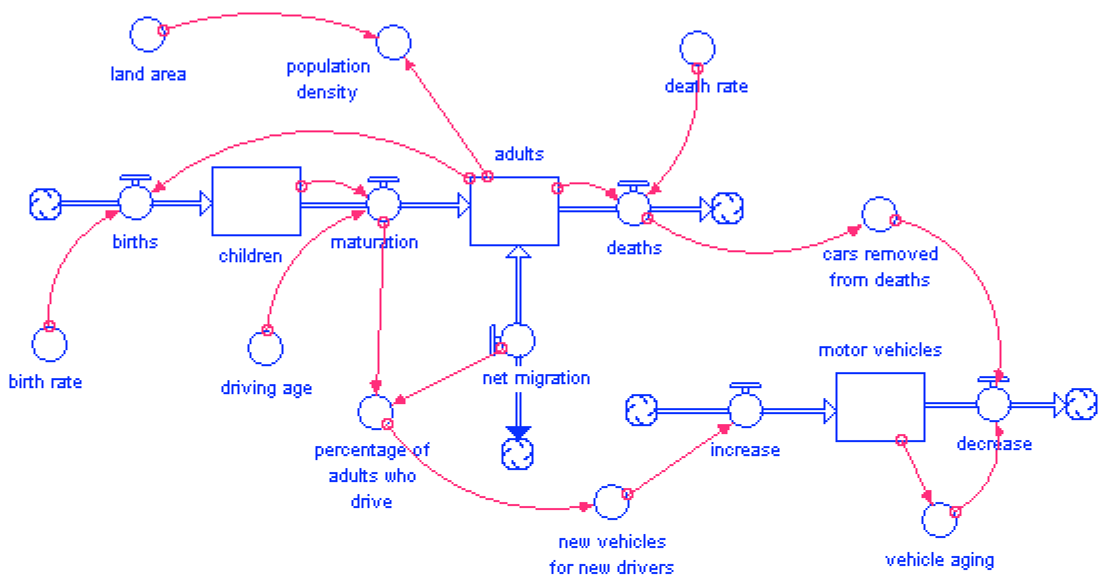

Figure 3. Motor vehicle stock connected to population stock, with maturation from children to adults.

This model created a number of problems, however. The motor vehicle stock decreased sharply until about 2050 without any apparent reason, then increased. I disconnected the parts of the model and let both of the stocks reach equilibrium by having their increases equal their decreases, to ensure that they worked properly. After connecting them by letting population reach equilibrium but letting vehicles increase as originally planned, vehicles increased then decreased steadily. The decrease could only be fixed by massaging the percentage of new vehicles bought by new drivers, the percentage of cars removed from deaths, and the average age of vehicles. Unless the average age of a vehicle was 115 years, the vehicle stock decreased—but then the stock of children decreased without reason.

After setting up a pollution stock and letting it reach equilibrium, I returned to the population-vehicle model and decided that it could be simplified. There was no need for including a stock of children and a maturation flow—a certain percentage of the population is able to drive, which is the same thing as the idea in Figure 3. Therefore I set an arbitrary amount of the population able to drive, a percent (of the ones able to drive) who *do* drive, and a percent (of the ones who do drive) who buy a new vehicle—which accounted for the increase in motor vehicles. This worked properly: population and motor vehicles both showed exponential increase, which was appropriate since there was no carrying capacity in the model. When I set the birth rate equal to the death rate plus the migration rate (which was negative), both population and vehicles reached equilibrium (Figure 4).

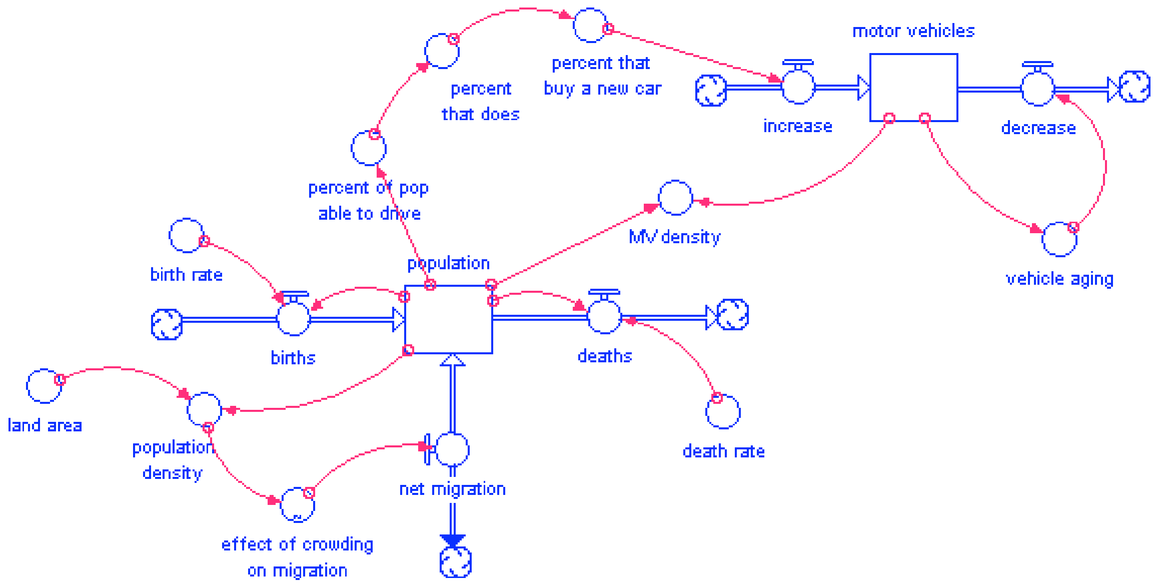

Figure 4. Population connected to motor vehicles in a way similar to that of Figure 2.

After establishing that both population and vehicles worked as they should, I moved on to pollution, deciding to use carbon monoxide. The main problem with this was how to measure pollution, since I had seen it in tonnes, grams, micrograms, percentages, and parts per million. Mr. Guthrie showed me that it should be measured in parts per million per days, and that to find the increase in pollution (with which I had the same problem as vehicles) I should find out how much pollution is emitted per mile, and how far the average commute was. Since pollution emitted per mile depends on average commute and the number of vehicles driven (vehicle stock), I connected the pollution stock with the vehicle stock and, since pollution affects population deaths, I made that connection as well.

When I added a carrying capacity in the form of the effect of population density on the death rate, all three stocks evened out to a steady-state. After adding an effect of pollution on the death rate, all three stocks showed oscillating behavior. The only problem left was to fix the number for pollution emitted per kilometers driven; changing it to the correct number made the carbon monoxide stock increase far too much, while population and vehicles didn't increase at all. So on Mrs. Fisher's suggestion, I added a normal population density and a normal CO concentration, so that the effect of population density and pollution multipliers could compare the normal values (constants) with the actual values (variable); the comparison of normal with actual values provided the "effect of" multipliers.

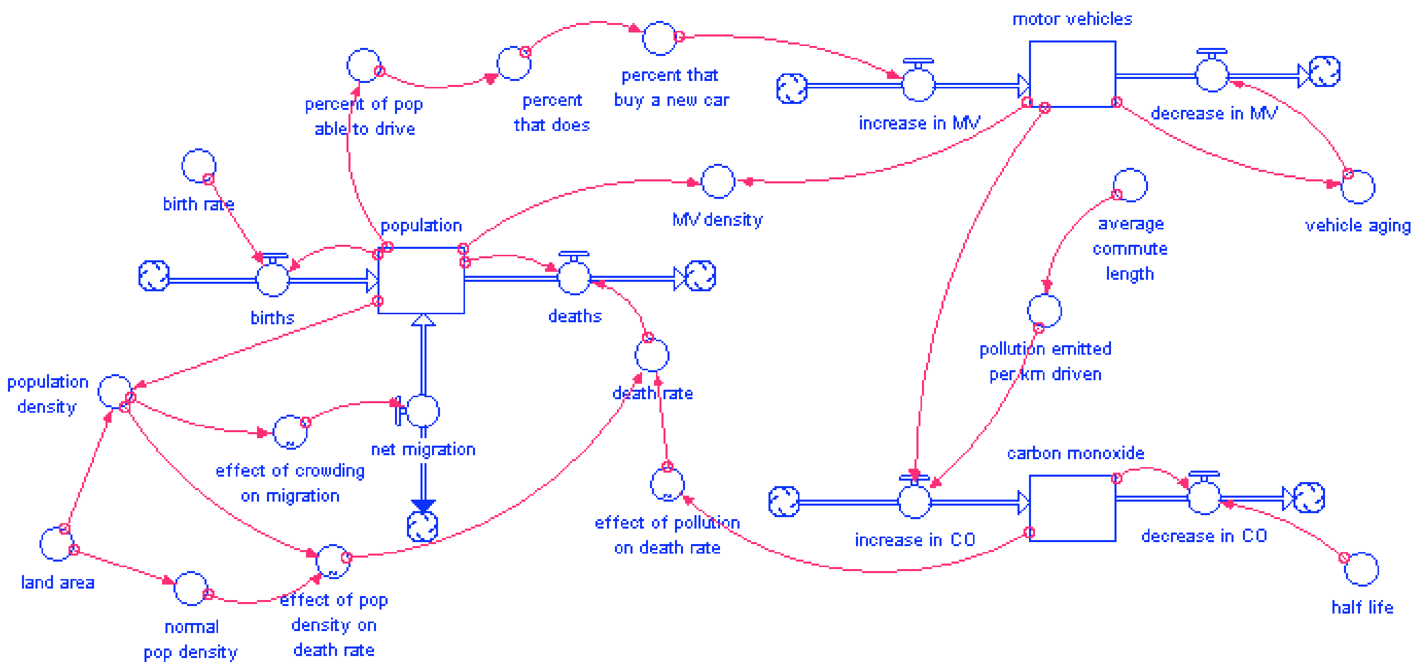

Figure 5. The three stocks connected, before the final fixes.

When I turned this model (Figure 5) in to Mrs. Fisher to be graded, it became apparent that there were still things to be fixed. I had neglected to create ratios comparing normal and actual values for several of the multipliers, which is the correct way to go about it. This was fixed by adding normal rates for the comparison to the effect of pollution on death rate (normal pollution), death rate from pollution (normal death rate), effect of crowding on migration (normal density and migration), and effect of population density on death rate (normal density).

The second major problem was the percent of the population able to drive. By having this be a percent of the population stock, some people were counted more than once (since the stock is cumulative). This was solved by making the part of the population able to drive the difference between those able to drive this year and those able to drive last year.

For another problem, there was a great deal of inconsistency in determining the pollution increase and decrease from the number of motor vehicles. Previously, I had had the average commute length times the pollution emitted per kilometer driven, multiplied by the increase in vehicles; decrease in vehicles connected directly to decrease in pollution. Instead of this, the product of average commute length and pollution emitted per kilometer now determines pollution emitted per kilometer per vehicle per year. This latter value is multiplied by the increase and decrease in vehicles to determine the increase and decrease in carbon monoxide.

After making these major changes, the model is now fairly consistent and its mathematical background makes more sense.

The Finished Model and How It Works

The finished model (Figure 6, next page) is comprised of three parts put together: population, motor vehicles, and carbon monoxide pollution. The relationship between these three stocks and how they interact has been greatly simplified from real life, which is necessary in model building, but it can still be understood fairly easily.

The model is based on the population stock, a measure of how many people (cumulatively) are in the model at any given time. At each time interval, the population increases or decreases with people flowing in and out from the births, deaths, and net migration flows. The birth, death, and migration rates—how many people die, are born, and migrate in or out of the city per thousand people per year—determines the value of the flows into and out of the population stock.

The death rate is affected by several factors, including population density and pollution. Actual population density, the model's calculation of the ratio of the number of people to land in square kilometers, is compared to the normal population density, a constant determined by the initial values of the population stock and land area. This comparison of normal to actual population density generates a number between -2 and 2 that is multiplied by the migration rate. A similar scenario is set up to change the normal death rate. So if the population density gets too large, people will begin to migrate out of the city and the death rate will rise. If the population density becomes smaller, the death rate may not be affected, but people may immigrate into the city.

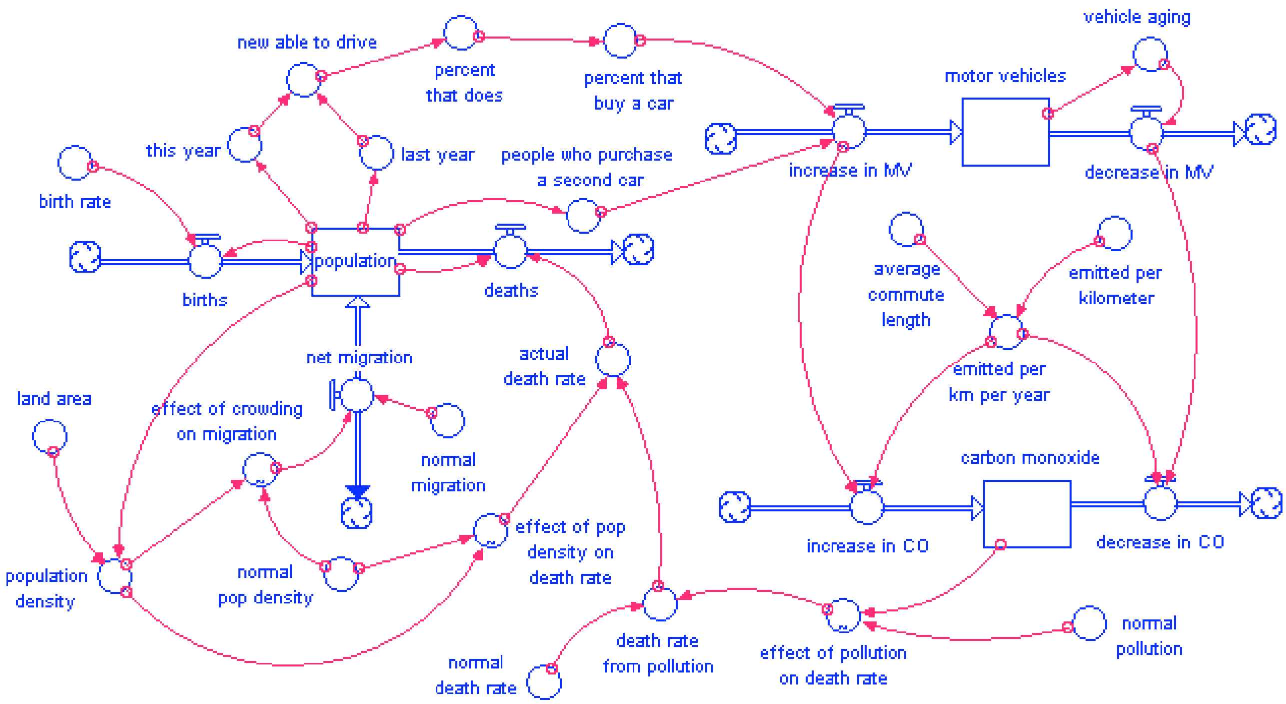

Figure 6. The finished model.

From the population stock, the percent of the population that is able to drive is found by subtracting the percentage of the population that was able to drive last year from the percentage that is able to drive this year. In this way, it is ensured that the same people, since the stock is cumulative, will not be counted more than once. A percentage is taken of those able to drive, which becomes the percent of people who actually do drive; similarly, a percentage of this value is taken to become the percentage of people who buy a vehicle. A small fraction of the population buys a second vehicle.

These last two values determine the increase in motor vehicles. Decrease in motor vehicles is calculated by vehicle aging, a "dwell time," or time that a vehicle stays in the fleet before it becomes obsolete and is junked or sold. In North America, the average lifetime of a car is probably somewhere around five years; in a less developed country, a vehicle's lifetime is more likely to be around fifteen or twenty years. Unfortunately, having an exponential decay rate offsets the linear increase by a great deal, so that vehicle aging must be a small value: consequently, vehicle lifetime becomes an unrealistically high number.

To determine the increase and decrease in carbon monoxide from the vehicle stock, average commute length per year is multiplied by the average pollution emitted per kilometer to find the amount of pollution emitted per kilometer per vehicle per year. This value is multiplied by the increase and the decrease in vehicles, which establishes the carbon monoxide stock.

Completing the model, the population death rate is affected by the concentration of carbon monoxide, as well as by population density. The actual amount of pollution is compared to the normal amount of pollution (which is, again, the initial value of the pollution stock). The death rate from pollution is determined by multiplying the normal death rate by the effect of pollution on death ratio. When there is little carbon monoxide, there is little effect on the death rate; when there is a great deal of pollution, however, the death rate increases.

When taken separately and together, the three parts (the stocks and their corresponding flows and converters) reach equilibrium, the sign that a model is able to work correctly. Though many factors have been left out, the ones included are essential, and though their numerical values may be off target, the simplified mathematical equations behind the visual conceptions make sense both together and separately. There are several ambiguities, however, when changing certain factors, which create problems that make little sense. I am not sure how to fix these problems, nor why they appear, but I am satisfied that the basic model structure makes sense.

The Model Feedback and Loop Story

The feedback loops of the model are fairly straightforward. Each stock—population, motor vehicles, and carbon monoxide—has its own simple reinforcing loop. The birth rate, or increase in the case of vehicles and carbon monoxide, taken with no other factors, causes the stock to increase; the death rate or decrease causes the stock to diminish. In each case the increase is larger than the decrease, indicating positive feedback dominance (i.e., the growing stock creates a greater increase, which makes the stock grow even more).

When the entire model is taken as a whole, it shows counteracting behavior in the latter part of the simulation. Population increases with little bound for the first hundred years or so, but it can only get so large in an area with a fixed amount of land. When the population gets too dense, meaning that the population of vehicles has also increased, pollution from so many vehicles starts to have a noticeable effect on the death rate (Figure 7). The large concentration of carbon monoxide causes people to start dying off. Eventually a steady-state is reached, wherein the increases and decreases of the three stocks are equal (Figure 8).

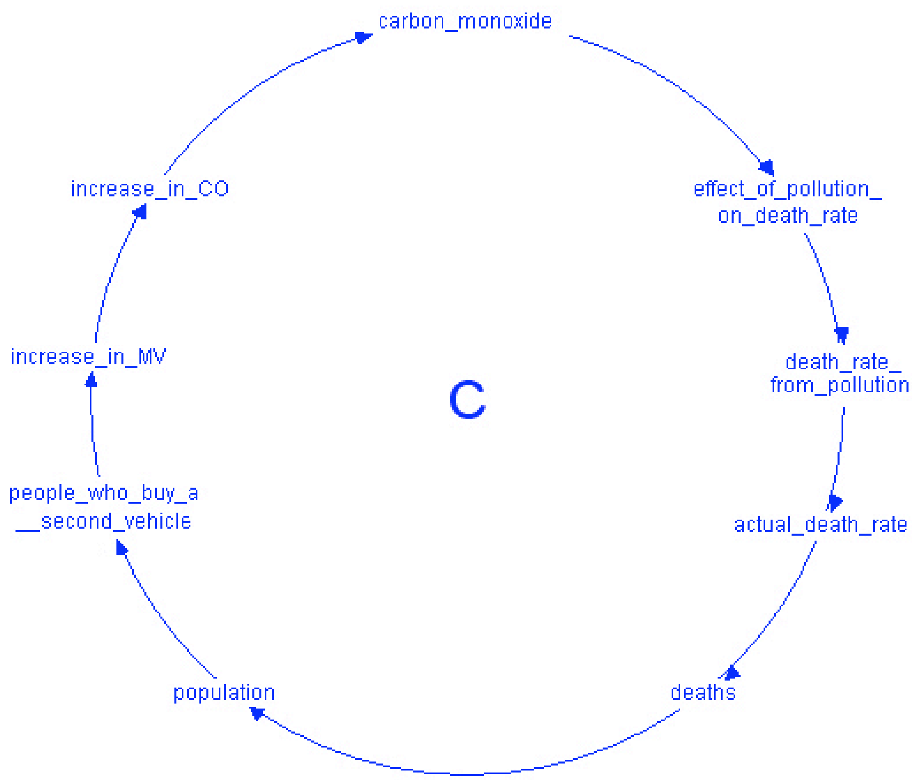

Figure 7. Carbon monoxide and population feedback loop.

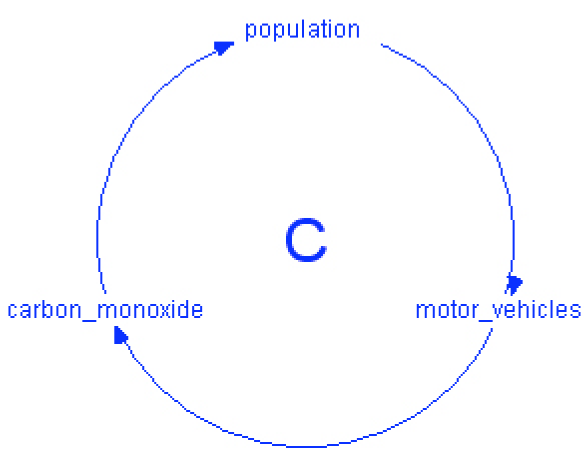

Figure 8. Feedback loop of the whole model.

The Model Boundaries

As has been stated, the model is greatly simplified from real life. Many factors have been left out, the most important being perhaps the fluctuations in pollution concentration that the seasons produce. Carbon monoxide is at its maximum concentration during the winter and at its minimum during the summer; local weather also has a strong effect. I excluded seasonal fluctuations, however, because on the time scale that the model uses, these fluctuations would not be noticeable. In the same manner, there are daily variations in the level of carbon monoxide; there is more during rush hour and less in the mid-afternoon and night. There is no need to include this because it has no noticeable effect over a two-hundred year time span.

I chose to make the time scale in years rather than months or decades because I am more interested in the effect that pollution has on population over the long term. Pollution will act as a carrying capacity (as in this model), where its toxicity sets a limit on the number of humans that a population can support, or it will act as a crisis inducement, where the high level of pollution causes oscillations in all three stocks, as it lowers the population stock to a more reasonable level then, when the population rises again, induces another crisis. It is this behavior that holds more interest for me than seasonal or even daily variations, since that small-scale behavior has little effect on humans in the short term.

Model Testing

Several experiments were made producing sensitivity graphs to further explore the model behavior. Altered values included normal population density (Figure 9), age of the vehicle stock, the number of people who purchase a second vehicle, and average commute length. These factors are all attributes of a city's size and average level of affluence: a large, wealthy city will have many people who buy a second or third vehicle, a long commute length, a dense population, and vehicles that last for only a few years before being sold or junked, which affects pollution levels. A small, poor city, on the other hand, will likely have mostly the opposite values: long vehicle life, a short commute, few vehicles bought past the first, and a dense population.

With all other factors held constant, then, these attributes were tested, producing sensitivity graphs. Depending on whether normal population density was set high or low, the population stock either increased a great deal or decreased a little bit, then came to a steady-state (Figure 9). When vehicle age was small, it caused a pollution crisis, and when vehicles lasted for a very long time, the population was able to increase while pollution decreased (because vehicles lasted longer, fewer of them were purchased). When few people bought a second vehicle, population evened out and pollution decreased (because second vehicles provided a lot of the pollution produced); on the other hand, when a large number of people bought a second vehicle, all three stocks came to equilibrium. Commute length, when it was shorter, let the population increase more, and when it was longer, population began to decrease because of more pollution.

In an affluent society, then, one in which there are a lot of people who buy more than one vehicle and vehicles don't last for long, pollution increases off the chart as population declines. In a poor society, with the opposite conditions, population came to equilibrium while both vehicles and pollution decreased until there were no more left of either one. This last fact is clearly unrealistic, but overall it shows that a culture such as the United States shows unsustainable activity in its demand for vehicles, and that a small community will likely not be overwhelmed by deaths from pollution unless they live in proximity to a large consumer society.

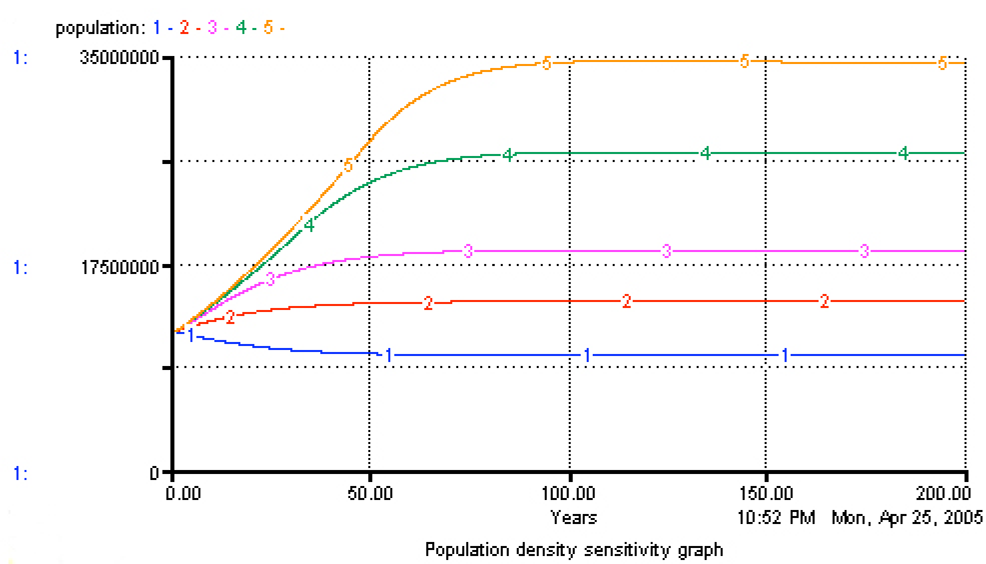

Figure 9. Population: (1) 10,000 people/km²; (2) 15,000; (3) 20,000; (4) 30,000; (5) 40,000.

The Results of Modeling and Thinking

Using the graph and table features of a model are essential to gaining understanding of a model. At one point in the development of the model, the carbon monoxide stock was decreasing very sharply on the graph, and I didn't know why. With the help of the tables, I found that not only was the decrease in pollution much larger than its increase, but that the effect of crowding on migration was fluctuating strangely. It turns out that I had made mistakes in setting the graphical function of the multiplier, and that the large decrease in pollution was due to the fact that the decrease in vehicles is exponential and the increase in vehicles is linear. To fix the latter problem, I added a converter to the effect that some people purchased a second vehicle, since there are affluent people in every society that are able to buy more than one vehicle.

At another point, there were some very strange oscillations with a very small period in the graph of pollution. This was a mystery until I looked at the tables and saw that there were zeros in random places in many of the flows and multipliers. Again, this was due to mistakes in the graphical functions, which I was able to fix easily. To wit, the graphs and tables were very useful in finding errors in the model's structure and in understanding why the model behaved as it did.

The final graph (Figure 10, next page) shows the three stocks, population (1), motor vehicles (2), and carbon monoxide (3). With relatively little pollution in the beginning, the population increases, as do motor vehicles, since more people will want more vehicles. This produces a great deal more pollution, which causes the death rate to increase enough so that it is approximately equal to the birth rate. This is when the population levels off, at around fifty years, and with a fairly constant population, the vehicle stock stays constant as well. With no more vehicles being produced, pollution begins to increase less and less until it almost reaches equilibrium. With the high level of pollution, however, the death rate becomes just barely larger than the birth rate, and population starts to decrease very slightly. If the graph continued past two hundred years, slight oscillations caused by small pollution crises would be apparent. If the level of pollution were a great deal higher, the oscillations would occur sooner and would be more obvious; however, in the final scenario, they are very small.

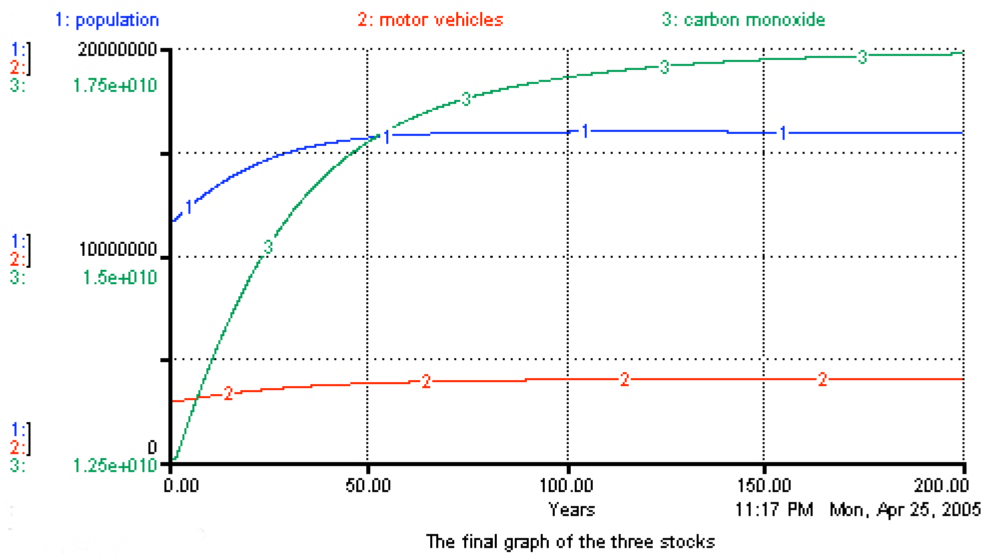

Figure 10. The final graph of the three stocks. Notice that carbon monoxide is on a different scale.

The final table (Figure 11) is even more telling in the story of the model. As stated, in the beginning there are many more births than deaths, until both they and the increase and decrease in vehicles and pollution comes to a steady-state in which the increase (almost) equals the decrease. As the city gets denser (last column), people migrate out and the death rate gets higher.

11:21 PM Mon, Apr 25, 2005 Table 1 (The major stocks and flows)

Years	births	deaths	increase in MV	decrease in MV	increase in CO	decrease in CO	net migration	actual death rate	population density
.0	246,897.08	67,880.42	59,598.24	56,956.04	260,480,048.27	248,932,050.36	-7.003454e-005	5.810000e-003	17,026.59
10.0	280,122.63	147,148.14	89,409.83	62,653.24	390,774,595.25	273,832,235.46	-7.606803e-005	0.011134	19,323.05
20.0	303,551.39	214,611.69	87,229.02	67,313.18	381,243,154.05	294,198,976.69	-8.032251e-005	0.015001	20,943.22
30.0	318,648.41	263,490.34	84,825.38	70,693.36	370,737,811.68	308,972,410.56	-8.306400e-005	0.017553	21,987.63
40.0	327,774.41	295,314.74	82,948.62	73,069.63	362,535,244.57	319,358,142.86	-8.472121e-005	0.019131	22,619.13
50.0	333,048.75	314,656.57	81,687.25	74,733.84	357,022,301.17	326,631,721.69	-8.567899e-005	0.020064	22,984.17
60.0	335,994.32	325,897.31	80,901.61	75,914.84	353,588,591.67	331,793,400.42	-8.621388e-005	0.020600	23,188.07
70.0	337,588.10	332,227.21	80,431.13	76,771.03	351,532,295.77	335,535,465.41	-8.650330e-005	0.020902	23,298.41
80.0	338,418.66	335,698.32	80,154.61	77,406.38	350,323,727.72	338,312,316.88	-8.665412e-005	0.021069	23,355.93
90.0	338,827.81	337,548.03	79,993.09	77,888.12	349,617,820.20	340,417,828.47	-8.672842e-005	0.021159	23,384.27
100.0	339,009.54	338,495.91	79,898.54	78,260.08	349,204,566.30	342,043,513.99	-8.676142e-005	0.021208	23,396.87
110.0	339,072.13	338,951.34	79,842.69	78,551.42	348,960,449.47	343,316,831.97	-8.677279e-005	0.021232	23,401.22
120.0	339,075.08	339,143.76	79,809.19	78,782.10	348,814,057.51	344,325,036.78	-8.677332e-005	0.021244	23,401.43
130.0	339,050.54	339,200.12	79,788.68	78,966.21	348,724,418.60	345,129,721.36	-8.676887e-005	0.021249	23,399.75
140.0	339,015.47	339,189.70	79,775.79	79,114.01	348,668,068.26	345,775,672.46	-8.676250e-005	0.021251	23,397.33
150.0	338,978.46	339,149.66	79,767.43	79,233.13	348,631,535.74	346,296,324.97	-8.675578e-005	0.021251	23,394.77
160.0	338,943.60	339,099.38	79,761.83	79,329.43	348,607,040.08	346,717,191.98	-8.674945e-005	0.021250	23,392.37
170.0	338,912.58	339,048.56	79,757.94	79,407.42	348,590,042.05	347,058,082.19	-8.674382e-005	0.021249	23,390.22
180.0	338,885.86	339,001.66	79,755.15	79,470.69	348,577,855.82	347,334,579.75	-8.673896e-005	0.021247	23,388.38
190.0	338,863.28	338,960.39	79,753.09	79,522.05	348,568,861.95	347,559,065.64	-8.673486e-005	0.021246	23,386.82
Final								0.021245	23,385.52

Figure 11. Increase and decrease of the three stocks, as well as the actual death rate and population density.

Learning From the Modeling Process

Computer modeling is not a direct means to a well-defined end: it is during the process that understanding of the situation that one is trying to model is gained. The process of model-building, in fact, is meant to make the builder realize the complexity of the situation, and in attempting to discover a way to construct a simulation of real life on a computer, real learning is achieved. A model does not always work correctly, nor does it need to, in the end; it is the understanding of how to build a model and understanding the dynamics of the model that is important. My model of vehicular pollution didn't come out quite the way I expected, but as the first model that I have constructed independently of a class assignment, I learned a great deal about how to use the STELLA software to build a model, and about the ways in which pollution interacts with the environment. I learned:

- That dimensionless multipliers (i.e., the "effect of…" converters) use a ratio, that is, a normal value compared to an actual value, instead of simply the actual value itself. This way, instead of making the axes of the graphical function custom-made, which has to be adjusted for changes in the model, the axes can be a great deal smaller and they don't have to be constantly adjusted. I had learned this before, but never really understood why until I made the mistake of not creating ratios.
- That having consistent units in a model is very important. When I tried to come up with a way to convert vehicles to pollution, the model didn't work until vehicles were multiplied by the pollution emitted per kilometer per vehicle per year to create an increase and decrease in pollution.
- How to properly use and distinguish between dwell time, growth and decay rates, and linear flows versus exponential flows. Dwell time, an exponential flow, is used for the decrease in motor vehicles, while the increase in vehicles is a direct linear flow, the percentage of people who buy vehicles. This means that the motor vehicle stock does not show much growth. Rates, on the other hand, are used in the population part of the model for the birth and death rates.
- The importance of using the tables and equations to find problems (see also *The Results of Modeling and Thinking*). Before building this model, it had never occurred to me that tables had much use; however, in the building process, I used them to gain understanding of several problems in the model structure, which enabled me to fix

the problems. Looking over the equations, as well, I was able to see that not all of the model parts had units, or had issues in the mathematical equations.

- How to create an interface, using the Stella software fully. As a first-year student of systems dynamics, the most important part of learning the software was building simple models, not making the models user-friendly. This model, however, gave me the opportunity to begin to learn the intricacies of the software, and I look forward to continuing this in the future.
- That simplifying real life into a computer model isn't nearly as easy as it would seem. In the very beginning of this project, when I didn't know quite what I was supposed to be doing, I had grand ideas of making models that would (I now know) be very difficult to build. Even the way pollution kills people off is a great deal more complex than I first imagined.
- That there are many more factors affecting pollution than I had ever imagined. For example, I learned that the Valley of Mexico itself obstructs dispersal of pollution, creating a toxic smog that gives fully half the area's children respiratory problems. Vehicular pollution is mainly caused by obsolete technology, inefficient and leaded fuel, traffic congestion, and road conditions, all of which are tied together in a complex web of causation. All over the world, many of these problems have been slightly alleviated, but are offset by suburbanization increasing commute distance and road length; in other words, cleaner vehicles are counterbalanced by increased vehicle use. As dependence on vehicles increases, fuel consumption rises exponentially because of congestion and inefficiency.

Has the question of the pending vehicular pollution crisis then been answered? As I have emphasized, the point of model-building lies not in gaining an answer, but in gaining understanding of the question at hand. Though my model shows sigmoid growth, I believe (having learned from my research and model-building) that vehicular pollution is ultimately undesirable and will likely lead to overshoot or oscillation. As long as we understand the problem, we can work towards a solution. This model may be a good starting place for adding policies and other factors, but right now that is outside its scope. It has successfully helped me—as for what will happen in several hundred years, only time will tell.

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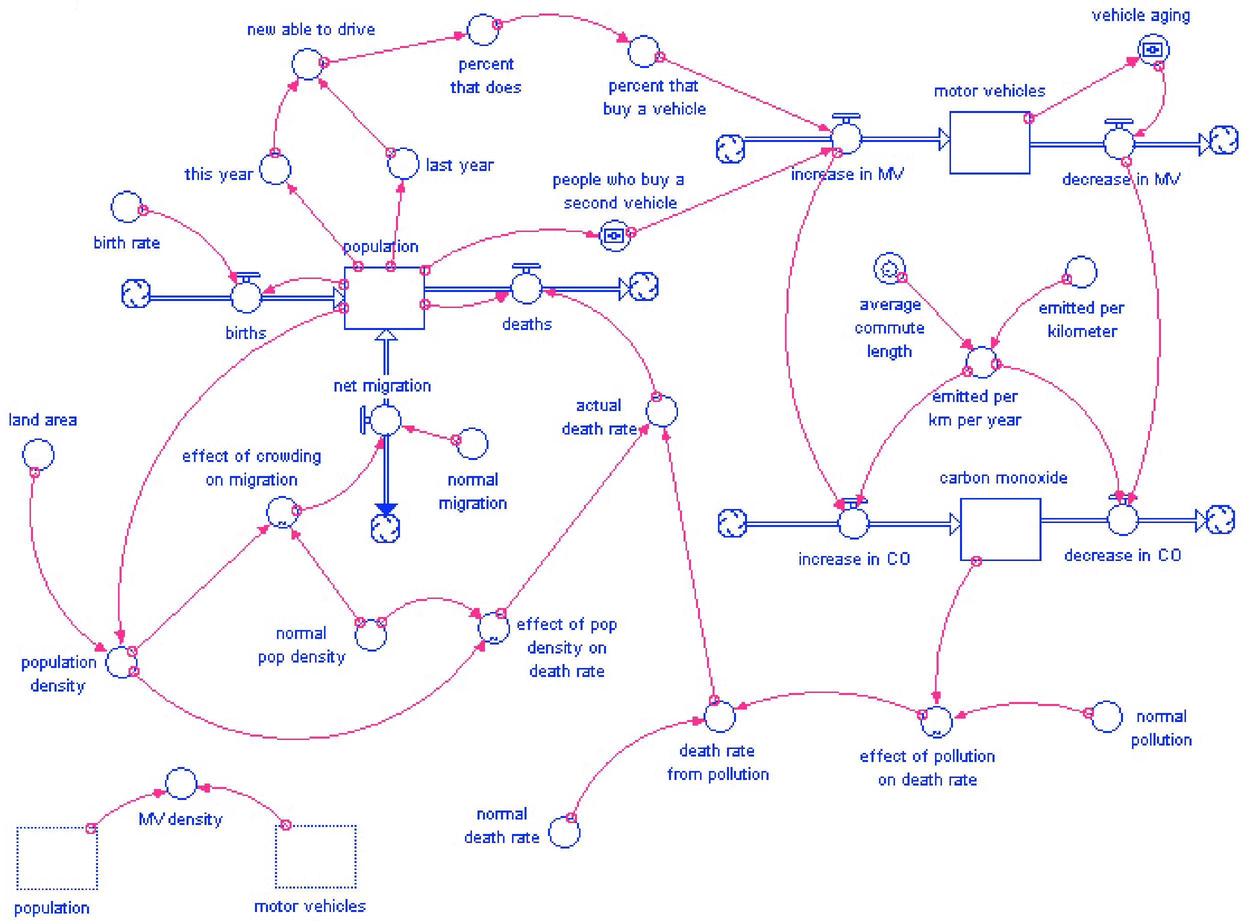
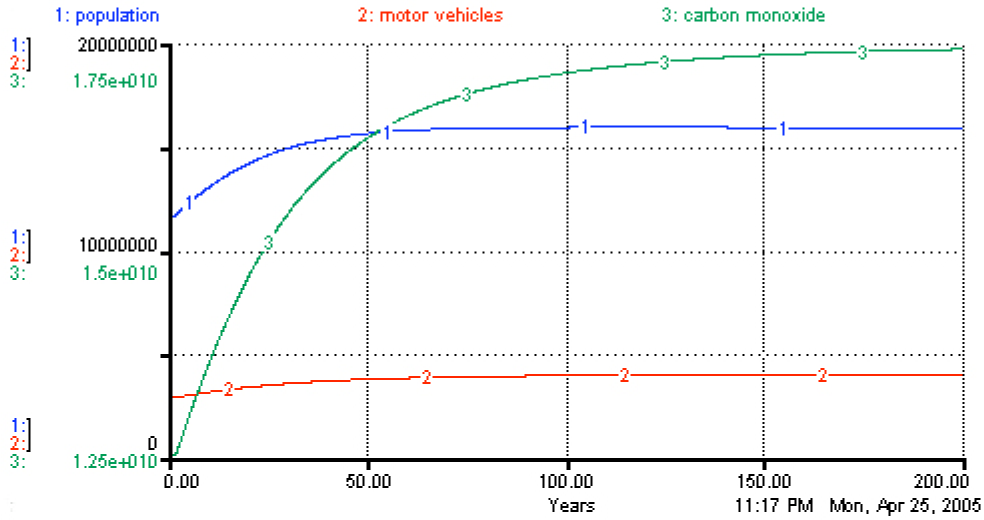
Appendix A: Equations

Omitted

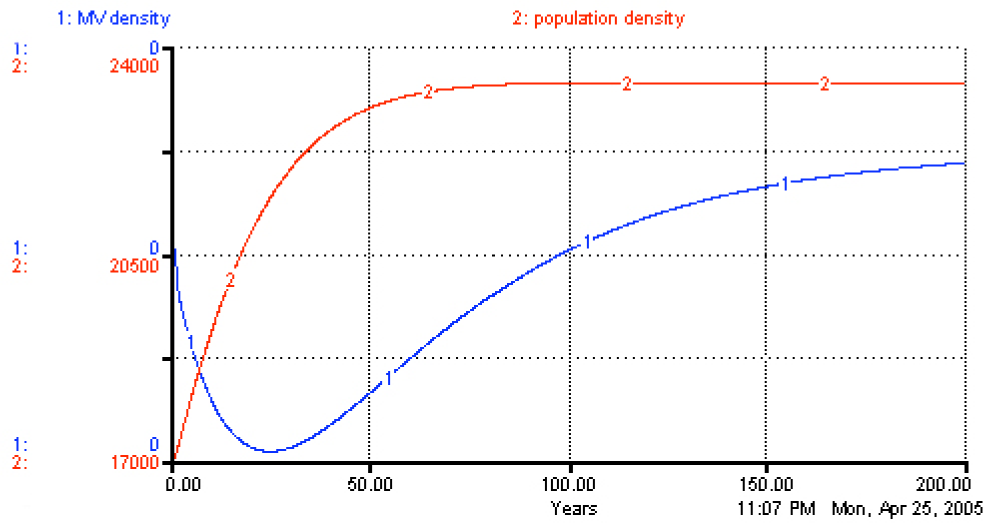
Appendix B: The Model Diagram



Appendix C: Graphs



The final graph of the three stocks



Motor vehicle and population density

Appendix D: Tables

11:44 PM Mon, Apr 25, 2005 Table 2 (Stocks

Years	population	motor vehicles	carbon monoxide
.0	11,615,202.00	2,847,695.00	12,500,452,556.30
10.0	13,181,795.15	3,131,342.39	13,740,161,828.88
20.0	14,287,046.58	3,364,675.39	14,759,967,032.85
30.0	14,999,518.80	3,533,969.11	15,499,882,170.06
40.0	15,430,315.87	3,652,992.19	16,020,084,455.64
50.0	15,679,340.59	3,736,346.83	16,384,394,226.13
60.0	15,818,436.32	3,795,494.02	16,642,902,939.15
70.0	15,893,710.19	3,838,369.21	16,830,293,270.93
80.0	15,932,945.67	3,870,181.84	16,969,333,547.13
90.0	15,952,280.88	3,894,301.03	17,074,748,852.05
100.0	15,960,875.47	3,912,922.22	17,156,134,634.69
110.0	15,963,841.77	3,927,506.38	17,219,876,187.85
120.0	15,963,990.20	3,939,053.51	17,270,344,059.89
130.0	15,962,838.99	3,948,269.39	17,310,622,969.73
140.0	15,961,188.82	3,955,667.15	17,342,955,636.41
150.0	15,959,446.25	3,961,629.83	17,369,016,132.24
160.0	15,957,804.38	3,966,449.68	17,390,081,767.93
170.0	15,956,343.05	3,970,353.59	17,407,144,191.01
180.0	15,955,083.86	3,973,520.05	17,420,983,520.43
190.0	15,954,020.07	3,976,090.86	17,432,219,504.37
Final	15,953,132.58	3,978,179.47	17,441,347,993.43

11:47 PM Mon, Apr 25, 2005 Table 3 (Flows)

Years	births	deaths	increase in MV	decrease in MV	increase in CO	decrease in CO	net migration
.0	246,897.08	67,880.42	59,598.24	56,956.04	260,480,048.27	248,932,050.36	-7.003454e-005
10.0	280,122.63	147,148.14	89,409.83	62,653.24	390,774,595.25	273,832,235.46	-7.606803e-005
20.0	303,551.39	214,611.69	87,229.02	67,313.18	381,243,154.05	294,198,976.69	-8.032251e-005
30.0	318,648.41	263,490.34	84,825.38	70,693.36	370,737,811.68	308,972,410.56	-8.306400e-005
40.0	327,774.41	295,314.74	82,948.62	73,069.63	362,535,244.57	319,358,142.86	-8.472121e-005
50.0	333,048.75	314,656.57	81,687.25	74,733.84	357,022,301.17	326,631,721.69	-8.567899e-005
60.0	335,994.32	325,897.31	80,901.61	75,914.84	353,588,591.67	331,793,400.42	-8.621388e-005
70.0	337,588.10	332,227.21	80,431.13	76,771.03	351,532,295.77	335,535,465.41	-8.650330e-005
80.0	338,418.66	335,698.32	80,154.61	77,406.38	350,323,727.72	338,312,316.88	-8.665412e-005
90.0	338,827.81	337,548.03	79,993.09	77,888.12	349,617,820.20	340,417,828.47	-8.672842e-005
100.0	339,009.54	338,495.91	79,898.54	78,260.08	349,204,566.30	342,043,513.99	-8.676142e-005
110.0	339,072.13	338,951.34	79,842.69	78,551.42	348,960,449.47	343,316,831.97	-8.677279e-005
120.0	339,075.08	339,143.76	79,809.19	78,782.10	348,814,057.51	344,325,036.78	-8.677332e-005
130.0	339,050.54	339,200.12	79,788.68	78,966.21	348,724,418.60	345,129,721.36	-8.676887e-005
140.0	339,015.47	339,189.70	79,775.79	79,114.01	348,668,068.26	345,775,672.46	-8.676250e-005
150.0	338,978.46	339,149.66	79,767.43	79,233.13	348,631,535.74	346,296,324.97	-8.675578e-005
160.0	338,943.60	339,099.38	79,761.83	79,329.43	348,607,040.08	346,717,191.98	-8.674945e-005
170.0	338,912.58	339,048.56	79,757.94	79,407.42	348,590,042.05	347,058,082.19	-8.674382e-005
180.0	338,885.86	339,001.66	79,755.15	79,470.69	348,577,855.82	347,334,579.75	-8.673896e-005
190.0	338,863.28	338,960.39	79,753.09	79,522.05	348,568,861.95	347,559,065.64	-8.673486e-005
Final							

11:49 PM Mon, Apr 25, 2005 Table 4 (Densities and multipliers)

Years	actual death rate	MV density	population density	effect of crowding on	effect of pollution on	effect of pop density
.0	0.01	0.25	17,026.59	1.00	1.00	1.00
10.0	0.01	0.24	19,323.05	1.09	1.01	1.89
20.0	0.02	0.24	20,943.22	1.15	1.03	2.52
30.0	0.02	0.24	21,987.63	1.19	1.03	2.92
40.0	0.02	0.24	22,619.13	1.21	1.04	3.17
50.0	0.02	0.24	22,984.17	1.22	1.04	3.31
60.0	0.02	0.24	23,188.07	1.23	1.05	3.39
70.0	0.02	0.24	23,298.41	1.24	1.05	3.43
80.0	0.02	0.24	23,355.93	1.24	1.05	3.45
90.0	0.02	0.24	23,384.27	1.24	1.05	3.46
100.0	0.02	0.25	23,396.87	1.24	1.05	3.47
110.0	0.02	0.25	23,401.22	1.24	1.05	3.47
120.0	0.02	0.25	23,401.43	1.24	1.05	3.47
130.0	0.02	0.25	23,399.75	1.24	1.05	3.47
140.0	0.02	0.25	23,397.33	1.24	1.05	3.47
150.0	0.02	0.25	23,394.77	1.24	1.05	3.47
160.0	0.02	0.25	23,392.37	1.24	1.05	3.47
170.0	0.02	0.25	23,390.22	1.24	1.05	3.47
180.0	0.02	0.25	23,388.38	1.24	1.06	3.47
190.0	0.02	0.25	23,386.82	1.24	1.06	3.47
Final	0.02	0.25	23,385.52	1.24	1.06	3.46