A Proactive Approach for Particulate Matter Air Pollution Management

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Abstract

This paper analyzes the management approach used in the Las Vegas Valley to manage particulate matter (PM) pollution, demonstrates that system dynamics concepts can improve the current strategy, and proposes a more proactive approach to management. A retroactive policy analysis, beginning in 1960, was performed to analyze the benefits and tradeoffs of using a system dynamics approach. The analysis showed that including a system dynamics perspective improves the utility of the model for policy analysis. Analysis supports the hypothesis that a proactive approach to management could have prevented PM exceedances in the Valley, and provides greater flexibility in managing the problem, but in some cases may have prohibitively high initial and/or sustained costs.

Keywords: air quality management, proactive management, reactive management, particulate matter, air pollution, rapidly growing urban areas, sustainable development

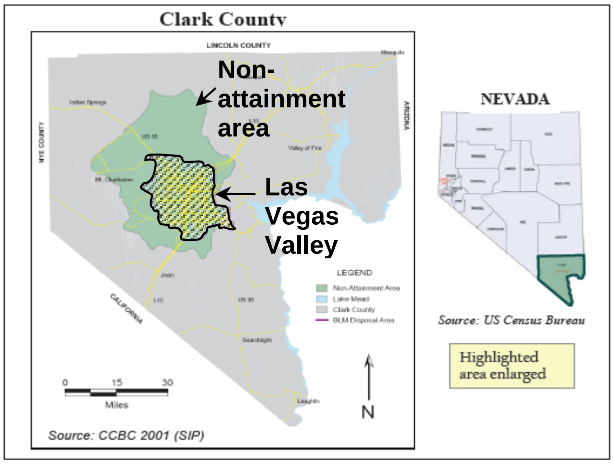
I. Problem Statement

Introduction

Although the Clean Air Act (CAA) of 1970 has led to improvements in air quality over the past few decades, problems with air pollution and air quality management still exist (National Research Council [NRC] 2004, EPA-4 2003). The concentrations of pollutants throughout the United States on average have decreased, but in some areas concentrations remain above standards (NRC 2004). Air quality management in the U.S. is often characterized by a short-term perspective that focuses on meeting CAA requirements. Additionally, since the system is constantly changing -- politically, socially, and physically -- managers often find themselves in a situation of crisis-management. As we have learned through many applications of system dynamics, such situations can lead to counter-intuitive behavior (Forrester 1995, Sterman 2000).

One troublesome element of current air quality management is particulate matter pollution, ten micrometers (10µm) or smaller in diameter (Environmental Protection Agency [EPA] 1996B, EPA 2004, Department of Air Quality and Environmental Management [DAQEM] FAQ). PM consists of extremely small solid or liquid particles, made up of a great variety of minerals and chemicals (EPA 1996B, EPA-4 2003, EPA 2004, DAQEM). Over 300 counties did not meet PM standards when standards were first established in 1971 (Chay, Dobkin, and Greenstone 2003). In 1992, the Environmental Protection Agency (EPA) changed the status of eight nonattainment areas from moderate to serious (EPA-10 2007). In 2006, there were still eight serious nonattainment areas for PM_{10} and over 75 moderate nonattainment areas across the United States (NRC 2004, EPA-10 2007).

Figure 1 Map of Clark County, Nevada



Source: CCBC 2001 (SIP)

Source: US Census Bureau

In this study, we use the case of particulate matter pollution in the Las Vegas Valley (LVV) to examine the benefits of using system dynamics for policy making. The LVV, located within Clark County, Nevada as shown in Figure 1, may have local geologic, geographic and meteorological characteristics reinforcing PM pollution problems in the area, and rapid urban development has played a key role in creating the problem that has plagued the area for over 30 years. The current management approach in Clark County has been focused on responding to changes in legislation and growth in the area, leading to the trends described in the following section.

PM Trends in the LVV

The current national standard requires that PM_{10} concentrations not exceed an average of 150 micrograms per cubic meter ($\mu g/m^3$) in any 24-hour period (EPA 2004, NRC 2004)[1]. Monitored concentrations above this limit are called "exceedances," (EPA-7 1999). An area with regular exceedences is considered to be a non-attainment area (NRC 2004, Kubasek and Silverman 2005, EPA-7 1999). In 1993, the LVV was declared a serious non-attainment area (CCBC 2001).

Figure 2 shows the reference mode of historic and projected PM_{10} concentrations in the LVV. The trends show PM_{10} levels exceeding standards for several years but presently on a downward trend that should stabilize in the future. These concentrations are based on both monitoring data as well as estimates in EPA documents (Fed. Reg. 69:54006, 2004). Even though trends currently show a decrease and may drop below standards in the near future, the long history of PM_{10} management problems provides an excellent case for examining air quality management in rapidly growing areas.

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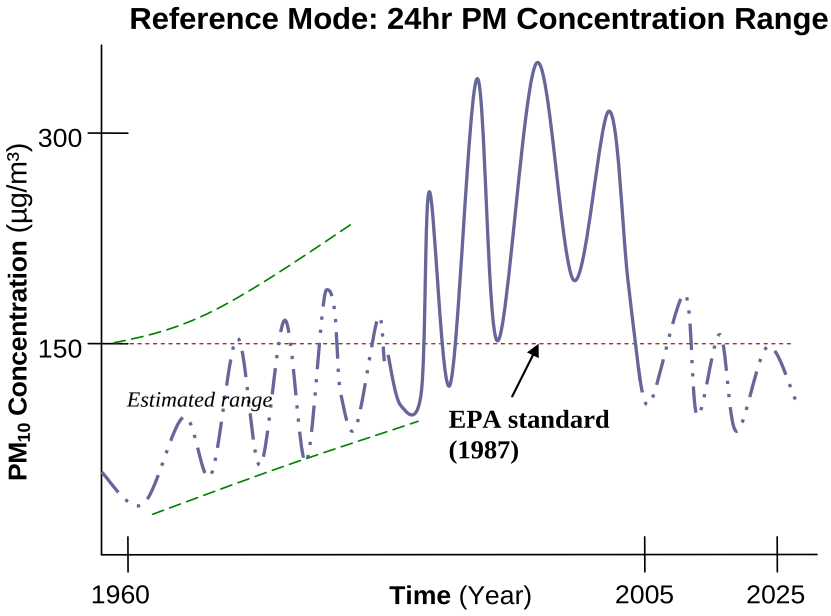
[1] The annual standard was recently discarded by the U.S. Environmental Protection Agency (EPA) for lack of sufficient evidence relating long term average concentrations to significant health effects (EPA-8 2006).

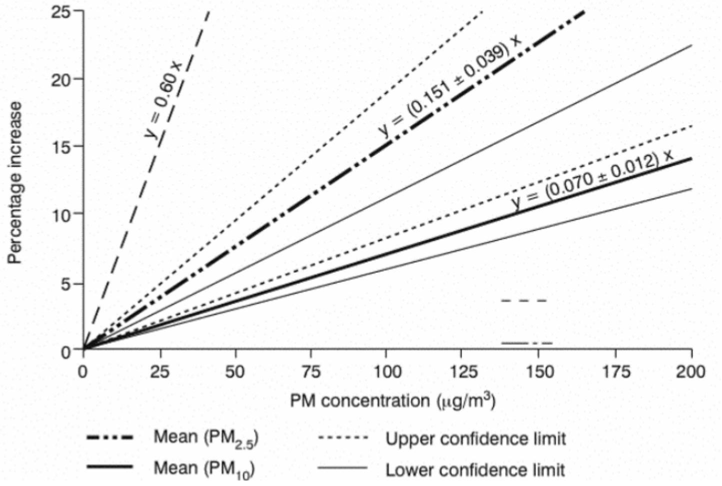
Figure 2 Reference Mode for PM_{10} 24-hour Standard



PM Impacts

In 2003, 97 counties in the U.S. had monitored levels of PM pollution above either the PM_{10} or $PM_{2.5}$ standards or both—this represents 62 million people exposed to very unhealthy levels of PM pollution (EPA-4 2003). PM_{10} particles are inhaled into the lungs where they accumulate in the bronchia and can cause increased incidence of coughing, painful breathing, and decreased lung function, aggravation and increased potency of pre-existing respiratory conditions (e.g. asthma), increased absences from work and school, area-wide increased hospital admissions and emergency room visits, and premature death (CCBC 2001, EPA-2 2003, EPA-4 2003, Lippmann 2003).

Figure 3 Increases in Daily Mortality Based on PM Pollution



Source: Schwela 2003

Significant epidemiological evidence has demonstrated that that the dose-response curve for mortality is linear as shown in Figure 3 and there is no threshold for PM_{10} (Schwela 2003). Less severe health effects have an even steeper relationship and are much more likely to occur. Any change in PM_{10} pollution poses considerable consequences for human health (Schwela 2003).

PM can also cause aesthetic deterioration to an area through haze, reduced visibility, and physical damage to building surfaces (EPA-4 2003). Degradation of vegetation and entire ecosystems can also be caused by PM pollution (EPA-4 2003). Exceeding federal PM_{10} standards can be very costly in terms of increased procedural burdens, potential loss of federal highway funds, and forced adoption of increasingly expensive (some with marginal benefits) control strategies.

PM_{10} pollution is not unique to the United States. It is a problem being faced by many countries, especially rapidly-developing areas (McGranahan 2003). While other air pollutants are very dangerous to human health, both cohort studies and time-series studies have concluded that premature deaths from air pollution are caused predominately by PM as opposed to other criteria pollutants (Molina and Molina 2004).

Current Management Strategies for PM

There has been little improvement in non-attainment areas, indicating either persistent problems in these areas or insufficiencies in the current management strategy. The general management strategy for air quality includes the development of a state implementation plan (SIP) when an area exceeds standards. SIPs describe the non-attainment area's characteristics, present monitoring data, detail emission sources, and describe any mitigating actions or controls an area will implement to stay below standards (EPA-3, Plater *et al.* 1998, NRC 2004). Although standards will inevitably change, managers tend to respond to new regulations as they occur instead of planning for continual air quality improvement and anticipating those changes. Standards have typically become more stringent with time (NRC 2004, EPA 2004), yet air quality goals in most areas are usually set at these levels and not below (NRC 2004).

Therefore, when standards are changed, a crisis-management situation is sparked—managers rush to complete new documents and requirements while attempting to simultaneously lower emissions. Coupling this with the fact that air quality systems are slow to change (both due to chemical and physical inertia and to the time necessary to develop, implement, and enforce new regulations on industry and individuals), the result is often that a given area is classified as a non-attainment area. This paper proposes that a system dynamics approach could help managers anticipate changes in standards, develop more proactive management strategies, and potentially avoid non-attainment classification.

Proportional Rollback Model

The Clark County Department of Air Quality and Environmental Management (DAQEM) developed a model in support of the 2001 SIP for demonstrating that PM_{10} in the LVV would be below standards for the year 2006. The major limitations of the original format of the model are detailed in Fincher and Stave (2006) and include a fragmented structure, a manual and error-prone process for running policy analysis, limited policy options, static representation of causes (usually exogenous), unclear representation of controls and other calculation, and exclusion of several significant mechanisms.

The model is an empirical rollback model, using observed relationships between pollutant concentrations and emissions and not representing many chemical and physical processes causing pollutant levels (NRC 2004). Functionally, the original model consisted of a series of independent spreadsheets that required manually copying and pasting calculations from one sheet to another. The newer version developed in Fincher and Stave (2006) has a more user-friendly, explicit, and integrated context, although it still relies on the original underlying assumptions and calculation methodology to determine emissions.

To determine 24-hour emissions the model uses a "design day". The design day is defined as a day with normal conditions (i.e. wind speeds are assumed to be low and there is no precipitation). The model does not calculate PM_{10} levels on different days and so does not represent a continuous trend in emissions but rather shows how conditions on the one representative day would change in response to policy changes.

Figure 4 Causal Loop Diagram (CLD) of DAQEM Proportional Rollback Model

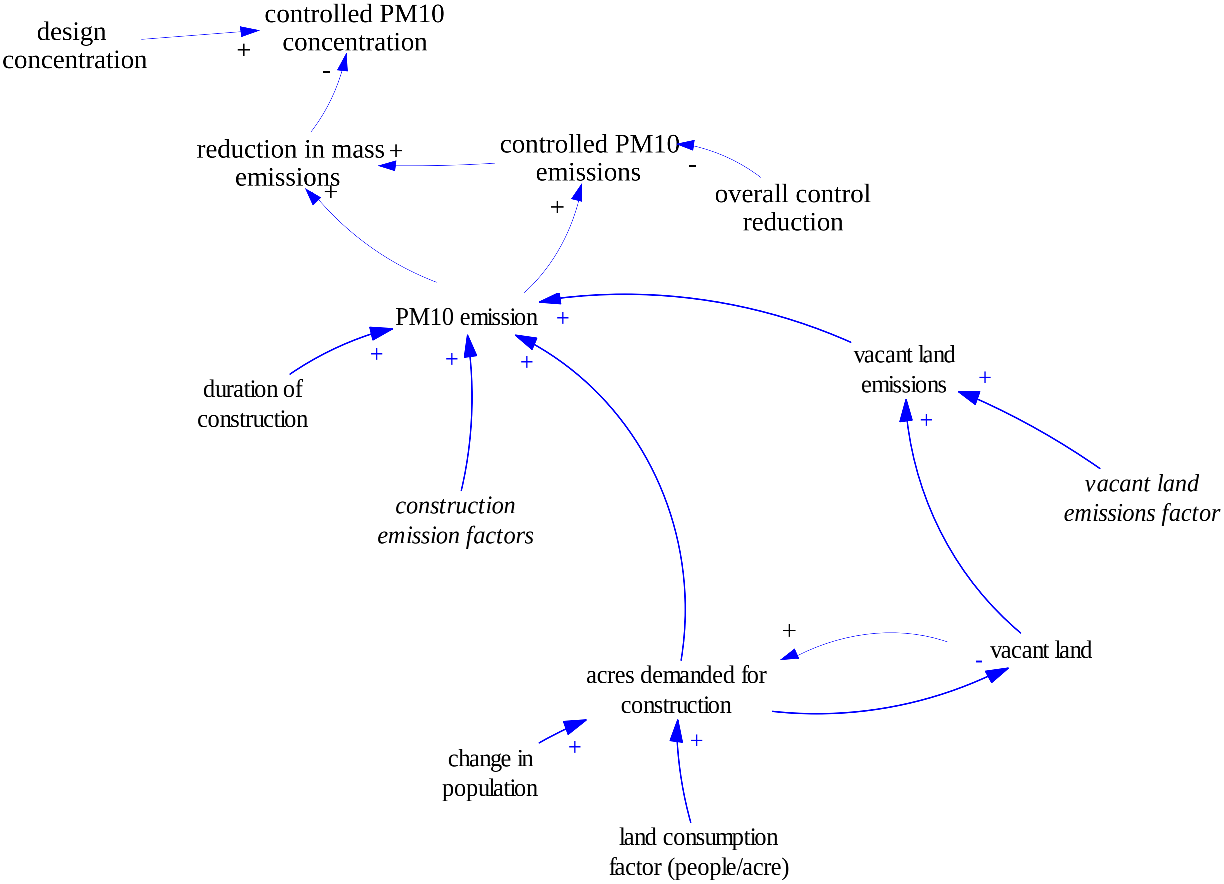


Figure 4 shows the causal loop diagram representing the structure of the Proportional Rollback Model. The major driver of emissions is population (an exogenous input table). Increases in population increase the number of acres in construction and thus raise emissions from construction activities. Balancing emissions and construction is the depletion of vacant land over time. As the amount of vacant land decreases, land-based emissions decrease, which decreases total emissions.

Fincher and Stave (2006) describes how the Proportional Rollback Model structure was converted into a system dynamics representation. The main purpose of the Proportional Rollback Model is to determine the concentration that would result from an already designed policy. Although alternative policies could be tested to determine the preferred choice, the model was not designed to be used for policy development. The major limitations of this model for policy analysis included restricted policy options, a short time horizon, high sensitivity and poor response to extreme tests (and even many reasonable policy changes). Results do not provide a context for understanding the given concentration and how policies are affecting pollution with time.

This paper shifts the focus to exploring the benefits of using a system dynamics approach for managing PM_{10}. A system dynamics model was developed for the case of PM_{10} in the Las Vegas Valley, as described in the following section. It was hypothesized that a system dynamics approach would allow a better representation of feedback, more policy testing and evaluating assumptions, and help managers better understand the system instead of focusing on point estimates. The paper describes the model development and hypothesis testing.

II. Model Development

Physical Site Characteristics

The non-attainment area of the Las Vegas Valley covers roughly 4,000 km^2 (DRI 2002). There is great diversity of land classifications and uses in the area, which causes a variety impacts on air quality. Valleys often have more persistent and problematic air pollution issues than areas without mountains (CDSN and DAQEM 2003), since mountains act as physical barriers, trapping air and thereby slowing dispersion of pollutants (Spellman 1999). DAQEM estimates that particles are settle within four kilometers of their sources (CDSN and DAQEM 2003, EPA-4 2003). PM_{10} travels relatively short distances, ranging from <1 to ten kilometers (Lippmann 2003).

The LVV has distinct seasons and strong winds. Winter and spring winds affect large areas while summer winds have more localized effects (Gorelow 2005). Wind both removes particulate matter from and adds it to land surfaces (CDSN and DAQEM 2003. In dry, calm weather and without input from other sources, PM_{10} is balanced between suspension and settling (Lippmann 2003). In winter months, the LVV is subject to inversions and low wind velocities, which trap pollutants (CDSN and DAQEM 2003). PM_{10} concentrations follow seasonal patterns due to these annual fluctuations.

Emissions from large areas of land are a major problem for Clark County and one of the major reasons why previous SIPs were not approved (DAQEM). When desert land is in its natural state fugitive dust emissions are low, but disturbance to the desert crust, such as disturbance for urban construction, results in high particulate emissions (CDSN and DAQEM 2003). Chow *et al*. (1999) reported that fugitive dust accounted for 80-90% of all PM_{10} emissions in residential areas.

Boundaries of the Model

The key variables are identified in Table 1. PM pollution varies seasonally depending on weather components such as temperature, humidity and wind (EPA-4 2003). Although temperature and atmospheric pressure may control how air rises and falls (Spellman 1999), the processes controlling these conditions are quite complex and beyond the level of detail needed in this regional policy-making model. Daily temperature fluctuations are also not represented since night and day variations would average when looking at an entire day.

Table 1 Key variables by sector

Sector	Endogenous	Exogenous	Omitted
PM10	Stable PM_{10} on surface Unstable PM_{10} on surface	Normal removal & settling rates	Other meteorological factors

	PM_{10} in air rate of disturbance and stabilization Area source emissions Mobile source emissions Volume of the air shed Actual removal & settling rates	Wind factor and normal rain event† Height of boundary layer† Silt loading factors Point sources Emission factors* Control reductions*	Spatial dispersion/hot spots PM_{10} characteristics *(e.g., subcomponents, chemicals)*
Land	Native Desert acres Unstable acres Stable acres Acres in construction Developed/Urban area Residential capacity* Annual construction demand Disturbance rate	Designed density Land stabilization time Emission factors* Control reductions*	Spatial variation
Population	People desiring to move to LVV Population in LVV Residential capacity* actual in-migration and out-migration actual death rate Attractiveness	Birth rate Normal death rate	Sensitive populations Population characteristics *(e.g., age, sex)*
Transportation	Paved road Lanemiles actual planned acres of roads and support Unpaved roads Unpaved shoulders personal trips per person per day Vehicle miles traveled Effective lanemile capacity	normal planned roadway demand obligatory trips per person per day Emission factors*	Types of roadways and lanemiles *(e.g., freeway, arterial)*

* crosses sectors † seasonal

The model is not spatially distributed. It is not intended to analyze specific “hot spots”. Its focus is regional management of particulate matter. It aggregates particulate matter across the entire region. However, there is great variation in localized PM_{10} levels resulting from buildings and especially nearby land use (E.g, construction sites), making some monitoring stations prone to higher recorded levels. Chow *et al.* (1999) showed concentrations differing by a factor of five for sites experiencing similar meteorological conditions but located in different areas.

Precipitation, wind, and boundary layer height were chosen as parameters representing essential meteorological effects. The first two parameters affect PM addition and removal processes, while the boundary layer height is vital for determining the volume of air in the valley and thus the concentration of PM_{10}. This model is not intended to be either a meteorological or predictive model. Therefore, average seasonal values, based on historical trends, were used for these factors. For precipitation, seasonal information included the maximum probability of rain days for each month (with a minimum of zero). The height of the boundary layer depends on the valley's depth as well as the intensity of radiative cooling (Spellman 1999). The value of this parameter is driven by many complex meteorological processes but tends to follow a seasonal trend. Therefore, an average boundary layer height for each month of the year was developed based on historical experience.

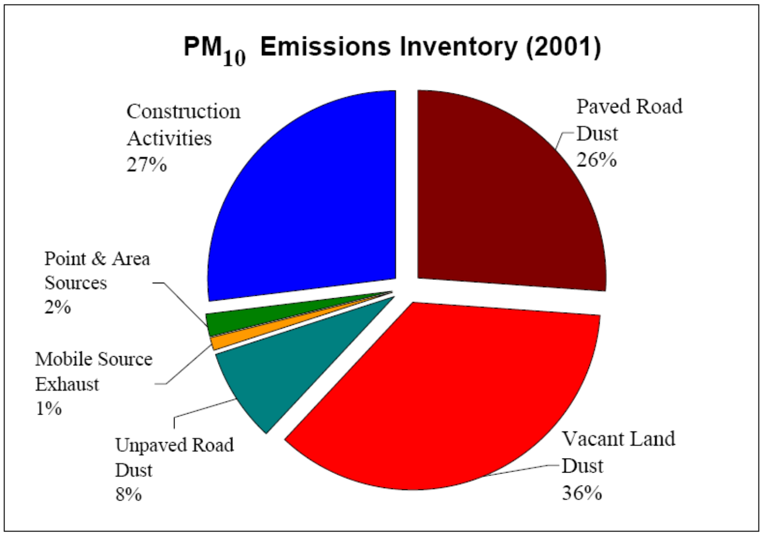
Using data from a monitoring site, the minimum and maximum average daily wind speed for each month were used to generate a random daily wind speed using a beta distribution. This was then divided by the annual mean derived for over 40 years of NOAA data (see Gorelow 2005), giving a wind factor seasonally varying around 1.0. The wind factor modifies certain normal emissions factors to determine an actual emission factor.

PM_{10} Sources in the LVV

Emissions are divided according to their source as area, point, or mobile emissions (Solomon 1994). Area sources in the LVV include vacant land emissions, emissions from land disturbed by construction activity, and minor emissions such as residential firewood burning. Mobile sources include direct emissions from vehicles, brake dust, and particles that are entrained (emitted) from road surfaces (DAQEM). PM_{10} emissions from paved roads are entrained by vehicles but the source of dust is actually nearby area sources (RTC 2004). However EPA tracks the source as the actual physical manner of entrainment and not the source of particles. PM_{10} can build more rapidly on paved surfaces near construction sites or construction- or off-road vehicles tracking dust onto surfaces (RTC 2004).

The major PM_{10} sources in the LVV for 2001 are shown in Figure 5 and include vacant land dust (36%), construction activities (27%), paved road dust (26%), unpaved road dust (8%), point and other area sources (2%), and mobile source exhaust (1%). The major industries (tourism, gaming, defense, chemical manufacture, sand and gravel operations, utilities, and construction; DAQEM) are not pollution intensive, except as indirectly encouraging longer commute distances (DRI 2002). Although managers realize that the distribution of sources will change, plans and control strategies are implemented following this static breakdown of sources.

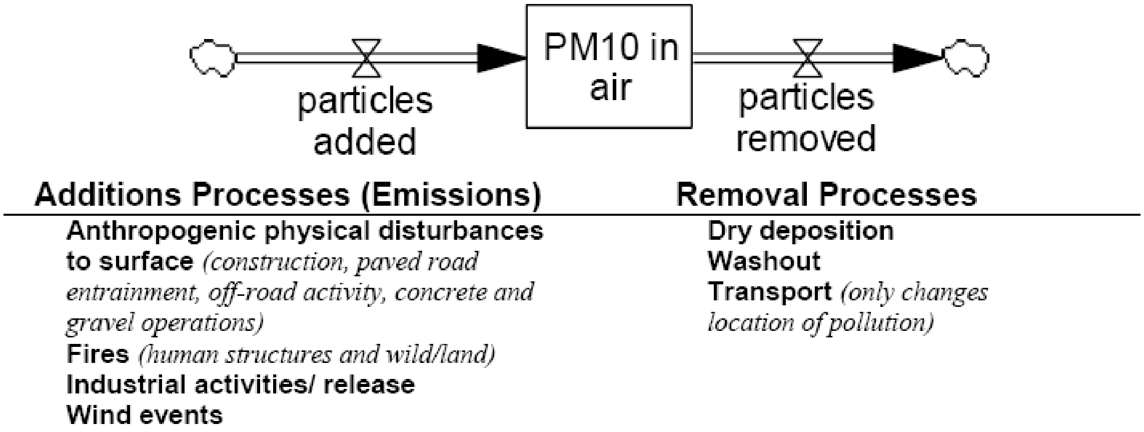
Figure 5 Emissions for Clark County



Model Structure

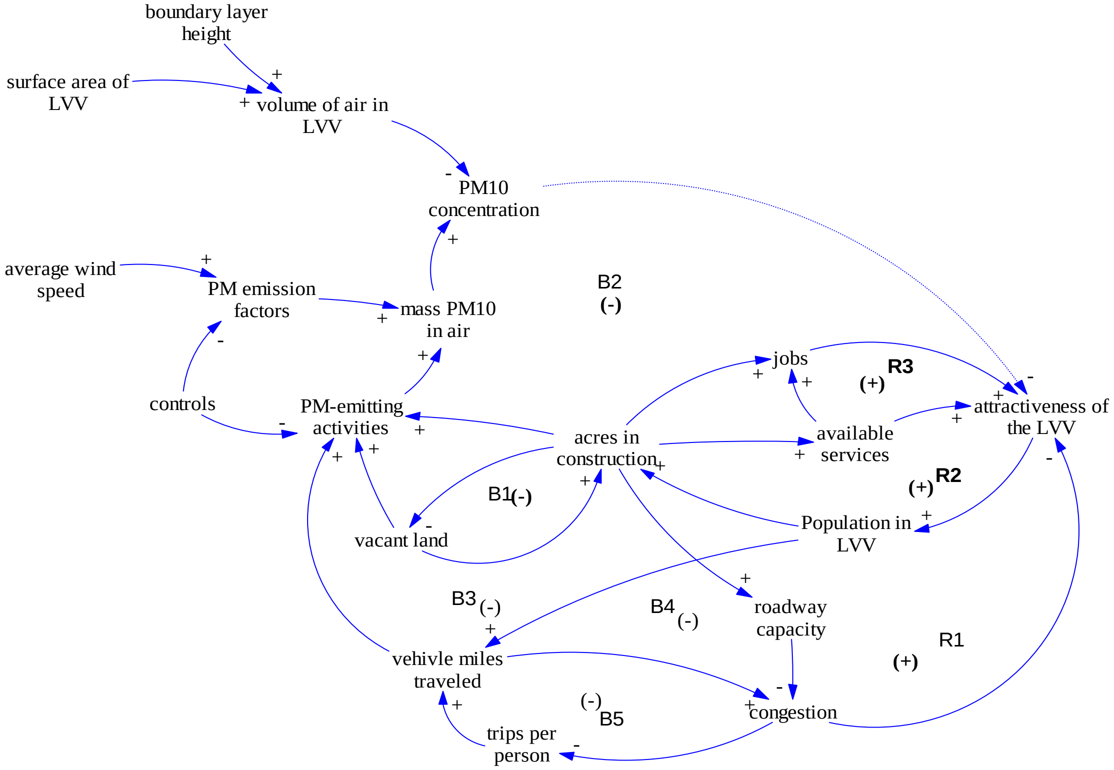
Representing PM_{10} in the atmosphere at its simplest requires tracking addition and removal processes, as shown graphically in Figure 6**.** PM_{10} is added by emissions processes of direct human disturbance or secondary entrainment from wind. Pollution in the air eventually returns to the surface through deposition. The two primary deposition processes are washout and rainout, with particles attaching to water droplets, or dry deposition, commonly referred to as settling or fallout (Spellman 1999, Society for Risk Analysis). Another removal and addition process includes PM pollution transported in or out of the area. This is considered a minor source because PM_{10} does not travel far in suspension.

Figure 6 Stock and Flow Diagram of Simple PM_{10} model.



In general terms, the structure of the model is similar to that of the Proportional Rollback model: growing population drives PM-emitting activities, which increase the amount of pollutants in the air. However, rather than using an average conversion factor to convert mass PM_{10} (tons) to a concentration ($\mu g/m^3$) as was done in the Proportional Rollback model, the CLD shown in Figure 7 represents concentration as a function of the mass of PM$_{10}$ particles in the air and the volume of air in the LVV.

Figure 7 CLD of SD model structure



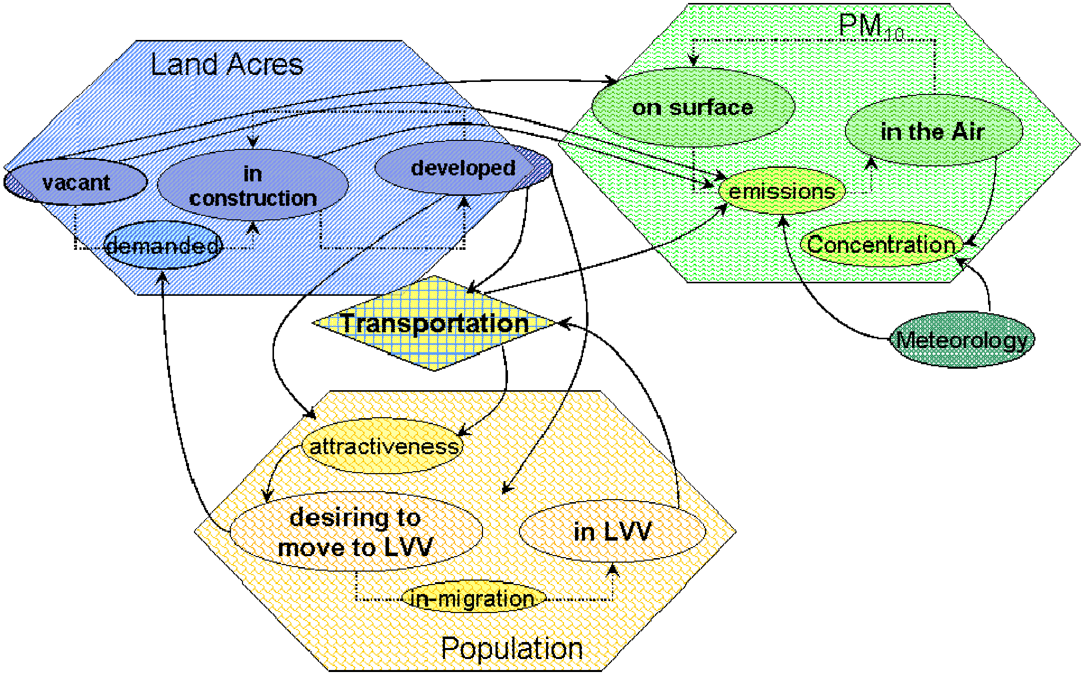
The PM$_{10}$ concentration depends on the *mass PM*$_{10}$ *in air* and *volume of air in LVV*, which depends on the *boundary layer height* and the *surface area of LVV*. The mass particulate matter is a function of emission activities, which are reduced by *controls*. *PM-emitting activities* and *PM emission factors* also depend on wind speeds. The majority of emissions are from *vacant land* and *acres in construction*. However, as *acres in construction* increases, they decrease *vacant land* forming a balancing loop (B1). Acres constructed depend on the population which is driven by attractiveness factors. There is a dotted line connecting *PM10 concentration* to the attractiveness (B2) because increased pollution does not necessarily slow growth (by reducing attractiveness), although it would for some.

As the population grows, there are increased *vehicle miles traveled* (VMT). These miles add to *PM-emitting activities*, which increase the concentration of particulate matter, decrease the attractiveness and therefore decrease the population change, forming the next balancing loop (B3). As VMT increases, *congestion* also increases, which reduces attractiveness, population change, and VMT, thereby forming balancing loop B4. City planners recognize the impact of congestion and so as the population grows, there are more *acres in construction* for roads which increases *road capacity*, decreases *congestion* and increases attractiveness, forming the first reinforcing loop (R1).

Planners are not the only ones who respond to congestion. As congestion increases, individuals reduce the number of unnecessary trips decreasing *trips per person* which decreases VMT and therefore relieves traffic, (B5). Additionally, growth is also driven by availability of services as development progresses, which increases the attractiveness, further increasing population and leading to more acres constructed. Likewise, construction and increased urban development leads to more jobs which increases attractiveness and leads to more in-migration and further development.

The model is simulated in days. The time horizon chosen for this model is from 1960 to 2025 to incorporate the historic trends of development and management that lead to the current situation for particulate matter pollution. The major sectors of the model include land development, population, and PM_{10}. The major processes that occur in each of these sectors are shown in Figure 8. Land is goes through a process of development changing it from vacant, to under construction, and finally developed. Particles are either on the surface or suspended in the air. Population in the LVV grows when people desiring to move to the Valley migrate, which depends on development of space. The population affects transportation (which crosses both the population and land sectors) and the desiring population drives demand for construction.

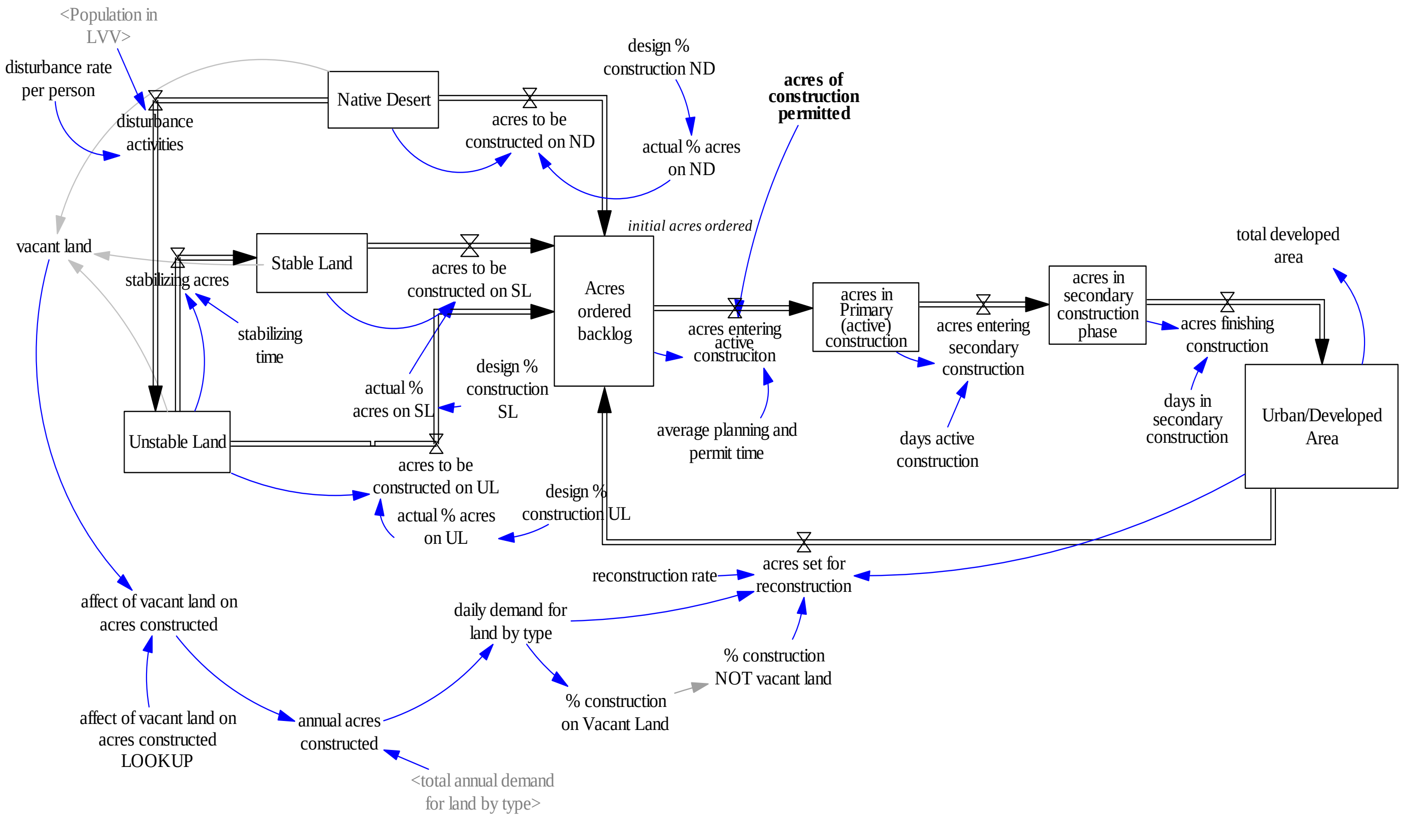
Figure 8 Major sectors in model



The land and demand for land sectors of the model are subscripted according to construction project type (such as airports, commercial, residential homes, and so forth). Figure 9 shows the stock-and-flow representation of the land sector of the model. Vacant land is represented as either "Native Desert", "Stable Land" or "Unstable Land." "Annual acres constructed" is determined by factors such as acres of services required per capita and grows with time. These acres are allocated across the three land stocks and flow into the "Acres ordered backlog" stock where they await construction.

From "Acres ordered backlog," acres are either limited by "acres of construction permitted" or simply remain backlogged before moving into "acres in primary (active) construction," defined as the disturbance-intensive part of construction activities with major earth-moving operations. The duration spent in this stock depends on the level of disturbance of the construction project and the total duration of the project. A similar flow moves land into "acres in secondary construction" where emissions from construction activities are greatly reduced. Acres then finish construction and become part of the completed “Urban/developed area” stock. A percentage of annual construction is reconstruction of built land which takes “Urban/developed area” acres and puts them back into the “Acres ordered backlog” stock, where they begin the construction cycle again. It is assumed that acres are only reconstructed for the same type of project (i.e. from commercial to commercial acres), based on land use zoning. Emissions are based on acres in each of these stocks, with the exception of “Urban/Developed Area” for which only highway acres are used.

Figure 9 Land Sector of SD model



Validation

Model results are shown in Figure 10 and replicate the behavior shown in the reference mode in Figure 2. Fluctuations come mostly from weather factors including wind and precipitation. Variables were compared to historic and estimated data from local planning and management entities to check validity. Figure 11 shows the model output for vacant land since the 1960’s. These curves are relatively close for all historic data but begin to level off for future estimates.

Figure 10 Output from Base Run of Model

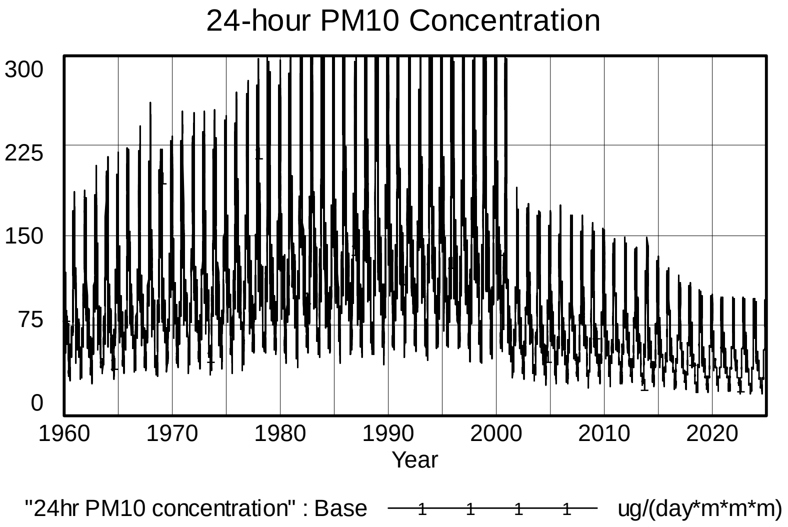
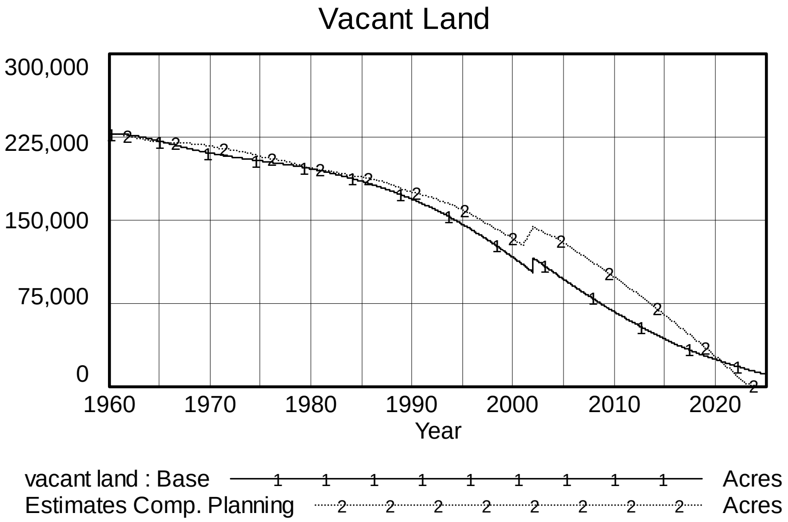


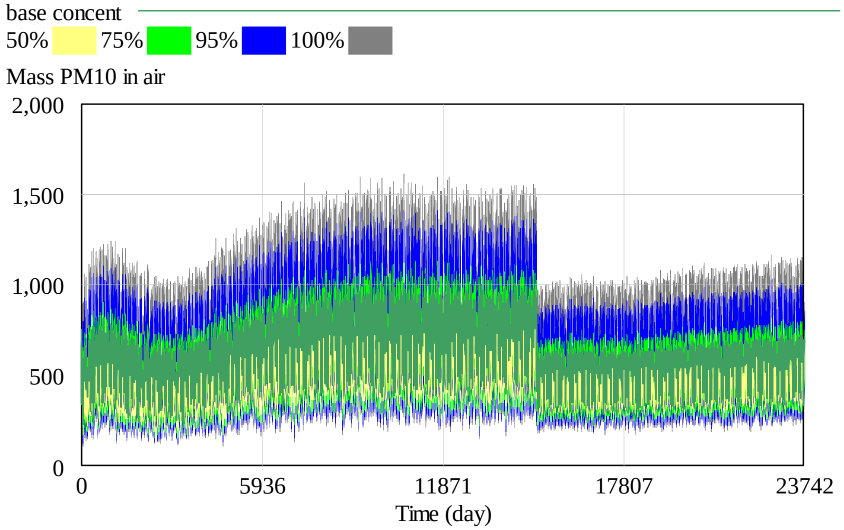
Figure 11 Validation of Vacant Land



Sensitivity

The model was tested for sensitivity to certain parameters as well. Since most variables driving the removal of PM_{10} from the air were based on estimates this was the first test performed. The results for this test are shown in Figure 12 and show that these variables may greatly influence levels and that it would be worthwhile to investigate specific rates of settling, washout, and transport. However, because it is accepted that the majority of particles settle within the LVV, the higher estimates are unlikely because they assume all of the lowest settling rates at one time and presume that around 60 to 80 percent of emissions stay in the air at all times.

Figure 12 Sensitivity of PM_{10} in the air to removal rates



Population trends were also analyzed to determine their dependence on the socio-economic factors driving in- and out-migration. The results for this analysis are shown in. Population follows the same trend for the majority of the cases, but does level off at different points. Again, many of the lower estimates for attractiveness effects factors could be removed since they would not be able to replicate the population trends that were seen historically.

Figure 13 Sensitivity analysis of population based

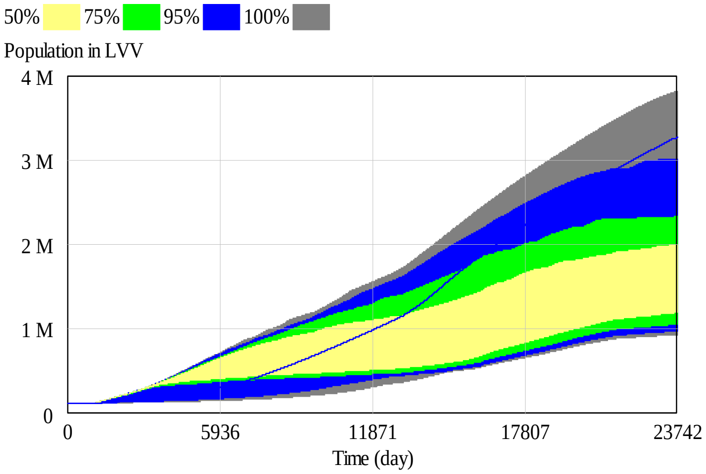
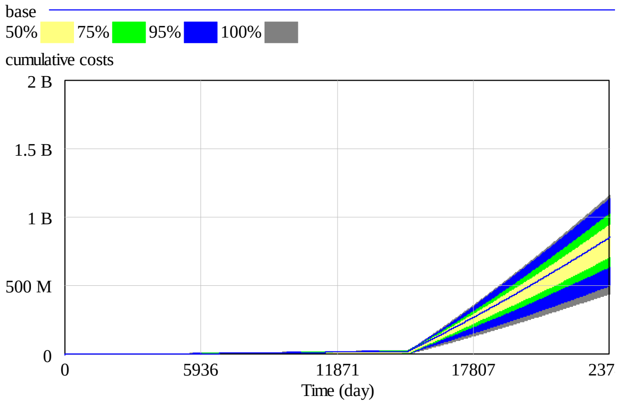


Figure 14 Cumulative cost sensitivity on attractiveness factors



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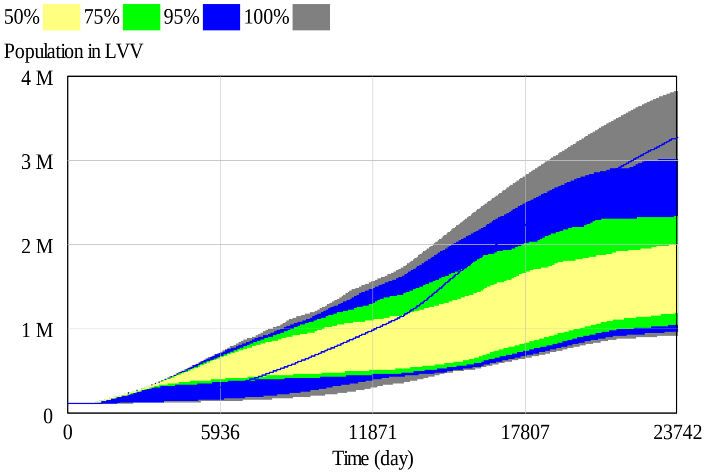

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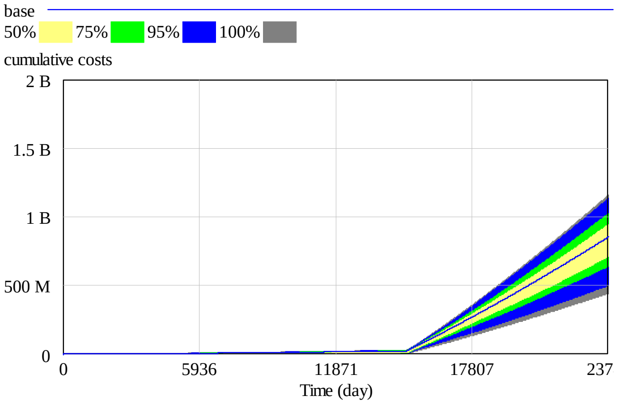


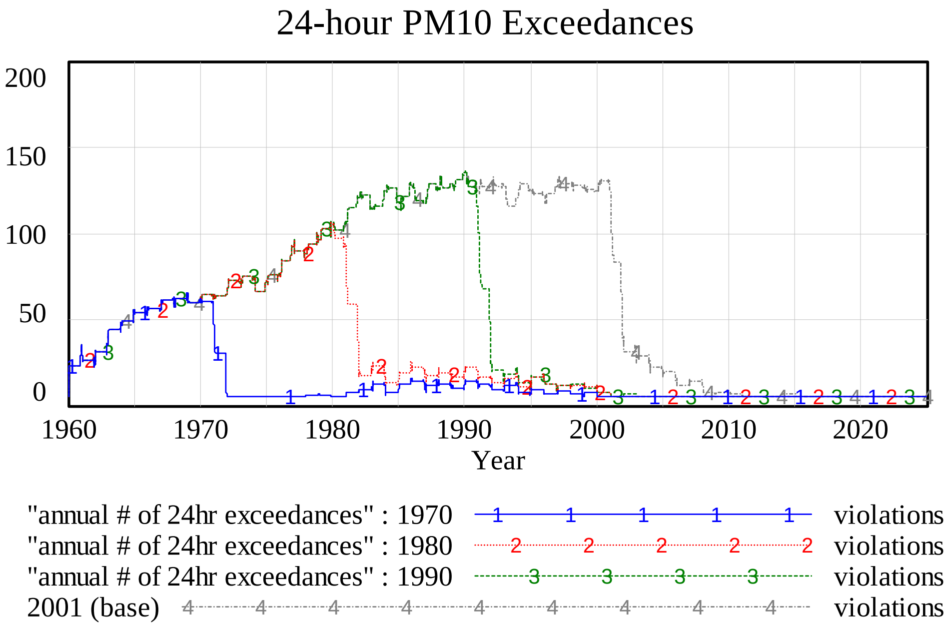
Another important area for determining sensitivity is costs. The range of costs for each control method comes from the 2001 State Implementation Plan (CCBC 2001). The sensitivity of costs is shown in and shows the upper and lower limits of costs. The high and low estimates of costs will give a range of costs, but when an average of all costs is chosen the simulation results are basically in the center of the range. Therefore, the average value was set for all cost variables, although policy-makers may be interested in knowing the maximum possible value they may have to pay which can vary up to around an extra $200 M.

III. Results

One of the major benefits of the SD model is that it allows for policy analysis dating back to 1960 and projecting to 2025. This gives more perspective in determining the effects of controls and development strategies on PM_{10} concentrations in the Valley. Although several tests were performed using the model, only a selected few are presented here.

The first policy test was to keep the same policies that were set in 2001 as a result of the SIP process, but set the policy implementation year 10 years earlier. This test was performed three times, each time implementing the policy a decade earlier back to 1970. The result of these tests are shown in Figure 15. The results show not only a decrease in the overall length of time that standards were exceeded but also a reduction in the overall magnitude of the problem.

Figure 15 Results of Implementing Same Controls Earlier



The impacts of implementing the strategy in 1970 would have kept PM_{10} levels below standards, thereby reducing the number of deaths resulting from PM_{10} exposure by a couple hundred thousand individuals as represented in Figure 16.

However, these decreases in PM_{10} levels and cumulative deaths come at a fairly high cost as demonstrated in Figure 17 and Figure 18. Policy enforcement and strategy begins earlier thereby increasing overall costs, while daily costs of implementing policies increase with time until they are about the same as the current policy.

Figure 16 Cumulative Deaths from PM_{10} Exposure

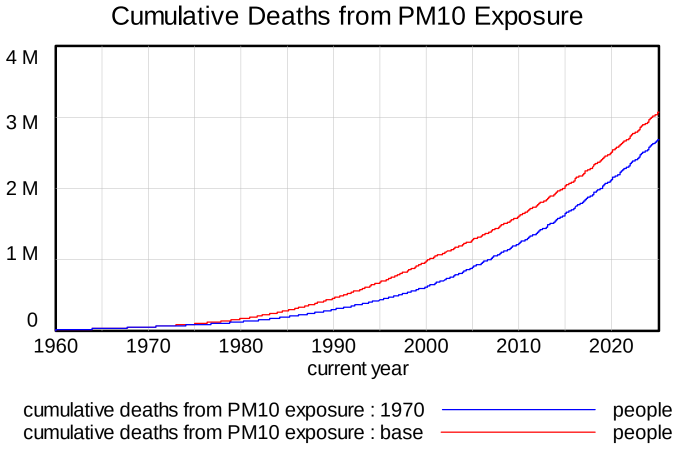


Figure 17 Cumulative Costs of Implementing Policies in 1971

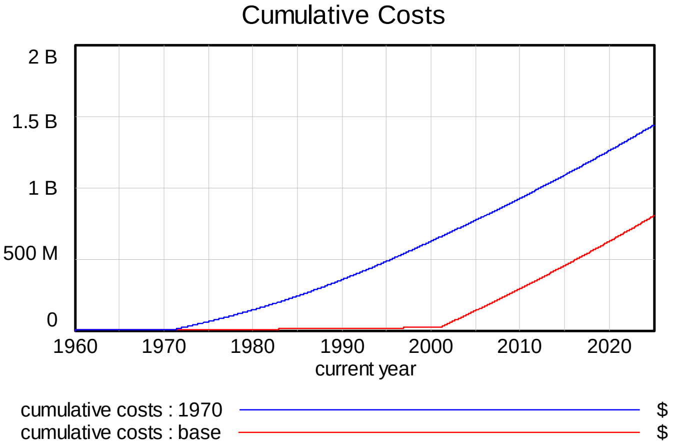
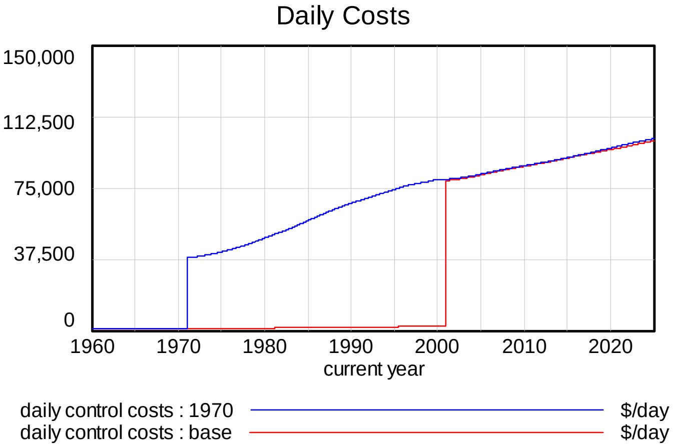
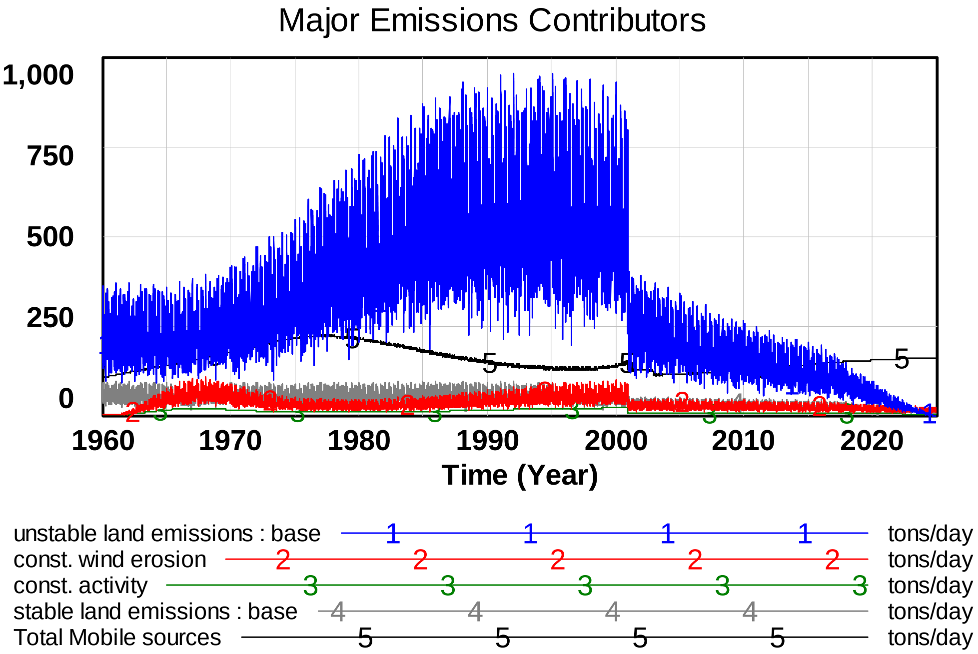


Figure 18 Daily Costs of Implementing Controls in 1971



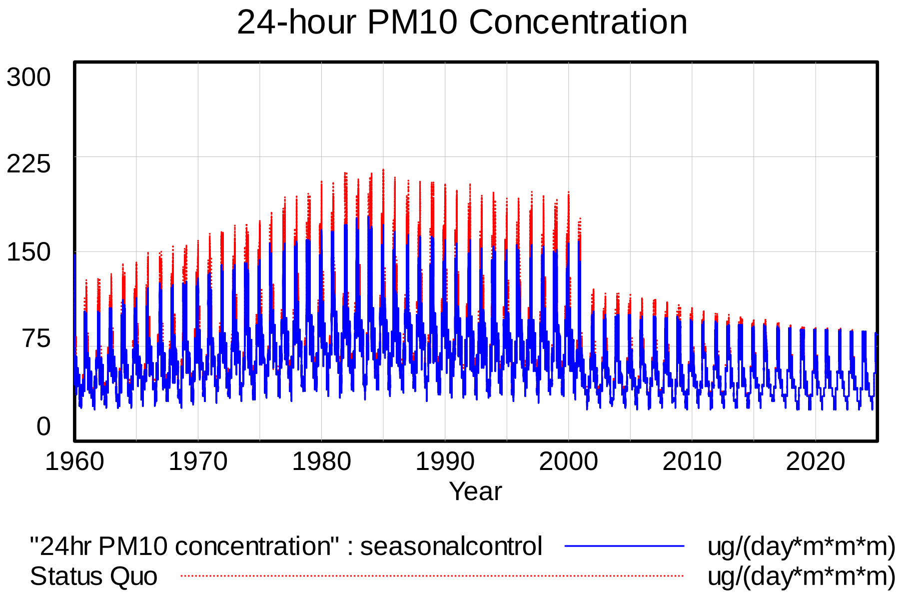
Another major policy test is to examine the major sources of particulate matter as a trends over time. Figure 19 shows how sources of emissions can change. In contrast to the static distribution of sources as seen earlier in Figure 5, different sources may dominate at different times. Unstable land emissions account for the vast majority of emissions (using the emission factors provided by the DAQEM) until vacant land decreases in later years and then mobile emissions are higher.

Figure 19 Major Sources of Emissions Through Time



Additionally, including seasonal factors allows managers to test the effects of implementing extra controls during these seasonably high concentration times. Figure 20 shows the results of introducing a seasonal control.

Figure 20 PM from Seasonal Controls



Combination policies were also tested to determine whether it would be possible to have a proactive policy that could have avoided the magnitude of the peak in emissions without dramatically increasing costs. Figure 21 shows the concentration resulting from a combination policy, giving levels below standards from the 1980s onward. The resulting decrease in deaths is shown in Figure 22, and reduced costs—both annual and cumulative—in Figure 23.

Figure 21 Concentration of combination policy

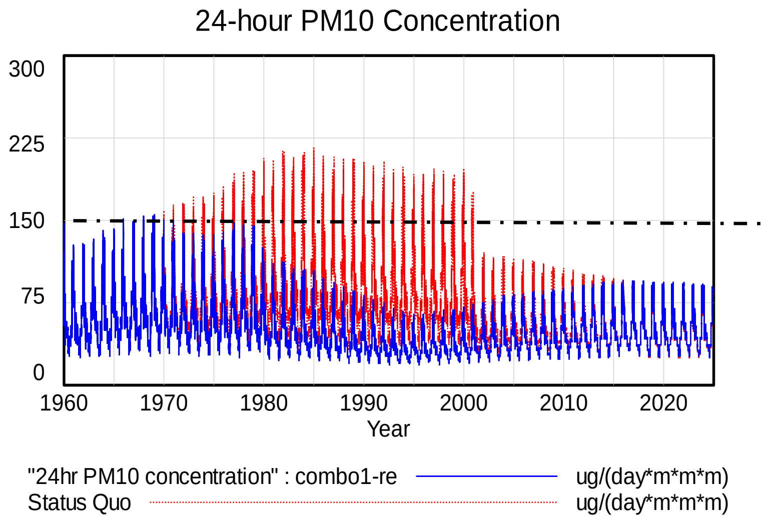


Figure 22 Cumulative Deaths Status Quo v. Combination

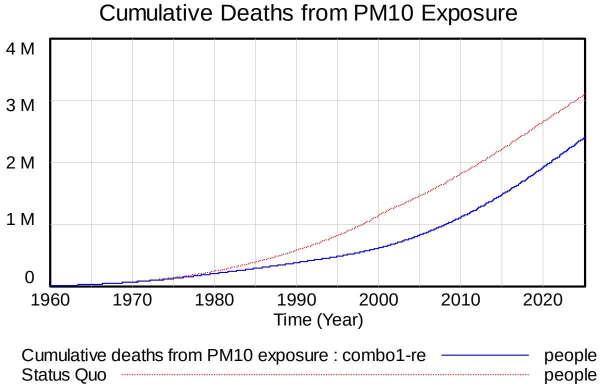
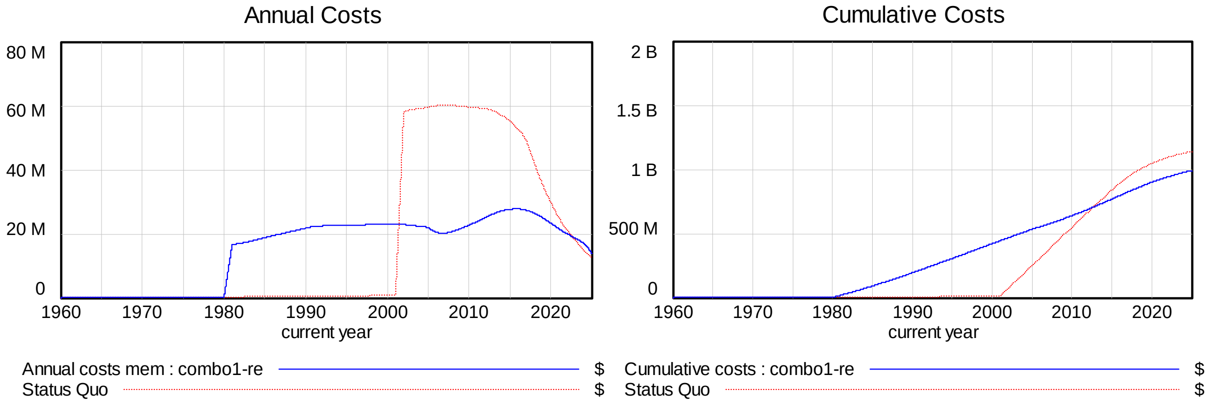


Figure 23 Annual and Cumulative Costs Comparison



IV. Discussion

Introducing systems concepts into the PM_{10} management decision support system provides more flexibility for policy testing, incorporates feedbacks and consequences of policies for both PM_{10} concentrations and development of the LVV. Results have greater utility than the Proportional Rollback Model (PRM) when used for policy testing. Including seasonal controls allows for testing a variety of policies as well as better isolating problems. Although costs were not tied in specifically to the seasonal control test, this would be a beneficial area to explore.

The narrow scope of the PRM important feedbacks which could potentially lead to the kind of policy resistance described by Sterman (2000) and policies further exacerbating the problem. One example is the interplay of vacant land and emissions. In the PRM representation, increasing the rate of vacant land development speeds the transition to the “Urban/Developed Area” and reduces emissions from vacant and constructed land. This appears to solve the problem of fugitive dust from vacant land areas. However, in reality, there are a host of other problems associated with rapid conversion of vacant to built land that keep this from being an ideal strategy. Sprawl leads to greater distances traveled per vehicle-trip, increased congestion and time in traffic, increasing the total vehicle-miles traveled and vehicular emissions. These include two other pollutants which the LVV is currently listed as non-attainment status: carbon monoxide and ozone.

The SD model gives managers information for comparing costs and effectiveness of control strategies. It provides more information than the Proportional Rollback model provides. It includes a variety of policies that can be tested. Additionally, the explicit representation of the causal structure makes it easy for policies requiring structural changes to be easily added to the model. The SD model also allows for learning about how changes to the system influence a variety of variables, hopefully improving the understanding of managers and allowing for better questions to be asked of the model.

The graph showing the major contributors confirms that unstable or disturbed land is the major reason why PM_{10} levels were so high historically. It also points to the major leverage points in the system at different stages of development. Since unstable land is so important, determining how the number of developed acres grew helps show what could be done to avoid problems caused by rapid development. A major particulate matter contributor was residential disturbance of vacant land (through offroad vehicle use, for example). Tests changing the development rate showed a strong leverage point.

The SD model also makes assumptions and relationships between variables explicit. These assumptions and relationships can be easily updated to incorporate improved understanding or parameter values. The model's flexibility in what can be tested, the ease with which this can be done, and the ability to represent a variety of variable types also make these models useful for managers. The ability to examine different time horizons is also useful feature of the SD model. As the retroactive policy analysis of the Las Vegas Valley shows, there may be ways in which a proactive strategy can improve air quality and prevent exceedances.

While this analysis demonstrates considerable benefits of a proactive systems-based management approach, several barriers to the use of causal models in air pollution management exist. First, because managers must meet regulatory requirements in a timely manner, it may be difficult to find the time or support to embrace and begin new techniques for decision-making. There may also be an additional burden of proof that areas must undergo to demonstrate the method as valid. Secondly, inclusion of soft variables into models is still not widely accepted despite the significant uncertainty in readily accepted meteorological data. Nevertheless, there is strong support of benefits, even from a retroactive application. Current non-attainment areas, or those that may soon become non-attainment areas, stand to gain the most from a proactive approach. A system dynamics approach can help focus the problem, examine major assumptions, and develop policies that will help improve or avoid future problems.

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