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Evaluating the benefits of a systems approach to particulate matter air pollution management

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EVALUATING THE BENEFITS OF A SYSTEMS APPROACH TO PARTICULATE MATTER AIR POLLUTION MANAGEMENT

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ABSTRACT

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Although air quality has improved in the United States over the past thirty years, some air quality management areas continue to have serious problems with air pollutants such as particulate matter (NRC 2004). I hypothesize that using a systems approach would have benefits for PM_{10} management, including improved results and understanding, as well as identification of ineffective policies. A system dynamics model was developed for PM_{10} in the Las Vegas Valley. Policy analysis revealed real-world behavior, important dynamics of the system, and potentially harmful policies. Results support the importance of a systems and long-term perspective, and show that PM_{10} pollution could have been reduced or avoided by other strategies. Recommendations for the model, problematic assumptions, and implications of results for air quality management are discussed.

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AQM	Air quality management
CAA	Clean Air Act
CCCP	Clark County Department of Comprehensive Planning
CLD	Causal loop diagram
DAQEM	Clark County Department of Air Quality and Environmental Management
DSS	Decision support system
EPA	U.S. Environmental Protection Agency
NAAQS	National Ambient Air Quality Standards
NRC	National Research Council
PM	Particulate matter
PM_{10}	Particulate matter, 10 µm in diameter or less
PRM	Proportional Rollback Model
SD	System Dynamics
SIP	State implementation plan
VMT	Vehicle miles traveled

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CHAPTER ONE

PROBLEM STATEMENT

Although the Clean Air Act (CAA) of 1970 and other pieces of environmental legislations have led to improvements in environmental quality over the past few decades (Brewer 2005, Davies and Mazurek 1998 in Mazmanian and Kraft 1999), problems with air pollution and air quality management still exist. Many of the major goals of the CAA have still not been achieved and new evidence demonstrates that even greater improvements will have to be met than was anticipated in those goals (National Research Council [NRC] 2004). Concentrations of pollutants have decreased, but not below standards in some areas (NRC 2004). Furthermore, achievements in environmental quality may be short lived as pollution production increases and new threats are discovered (Mazmanian and Kraft 1999: 3).

One example of a troublesome aspect of current air quality management is particulate matter pollution. Particulate matter is most commonly described by the size of particles—PM_{10} is particles with a diameter (or aerodynamic size) of ten micrometers ($10\mu m$) or smaller (Environmental Protection Agency [EPA] 1996B, EPA 2004, Department of Air Quality and Environmental Management [DAQEM] FAQ). To illustrate the relative size of these particles, 10 μm is roughly equivalent to $1/7^{th}$ the size of the diameter of a human hair (DAQEM FAQ). Particulate matter (PM) consists of many components, including dust, soot and other pieces of small, solid or liquid materials or chemicals suspended in the air (EPA 1996B, EPA 2004). PM_{10} is also called the inhalable coarse particles or coarse fraction of PM (EPA 2006). PM_{10} is one of the criteria air pollutants managed by the Environmental Protection Agency (EPA) under the CAA in order to protect public health (NRC 2004).

PM_{10} consists of particles which are inhaled into the lungs and accumulated in the bronchia, leading to a variety of serious health issues including: increased incidence of respiratory disease and symptoms—coughing, painful breathing, and decreased lung function; aggravation and increased potency of pre-existing respiratory conditions (such as asthma or bronchitis); increased absences from work and school; area-wide increased hospital admissions and emergency room visits; and even, premature death (Clark County Board of Commissioners [CCBC] 2001, EPA 2003a, EPA 2004, Lippmann 2003). Exposure can also lead to increased susceptibility to infection (Romieu and Hernandez-Avila 2003). The most vulnerable segments of the population for this pollutant are the very young or old, as well as people with weakened immune systems (EPA 2003a).

The Problem

Over 300 counties did not meet PM standards when they were first set in 1971 (Chay, Dobkin, and Greenstone 2003). The CAA states that when a new federal standard for air quality is established, air quality management areas are classified as nonattainment, attainment, or unclassifiable areas, depending on whether they meet new standards and requirements (NRC 2004, CAA). The original goals of the CAA were to have every air quality management area (or county) meeting standards by 1977 (NRC 2004). After the initial classification of areas, some were promptly removed from nonattainment status as they took relatively simple steps to control PM_{10} air pollution.

However, several areas did not improve and remained in nonattainment status. When most areas failed to meet this deadline, Congress amended the CAA and among the changes was an extension of the deadline to1987 (NRC 2004: 124). Despite the potential to receive newly added penalties (NRC 2004, CAA, Kubasek and Silverman 2005) many areas still failed to meet deadlines for attainment. In 1990, the CAA was amended again. New deadlines were set according to the severity of the exceedance and the status of the air quality management area could worsen if improvements and deadlines were not reached (NRC 2004).

In 1992, EPA concluded its review of the effect of the new regulations on areas and moved eight of the moderate nonattainment areas into serious nonattainment status (EPA 2007). In 2006, there were still eight PM_{10} serious nonattainment areas and over 75 moderate nonattainment areas across the United States (NRC 2004, EPA 2007). Two of these serious nonattainment areas—Phoenix, Arizona and Owens Valley, California—are being scheduled for an official classification as "failures of attainment" in 2007 (EPA 2007, Fed. Reg. 2007: 13723-13726). These areas failed to meet the standards by the end of 2006 (the latest deadline) and now have one year to submit a plan that shows they can reduce emissions by a minimum of 5% reductions annually until standards are reached (Fed. Reg. 2007: 13723-13726, CAA §189 [b] [A] [ii]). If the counties fail to comply, they will most likely be required to implement a federal implementation plan in which the EPA mandates how they will control and manage PM_{10}.

The map in Figure 1 shows the areas in the U.S. currently exceeding national PM_{10} standards. Levels of PM_{10} are higher in the West and PM_{10} makes up a greater percentage of the total PM pollution than in other areas of the country (EPA 2004).

Nearly all serious nonattainment areas are in the Southwest. Figure 1 also shows that some of these areas are not improving and some (such as the two counties described above) are actually getting worse.

The Southwest also faces accelerated rates of growth and increased difficulties from the arid climate. However, PM_{10} problems are not unique to the Southwest or even to the United States. In fact, PM pollution is a problem being faced by many countries, especially regions or cities in rapidly-developing countries (McGranahan 2003). While other air pollutants are very dangerous to human health, both cohort studies (following individuals for many years to determine if a link exists for long-term exposure and mortality) and time-series studies (which track sudden spikes in air pollution and link them to reported deaths occurring on days of highest increase or immediately afterward) have concluded that premature deaths resulting from air pollution are caused predominately by PM as opposed to ozone and other criteria pollutants (Molina and Molina 2004).

Another air quality problem is the increasing number of people being exposed to unhealthy PM levels. In 1996, the U.S. Environmental Protection Agency (EPA) calculated 7 million people in 15 counties were being exposed to PM_{10} pollution levels above standards (EPA 1996: 32). In 2003, an estimated 21 million people in 37 counties were being exposed to measured concentrations above PM_{10} standards (EPA 2004)[1]. Although population growth in the country can account for part of these increases, the number of counties violating standards has increased with time as well.

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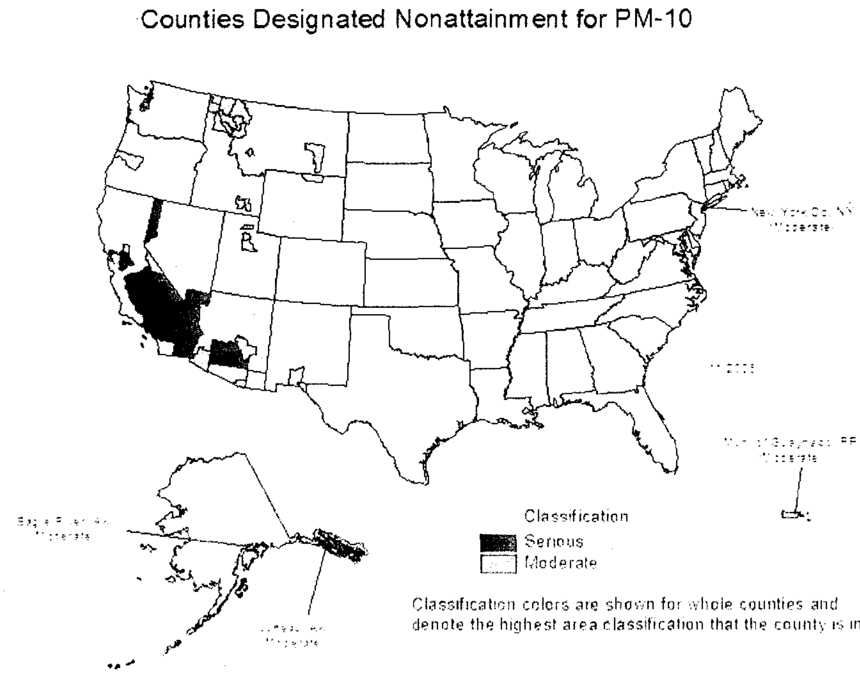
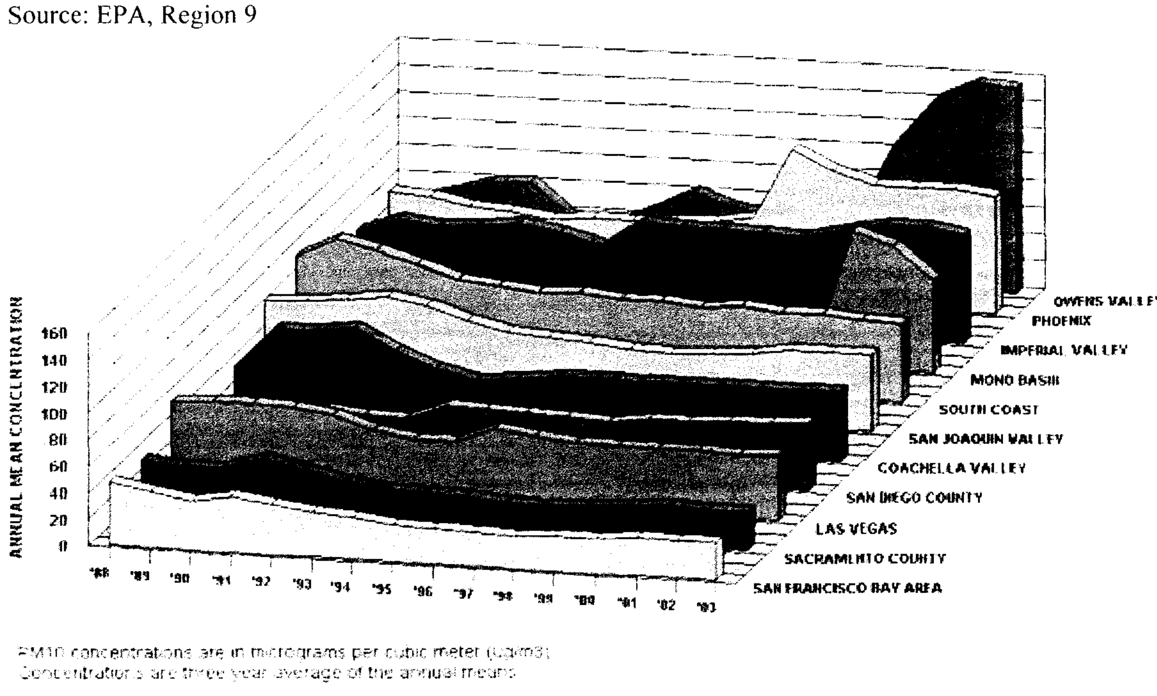
[1] Including the 1997 $PM_{2.5}$ standard, approximately 62 million people, in 97 counties, were exposed to levels of PM pollution above either the PM_{10} or $PM_{2.5}$ standards or both (EPA 2004).

Figure 1 Map of PM10 nonattainment counties and their trends



Source: EPA

Source: EPA, Region 9



In short, PM_{10} management is not as effective as it needs to be to meet the CAA's legislative goals of protecting the health and welfare of the U.S. public. If the current approach is not working, the question is: how can air quality management be improved? One area where managers can change their approach while still following federal mandates is in the decision support systems (DSS) used for developing and deciding among policy options to manage air quality.

In this thesis, I argue that incorporating a systems perspective in air quality modeling or decision-making can improve the ability of managers to meet standards. PM_{10} in the Las Vegas metropolitan area is used as a case study to demonstrate the benefits of incorporating a systems view for managing PM_{10} in this area. The Las Vegas Valley (LVV) is one of the eight serious non-attainment areas (DAQEM 2001, DAQEM 2005A, EPA 2007) and has been one of the fastest growing areas in the country for the past few decades (US Census Bureau 2006).

Particulate Matter Pollution

Understanding Particulate Matter

Particulate matter varies greatly in chemical components as well as particle shapes and sizes (EPA 2004, Lippmann 2003). Although PM is made up of a large variety of chemicals, there are no standards in the U.S. on specific components of PM other than those previously established (e.g., lead) and only the total mass concentration of particles is regulated (Lippmann 2003).

Regulation of air quality in the United States is mandated by the 1970 CAA and is enforced by the EPA (EPA 1996b, Plater *et al.* 1998). The CAA set National Ambient Air Quality Standards (NAAQS) for particulate matter and five other criteria air pollutants: sulfur dioxide, nitrogen oxides, carbon monoxide, ozone, and lead (Kubasek and Silverman 2005). The standards set for these pollutants are considered "harm-based" standards because the levels are set by looking at the harm to human and environmental health and setting a limit that provides an "adequate margin of safety" (Plater *et al.* 1998).

The original particulate matter standard limited total suspended particulates (TSP) with aerodynamic diameters of 40 micrometers (μm) and smaller. These standards were followed by newer limits concerning particles with a diameter equal to or smaller than 10μm (PM_{10}) in 1987, and then in 1997, new limits on particles smaller than 2.5μm ($PM_{2.5}$) also called fine particles (Federal Register 2004, EPA 2004, Molina and Molina 2004, EPA 1996, McGranahan 2003). For clarification, the EPA has begun to refer to PM_{10} as particles less than 10 μm in diameter, but greater than 2.5[2] (EPA 2006).

PM can be either primary—directly emitted into air—or secondary pollution—formed indirectly from other emissions and sources already in the air (EPA 2004). PM_{10} is usually primary particles, physically added to the air (Lippmann 2003). Large, coarse particles tend to settle faster than fine particles and are usually found close to their emission source (EPA 2004, DAQEM 2005b). In dry, calm weather, the amount of coarse particles in the air is balanced between suspension in the air and fallout from gravity (Lippmann 2003). Fine particles can travel long distances and can be found thousands of miles from where they were formed (EPA 2004). PM pollution varies seasonally, by location, and is affected by weather components such as temperature, humidity and wind (EPA 2004).

[2] This is sometimes indicated by "$PM_{2.5-10}$," however PM_{10} will continue to be used to refer to this category throughout the text.

Particulate Matter and Mortality

Significant associations have been demonstrated between concentrations of PM in the air and mortality and morbidity rates in humans[3]. Health impacts of PM depend on the size of particles. The largest PM (geologic PM, of sizes >10 microns or micrometers) may cause strong, but temporary, fits of coughing during exposure but do not travel very far into the lungs and have fewer human health impacts (CCBC 2001, EPA 2003a, EPA 2004). The fine fraction or $PM_{2.5}$ is now considered to be the most significant in causing health problems (McGranahan 2003, EPA 2006). As understanding about the health effects of PM has grown, legislation has followed suit (sometimes delayed) by setting standards for smaller and smaller sizes of PM.

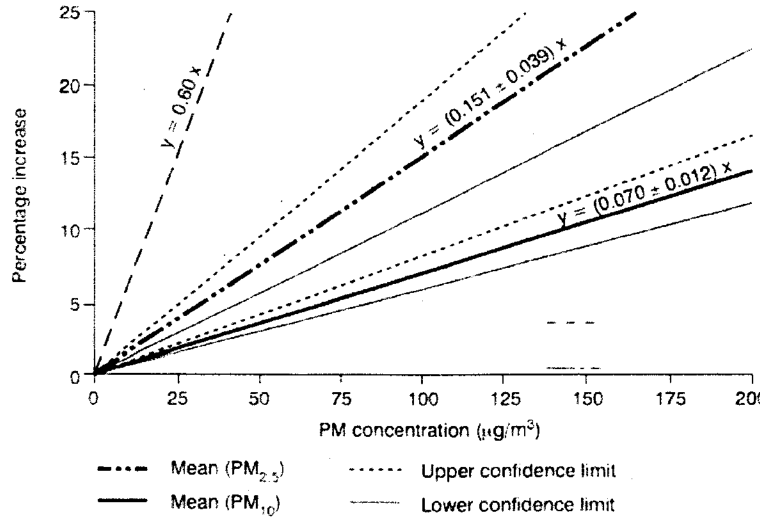
This thesis focuses on PM_{10} because, although it has been the focus of air quality management (AQM) since 1987, 20 years after regulation began there are still major issues with this pollutant. New PM standards (for fine and ultrafine particles) may pose even more significant management and health problems in the future, but the previous PM_{10} problem areas must be addressed and not ignored in the face of even more stringent regulations. Although $PM_{2.5}$ may be more strongly associated with health problems, epidemiological evidence shows a relationship between short term peaks in PM_{10} pollution and public health responses (i.e., occurrence and tracking of related symptoms), including increased hospital admissions, respiratory symptoms, and deaths (Lippmann 2003).

The symptoms that individuals exhibit depend on the individual as well as levels and durations of exposure to the pollutant. The most serious responses (e.g., death) are the least common, except in the highest of doses. Considerable research and

[3] see Lippmann 2003, Schwela 2003 for a literature review of these studies

epidemiological evidence has demonstrated that there is no threshold for PM_{10} and the dose-response curve for mortality is linear as shown in Figure 2 (Schwela 2003: 75). The direct relationship between PM pollution levels and mortality provide both a challenge and an opportunity, because even incremental reductions would directly reduce deaths and other symptoms. Although quantitative relationships between mortality and morbidity are well-documented, more information is needed on the biological mechanisms responsible for these relationships and the toxicities of the numerous components comprising PM pollution (Lippman 2003).

Figure 2 Increases in Daily Mortality Based on PM Pollution source: Schwela 2003: 75



Continued exceedance of PM_{10} standards is also very costly in terms of increased procedural burdens, potential loss of federal highway funds and, in the case of a failed plan, mandated control strategies which may be more expensive than locally developed policies. PM can also lead to significant aesthetic deterioration of an area by causing haze and reducing visibility, a potentially significant problem for a tourism-based city such as Las Vegas. PM pollution degrades vegetation and ecosystems and causes physical damage to structure surfaces (EPA 2004, CAQEM 2004).

Air Quality Management

Linear Model of Management

Management, in general, is often initiated as a response to a stimulus, such as a problematic event or issue (Foundations of Success [FOS] 2004, Brewer 2005, Bennear and Coglianese 2005, Reagan 2006). Federally, a response is usually initiated by the legislature and takes the form of a statute or law, leading to regulations (Bennear and Coglianese 2005: 24). Air quality management is no different. As impacts of air pollution on public health, ecosystem health, and costs have been identified or have intensified, there has been a response of "increasingly complex and ambitions legislation," (NRC 2004: 29).

The industrial era emphasized an approach to management that followed top-down control and narrow objectives (Wondolleck and Yaffee 2000: 11). Objectives of managers were often based on specific standards for pollutants, which are established by management entities on the top of the hierarchy. Today, the majority of environmental laws follow the centralized creation and implementation of rules (Brewer 2005: 42).

Centralized rule development has been described as event-based or initiated as a response to some crisis or difficult situation (Bennear and Coglianese 2005, FOS 2004:18, Miles 2003, Reagan 2006: 819). In fact, air quality legislation was a reaction to devastating pollution episodes. Several severe air pollution events occurred historically, some as far back as the industrial revolution. City ordinances began in the late 1800s when pollution in industry-laden cities was quite high (Kubasek 2005, Environmental Institute of Houston [EIH] 2006). Several of these incidents are shown in --- (from EIH

2006) covering major air pollution related events from the early 1940's to 1963, when the first Clean Air Act was passed.

Table 1 Timeline of air pollution related events 1940-1963

1943	First recognized episodes of smog occur in Los Angeles in the summer of 1943. Visibility is only three blocks.
1945	The City of Los Angeles begins its air pollution control program, establishing the Bureau of Smoke Control in its health department.
1947	California Governor signs the Air Pollution Control Act, authorizing the creation of an Air Pollution Control District in every county of the state.
1948	The Los Angeles County APCD is established. It is the first of its kind in the nation.
1948	Donora, Pennsylvania, air pollution episode kills 20 people and numerous animals, and half of the town's 12,000 residents become ill due to uncontrolled emissions from industrial facilities.
1950	A smog incident in Poza Rica, Mexico leaves 20 dead and hundreds hospitalized.
1952	The Texas Department of Health conducts the first air study in Texas.
1952	Over 4000 deaths attributed to "Killer Fog" in London, England. Smoke is so thick that it stops traffic. Buses run only with a person on foot leading them while holding a lantern.
1952	Haagen-Smit discovers photochemical smog comes from the reaction of nitrogen oxides and hydrocarbons in the presence of sunlight forms smog.
1953	New York smog incident kills between 170 and 260 people.
1953	Los Angeles County starts "Smoke School Program" for black smoke, beginning the standardization of "Visible Emission Programs" nationwide.
1955	Federal Air Pollution Control Act is enacted, providing for research and technical assistance and authorizing the Secretary of Health, Education and Welfare to work towards a better understanding of the causes and effects of air pollution.
1955	"Killer Fog" envelops London, England, resulting in 1000 deaths above normal.
1959	California enacts legislation requiring the state Department of Public Health to establish air quality standards and necessary controls for motor vehicle emissions.
1962	Another London smog incident; 750 die.
1963	First Federal Clean Air Act enacted. Empowers the Secretary of the federal Health, Education, and Welfare to define air quality criteria based on scientific studies. Provides grants to state and local air pollution control agencies.
1963	Air pollution inversion in New York leads to 405 deaths.

The number of deaths and illnesses that occurred during the 1940's may have sparked control by states in the 1950s, which was quickly followed by the 1955 Federal

Pollution Control Act (Kubasek 2005). In 1960, the Motor Vehicle Exhaust Study authorized the regulating authority at the time, the Public Health Service, to study vehicle emissions and health (NRC 2004). 1963 marked the passage of the original Clean Air Act (CAA), but it wasn't until 1970 when the EPA was established and the CAA was amended, that the current regulatory basis of AQM in the United States was established (NRC 2004).

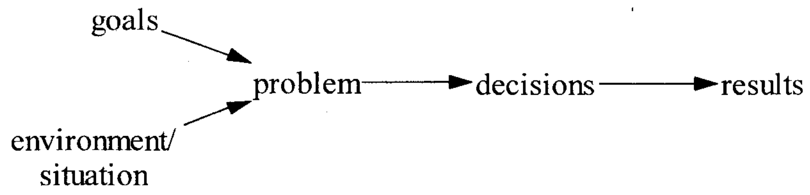
The CAA requires diverse entities (federal, state/tribal, and local agencies) to interact for AQM, with guidance and oversight by the EPA (NRC 2004). The EPA ensures that there is a basic level of air quality and provides general assistance in establishing methods to protect the public (NRC 2004). Air quality management areas in the United States are often based on hydrographic basins. In some cases, these areas may cross state boundaries, providing greater incentive for the need of federal regulation. In addition to a mix of levels of legislative entities, the CAA also requires judicial review in that federal courts review all proposed EPA rules and can force the EPA to take action when delayed (NRC 2004).

The EPA has been blamed for the large amount of time needed between submissions of plans and comments or rulings and for problems of meeting deadlines. In fact, the EPA rarely meets its obligation to quickly determine if an area did not meet standards by the deadline and increase (or "bump up") their nonattainment status (NRC 2004: 125).

After an event or problem triggers the management response, a management plan is developed, implemented, and the outcome is evaluated (Miles 2003, Bennear and Coglianese 2005). The sequence implies that no action is taken until after the entire planning stage has occurred (Miles 2003). Due to the linear and event-based nature of the process, management usually ends with an evaluation[4] of how the action changed the problem or situation. This process follows the diagram of Sterman's (2001) linear view of the world, shown in Figure 3.

Goals are federal air quality standards, which are compared to the monitored air quality data (the environment). When concentrations are above standards, this defines a problem. Decisions are made to reduce emissions and attempt to lower concentrations. In this phase a model is usually built to demonstrate that the decided plan of action will bring about the change in air quality as desired. The final steps involve measuring the actual reductions in concentrations to ensure that concentrations drop below standards.

Figure 3 Event-based view of the world (From Figure 1-3 in Sterman 2000: 10)



The National Research Council (2004) states the broad activities that define AQM operations are: setting air quality standards and objectives, designing and implementing control strategies to meet them, and assessing results. This defines the major components of the linear model above. However, they also state that these components occur in a changing scientific and technical foundation (NRC 2004). The constantly changing

[4] How this evaluation may occur is a constantly evolving process, for a good review of these approaches see Stem *et al.* 2005, Bennear and Coglianese 2005

context would then spark the re-evaluation of the first two activities after lessons have been learned in the third (NRC 2004).

While this may be the case for the EPA as a whole (evaluating standards, assessing how far the country is from meeting these standards, etc.), managers most often seem to respond to the changes enforced by the EPA instead of anticipating them and planning for improvement. Evidence for this comes from the fact that although the 1970 CAA Amendments envisioned states creating standards and controls more stringent than federal standards, but it is actually rare to see (NRC 2004). The goal for concentrations appears to be set just below standards. Additionally, many managers do nothing to further reduce emissions and stop searching for additional controls when attainment has been reached.

Therefore, when standards are changed (as should be expected), a crisis-management situation is sparked—managers must rush to complete new documents and mandated management plans 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 an area being classified as nonattainment.

State Implementation Plan

State implementation plans (SIPs) describe the actions and controls needed to meet NAAQS (EPA 1996B, Plater *et al.* 1998, NRC 2004). If an area meets new standards and does not contribute to another area not meeting standards, this may be a relatively simple process. These plans are submitted, commonly for each criteria air pollutant individually, based on requirements of the CAA (Kubasek and Silverman 2005, NRC 2004). States or regions may already be in the process of demonstrating compliance and (possibly future) attainment of a pollutant when a new standard is passed. Additionally, the EPA may review and approve some plans faster than others. This means that there may be numerous SIPs for different pollutant standards—new and revised—in different stages of review at any given time (NRC 2004).

In general, SIPs describe in detail all of the programs and regulations an area will use to control pollution and reduce emissions (EPA 1996b). For all areas, SIPs include emission limitations and controls, show monitoring data, ensure funding for implementation, include air quality modeling, and must demonstrate that the public and other affected parties were adequately allowed to participate in the process (NRC 2004). The attainment status of an area determines the regulatory requirements, usually more stringent for nonattainment areas (Chay, Dobkin, and Greenstone 2003). As was stated earlier, failure to comply with all requirements can lead to an area being moved to a more serious classification (NRC 2004).

The EPA evaluates SIPs for each of the criteria pollutants in exceedance to determine whether the plan is sufficient and able to effect attainment by deadlines. If the plan fails to gain approval, the state is required to redraft the SIP until it is approved by the EPA (Kubasek and Silverman 2005). These types of procedural processes have been difficult and frustrating for managers (FOS 2004, NRC 2004). They have also been criticized for their emphasis on procedural adherence rather than actual improvements in air quality (FOS 2004).

Extensions for areas in exceedance are filed when a nonattainment area cannot "practicably" meet standards by the attainment deadline (CAA §188, d and e). While failure to meet standards for some pollutants results in sanctions—such as withholding millions of dollars in federal highway funds (NRC 2004)—penalties are not usually imposed for PM_{10} violations. In extreme cases or the very unlikely case that a state refuses to redraft a plan, the EPA can impose a federal implementation plan that must be followed regardless of impacts on local economies (Plater *et al.* 1998, NRC 2004).

When the EPA determines that an area failed to submit an adequate SIP, an 18-month "sanctions clock" is started (NRC 2004: 125). At the end of this countdown, either federal highway funds must be cut or the area has to provide two-to-one offsets for any new or modified emission sources (NRC 2004).

Air Quality Modeling

An essential regulatory component of the air quality management process is showing compliance with NAAQS through air quality modeling. There are a variety of different model types used today throughout the United States and a host of models that have been used historically. Models are sometimes utilized by agencies to develop policies for controls. More commonly however, models are used to determine the effect of controls on air pollution and demonstrate future attainment. In this way, many models are predictive in nature.

In general, air quality models use techniques based on mathematical operations or numerical constants to simulate processes that affect pollutants and their dispersion, formation, or reactions in the atmosphere. They often use inputs that are specific to the area they describe such as the regional meteorological data, sources of pollutants, emission rates, and the stack height of industrial point-sources (describing the distance above the land where the pollutants mix and react).

The most basic types of models simply calculate the emission reductions needed in order to meet standards (NRC 2004). This amount of reduction sets a goal for control policies. However, most models are not used to determine which controls to implement, but instead determine the effect of a predetermined set of controls. When an area has concentrations that violate standards, managers determine how regional weather and emissions led to the exceedance and attempt to recreate the situation under which the violation occurred in a model (NRC 2004). Any projected change in emissions is incorporated and the new emissions inventory is then reduced by proposed emission-control activities. This determines whether a violation will occur under similar meteorological and emission situations (NRC 2004). Models can also be used to determine whether a potential new source will lead to an exceedance, providing a basis for granting permits to the new source (EPA 2004).

The EPA's *Guidelines for Modeling* are actually rules, given to EPA by legislative authority through the CAA (Brownell 1998). However, within these guidelines, room for interpretation exists as is evidenced by the variety of different applications that have been accepted in the past. Dispersion models are preferred by the EPA because they determine how a pollutant will disperse from a specific stationary source to a receptor downwind (EPA 2004). These types of models are especially useful for determining exceedances of the 24-hour standard, which is currently $150 \mu g/m^3$ (EPA 2006).

Criticisms of Approach to Air Quality Management

Environmental pollution management has been criticized for: having narrow objectives (Wondolleck and Yaffee 2000); being event-based (Bennear and Coglianese 2005, Miles 2003); focusing on command-and-control techniques (Mazmanian and Kraft 1999); being highly bureaucratic (Bennear and Coglianese 2005) and resistant to change (Wondolleck and Yaffee 2000: 55); using uniform strategies (Barrow 2006a-b) which are often inflexible (Mazmanian and Kraft 1999, Wondolleck and Yaffee 2000); lacking incentives to achieve environmental quality (Mazmanian and Kraft 1999, Barrow 2006a); preferring to maximize short-term benefits which leads to overlooking long-term effects (Barrow 2006b: 328); and lastly, concentrating on symptoms rather than causes of problems and so developing strategies to treat those symptoms (Barrow 2006b: 328).

In addition to the linear model of AQM described earlier, it is also event-oriented in its focus on the number of exceedance events instead of trends in emissions. The number of exceedances is usually determined by comparing a three year average or high percentile of monitored values to standards, although specific considerations vary by pollutant. The most important exceedance determination is for the area's attainment deadline and this specific date is usually the focus of all management controls and policies. Of course, required on-going ambient air quality monitoring helps place events within a context.

When exceedances result from extreme conditions outside of the control of managers, the CAA allows the event to be excluded (CAA §188 [f]). However, these exceedances may occur seasonally from site-specific factors and excluding them may disguise rising peaks in seasonal high-pollution episodes. Although the specific event may be triggered by an "uncontrollable" natural event such as extreme winds, the severity of the exceedance may be increasing due to anthropogenic activities. Therefore, the event-based view can lead to a picture which does not reflect the reality of the system. Likewise, allowing for the exclusion of these episodes, especially if human-caused changes to the landscape exacerbate their intensity, implies that areas do not have to make contingencies for these events. They are out of managers' control.

Determining whether an area's level of a given pollutant is below standards for the SIP process is a one-time demonstration of attainment (NRC 2004). The demonstration is usually the results of a model of future pollutant concentrations and dispersion for a single day in the future. Models do not show how pollution levels will change during the years following implementation of the control. Instead, models predict specific pollution levels and chemical interactions based primarily on projected activity levels and meteorology.

Models used by air quality managers are mostly predictive models used to demonstrate that air pollutants will be below standards. They are often simulated for only one day in the future and ignore social elements of decisions and policy impacts. Many models ignore feedback, at least for social dynamics[5]. As Sterman (1999:8) says, models without feedback have a narrow boundary and rely heavily on exogenous variables. The National Research Council states that a major challenge of the AQM and planning process is the "inability" for managers to use social and behavioral measures to improve air quality (NRC 2004: 116). Additionally, pollution is traced back to the

[5] feedback in the terms of a chemical reactions leading to changes and still further changes in the original pollutant are usually very thoroughly addressed in models. It is only the impact of policies on the system that is usually ignored.

sources of disturbance (e.g., reentrainment by cars on roads—called paved road dust) and not necessarily their original source (e.g., nearby vacant lands) (RTC 2004).

Pollution problems in models (both by local entities and federally) is not usually traced back through the complete causal pathway of the problem. Emissions are attributed only to their immediate physical sources and not to the factors driving those sources to change. Most plans do not consider human actions or policy levers within the system such as public education (Stem *et al.* 2005: 306, Power and Sharda 2007).

While the EPA typically recommends grid-based, chemical transport models to demonstrate attainment, such predictive models are designed to demonstrate future point values and not as an aid in understanding patterns of change (Ford 1999). These models require detailed meteorological information and equations for fate and transport of chemicals. Many of these data are highly uncertain and imply a high degree of precision despite their very uncertain foundation. Though comprehensive in their treatment of physical and chemical processes, these models do not usually contain a time horizon of sufficient length to analyze trends in their context and very rarely contain social aspects or drivers of the system. Finally, these models are not equipped to help managers determine policy levers but only to test the predicted pollution level given certain input variables.

In air pollution/quality management, a growing trend is for very technically detailed models that capture the physical movements or chemical transformations of pollutants that also ignore the major drivers and causal mechanisms of the inputs to those models. Variable inputs representing behavior-based emissions, such as vehicle-miles traveled are inputted based on assumed values for future populations and their driving habits. The models purport very precise and spatially explicit results, but they rely on inputs which are anything but certain.

These models have very important functions for decision-makers in many contexts, but cannot answer questions beyond whether certain inputs under certain conditions will lead to pollution levels above standards. These physical, chemical dispersion or transport models are therefore very limited for developing policies. The focus of modeling has become answering the question: *does this area meet the air quality standard for X pollutant?* However, this question actually means very little when considering the overall picture of managing air quality. In fact, if this question becomes the dominant issue, then it actually switches the focus further away from an integrated and holistic view of air quality.

Ford (1999: 10) argues that it does not make sense to construct very precise forecasting models for systems contingent on highly variable inputs (e.g., weather), since essential inputs cannot be measured or predicted. Air quality models predict very precise concentrations using meteorological data, topography, and understanding of chemical reactions and transport of pollutants. Some of these inputs or data sets are fairly certain and static (e.g., topography). However, meteorological predictions have a high degree of uncertainty for even a week in advance, let alone several years.

Managers often focus only on determining the cost effectiveness of all control strategies when making comparisons and it is rare to see comparative analysis between different policies of any other type (except matrices showing the standards in place in other air quality areas). Since other potential effects of policies are not strategically reviewed, decisions are made without considering these effects. Additionally, since understanding how the system works often leads to identification of policies and important intervention points, many locally applicable options may not be considered. If control options are especially limited, areas may be forced to implement all policies regardless of costs, in order to obtain the required emission reductions.

Air quality management is often limited to compliance with air quality regulations. Unfortunately, managers are put in a difficult situation of trying to meet regulatory requirements in a timely manner with possibly significant consequences if they fail. The approach to AQM focuses on short-term compliance and goals, tends to be narrow, not holistic and may be less effective than other approaches in some cases. However, it is the regulatory context of AQM that enforces this approach. Managers may be wary of embracing new approaches to modeling because the EPA may not approve or due to the extra burden of proof required to demonstrate the method as valid. More often than not, models are developed to demonstrate attainment of the standard but not as an aid in the planning of management strategies or to help understand the problem.

Decision Support Systems

In attempting to meet federal standards, states or AQM areas have the flexibility to decide on major policies. "There is generally more than one route to a goal," (Barrow 2006b: 175). Decision support systems[6] (DSS) are used to help policy makers decide between different courses of action. These tools can include physical models used to determine a likely outcome of a scenario with fairly certain inputs and clear rules for

[6] Throughout this thesis, I use the terms DSS and model synonymously. However, distinctions are often made between the two depending on the purpose. Usually models are considered to be a more formalized form of DSS. Sometimes models are a great deal more technical than DSS. At other times, models can be more conceptual tools while the DSS provides powerful simulation capabilities.

behavior (e.g., flood management scenarios, using topography and physical laws). Such models use vast amounts of data that may cross into geographical information systems and mathematical models.

DSS help managers make "informed" decisions and ultimately lessen the time and decision-making phases needed to find a "satisfactory" solution (Ahmad and Simonovic 2006: 392). DSS are used for a variety of applications, from business to social issues. There are many types, with varying specificity, complexity, and use of technology. In general, they are used to aid decision-makers in solving a particular problem or determining a course of action toward a solution. DSS provide a laboratory in which policy effects can be simulated to help managers make decisions (Sterman 2001).

A major benefit of DSS is that they allow for testing the outcomes of various policies relative to current practices, without actually having to implement them and find out results on a trial and error basis. It is possible to at least relatively quantify most changes to systems using a variety of tools, making a qualitative-only decision-making process "obsolete" (Ben-Ami, Ramp, and Croft 2006). However, this does not discount the importance of intuition in management. It is argued that DSS should assist—not hamper—the insight and intuition of decision-makers since insight plays an important role in making good decisions (Kersten 2000). Of course, defining what a good or appropriate decision is a difficult task of its own and outside the boundary of this study.[7]

DSS may focus on data but it is vital to recognize that technical factors are only <u>part</u> of "wise public choices" (Wondolleck and Yaffee 2000: 5). Quantitative data can be used to establish trends or to compare different site characteristics or strategies (Stem *et al.* 2005: 306). This is an important part of understanding important elements in the

[7] see Dietz 2003 and Scmidt *et al.* 1998

system or recognizing problems. Yet, qualitative data are essential because they explain the context of those trends and data (Stem *et al.* 2005: 306). Problems are more uncertain and complex now than ever (Wondolleck and Yaffee 2000, Power and Sharda 2007: 1044, Sterman 2001). Therefore, the focus should be on improving our knowledge and understanding and not just technical approaches (Wondolleck and Yaffee 2000). Even though there are many highly technical air quality models used in AQM, sensitivity analyses are not performed nearly enough on air quality DSS (NRC 2004).

Simulation modeling can help society at large and managers specifically deal with the world's growing complexity and make improved decisions (Sterman 2000, Sterman 2001). Applying a change first in a DSS helps at least assure relative effects of policies compared to others and provides some assurance that a policy will not actually make the situation worse (Sterman 2000, 2001).

Potential Benefits of a Systems Perspective

This thesis examines the benefits of incorporating a systems perspective into the management approach, specifically into decision-making tools and models. Improving air quality management is an important challenge, with the potential benefits of shared learning among managers and therefore, improved and more effective polices. Although managers are required to meet the legislative regulations placed on them, they can still take steps to improve how they go about meeting those requirements. There may be other means for improving management under the existing regulatory framework, but this project explores improvements in decision- and policy-making tools.

As Kersten (2000: 29) emphasizes, there is a high demand for decision-making tools that assist in making informed decisions, help decision-makers explore both the direct and indirect consequences of decisions, and lay groundwork for future decision-making. Additionally, because of the growing complexity and uncertainty of the world and therefore management decisions, any help that can be given to support managers in decision-making is important (Power and Sharda 2007: 1044).

A system dynamics model is used and the strengths, limitations, and applicability of these models to other areas are discussed. Improving understanding about the causes of PM_{10} problems and how development plays a part should provide new understanding useful to other areas facing similar growth or with the potential to have PM_{10} problems.

Research Question

Would a system dynamics treatment of PM_{10} in the Las Vegas Valley be beneficial for management of this pollutant?

Hypothesis

I hypothesize that a system dynamics model of PM_{10} management in the Las Vegas Valley would have major benefits including:

- Results which behave closer to what would be expected in the real world
- Improved understanding of how the PM_{10} problem developed
- Identifying (and possibly avoiding) potentially harmful consequences to policies
- Integrating major components of the system into one perspective
- Focusing on the long-term management goals of the area

The big-picture perspective that incorporates major feedback structures should provide for a model that produces the same general trends that are seen in the real world.

Additionally, the model would respond in ways that reflect reality, both intuitive and counterintuitive responses. Creating a model which can recreate how the problems developed in the Las Vegas Valley would provide insight into how the PM_{10} problem developed. Understanding may reveal connections to other major pollutants or problems in the Valley or, at least, provide useful information to other areas which may face PM_{10} pollution problems.

Since system dynamics models focus on the interconnections and feedback in the system, such models often show surprising consequences of policies. The outcomes of policies can be ineffective or possibly harmful—making the problem worse or causing other problems (Sterman 2000). Current air quality management practices appear to be isolated for different pollutants (NRC 2004), components of the system, and ultimate drivers for sources (population). Incorporating all of these elements should provide a multi-perspective context by which to evaluate policies and their effects.

Finally, a system dynamics model should use a time horizon that is relevant to the problem, extending back far enough to capture how it developed and into the future enough to show delayed consequences (Sterman 1991, Sterman 2000). A long-term perspective in the model would encourage managers to evaluate the future repercussions of policies implemented today, along with their short-term gains. Viewing potential future outcomes would provide managers with an incentive to determine future goals and possibly, to discover policies which may lead to those goals.

CHAPTER TWO

APPROACH

In order to determine the benefits of using a systems perspective, a system dynamics model was developed. The PM_{10} Proportional Rollback Model (PRM) was developed by the Clark County Department of Air Quality and Environmental Management's (DAQEM) to support the 2001 State Implementation Plan (SIP). The PRM is described as the current decision support system (DSS). This model represents how managers in the LVV are currently using decision-making tools to support AQM.

In a review of literature, Aggett and McColl (2006: 84) identified four major components for measuring DSS utility: transparency, flexibility, user-friendliness, and capability to incorporate and communicate stakeholder interests. Other DSS evaluation frameworks were reviewed[8] but they were limited to specific management aspects (e.g., public participation using graphic information systems) and not generally applicable to all DSS or to air quality. The other components deal with aspects of model use and functionality of the software. While possibly significant, these factors were not specifically addressed in this thesis. It is considered more important to analyze the perspectives and performance of the model instead of software issues.

Also, it is important to note that this thesis does not involve managers using and evaluating these models. Instead, components that can be evaluated qualitatively or

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[8] Other evaluation frameworks are shown in Appendix D

quantitatively are examined. Judgment choices such as whether managers would use the models or to what degree they are useful are not included.

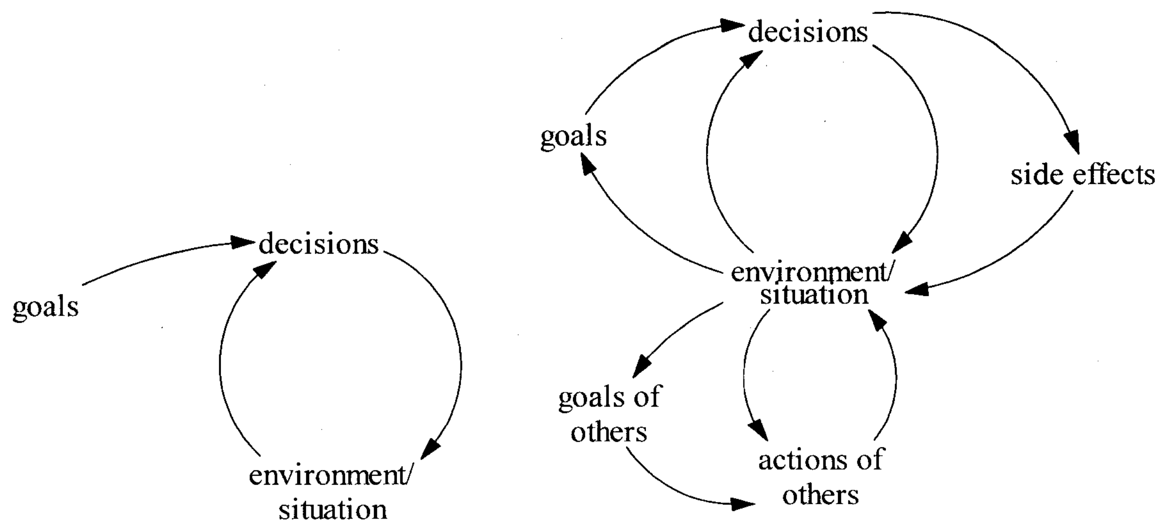
Support for a Systems Perspective

Although local and regional air quality managers cannot change the federal regulatory framework, they do have control over how they approach policy-making. A systems approach to air quality management decision-making tools provides an alternative approach. Systems perspectives in decision support systems (DSS) could allow managers to explicitly state and evaluate assumptions of how the system operates. The perspective of the systems approach has a big-picture view that incorporates essential system components and processes, many of which are normally excluded. This approach would augment current models to allow managers to test the effect of changing policy levers.

As opposed to the open-loop or linear view of the world (Figure 1 in Chapter 1), Sterman (2000) provides a representation of the interconnected view of the world shown in Figure 4. The systems perspective incorporates the changing nature of the state of the system. Our interventions influence the future situation we will face. In the linear and event-oriented view, results other than those desired are considered side effects. However, the right side of Figure 4 shows that "there are no side effects, there are just *effects*," (Sterman 2000: 11, emphasis in original). The impact on the environment is a result of our intervention and failing to include a large enough perspective only makes that impact a surprise, it cannot prevent the impact from occurring.

Changes to the environment drive our goals. Consider a theoretical case where society wants to have cheap widgets (goal) but in achieving that goal it is found that

Figure 4 Systems/feedback view of the world (Figure 1-4 in Sterman 2000: 11)



widget manufacture leads to severe water pollution (change in environment) and the death of *animal x* (side effect). Society may decide protecting *animal x* is more important than cheap widgets (new goal). Other actors complicate the picture further because they are also affecting the environment, based on their own goals.

Air quality issues fit this model. Not only is the physical environment (urban infrastructure, meteorology, etc.) changing, but the social and regulatory environments are changing as well. These situations are growing ever more complex. Air quality laws and regulations have become more thorough, specific, and complicated with time (EIH 2006, NRC 2004). Even pollutants are becoming more complex. Early air quality management (AQM) focused on large mixtures of chemicals such as smoke (EIH 2006). Now pollutants are treated at smaller and smaller constituents or species of chemicals. The dynamics of air quality problems and their growing complexity provide strong support for using both a systems and a long-term perspective for management.

Other support for a systems perspective comes by looking at the consequence of a non-systemic view. Understanding the world as events and ignoring feedback can result in policies which are generally ineffective or even harmful. Sterman (2000: 3) calls this "policy resistance," where reactions of the system (social or natural) to human inteventions can counteract the attempted solution.

Sterman (2001) describes several examples of policy resistance and examines how they occur, their consequences, and what can be done to counteract them. One example is low-tar and low-nicotine cigarettes; while designed to reduce the amount of chemicals inhaled, actually lead to consume more chemicals as smokers compensate by smoking more and holding the smoke longer (Sterman 2001: 9). Another pertinent example is that constructing roads, which aims to improve congestion, has actually increased traffic, delays, sprawl (Sterman 2001: 9).

Meadows (1991) argues that the current paradigm is dominated by non-systemic thinking. Many of the assumptions of how the world works, including: that one cause produces one effect; technology can solve any problem that arises; the future is to be predicted (not chosen or created); the world is linear, continuous, and there are no delays; the feedback we receive is correct and comes when we need it; and we can manage systems with simple cause-effect thinking (Meadows 1991: 4-5).

These views of the world are evidenced in AQM. There may be multiple causes of pollution, but they are traced back only to their direct emittance source (vehicle "kicks up" dirt that has been deposited on the roadways from other sources or mechanisms). The amount of dirt that falls onto roadways is partially dependent on the amount of vacant land nearby, local disturbance activities, and weather. For the most part however, these influencers of emissions rates are not included. Therefore, additional or distant causes are not necessarily tracked.

The focus on pollution-reduction has been primarily technology based (NRC 2004). Important connections to social factors or educational campaigns are not considered viable policy options. In fact, the CAA Amendments of 1990 specifically prevent the inclusion of any behavioral-based controls or policies (NRC 2004).

Prediction is often the goal of air quality models. They are not used to determine other impacts of policies, except to determine specific PM_{10} concentrations resulting from strategies. Additionally, they tend to be very comprehensive and time-consuming simulations and so only a few alternative strategies may be applied as a set. Some models have complex, non-linear relationships between chemicals and how they react under certain conditions, but use simple linear projections (or correlations) for population and travel demand forecasts. The level of dynamics incorporated in the model is not consistent for essential parts of the system.

Meadows (1991: 6) states that system concepts, even basic ones, can improve understanding of how the world (or part of it) works. Understanding simple interconnectedness, for example, would show that energy conservation strategies would save consumers money while also reducing air pollution, acid rain, greenhouse gases, production of waste, the trade deficit, and defense costs, among other effects (Meadows 1991: 6).

Other supporters of systems thinking and system dynamics argue that having a holistic, big-picture, perspective of the world would speed up the learning process and make it effective (Sterman 2001). The focus placed on distilling the worlkd into the main causal mechanism can aid identification of points in the system, called leverage points, where the greatest change can be achieved with relatively little effort (Sterman 2001). Finally, the systems view would help avoid policy resistance and therefore allow decision-makers to make decisions that ensure our "long-term best interests," (Sterman 2001: 10).

Sterman (2001: 17) emphasizes the need for tools with the ability to capture feedback mechanisms and dynamic complexity in order to "improve our ability to learn about and manage complex systems." These tools must aid in understanding how structures lead to problematic behaviors and policy resistance, while also allowing for evaluating the consequences of new policies and/or structures we might develop (Sterman 2001: 17). For these tools he focuses on causal mapping and simulation from the field of system dynamics.

So what constitutes a systems perspective[9]? Richmond (1991) states: "You are adopting a systems viewpoint when you are standing back far enough — in both space and time — to be able to see the underlying web of *ongoing, reciprocal relationships* which are cycling to produce the patterns of behavior that a system is exhibiting."

System Dynamics

System dynamics is a problem-based approach for understanding and managing systems exhibiting complex feedback (Sterman 2000, System Dynamics Society). The field was established by Jay Forrester, an electrical engineer, in the mid-1950's (Forrester 1995). The premise of System Dynamics is that structure generates behavior (Forrester

[9] For existing and developing research into the characteristics of systems thinking and systems thinkers, see Booth Sweeney and Sterman (2000) and Stave and Hopper (2007 [Paper at International System Dynamics Conference, in progress]).

1995, Sterman 2000), or that a certain problematic behavior occurs because of the way the world is "wired." Much like the way microphones and speakers are wired together to amplify sound, the structure of our systems and institutions may amplify or negate certain behaviors (Stave 2002a, Forrester 1995).

Structure is "the set of physical and information interconnections" causing behavior (Ventana Systems, Inc. 2004). System dynamics models attempt to capture the essential structure causing the problem, distilling the system down to its major feedback structures (Sterman 2000, Forrester 1995). The goal is to develop the system from the inside, looking at all the components and interconnections (including information) to understand why a problematic behavior pattern is occurring and develop interventions to improve that behavior (Forrester 1991). The understanding of the structure is developed into a simulation model which handles all of the complex calculations for these interactions, and help us deal with the time delays, feedback, nonlinearities, and other difficulties of systems (Sterman 2001).

Confidence in the model comes when the results, or behavior, of the model matches the actual, historical data or generalized problematic trend (called the reference mode). Once the model is capable of generating realistic behavior that closely matches the reference mode, we can be fairly sure that the essential structure has been captured and policy questions and other sensitivity or extreme scenario tests can be tested. If policy-makers wish to intervene in the system to change undesired behavior, they must change the structure (Stave 2003, Ventana Systems).

Similar to the approach used to train pilots, system dynamics models provide a "management flight simulator" to help decision-makers, or the public in general, learn about systems, feedback, dynamic complexity, policy resistance and the effect of various policies (Sterman 2001: 10). It is useful for managers to learn what types of controls they have at their disposal and become familiar with the relative effects of manipulating them.

One key distinguishing factor of system dynamics models is that they attempt to understand and represent the feedback in a system (System Dynamics Society, Sterman 2001). Rather than a view of the world as a short linear chain, from event to reaction and end results, the world is represented as feedback loops where actions or reactions in turn go on to affect or determine the future state of the system (Sterman 2001). System dynamics models therefore focus on dynamic problems—problems that are changing over time (Forrester 1995, Sterman 2000, Stave 2003).

System Dynamics Problem-Solving Method

There are several steps in the system dynamics approach, represented by many authors (see e.g., Sterman 2000, Ford 1999, System Dynamics Society, Stave 2003). With some variation, these procedures follow the same general sequence, beginning with identifying and representing the problem, moving to understanding of the system which culminates in hypotheses and models, testing the model for validity, and finally using the model for testing. The process is iterative, as results from initial simulation models suggest needed adjustments in the structure of the system. In this thesis, the first five steps[10] described in Stave (2003) will be used:

1. Define the problem
2. Describe the system
3. Develop the model
4. Build confidence in the model
5. Use the model for policy analysis

[10] this paper actually describes 6 steps of the system dynamics process, including a step for using the model for public outreach.

The first step involves determining the key variable (or a few variables) that clearly represent(s) the problem in a graph as a trend over time. This graph is referred to as the reference mode (Ford 1999, Sterman 2000) and defines the focus of the modeling effort.

Step 2 requires identifying the major variables that are causing the problematic behavior identified in Step 1. Once all major variables are determined, a dynamic hypothesis of the structure of the system is created. The dynamic hypothesis represents major variables, how they are connected, and how they react to changes in other variables (Stave 2002a, Sterman 2000, Ford 1999). Because system dynamics is based on the premise that structure causes behavior, the major hypothesis is a supposition about that structure.

There are two major ways to describe the structure of the system: causal loop diagrams and stock and flow diagrams (Sterman 2000). A causal loop diagram (CLD) shows system elements and traces the causal linkages between them. Variables are represented as connected pairs showing dependency, by the direction of the arrow, and the relationship between the variables as a symbol on the arrow (Sterman 2000). Another way of representing structure is a stock and flow diagram[11]. Stock and flow diagrams highlight the difference between accumulations (stocks) and rates (flows).Step 3 includes operationalizing the structure represented in the dynamic hypothesis into a model than can be simulated. Although CLDs are useful for demonstrating the causes and feedback

[11] There are different schools of thought on whether CLDs or stock and flow diagrams should be performed first. However, this study uses CLDs to demonstrate the major components of the system and how they are connected in the dynamic hypothesis. This is the final step of Step 2, describing the system. Of course, either representation of structure could serve as the dynamic hypothesis of the structure causing a problem.

in the system, they are not able to specify the exact nature (i.e., the equation) of the relationship (Sterman 2000).

Step 4—building confidence in the model—at its most basic, includes comparing the output of the model to the reference mode developed in Step 1. Other validation tests are often performed to test whether the model behaves logically under extreme conditions or demonstrates sensitivity under a range of probable values. Usually, this process demonstrates issues with the structure that must be resolved. This necessitates a return to Step 2 or Step 3, depending on the required changes to the conceptualization. This process repeats various times, until the structure generates the problematic behavior and responds reasonably to tests.

Once the structure is validated and seems fairly robust, the model is used for policy analysis in Step 5. The types of policy tests that will be performed depend on the nature of the problem and therefore the system in question. Key leverage points are usually discovered. This step promotes a vast amount of learning because although people may be able to diagram out how components are connected, they are nearly incapable of understanding how the dynamics of those interconnections will play out (Sterman 2001).

System Dynamics Applications

Models have been created using system dynamics for nearly every type of system, from social and business applications to theoretical mathematical applications (System Dynamics Society). A number of studies apply systems dynamics models to air pollution problems, especially to come to a management or policy result. Although SD models are capable of having a large model boundary, the scope and detail of the model are determined by the problem being addressed and the purpose of the model.

Several studies look at managing air quality with urban development. Specifically in Las Vegas, Stave and Little (2002) created a model of the LVV transportation system—paying particular attention to factors such as air quality, policy cost, traffic congestion and flow—to use with public participation to decide on future policy directions for the Valley. In this model, participants experienced insightful and surprising results, such as that increasing the vehicle occupancy rate (i.e., carpooling) was as effective as building roads at reducing congestion but had much greater reductions in air pollution (Stave 2003). The application of this model for public involvement and understanding demonstrates a valuable characteristic of SD models, especially when developed by a group of management and political entities.

Another SD application based in the LVV is the Land Use, Transportation, and Air Quality (LUTAQ) model. This model was developed by the LUTAQ Working Group, a diverse mix of transportation, land-use, air quality managers and technical staff Dwyer and Stave (2005). The model examines the effects of changes in land use and transportation practices on air pollution, population, and costs (Southern Nevada Regional Planning Coalition [SNRPC] 2006). A key finding was that increasing density by itself is harmful and worsens problems of congestion and air quality in the Valley (SNRPC 2006). This was a surprising result for managers, especially since densification is the growing trend in development. Results of policy analysis also showed that dramatic changes were not needed to bring about improvement, but that they would have to come from a combination of several characteristics and not one area alone (SNRPC 2006).

Many of these models show the benefit of looking at problems systemically. When certain policies are tested it is often found that no single answer will satisfy all criteria. There are tradeoffs associated with decisions. There is no "magic bullet." For air quality management this implies that simply looking at outcome for pollutant concentrations (and possibly cost effectiveness) is not sufficient. Systems are so interconnected, that effects are sure to be far-reaching. The potential for compensating feedback, or the counter-acting response of the system to policies (Sterman 2000), is high.

Tradeoffs of a System Dynamics Approach

SD models focus on relationships and feedback among variables, making assumptions about how components affect others explicit (Forrester 1995). Instead of numerous exogenous inputs, the model incorporates the relevant structure causing trends in variables and makes them endogenous (Sterman 2000). For example, instead of a fixed table of population values into the future, birth rates and death rates would be used to calculate population through time. Exogenous inputs are also based on many assumptions and a theoretical understanding of how the world works, but they are unexaminable when only the value is used (Sterman 1991).

As mentioned briefly, system dynamics is concerned with dynamic problems. However, SD is not applicable for every situation or problem. There are many problems which are not dynamic but are still important management issues with potentially severe consequences. Static problems such as determining a site for a new landfill are not suitable for a SD approach (Stave 2003).

Additionally, many decisions about the environment deal with spatial issues (Costanza and Voinov 2004). Most SD models have traditionally treated problems from a high or aggregated view and have not been spatially explicit. However, a new trend in SD is the use of landscape simulation models. These models use SD models within a grid-based geographic information system to determine dynamic changes through time in a spatial context (Costanza and Voinov 2004, Ahmad and Simonovic 2004).

The purpose of a system dynamics model is usually to gain insight and not to predict a particular point in the future (Ford 1999). In fact, the understanding gained through simulation is often more valuable than predicting the future with accuracy (Van den Belt 2004). General understanding leads to managerial "rules of thumb," which are used to make rapid decisions without having to think through the much more complex interactions and calculations they represent (Ford 1999: 11). Often the process of developing the model leads to improved understanding of the system and simulation may identify gaps in data that should be resolved (Sterman 2001: 21). Policy tests with SD models, and systems thinking in general, can improve decision-makers' conceptualization of the world and relationships. This learning can reach far beyond the current problem and aid managers in new situations.

Again, the output of system dynamics models is NOT predictive. Models are intended to replicate the general problematic trend of concern and show the *relative* effects of changes to the system. General trends and relative effects can be quite powerful for understanding major feedbacks within the system as well as determining leverage points, ineffective points to intervene in the system, and surprising dynamics. While complex chemical transport or dispersion models seem to be much more precise, they still rely on very uncertain information, making a predicted value erroneous and even possibly misleading.

AQM typically uses spatial chemical transport models to predict the dispersion of pollutants based on a variety of comprehensive data inputs. The major foundations of important data such as population and travel demand are not explored within the model and are usually exogenous (outside of the model boundary, fixed inputs). Since these values would have significant impacts on how much pollution would be in the air, is it reasonable to assume a very precise and spatial prediction for such uncertain inputs? Many meteorological predictions are not considered accurate even as few as days in advance.

Functionality

Some of the main benefits to using systems dynamics models are that they are very fast. This makes SD models ideal for managers in planning sessions where questions can be asked of the model on the fly. There are virtually no limitations on the numbers of scenarios that can be simulated. Results can be displayed graphically as well as in tabular form. Systems dynamics models can be adapted or updated easily, especially for parameter values. The documentation for variables is tied directly to where operational information (equations, etc.) is inserted.

The Case Study

In order to build a model and evaluate the benefits of a system dynamics approach, a relevant air quality problem case was needed. The case of particulate matter pollution (smaller than 10 micrometers) in the Las Vegas Valley (LVV) presents a difficult management case of a persistent air quality problem. Although new standards for a smaller subset of particulate matter were established in 1997 and recently updated in 2006 (EPA 2006), there continues to be a problem in many areas with attainment for previous standards established in 1987 (NRC 2004). Additionally, new fine particulate standards do not appear to pose a problem in the LVV and management entities in the LVV cite PM_{10} as the primary pollutant of concern (CDSN and DAQEM 2003).

PM_{10} in the Las Vegas Valley

The LVV in Clark County, Nevada is among the eight serious nonattainment areas for PM_{10} described in Chapter One (EPA 2007). Particulate matter ha been a concern there as far back as the 1960s and 1970s, when pollution levels were often above the standard at the time (Fed. Reg. 7 Sept 2004). After Nevada failed to meet the original total suspended particulate matter standards, a plan was submitted describing the steps the state would take to improve the air quality. The plan was submitted in 1981 and approved by the EPA the following year.

In 1987, the TSP standards were changed to the smaller PM_{10}. All air quality management areas above the standards of TSP were analyzed to see if they would meet the new requirements for PM_{10} and were grouped according to the likelihood that their current plan would lead to an exceedance (Fed. Reg.2004: 32273-32277). Nevada's plan was placed into Group I because, under the current plan, the area had a "strong likelihood" of violating new regulations.

In 1990, the Clean Air Act (CAA) was amended again, and all those areas in Group I were designated as "moderate nonattainment areas" and given a deadline of

November 15, 1991 to submit a new plan (Fed. Reg.2004: 32273-32277). Clark County, having now become the authority responsible for the area, submitted its plan in the end of 1991. Two years later, the EPA found the plan inadequate. As a result, the area was reclassified as a "serious nonattainment area," required to submit a new SIP, and demonstrate attainment by December 2001.

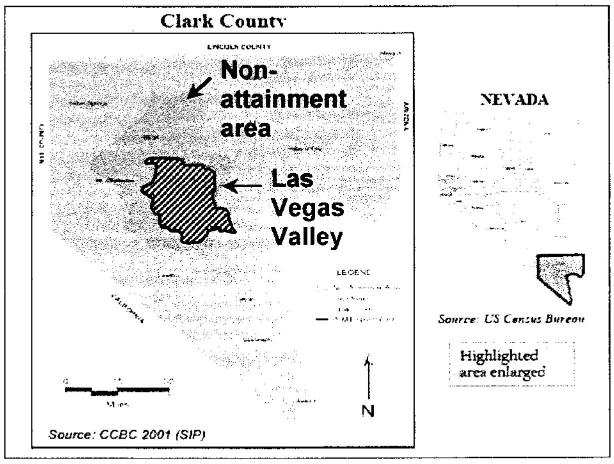
The County submitted plans again in 1994 and 1997 to meet the legislative requirements of the CAA, but was unsuccessful in demonstrating attainment of standards (CCBC 2001). The 1997 plan was found insufficient to meet the requirements of the CAA but the County withdrew the plan before a formal disapproval could be issued (Fed. Reg.2004: 32273-32277). In July 2001, the final revised submittal was received by the EPA. Several parts of this plan were immediately found adequate and after a two year review, the EPA proposed approval of the plan. The final rule for approval also extended the attainment demonstration from 2001 to December 2006 (Fed. Reg. 2004: 32273-32277).

Physical Site Characteristics

The air quality region that encompasses the LVV follows the same boundary as the U.S. Geological Survey designated Hydrographic Basin 212 (69 Fed. Reg. 32273, CCBC 2001). Figure 5 shows the geographical boundary of Clark County, Nevada and the LVV (labeled as the "BLM Disposal Area"). The basin has an area of roughly 4,000 km^2 and is surrounded by mountains up to 3,600 m in elevation (DRI 2002).

Over 99 percent of the population residing in this area lives within the smaller BLM Disposal Boundary, comprising approximately 1230 km² (CCBC 2001). Due to this concentration of people, and major sources, the DAQEM used the disposal boundary (i.e., the LVV) as the boundary for air quality management. Within this smaller region lay a great diversity of land uses and jurisdictions, leading to a variety air quality impacts and management difficulties.

Figure 5 Map of Clark County Nonattainment Area



Local topographical, meteorological, and industrial aspects may make an area prone to air quality problems (Spellman 1999). One of the local topographical factors reinforcing the PM problem in the LVV is the surrounding mountains. Areas either completely or partially surrounded by mountains often exhibit more problematic air pollution issues than areas without mountains (CDSN and DAQEM 2003). Mountains decrease wind speed and create physical barriers that can trap air, thereby slowing pollutant dispersal and keeping concentrations high (Spellman 1999). Smaller-scale topography can also play a role.

There is great variation in localized PM_{10} result from buildings and minor changes in elevations, making some monitoring stations prone to higher recorded levels. Chow *et al.* (1999) had results for sites experiencing similar meteorological conditions but located in different areas differ up to a factor of five. However, this thesis is focusing on regional levels and not on identifying where "hot spots" may develop or their impacts.

Meteorological factors also contribute to the problem. In winter months, the LVV is subject to inversions and low wind velocities, resulting in trapped pollutants (CDSN and DAQEM 2003). Wind demonstrates a complex interplay with PM_{10} because it can be seen as both a removal (blowing out of Valley) and an additions process (CDSN and DAQEM 2003).

Industrial characteristics of the area do not significantly contribute to air quality problems. Additionally, the major areas of industry (tourism, gaming, government/defense, chemical manufacturing, quarry operations, and construction) do not promote pollution, "except for their encouragement of greater driving distances between home and work," (Kuhns et al. 2002). In 2001, all stationary point sources accounted for less than one percent of total emissions (CCBC 2001, DAQEM 2003).

How Does the LVV Manage PM_{10}?

The DAQEM developed a decision support system (DSS) in 2001 for demonstrating that PM_{10} in the LVV would be below standards for the year 2006. This model, the Proportional Rollback Model (PRM), was part of the requirements of the State Implementation Plan (SIP) procedure and supports the 2001 PM_{10} SIP document[12]. The original PRM consisted of a series of spreadsheets that required the user to manually insert input values and move calculated values into other spreadsheets. In a project to improve the functionality of the model, it was converted into a system dynamics representation. The underlying calculation methodology was only modified for one component (described in the subsequent paragraphs).

[12] This document is cited as CCBC 2001 throughout this thesis.

Local management authorities[13] in the LVV worked together in order to provide the input variables for the PRM. Actual emissions from the 1998 base year were used to establish an emissions inventory. Emissions factors were determined using either local data or procedures developed by the Office of Air Quality Planning and Standards (a division of the EPA) and described collectively in the *AP-42* document (EPA 1995, EPA 2003b).

The PRM can be classified as an empirical rollback model because it is based on observed relationships between pollutant concentrations and emissions and does not represent fundamental chemical or physical processes causing the observed behavior (NRC 2004). The calculation methodology assumes that mass emissions (in tons) are directly related to the pollutant concentration (in $\mu g/m^3$). Therefore, a reduction in the mass emissions leads to a proportional decrease in the concentration.

To determine 24-hour emissions the model uses what the DAQEM calls a "design day" (DAQEM 2005b). 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 continuous days of PM_{10} levels and so does not represent an actual trend in emissions over time but rather how that one typical day might change. The design day is similar to the "design value" typically used in air quality modeling, which is determined from monitored concentrations and by making pollutant-specific calculations[14] (NRC 2004). This value is compared to the national standard. When modeling, the design day

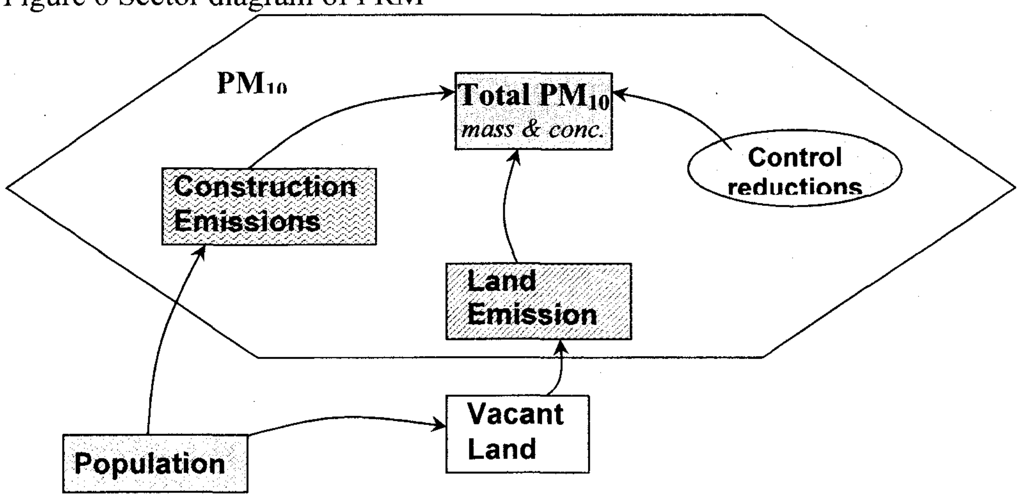
[13] Entities include: Clark County Department of Comprehensive Planning, Clark County Department of Air Quality and Environmental Management, Southern Nevada Regional Transportation Coalition

[14] For PM, the design value could be the 3-year average, 98th or 99th percentile value of all monitored emissions, depending on whether it is for PM_{10} or $PM_{2.5}$. There are also other methods for calculating the design value of ozone and other criteria pollutants. (NRC 2004, EPA 1999)

value serves as the foundation concentration which is reduced through controls (NRC 2004).

Figure 6 represents the higher-order sector diagram of the PRM. Total PM_{10} depends on emissions (construction and land-based) and is reduced by control reductions. Land emissions depend on the number of vacant land acres and this is determined by construction for growth in population. As acres are constructed, they reduce the vacant land. Control activity reductions are exogenous in this model because they are included as cumulative percentages of a variety of control activities.

Figure 6 Sector diagram of PRM



The three main sectors (Population, Vacant Land, and PM_{10}) can be expanded to reveal several important variables. These variables are shown in Table 2, according to whether they are endogenous (calculated within the model) or exogenous (directly inputted into the model, independent variables). Table 2 identifies other key variables in the system that may be important for modeling PM_{10} but were omitted.

Table 2 Key variables in the PRM

Sector	Endogenous	Exogenous	Omitted
PM10	Disturbed Vacant Land emissions Stable land emissions Native Desert emissions Construction activity fugitive dust Construction activity wind erosion Construction Trackout	Mobile source emissions Point sources Silt loading factors Emission factors* Control reductions*	PM_{10} cycles PM_{10} Concentration Meteorological factors Spatial dispersion PM_{10} characteristics Mobile emissions and roadway components
Vacant Land	Native Desert acres Unstable acres Stable acres Annual construction demand	Land consumption factor	Spatial variation Feedback of land *(esp. for demand)*
Population		Population	Population dynamics Sensitive populations Population characteristics *(e.g., age, sex)* Travel demand

A notable component of this structural representation is that several important drivers are considered exogenous. Exogenous variables have been created by assumptions and data sources that cannot be evaluated since they are outside of the boundary of the model (Sterman 1991). In the PRM, calculated PM_{10} emissions are limited to vacant land and construction-related emissions. Control reductions which dramatically influence both vacant land and construction emissions are not defined within the system. Furthermore, mobile emissions are not calculated within the model[15] and

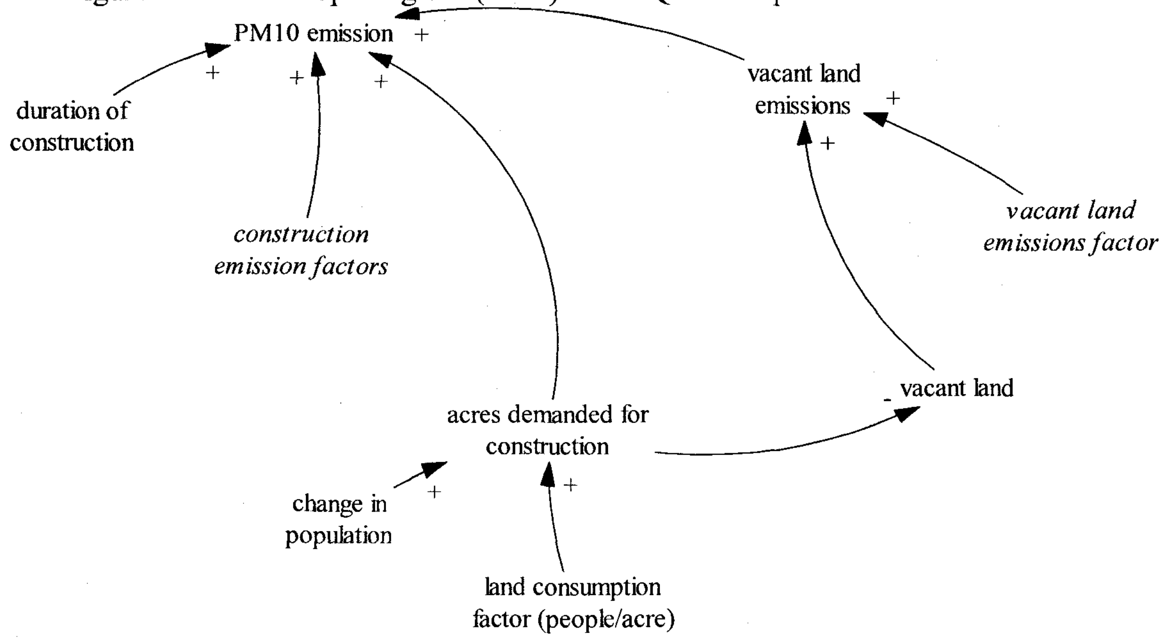
[15] The DAQEM relies on a separate MOBIL6 emissions model from the EPA to determine mobile emissions. However, there are no feedbacks included to show that policies could change population which would affect the final projected mobile emissions. The separation of the models also demonstrates the non-holistic view that managers are taking. The tools are not integrated or validated against one another, which also makes them more difficult to use for policy analysis.

these emissions, especially unpaved road emissions[16], are an important part of the dynamics of the problem but there is no way to determine how these emissions might change in the PRM. Population is also exogenous in the model. This means that no matter what policy change is tested in the model, there will be no impact on these variables (unless manually changed by managers).

The basic causal structure of the PRM as described is shown in Figure 7. "PM_{10} emissions" consist of "construction emissions" and "vacant land emissions." "Construction emissions" are caused by the annual "acres of construction" of different types and their respective durations and emission factors (including wind emissions, direct emittance from construction, and dirt tracked on to road surfaces near construction sites). The major driver of construction is increasing population, based on "land consumption factor" (i.e., determines the required land that would have to be developed to support a change in population based on a calculated average density of annual population change and the number of acres developed each year). The other source of emissions is "vacant land emissions" which depend on the "vacant land emission factor" for each type of land and the amount of "vacant land." Construction serves as a limiting factor for "vacant land emissions," since increases in "acres of construction" decrease the amount of available "vacant land" and therefore emissions.

[16] Calculated in a separate report (Regional Transportation Plan 2004) by the Regional Transportation Commission

Figure 7 Causal Loop Diagram (CLD) of DAQEM Proportional Rollback Model



The final step determines the effect of controls on emissions to calculate the final PM_{10} concentration and is represented in Figure 8 (the variable of interest "PM_{10} Emissions" is now on the bottom of the diagram in grey). The "overall control reduction[17]" reduces "PM_{10} Emissions," giving "controlled PM_{10} emissions." The reduction in emissions between uncontrolled and controlled emissions is used to calculate the percent "reduction in mass emissions."

Similar to the design day used to represent PM_{10} emissions in tons, the model uses a design concentration value. The DAQEM determined this value by looking at concentrations in the base year at various sites. A high-end value was selected and used

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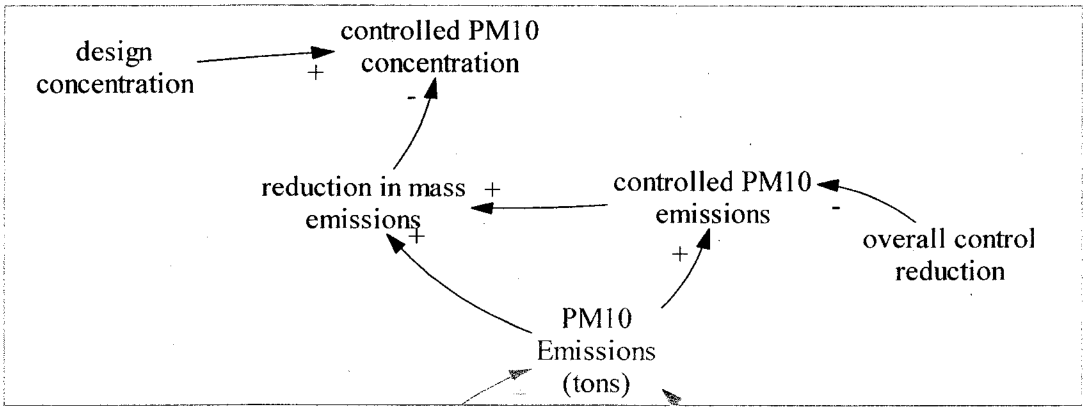
[17] This variable actually represents the product of three components listed in Appendix L of the 2001 SIP (CCBC): emission reduction, rule effectiveness, and rule penetration. The first component was interpreted to mean "control efficiency," (as detailed in NRC 2004). Control efficiency is the fraction of total emissions from a source that are controlled. Rule penetration refers to the fraction of the source that is subjected to the control. Rule effectiveness reduces the control efficiency due to uncertainties or failure in the control. Although these components were detailed elsewhere in the SIP, they were not included in the PRM spreadsheets.

to represent the corresponding concentration to the emissions inventory total tons[18]. This "design concentration" was reduced by the percent "reduction in mass emissions," to determine the final "controlled PM_{10} concentration."

Figure 8 Controls and concentration in PRM



Functionally, the original PRM model consisted of a series of independent spreadsheets that required manually copying and pasting calculations from one sheet to another. Certain calculations are carried over into other spreadsheets where further built-in calculations are performed. All of these steps were required to test only one policy scenario. Other variables used in the model are calculated in other supplementary spreadsheets, not included in the model and were therefore considered exogenous. Updates to this model required manually changing the values in all spreadsheets and re-simulating every scenario by manually selecting and copying values into other sheets.

The newer version of PRM, developed in Fincher and Stave (2006), has a more user-friendly, explicit, and integrated context, although it still relies on the original

[18] Although emissions in tons decreased over the few years of the demonstration dates, the DAQEM assumed the design concentration remained fixed. This was done to ensure a conservative measure and better protect local public health (CCBC 2001).

underlying assumptions and calculation methodology to determine emissions. For the purposes of improving its functionality, the model was integrated into a single-file model. The program used to develop the model was Vensim® Professional by Ventana Systems (2004). Although the look of the model changed due to the way variables and connections are represented in the software, almost all equations were exactly consistent to the spreadsheets provided by DAQEM[19]

The goals of the DAQEM were primarily to improve the use and functionality of the model rather than re-conceptualizing assumptions and structure within the model. However, the process of evaluating this model provided insight into how another approach may be useful. Demonstrating the benefits of a system dynamics model would ideally lead to the integration of a systems perspective, at least for planning purposes.

[19] It was believed these spreadsheets were the final output used in the 2001 SIP. However, it was discovered that the values had already undergone some policy simulations and updated parameters, thereby changing the final results from what was included in the SIP. The calculation methodology and equations were unchanged and therefore remain consistent between the original Proportional Rollback Model and the model originally created to replicate it.

CHAPTER THREE

METHODS

To evaluate the benefits of a system dynamics (SD) PM_{10} management model, I first needed to create the model. The outline of the methodology follows the structure shown in Table 3. Part I of this chapter describes the method used to create the SD model following the first four steps of the system dynamics problem solving process. Part II describes criteria for determining whether the model meets utility measures, described primarily from a systems perspective.

Table 3 Outline of Methods

I. Developing a system dynamics model
    a. define the problem
        1. reference mode
    b. describe the system
        1. key variables
        2. sector diagrams
        3. dynamic hypothesis (CLD)
    c. develop the model
        1. stock and flow
    d. build confidence in the model
        1. validation
        2. extreme conditions
        3. sensitivity

II. Evaluating benefits of model

Part I: Development of System Dynamics Model

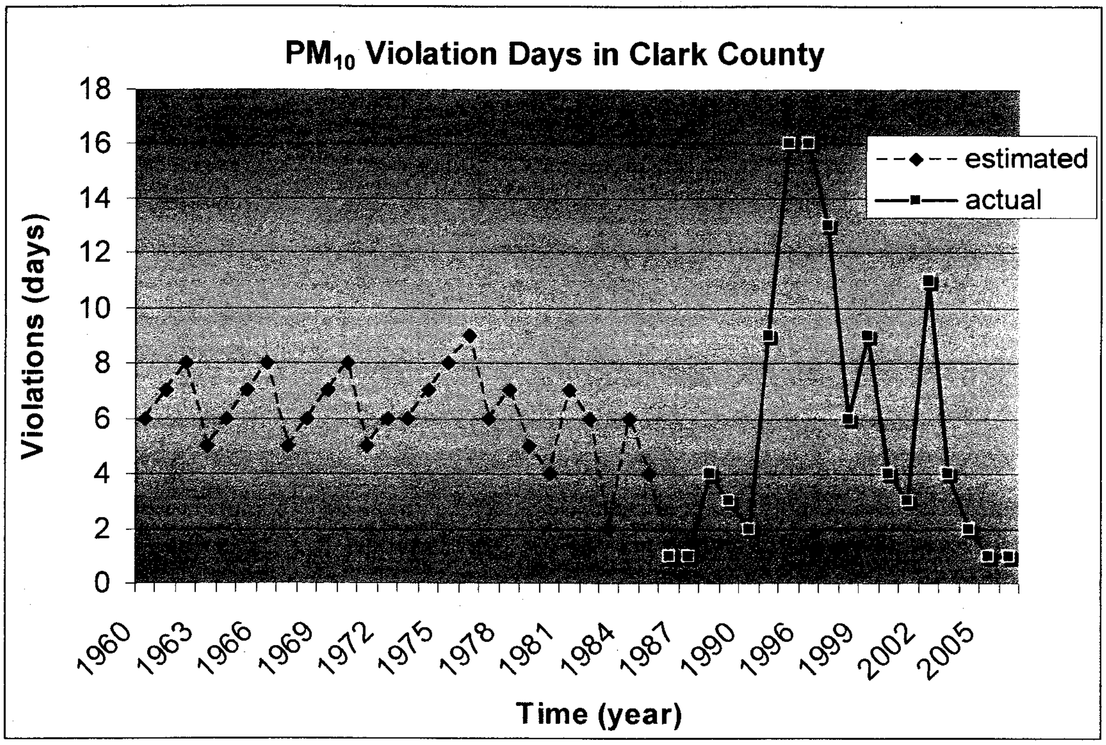
The following sections follow the system dynamics problem solving method, briefly explained in Chapter 2 on page 34.

1. Define the problem

Data for Clark County PM_{10} levels before 1990 is not readily available[20] (Chay, Dobkin, and Greenstone 2003). However, the EPA refers to the number of average exceedances in Clark County during the late 1970s in the *Federal Register* as 14 per year (Fed. Reg. 7 Sept 2004). These exceedances refer to total suspended particulates (TSP) standards set before 1987. Comparing these exceedances to PM_{10} exceedances in not accurate but it does provide a basis for historic trends. Since the standard for TSP was significantly higher (at 260$\mu g/m^3$) with a larger size range of particles (up to 40 μm) (EPA 2003c), it was assumed that for early years the PM_{10} exceedances were about half of the TSP exceedances. Figure 9 shows these estimates (dotted line) along with the actual exceedances reported from 1986 forward. Violation days are used to avoid counting multiple exceedances, at different locations, on the same day.

[20] States are required to follow strict guidelines for monitoring the ambient levels of PM pollution (NRC 2004). However, emission information in the past was not required to be disclosed in the same way as it is currently. Some researchers (Chay, Dobkin, and Greenstone 2003) have requested information from the EPA using the Freedom of Information Act request. Actual numbers of exceedances as near as they could be determined are shown in Appendix C, under Historic Exceedances.

Figure 9 PM_{10} violation days in Clark County, estimated and actual



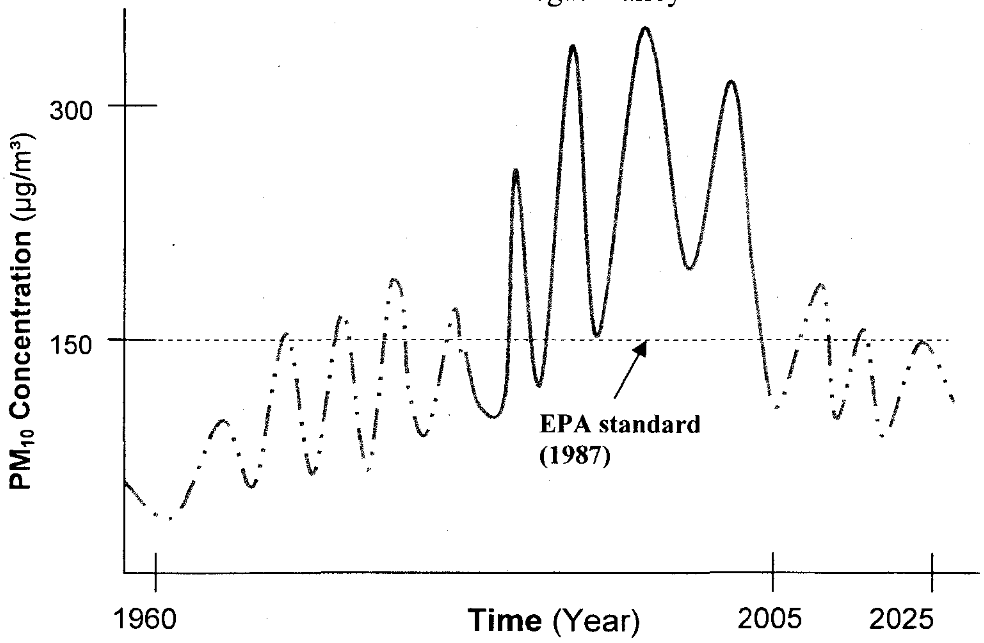
source: DAQEM 2005 and DAQEM data.

From this information a general trend was approximated. It was assumed that concentrations start out relatively low, although several exceedances would occur throughout the year. Concentrations peak through the 1980s and 1990s and then begin to significantly decline after 2000, when application of control measures increase and acres of vacant land (a major source of PM_{10} pollution) decrease. This trend is shown in Figure 10 and represents the problem with PM_{10} graphically, called the reference mode. Current NAAQS[21] for PM_{10} require concentrations to fall below the limit of 150 micrograms per cubic meter ($\mu g/m^3$) in a 24-hour period, labeled as a dotted line. Actual concentration trends would show significantly more variation than the Figure 10. However, the trend

[21] The annual standard was recently discarded by the EPA at the end of 2006 because it was found not to be linked with health effects (EPA 2006).

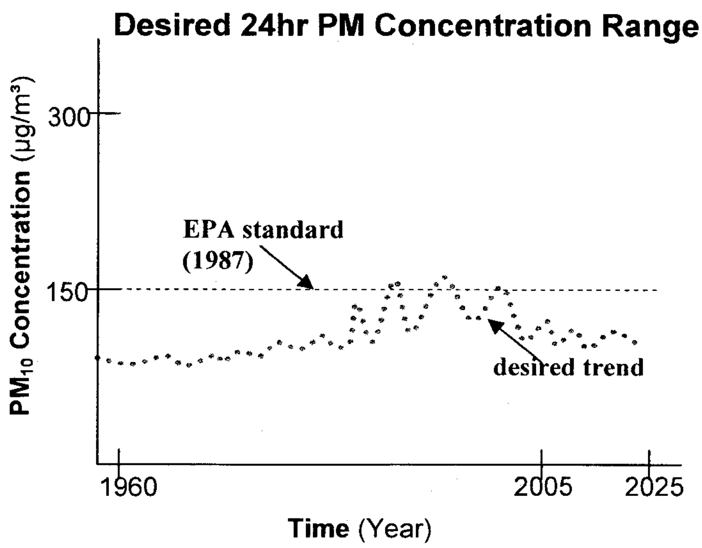
was smoothed to simplify the information while still demonstrating that concentrations may go above or below standards throughout a given year.

Figure 10 Reference Mode for PM_{10} Annual and 24-hour Standards in the Las Vegas Valley



The challenge is to understand how the problem developed and avoid future exceedances as well as discover if historic exceedances could have been avoided. A desired trend is shown in Figure 11. There are a few years which still show exceedances, but it is less than the number of exceedances actually exhibited historically. In fact, any trend with concentrations either below actual levels or, ideally, below the federal standards would be a vast improvement. There is great incentive for any reduction, considering all of the health impacts and deaths that are directly related to PM_{10} levels.

Figure 11 Desired Trend



2. Describe the system

Sources/ PM-Producing Activities

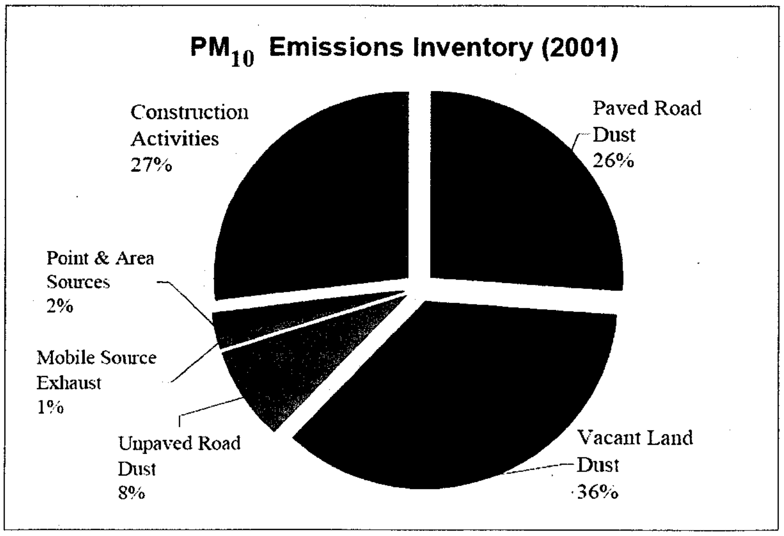
Although dust might intuitively be considered a natural and regular occurrence in a desert, native desert actually has very low emissions (CDSN and DAQEM 2003). This is because desert land forms a crust on the topmost layer trapping dust particles underneath that is easily regenerated with natural levels of wind and rain when disturbance is minimal (CDSN and DAQEM 2003). Land construction in the LVV this protective layer on the surface and also requires moving large quantities of earth for razing or infill. Piles of uncovered dirt can often be seen near construction sites. These have been located near areas with frequent disturbances, such as freeways, resulting in clouds of particles which dramatically reduce local visibility. Disturbed land and exposed earth poses even more of a problem if an area is prone to windy conditions.

Fugitive dust, regardless of its source, is a major problem for Clark County and also one of the reasons why previous SIPs were not approved (DAQEM). In a study of residential areas by Chow *et al.* (1999), fugitive dust accounted for 80-90% of PM_{10} while motor vehicle exhaust was only 3-9% of all PM emissions in those areas.

Rapidly-growing areas often suffer from intense construction periods which can cause subsequent spikes in PM pollution. Additionally, dust that has been emitted into the air settles back onto the land and road surfaces, where it is then re-entrained into the air by passing traffic (RTC 2004). If no further PM material is added, an equilibrium value should be reached between the amount of re-entrained particles and particles settling onto the surface (EPA 2003b). Yet, in the early stages of growth, more and more acres are disturbed, adding more material to the emitted/re-emitted cycle. As development occupies vacant land, the production of dust decreases and there is a subsequent decline in dust emissions from roadways in those areas (RTC 2004).

The major PM_{10} sources in 2001 for the LVV are shown in Figure 12. While background geologic PM is emitted, its levels are considered mostly part of background emissions and not an emission source that can be controlled. Fortunately, the majority of these geologic particles are large enough (>10 μm) that they do not pose much of a health threat as opposed to their smaller counterparts (DAQEM). Human-caused emissions include point, area, and mobile sources. Point sources come from facilities with a fixed location, usually containing a stack of closely monitored emissions (Solomon 1994). Area sources can be either stationary or mobile (excluding on-road vehicles), are too numerous and low to be treated individually but have significant impacts when aggregated (Solomon 1994).

Figure 12 Emissions sources for 2001 emissions inventory in the LVV (DAQEM)



Mobile sources come principally from on-road sources and include direct emissions from vehicles, brake dust, and particles that are entrained ("kicked" up into the air) from road surfaces (DAQEM, Solomon 1994). The network of paved roads is not directly responsible for these emissions even though they are considered mobile sources (RTC 2004). Dust from nearby areas including construction sites or vacant land is either blown by wind or tracked onto paved surfaces by construction or off-road vehicles (RTC 2004). As vehicles drive on these roads, dust is re-entrained into the air (RTC 2004).

Control Measures

Control measures reduce either the emission factor of certain sources or the amount of activity that is leading to emissions (i.e., imposing permits to control the amount of acres that can be constructed in a given year reduces construction activity and therefore directly reduces construction emissions). The most common mitigative control measure used in the LVV for construction dust is spraying water on disturbed land, construction sites, and their entryways. Other types of controls include other forms of stabilization such as building wind breaks or fences, or spraying other dust suppressants (CCBC 2001).

Social Factors

In addition to understanding PM_{10} and the sources and controls specific to the LVV, it is also necessary to understand how the social system is changing. This includes population dynamics, especially population growth. The LVV contains several cities which have been among the fastest growing cities in the United States for more than the past decade (US Census Bureau 2006, CCBC 2001, DAQEM 2001, DAQEM 2005A). Many emissions are based on the population in the LVV, directly or indirectly. Travel demand is a function of the population, the average number of trips per person and the average distance traveled per trip. Travel demand leads to vehicle miles traveled which is a direct source of vehicle emissions and responsible for reemitting PM material on road surfaces. Population depends on in-migration which is driven by the attractiveness of the Valley. Attractiveness is the cumulative effect of the factors that cause people to move to or away from an area (Forrester 1995:8). Understanding these dynamics helps in understanding how the Valley developed, how that development affected PM_{10}, and what could have or could still be done to alleviate the problem.

Sector Diagram

Based on the information above, three major sectors of the system were identified: land, PM_{10} emissions and cycle, and population. A high-order representation of the major sectors interacting to form PM_{10} this problem is shown in Figure 13.

Population, through demand factors, drives the development of land and also cause disturbance of native desert. Land, both vacant and under construction, has emissions which influence PM_{10}. Population growth is driven by available land for new residents and other land characteristics (e.g., services available).

Figure 13 High-order representation of model

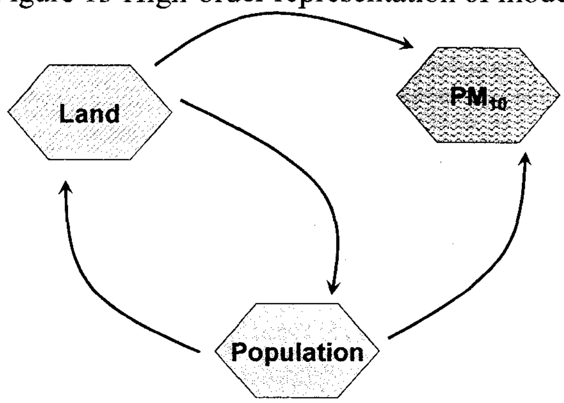
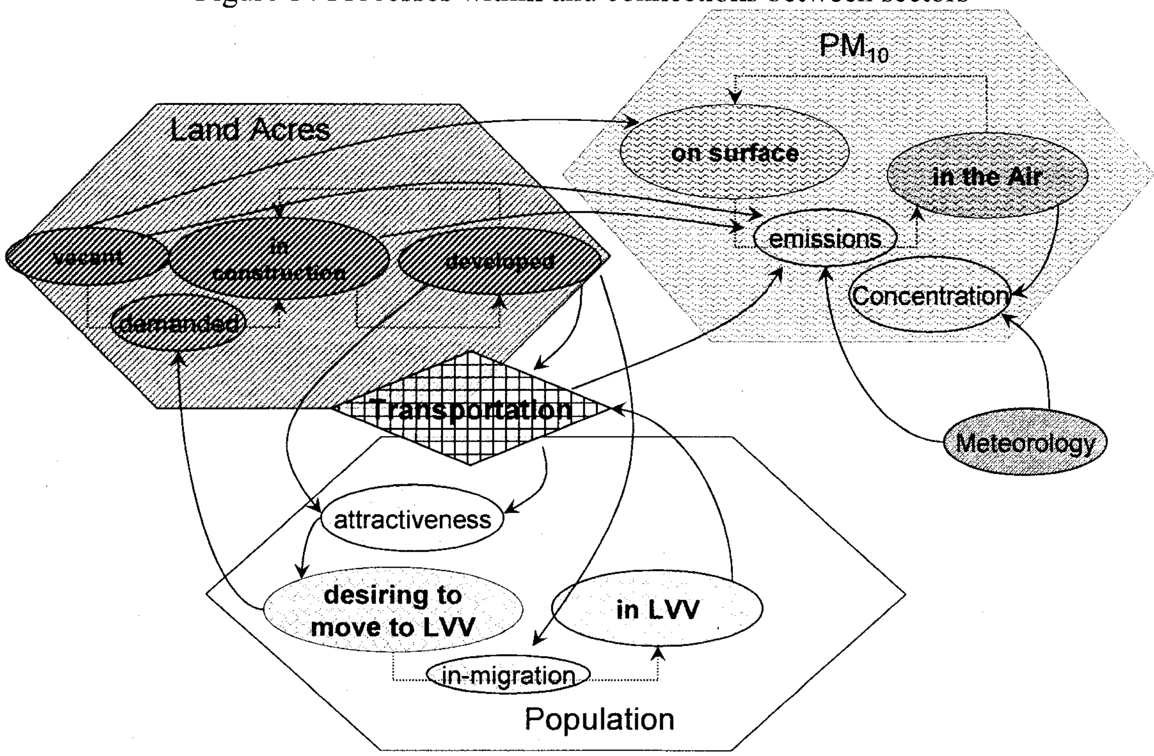


Figure 14 shows the processes that occur within each sector and how components within sectors affect other sectors. Within the land sector, vacant land is constructed and becomes part of the developed area. This development is based on the population desiring to move to the LVV. Vacant land drives the amount of "loose" or disturbed PM particles on the surface and also leads to emissions. Additionally, construction on these acres is for different land-use categories (e.g., residential homes, commercial, flood control) which have different associated durations and emissions. Developed land acres drive attractiveness and limit the amount of people who can move into the Valley (i.e., in-migration). Developed land also determines the transportation network of roadways. Transportation (the diamond in Figure 14) crosses sector categories because it represents both the physical set of paved roads/road capacity and the travel demand.

Figure 14 Processes within and connections between sectors



The population desiring to move to the LVV depends on attractiveness factors (e.g., time in traffic). The LVV population drives travel demand and unpaved road disturbance (Transportation) and therefore mobile emissions. Emissions (in the PM$_{10}$ hexagon), depend on Transportation (paved and unpaved), acres in various categories of land, and meteorological factors such as wind and precipitation. PM on the surface is put into the air through these emissions and the concentration of PM$_{10}$ is determined by these mass emissions in the air and the volume of air in the Valley (which varies seasonally). All of these factors are well as other important variables are identified in Table 4.

Boundaries

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 for this project. Daily temperature fluctuations are also not tracked since night and day variations would average when looking at an entire day. The model is not spatially distributed or seeking to reveal hot spots since the question of concern is regional management and aggregated effects. However, it should be realized that there would be a wide distribution of concentrations throughout the LVV. A maximum exposure factor may be useful to give an upper limit of concentrations that individuals may be exposed to.

Only primary PM_{10} was modeled. The justification for this is that PM_{10} is usually primary particles, mechanically added to the air (Lippmann 2003), while secondary particles are predominantly $PM_{2.5}$ (EPA 2004). PM_{10} was not differentiated into the specific chemical components which compose it because there are no standards in the U.S. for these other than other regulated chemicals, like lead (Lippmann 2003). The makeup of PM_{10} could, however, play an important role for health, but this was considered beyond the scope of the current project.

Table 4 Key variables by sector

Sector	Endogenous	Exogenous	Omitted
PM10	Stable PM_{10} on surface Unstable PM_{10} on surface PM_{10} in air rate of disturbance and stabilization Area source emissions Mobile source emissions Volume of the air shed Actual removal & settling rates	Normal removal & settling rates Wind factor and normal rain event† Height of boundary layer† Silt loading factors Point sources Emission factors* Control reductions*	Other meteorological factors 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)*

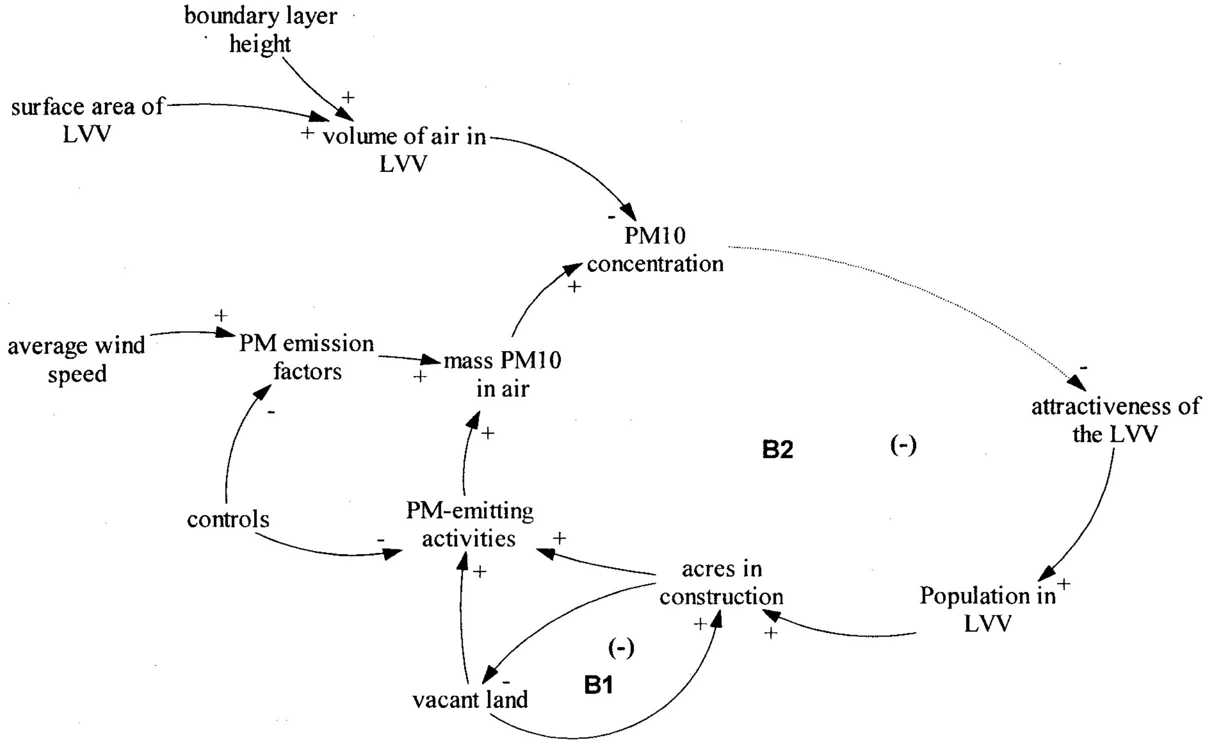
* crosses sectors † seasonal

PM pollution varies seasonally, by location, and is affected by weather components such as temperature, rain and wind (EPA 2004). This model is not intended to be a meteorological or predictive, and so relative seasonal factors were used to capture these effects. Meteorological factors included the probability of rain for each month (every day a probability is selected randomly from the monthly minimum and maximum), monthly ranges for wind speeds and the average height of the boundary layer every month.

Dynamic Hypothesis

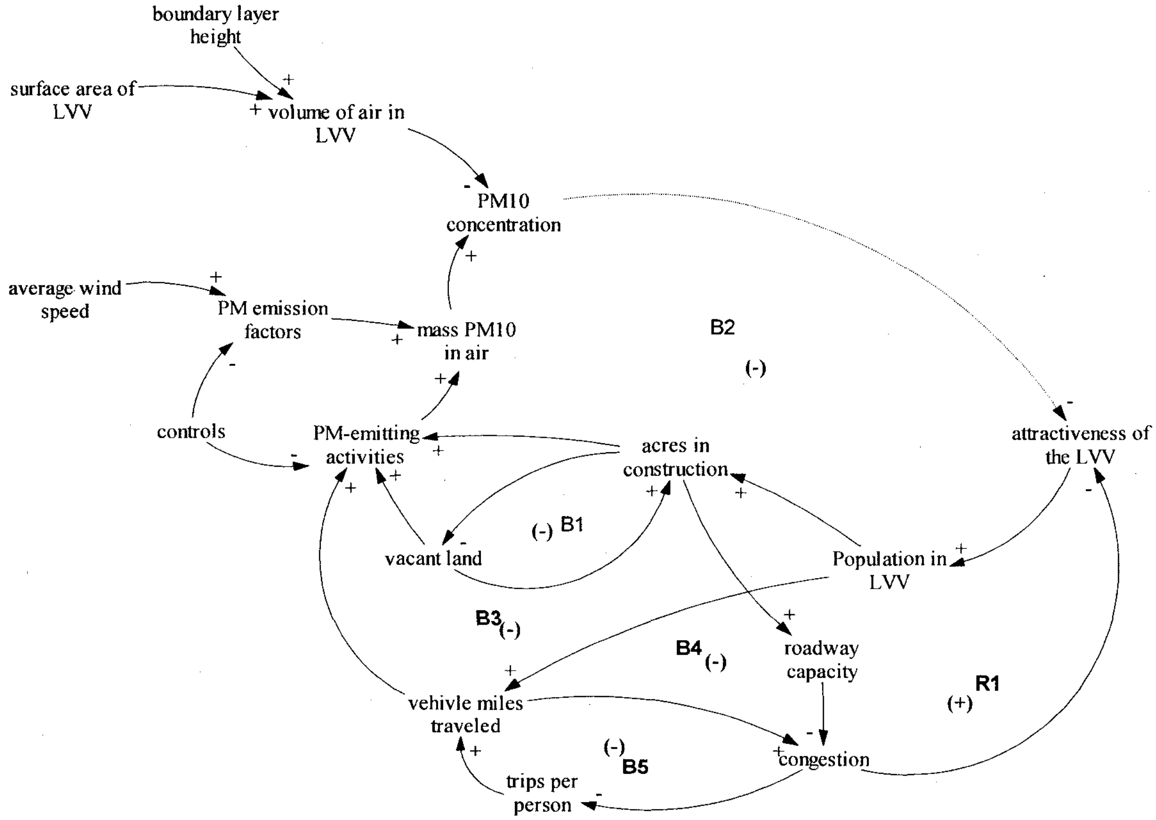
The causal structure is similar to that of the Proportional Rollback Model: growing population drives PM-emitting activities, which increases the amount of pollutants in the air. However, the SD representation expands the PM-emitting activities, their causes, and feedbacks in the system. Figure 15 shows a causal loop diagram (CLD) starting with PM_{10} concentrations and tracing backward through its basic causes. The PM_{10} concentration depends on the "volume of air in LVV" and the "mass PM_{10} in air." This volume depends on the "boundary layer height" and the "surface area of LVV."

Figure 15 CLD of basic structure of emissions in SD model



"Mass PM_{10} in air" depends on various "PM-emitting activities" and "PM emission factors" for those activities. "Controls" reduce emission factors or "PM-emitting activities" and "PM emission factors" also depend directly on wind speeds. Continuing from "PM-emitting activities," "vacant land" and "acres in construction" are both major PM sources. However, as "acres in construction" increases, they decrease "vacant land" forming a balancing loop (B1 in Figure 15). "Acres in construction" depends on the "Population in LVV," which depends on "attractiveness of the LVV." There is a dotted line connecting "PM_{10} concentration" to the attractiveness because it is not always the case that bad pollution slows grow (or reduces attractiveness), although it would for some. When this line is drawn it closes the second balancing loop (B2).

Figure 16 CLD with mobile sources included



However, this structure is not complete. As Figure 16 shows, when the "Population in LVV" increases, so do "vehicle miles traveled." These vehicle miles further increase "PM-emitting activities," which increase the concentration, decrease the attractiveness and therefore decrease the population change, forming the next balancing loop (B3). As "Vehicle miles traveled" (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" including 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 reduces "congestion," (B5).

In the preceding diagram, population, through attractiveness, is driven only by congestion and PM_{10} pollution (which generally reduce attractiveness when population increases except for road building, R1, which reduces congestion). However, there are other factors which are driving population growth in the Valley.

Figure 17 CLD of jobs and service drivers of attractiveness

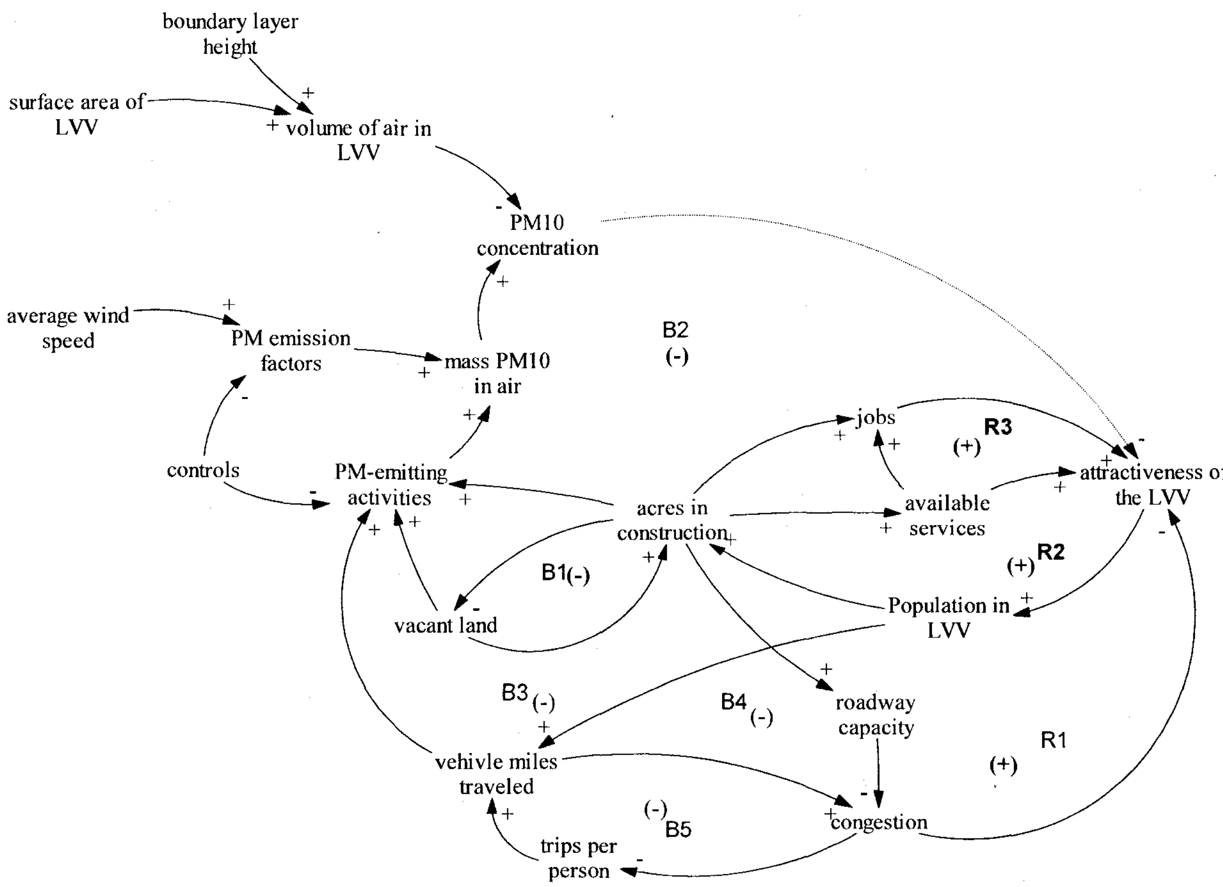
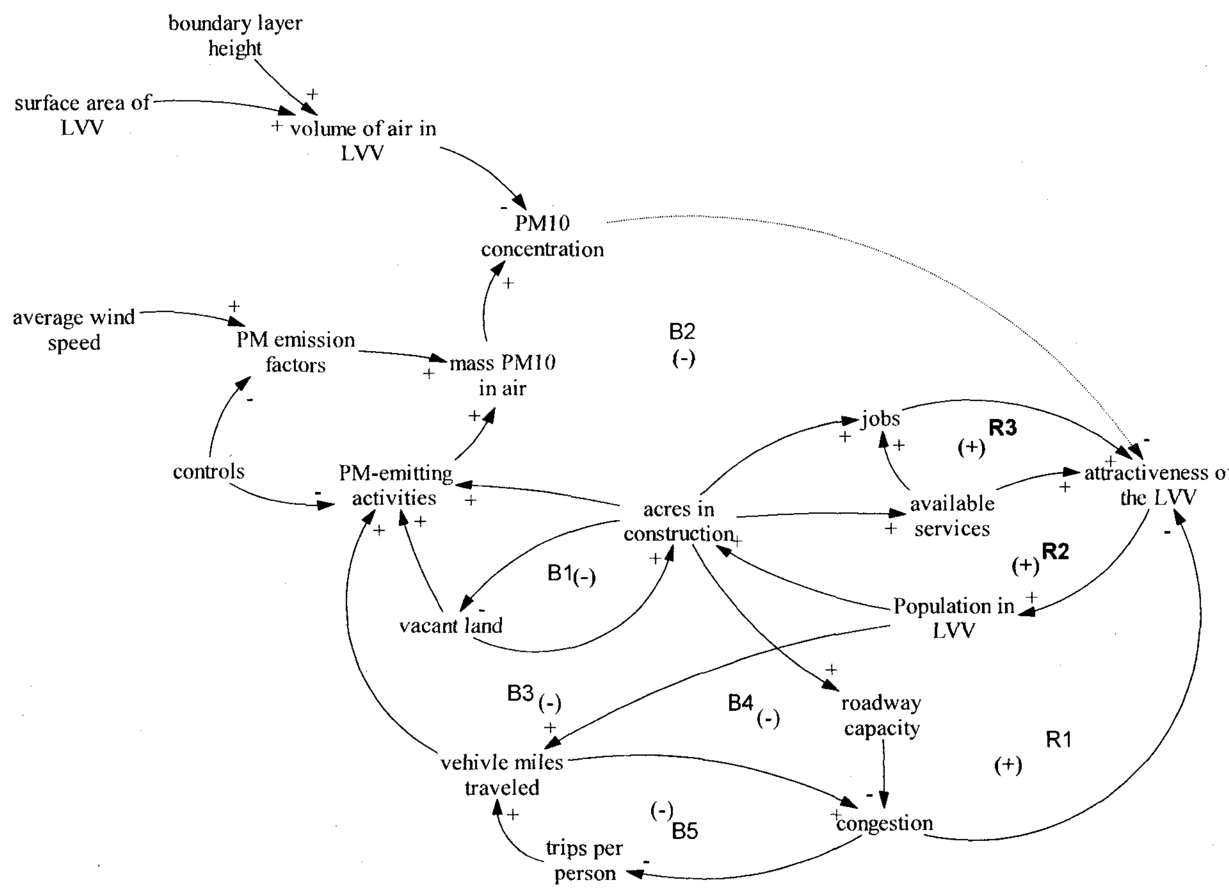


Figure 16 shows that when “acres in construction” increases, there is an increase in “available services,” which increases the attractiveness, further increasing population and leading to more acres constructed. Likewise, construction and increased urban development leads to more jobs which increases attractiveness and leads to more in-migration and further development. This diagram represents the final dynamic hypothesis of the structure causing PM_{10} in the LVV.

Figure 17 CLD of jobs and service drivers of attractiveness

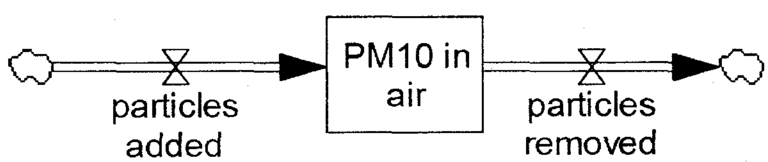


3. Develop the model

Stock and Flow Structure

Representing the physical structure of PM_{10} movement at its simplest requires tracking the processes that add and remove it from the air. Figure 18 shows PM_{10} is added by emissions processes of direct chemical or physical human activities (burning in combustion of cars and industrial processes or physical disturbances such as tires displacing surface dust into air), wild and structure fires, wind entrainment, and transport. PM pollution in the air eventually returns to the surface through deposition. The two primary ways 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 2007). Another minor removal and addition process includes PM pollution transported in or out of the area.

Figure 18 Simplified Representation of the Physical Structure



Addition Processes

- **Anthropogenic disturbance** *(chemical or physical)*
- **Fires** *(human structures and wild/land)*
- **Wind disturbance and entrainment**
- **Transport**

Removal Processes

- **Dry deposition/Fallout**
- **Washout/Rainout**
- **Transport**

Emission Source Categories

- **Point** *(Industrial Sites, gravel operations)*
- **OnRoad Mobile** *(personal vehicles, paved and unpaved road emissions)*
- **NonRoad Mobile** *(airplanes, trains)*
- **Area Sources** *(vacant lands, construction activities, wind erosion, multiple point sources, e.g., barbeque activities)*

Figure 18 also shows the source categories of emissions defined by the EPA. Although nearby area sources lead to the dust falling on roadways, the EPA tracks the source of these emissions only back to the source of their direct emittance into the air, therefore classifying these emissions as mobile sources (RTC 2004).

As was described earlier in the sector diagram section, interactions between land, population, and PM needs to be represented. The following diagrams combine the physical representation of components of the system (amount of vacant land, number of people in the valley) and how they increase, decrease, or change (vacant land becomes developed land). The causal dependencies are also incorporated and expanded as they are connected to the physical structure.

The stock and flow representation of the PM_{10} sector of the model is shown in Figure 19. Particles, in tons, are either "Stable PM_{10} on surface" which can be disturbed and therefore destabilized, represented as "Unstable PM_{10} on surface." These particles are then emitted through a variety of emission activities so that they become "Mass PM_{10} in air." "Mass PM_{10} in air" can also be added to by point source emissions. These particles can fall out and become "Unstable PM_{10} on surface" or when there is precipitation, "Stable PM_{10} on surface." Particles can also be transported to other areas or be removed to streams and lakes. The "Mass PM_{10} in air" is divided by the volume of air in the LVV to determine the daily PM_{10} concentration.

The population sector is not shown here, but it consists of a stock of the "Population in LVV" as well as the population of "People desiring to move to LVV." "In-migration" is the flow that connects these two stocks. The attractiveness sector determines how in-migration and out-migration will change with time. The major parameters affecting attractiveness were job availability, service availability and effectiveness, congestion or time in traffic, and air quality[22].

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 20 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 construction emissions are reduced. Acres finish construction, becoming part of the "Urban/developed area." Some construction is reconstruction, which is the redevelopment of previously built acres (moves acres into the "Acres ordered backlog" stock, where construction cycle begins 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.

[22] This last attractiveness factor was included as a switch since there has not been a strong impact on slowing growth even as air quality worsened and literature does not strongly support this connection.

Figure 19 Stock and Flow of PM_{10} sector

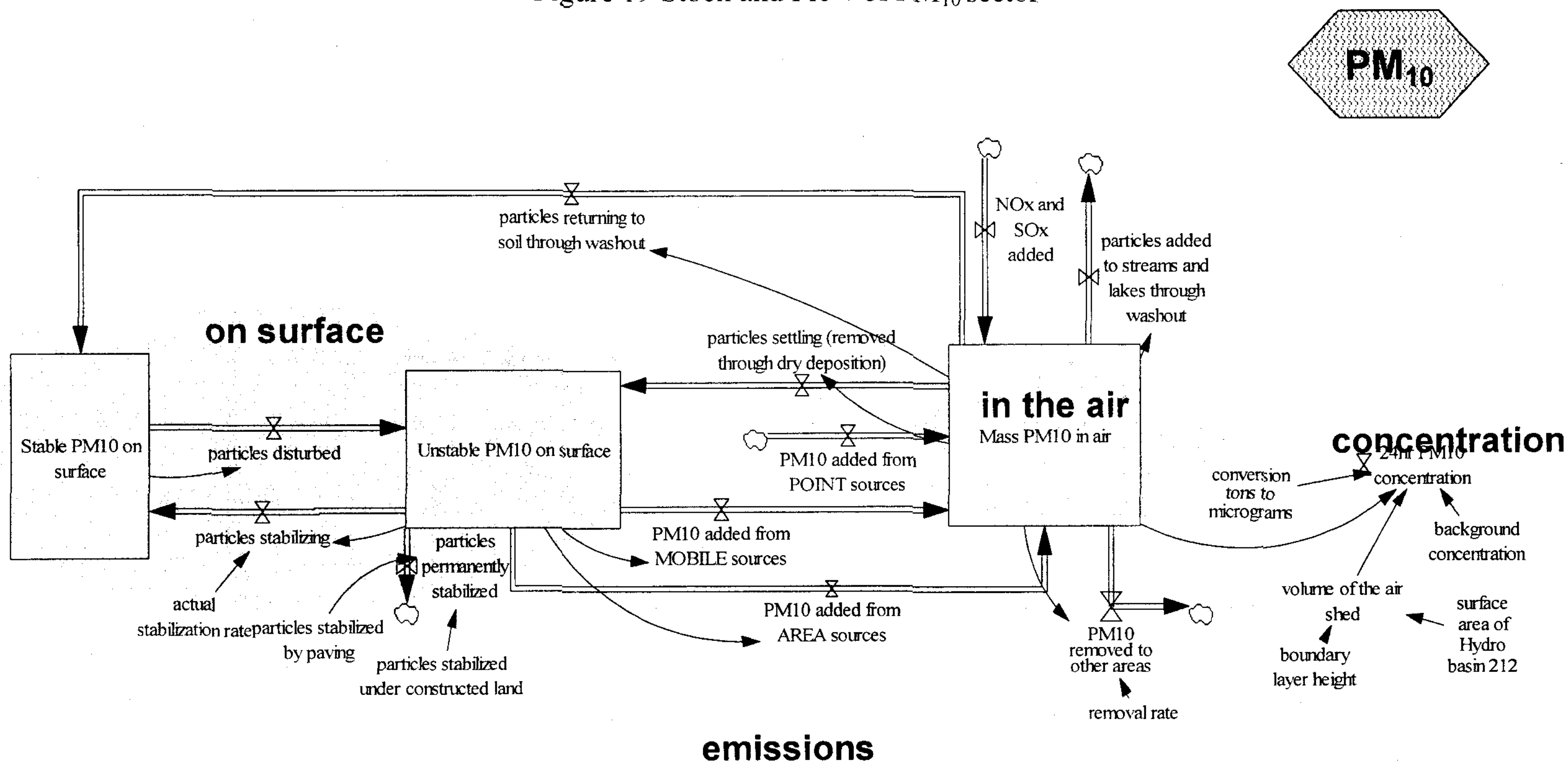
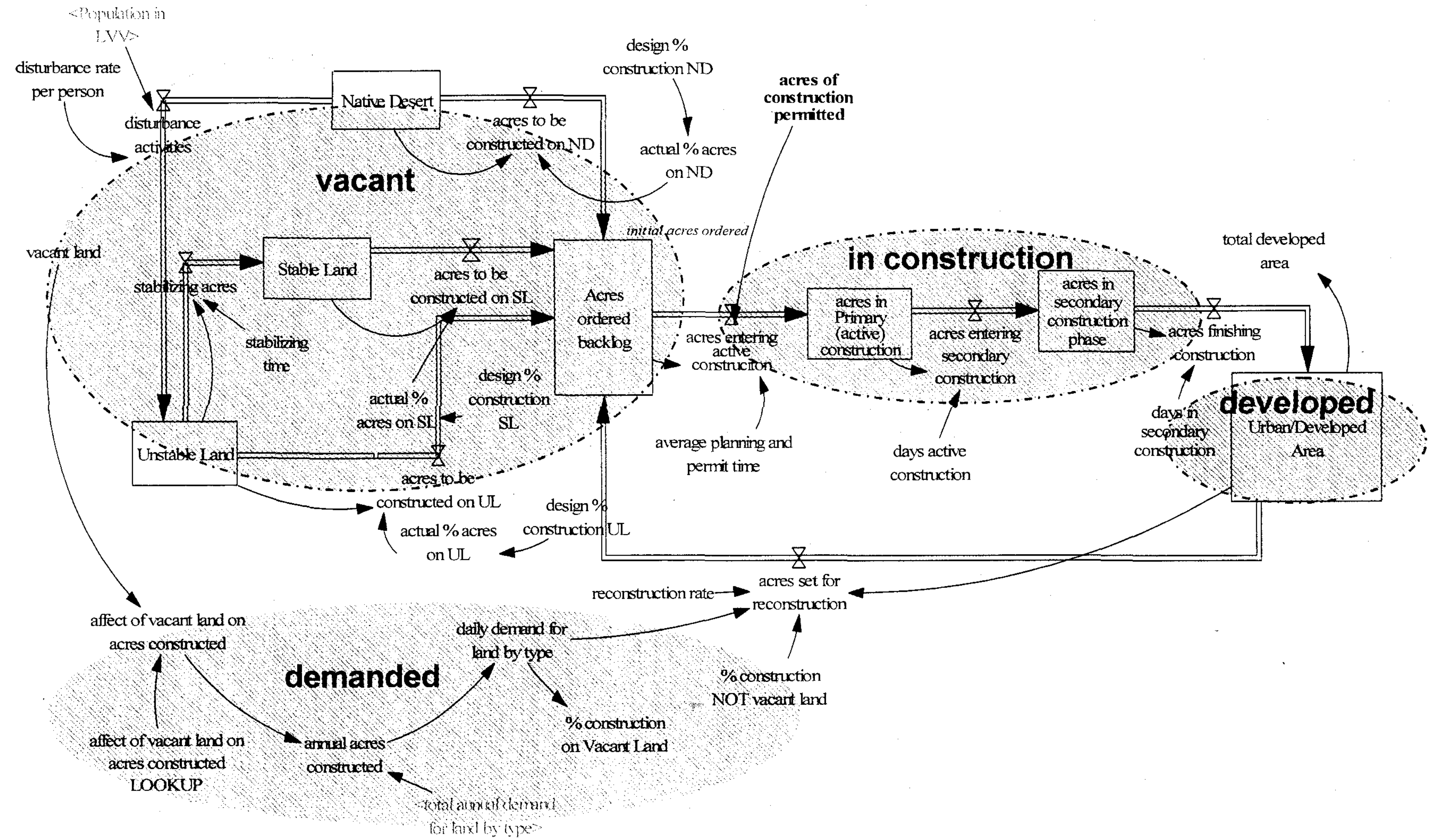


Figure 20 Land Sector of SD model



Assumptions in the Model

The model is simulated in days to best capture the 24-hour concentration. The time horizon chosen reaches back to 1960, before major development had occurred in the LVV. This is also just prior to the Clean Air Act. The time horizon extends out to 2025 which is around the time that growth is projected to slow.

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, relative seasonal factors were determined and used to drive the impacts. 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 does tend to follow a seasonal trend. Therefore, an average boundary layer height for each month of the year was developed.

Using data from a monitoring site[23], the minimum and maximum average daily wind speed for each month are used to generate a random daily wind speed using a beta distribution. Since this data came from an actual year, the maximum values were increased by a factor of four to allow for more variation in wind speeds. The random daily wind speed is then divided by the annual mean derived from over 40 years of

[23] See the list of Text references in Appendix A for the description of DAQEM data that was used (JD Smith monitoring site in 2004).

NOAA data (see Gorelow 2005), giving a normalized wind factor varying around 1. The wind factor is then multiplied by the normal emissions factors, for emissions influenced by wind, to determine an actual emission factor (i.e., when the wind factor is 1.25, emissions factors will be 25% higher than normal).

When data specific to the Valley was not available for the entire time horizon (specifically back to 1960 or from 2006 to 2025), parameters were divided by the current population in the year they were estimated to determine per capita estimates. Many of the equations used in the model are logical material flow arguments (i.e., total population is the sum of the inputs of in-migration and births minus the outflows of deaths and out-migration). However, some calculations are based on EPA-developed equations that are not so intuitive. For a list of equations see Appendix A.

4. Build confidence in the model

Validation

Models are abstractions of reality and so are never truly valid (Ford 1999, Sterman 2000, Shreckengost 1985). However, model validation includes tests that can increase the confidence in the model. Model validation begins by a face validity test, which Ford (1999: 286) describes as a check that model structure and parameters make sense. All parameter values were based on widely accepted data sources (listed in Appendix A), or based on available information with certain assumptions. If no source could be found, an estimate was given and described in the model documentation. The structure of the model is based partially on other models (listed in Appendix A) and common system structures (especially from Sterman 2000). The face validity test usually occurs automatically during model development and so in early phases, structural elements were evaluated for their logic and several modifications and iterations were performed.

Other tests involve comparison to historic data. When the model generates results close to the reference mode, it is believed to contain the essential structure causing the problem. Extreme conditions testing and sensitivity testing are a two other major validation tests. Model performance under extreme conditions tests add to confidence in the model as well as its utility for evaluating policies (Shreckengost 1985:3). This can include forcing the system to perform in ways that would normally be considered abnormal (e.g., what if population doubled tomorrow?). Sensitivity analysis is performed to consider how model outcomes might change if other feasible assumptions were made (Sterman 1991: 13). Since most social systems are stable, small changes in parameter values should not lead to radical behavioral changes (Shreckengost 1985:6).

Comparing Output to Reference Mode.

The next major test for validation is comparing the output of the model to the reference mode. The CLD and stock and flow simulation model represent a hypothesis of the dynamic structure causing a problem. When that structure is capable of generating the problematic behavior, there is support that the model captures the essential structure of the system (Ford 1999). Figure 21 shows the reference mode that describes the problematic trend being analyzed. The shaded portion represents the range of values that could be taken in the early stages of development.

Output from the model for the 24-hour PM_{10} concentration is shown in Figure 22. The results gave PM_{10} levels above the 150 $\mu g/m^3$ standard somewhat frequently at first, followed by a period of time where exceedances were much more common and of higher intensity. After control policies were developed and implemented in 2001, emissions drop significantly. There are still occasional exceedances, due to seasonal factors which make PM_{10} concentrations rise (e.g., when the boundary layer is low and the same amount of particulates are dispersed in a smaller volume of air).

Figure 21 Reference Mode with estimated range of PM10

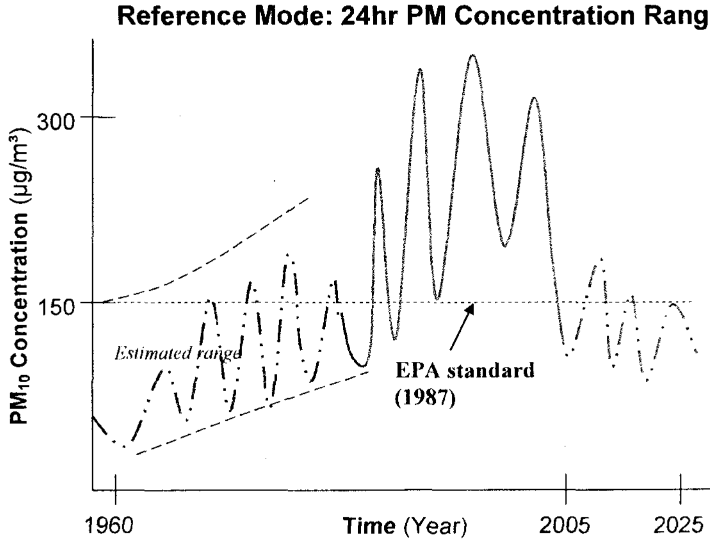
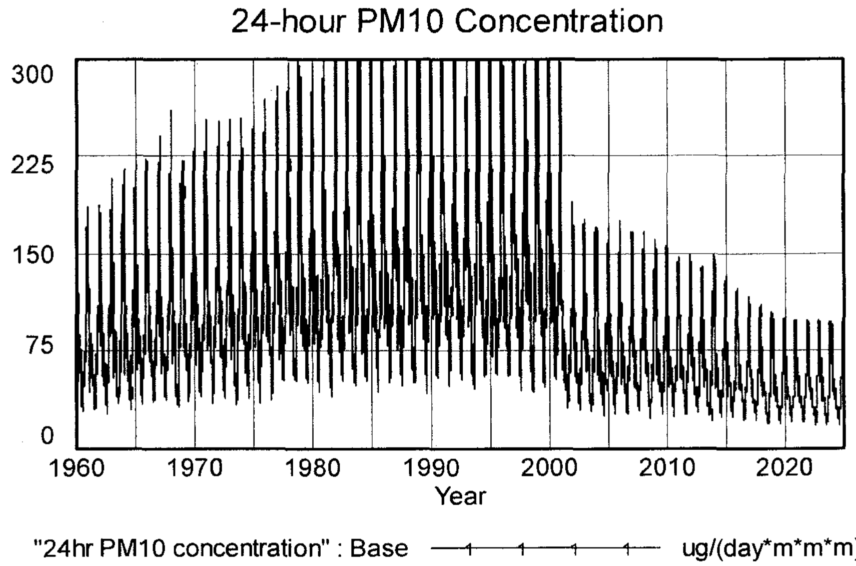


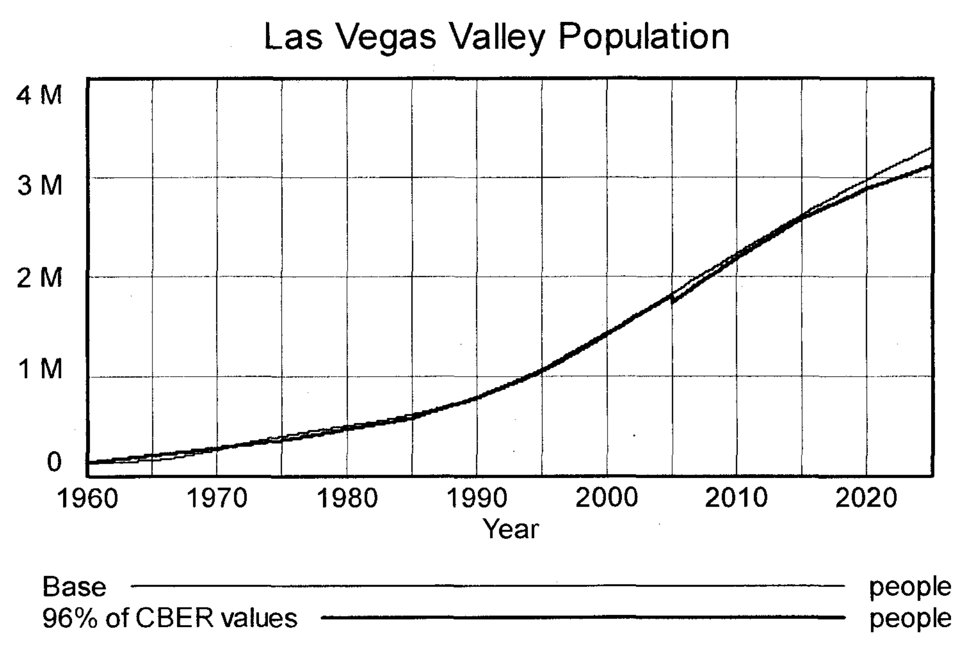
Figure 22 Model output for 24-hour PM10 concentration



Comparing Output to Historical Behavior.

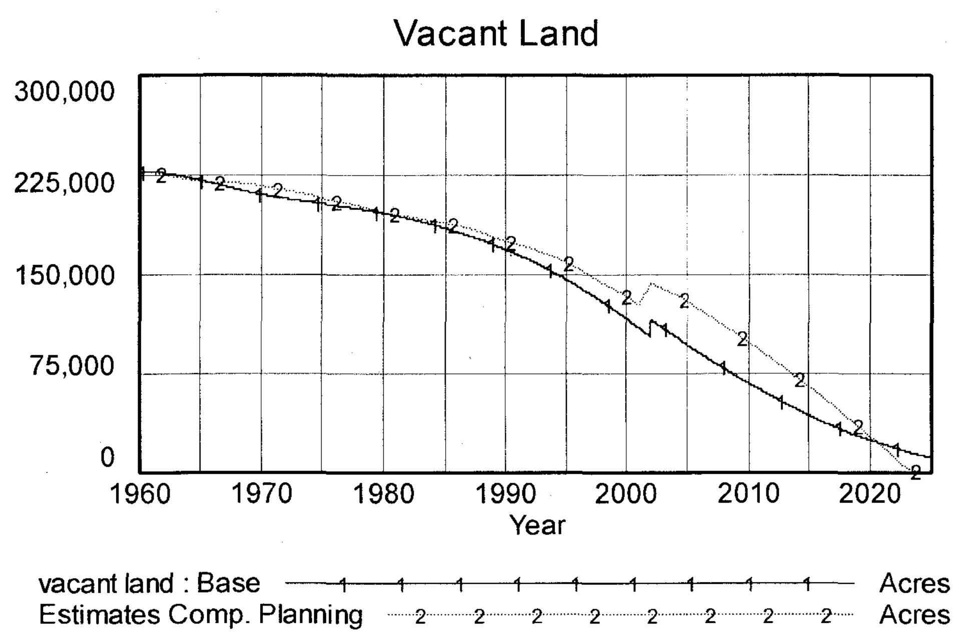
In addition to the concentration of PM, there are several other key variables that can be compared to their historic trends. Population is the ultimate driver for many types of disturbances and emissions. Population values were therefore compared to historic values from the U.S. Census Bureau and the Clark County Department of Comprehensive Planning (CCCP) and estimates made by the Center for Business and Economic Research. The result of this comparison is shown in Figure 23. Population values are very close to historic and estimated values. The sudden shift in the actual values (thick line) is due to a switch between the data sources listed above and does not represent a sudden decline in the population. For future projections, the model's population is slightly higher than the estimates.

Figure 23 Population validation



Since land emissions are a significant contributor to PM_{10}, the model output was also compared to the trends listed by the CCCP. Figure 24 shows the comparison of vacant land in the model (solid line, labeled "1") and CCCP historic and estimated values (dotted line, labeled "2"). The two trends are close for historic values, but become more divergent toward the final years of the simulation, until they cross in 2020. The estimates from CCCP are actually linear after 2003, which explains this difference. The model shows an exponential decay that slows as zero is approached. This is because the model assumes that as less vacant land is available, land becomes increasingly difficult to obtain for development[24]. Complete validation and calibration (where input parameters were uncertain) were performed on the model and are shown in Appendix B.

Figure 24 Vacant Land validation

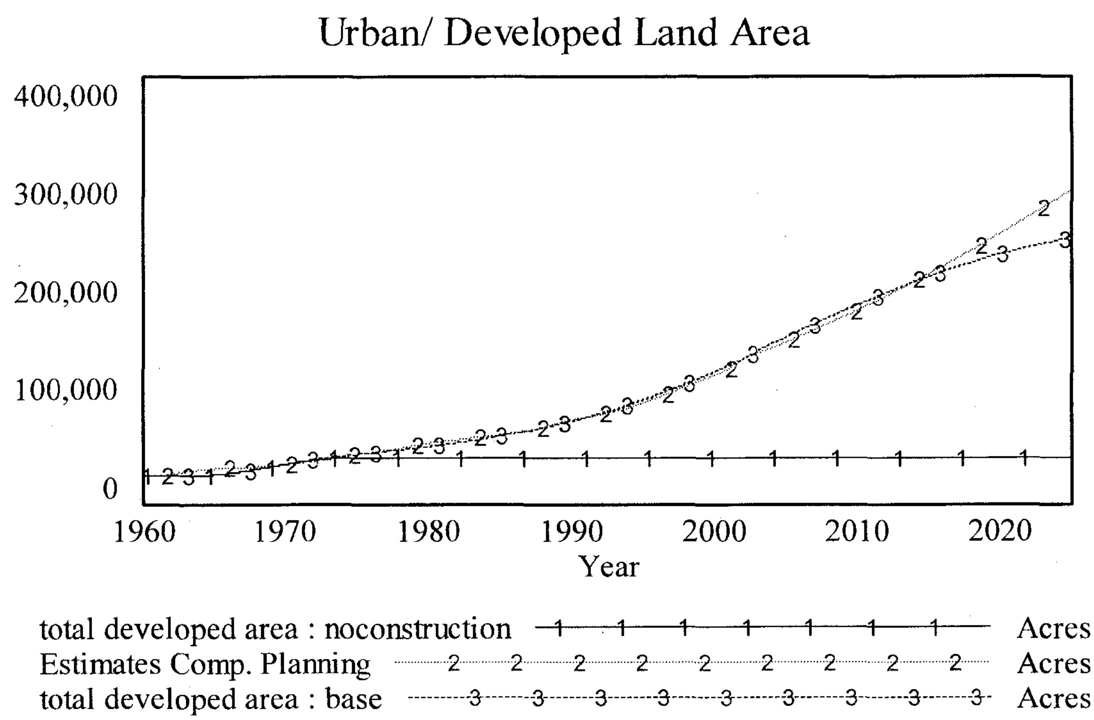


[24] This could be from increased costs, other regulations or limits on the amount of land that can be constructed or other policies. The model does not detail the mechanism for this, but rather just uses a non-linear relationship of development as land becomes scarce—even if demand remains high.

Extreme Conditions Tests.

Ford (1999: 287) states that extreme behavior tests are one of the most "revealing" tests on models: these tests involve making a major change in model parameters to determine if the response is reasonable. For this test, construction was suddenly forced to a halt in 1970. The results are shown in Figure 25 and, as expected, the developed area becomes a flat line in 1970. Emissions continue and because vacant land is not being reduced, there are greater vacant land emissions than during the base run.

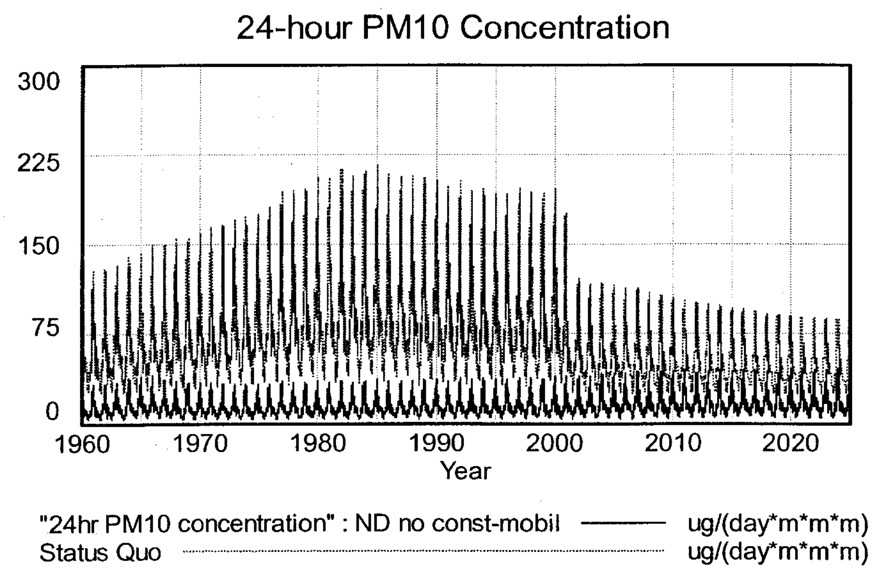
Figure 25 Developed area when construction stops in 1970



Another test was to see what would be the combined effect of stopping construction, removing mobile emissions, and assuming all land was in the "Native

Desert" stock. The expected result would be emissions close to background emissions levels. This also tests whether settling and transport rates are within an appropriate range. The trend is shown in Figure 26 and the average of the variations is about 14μg/m^3. Background concentrations, taken from average concentrations at a site outside of the LVV, are reported as 10.5 μg/m^3 (DAQEM).

Figure 26 Background concentration

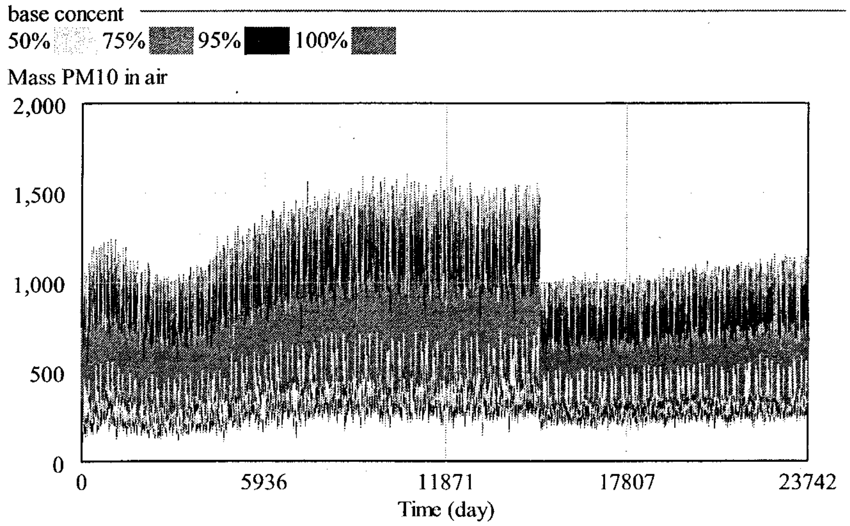


Sensitivity Tests.

The SD model was tested for sensitivity of certain variables to reasonable changes in values. Since most variables driving the removal processes of PM_{10} in the air were based on estimates this was the first sensitivity test performed. The results for this test are shown in Figure 27 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 a compounding of the lowest settling rates and assume that around 60 to 80 percent of emissions stay in the air at all times.

Figure 27 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 Figure 28. 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 factors could be removed since they would not be able to replicate the population trends that were seen historically.

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 Figure 29 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.

Figure 28 Sensitivity analysis of population based on attractiveness factors

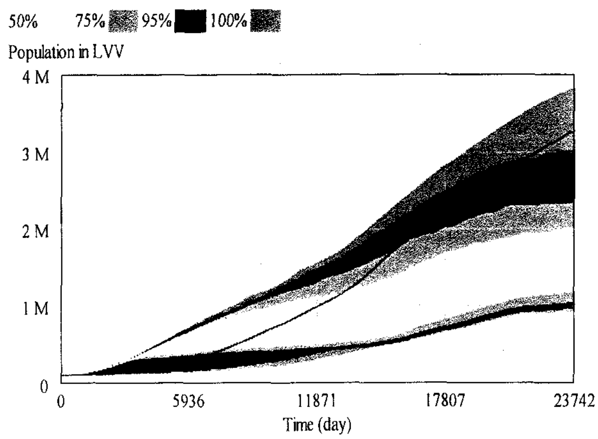
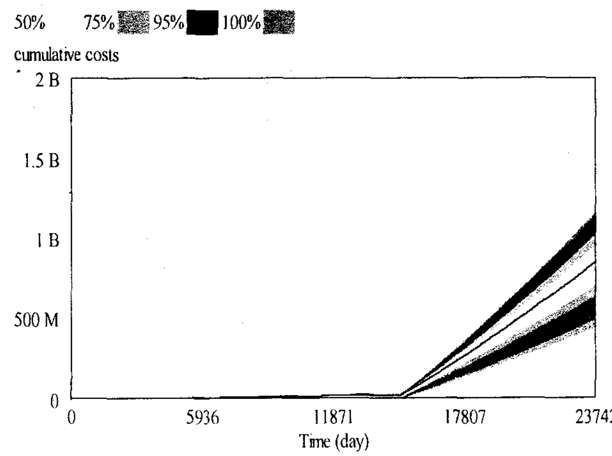


Figure 29 Cumulative cost sensitivity



5. Use the model for policy analysis

The results of using this model are described in Chapter Four. Analysis results are organized according to the utility criteria described in the following section.

Part II: Evaluating Benefits of the Model

Since all models are abstracted from reality, no model can ever be truly valid; therefore, instead of validity, a more practical concern would be usefulness, instructiveness, or some other descriptive criteria (Sterman 2000, Ford 1999, Shreckengost 1985: 1). This thesis focuses on the benefits of a systems perspective, especially for PM_{10} management.

There are a variety of ways that decision support systems (DSS) in general could be analyzed for utility. The first way involves looking at model utility criteria for air quality managers. Another method for testing utility in DSS would be determining the soundness of the model. Still another method would be to ask specific policy questions of the DSS. Policy testing can lead to insight about the problem and reveal faulty assumptions in how the model was structured.

I selected a combination of these criteria[25], shown in

Table 5, to serve as the foundation for exploring the benefits of a systems perspective. These criteria can also be used to perform a general analysis of the utility of a model. Many of the evaluation questions are from a system dynamics perspective but support and criteria from other management and DSS application are also included. Usually, tradeoffs exist between criteria, so strong performance in one area could be offset by poor performance in another (Aggett and McColl 2006). The general criteria were given a specific LVV application question or various questions to aid in analysis.

[25] To see a more comprehensive list of possible evaluation methods see Appendix D

Table 5 Evaluation Criteria

	Evaluation Criteria	Source	Description	Specific Application to LVV
1	Are model results realistic?	Shreckengost, 1985; Sterman 2000	- Results should make sense in the real world - Model should perform reasonably to extreme conditions tests - Includes time delays and bottlenecks of material flows	How well does the model - Replicate the reference mode and historic trends? - Respond to extreme conditions tests? - Represent delays and possible bottlenecks in construction?
2	Does the DSS meet the main/designed purpose? What is the purpose?	Sterman, 2000	- Model must meet at least the main purpose to have utility for managers	How does the model answer whether policies reduce or prevent PM_{10} exceedances?
3	Is the model flexible and adaptable? Does it allow for diverse policy questions to be asked of it?	Niemann and Limp, 2004; Aggett and McColl, 2006	- A model which provides answers to questions beyond the main purpose, including those that may develop through testing is more useful than one that cannot - Few limits in the questions that can be asked of the DSS - Allows a variety of scenarios to be tested	How does the model perform for the following: – Input and output options (variety of tests that can be performed) o Answering questions beyond the original purpose

	Evaluation Criteria	Source	Description	Specific Application to LVV
4	Is the boundary clear and appropriate?	Sterman, 2000	- Clearly distinguishes between what is part of the system and excluded - Should be broad enough to incorporate important drivers - Factors that might change significantly over time should be included	How well does model incorporate important drivers of PM_{10} pollution? Is the amount of detail for the problem appropriate?
5	Is the time horizon sufficient? Can model show long term impacts?	Sterman, 2000; Aggett and McColl 2006	- Time horizon should be long enough to capture how the problem developed and any delayed or indirect effects of changes to the system	How well does the model: - Show how PM_{10} became a problem - Show possible future problems with PM_{10}
6	Are appropriate causal mechanisms included? Are feedback effects properly taken into account?	Sterman 2000	- Problems traced back to their causes - Feedbacks and interactions among components in the system are included - Model captures possible side effects both positive and negative - Open-loop or linear causes do not dominate the model	How does the model - Trace problems back to their causes? - Incorporate the demand drivers for construction and therefore PM_{10}? - Show potential side effects from policies?
7	DSS captures human response to policy changes?	Aggett and McColl, 2006; Sterman 2000; Ford 1999	- Social factors and responses to policies are important and if excluded can recommend a policy that might otherwise fail	To what degree does the model show how the LVV population might respond to interventions?

	Evaluation Criteria	Source	Description	Specific Application to LVV
8	Does the model aid in learning and understanding about the system?	Ford 1999; Sterman 2000	- Focus should not be on point prediction, but understanding - Learn how to understand and avoid problems	How would the model answer: – What could have been done to prevent or better alleviate PM_{10} problems in the LVV? – What are the major leverage points in the system for controlling PM_{10}?
9	Does the DSS help decision-makers develop effective policies or improve management?	Sterman, 2000; Ford, 1999	- helps managers decide on policies to implement and leads to improved policies - goes beyond simply providing a numerical answer, but enhances learning - learning and insight can be applied to new situations	What insights does the model provide into how PM_{10} management could have been improved?

CHAPTER FOUR

RESULTS

To determine the benefits of incorporating a systems perspective into the air quality management for the Las Vegas Valley (LVV), policy analysis was performed. Only a small selection of these results is included in the thesis.

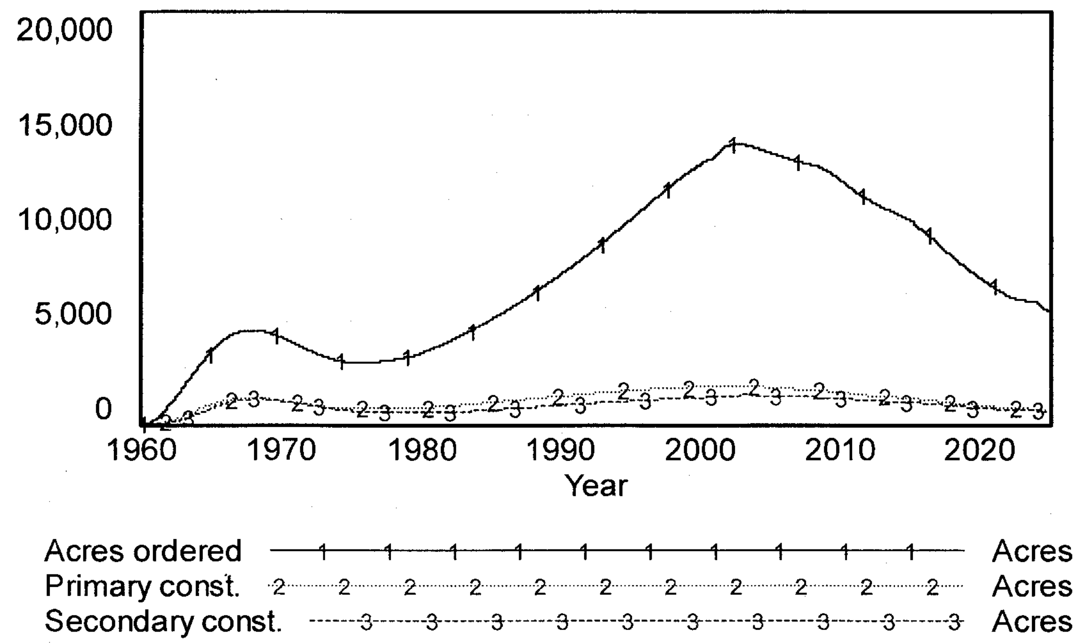
The first criterion deals with reality of results. The first two components of that criterion were addressed in the previous chapter (see validation section starting on page 75).

Are Results Realistic?

How Does Each Model Represent Time Delays and Bottlenecks?

The development of vacant land into urban area is one of the major material flows in the model. The number of acres in the construction stream is responsible for a large percentage of total emissions. The SD model first calculates demand for construction, which places acres on order for construction. Figure 30 shows how, at any given moment, there is more land in the ordered stock, than in the two phases of construction. Acres accumulate in the land ordered stock as permits for construction or other plans are being developed. If new construction were to stop, there would be a delay before all construction would stop since there are acres in every phase of construction at all times.

Figure 30 Results for acres in development stream



Another component of delay and example of a restricted flow in the system is the population moving to the LVV.

Figure 31 Population stock and flow structure

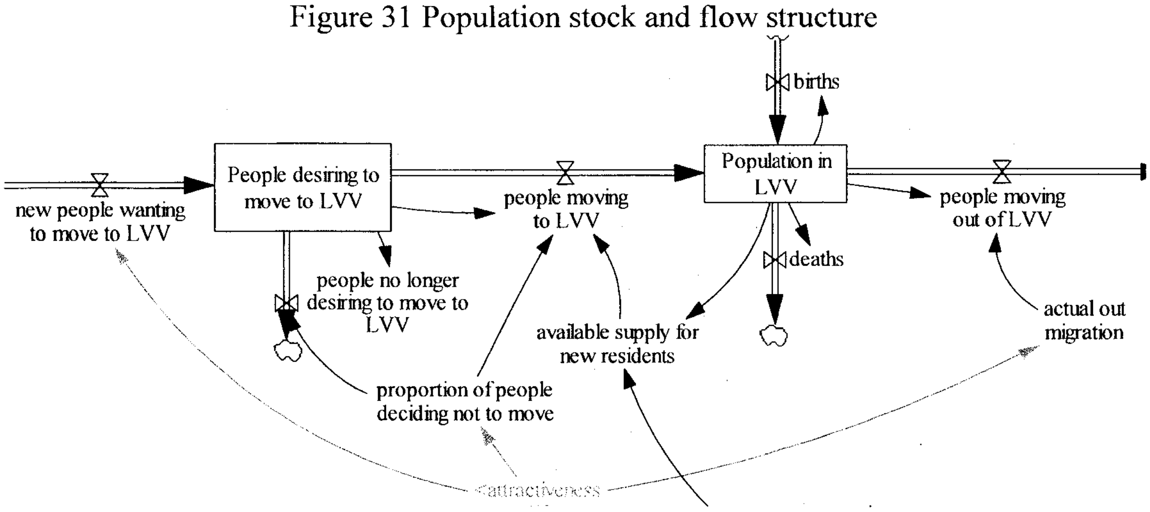
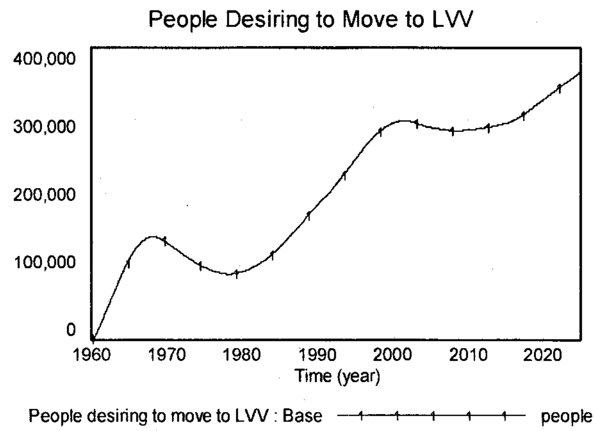


Figure 32 Population desiring to move to LVV



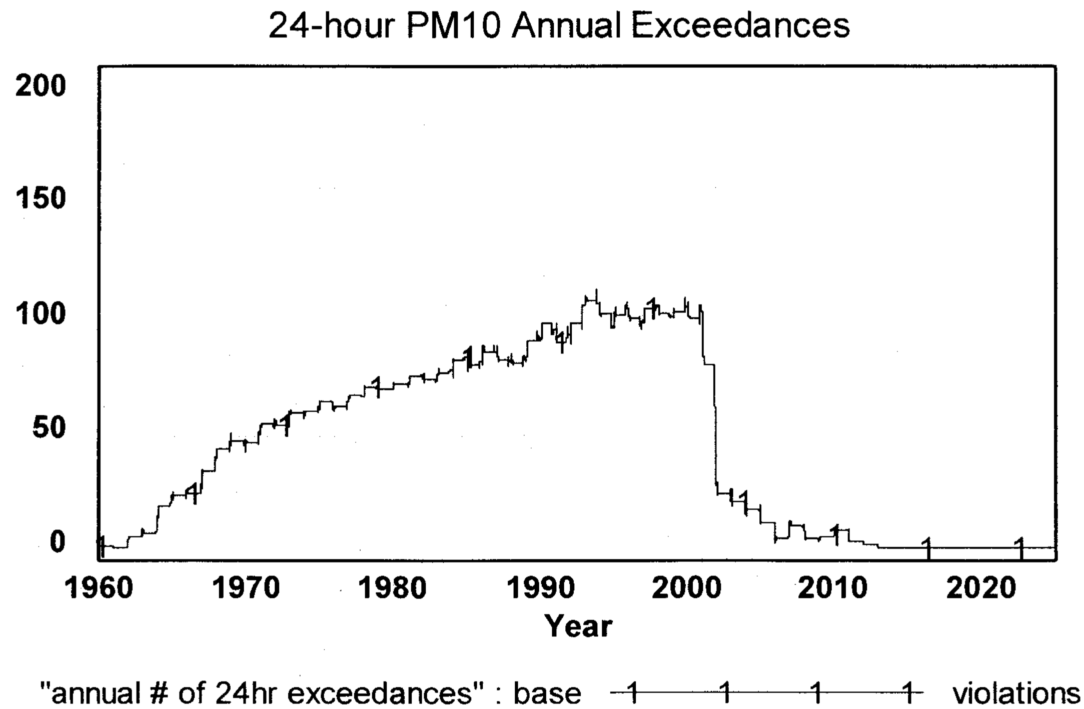
The structure of this backlog is shown in Figure 31 with the stock of "People desiring to move to LVV" and the "Population in LVV." Figure 32 shows the population of people desiring to move to the LVV and part b below shows actual in-migration to the LVV. The flow is limited by the amount of "available supply for new residents" in Figure 31, which is determined by construction of new homes. The stock of people desiring to move to LVV continues to grow throughout the simulation, even though the population has begun to slow.

Does the Model Show How Policies Change PM_{10} Exceedances?

As can be seen even from the comparison to the reference mode, the model shows the concentrations of PM_{10}. These calculated concentrations are compared to the standard internally and the number of annual exceedances is tracked. The number of calculated exceedances for the base simulation is shown in Figure 33. "Exceedances" here is considered the raw number of days per year that concentrations may go above standards. However, when actually calculating exceedances, the EPA uses a different calculation method that may transform actual emissions to determine a design value for the year to make the comparison to the standard only once.

The trend in Figure 33 shows a rapid decline in exceedances from 2000 to 2003. The model calculates new exceedances when policy changes are made, based on the resulting concentration trends. The model would allow for new values for standards if they were changed in the future. Additionally, users could update the calculation methodology to represent the method EPA uses to determine if an area meets the air quality requirements for an area, possibly replacing the raw number of exceedances per year (Figure 33) or using it as an input.

Figure 33 Number of exceedances per year



Is the Model Flexible for Policy Testing and Analysis?

Does the Model Have Several Policy Test Options?

A specific policy scenario dealing with construction was chosen to analyze the availability of input and output options and tests available for managers. Construction activities are responsible for a great portion of PM_{10} emissions in the LVV so, to be more effective managers might begin by focusing on a problematic emission source category.

A comparison between the SD model and the Proportional Rollback Model (PRM) for this scenario is shown in Table 6. For this and most other policy scenarios, the SD model had much more numerous options, with greater flexibility and correspondence with reality (i.e., the policy option is intuitive and makes sense in the real world). The SD model allows for testing specific effects of permitting, adjusting planning and permitting time, and implementing a new control of extra watering. Structural differences in the SD model allow an analysis of the effects of changing the duration construction projects stay in the active phase of construction (i.e., earth moving and grading). When analyzing input and output options the comparison to the PRM was performed to establish a baseline.

In general, the SD model has more input and output options for simulation scenarios. There are however, a few instances where the options for both models are comparable in number but qualitative differences in inputs (e.g., how intuitive they are, correspondence with real system) are improved in the SD model.

Table 6 Construction Activities Policy Analysis

DAQEM Proportional Rollback	Systems Dynamics
Policy options available (variables, switches)	
Density/Land consumption per capita*	Normal construction duration
implementation rate (ea. Construction project)	Percent of construction in active construction (phase I)
Control efficiency	Implementation rate (ea. project)
duration of each project	Control efficiency
emission factor	emission factor (phase I)
Overall control reduction*	emission factor (phase II)
	Average planning and permit time
	Permits issued
	Stabilization (e.g., dust suppressants, paving) on a set percent of land (unstable, stable)
**requires explanation of how calculation works in order to understand*	Extra watering (switch)
Result/ Output options for analysis	
Demand for new development	Annual or daily demand for construction
Vacant land	PM_{10} emissions (mass and concentration)
24-hour construction wind erosion emissions	Acres ordered backlog
24-hour construction activity emissions	Acres in primary/active/phase I construction
Total PM_{10} emissions (mass and concentration)	Acres in secondary construction
	Wind erosion emissions
	Construction activity emissions (ea. phase and total)
	Developed urban area
	Total PM_{10} emissions (mass and concentration)
	Costs (cumulative, daily)

Does the Model Answer Questions Outside of Original Purpose?

One question used as an example of this was determining whether control options could be used in a different mix to achieve the same reductions in PM_{10} concentrations, with reduced costs. Not all controls that were listed in the state implementation plan were included in the SD model. However, the most common measures of paving, dust

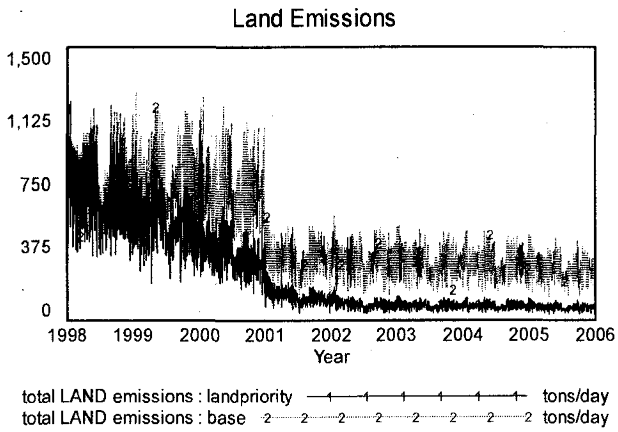
A variety of results are possible when changing the control options: much greater control costs that actually increase PM_{10} concentrations, lower costs with increases in pollution, higher costs with significantly reduced emissions and, the ideal outcome, lower costs with decreased emissions. In general, policies which do not focus on mitigative control strategies and instead develop the area to avoid PM-producing activities tend to be the cheapest. Policies which relate to the development of the Valley are described in the final sections of this chapter.

A test was also performed to show the effect of forcing construction to begin with unstable land and then move on to other types after. Unstable land has a much higher emission factor than stable or native desert land. If unstable land is built first, it would remove a great majority of emissions without requiring a change in the amount of acres developed in the area. No other changes were made to demand for construction.

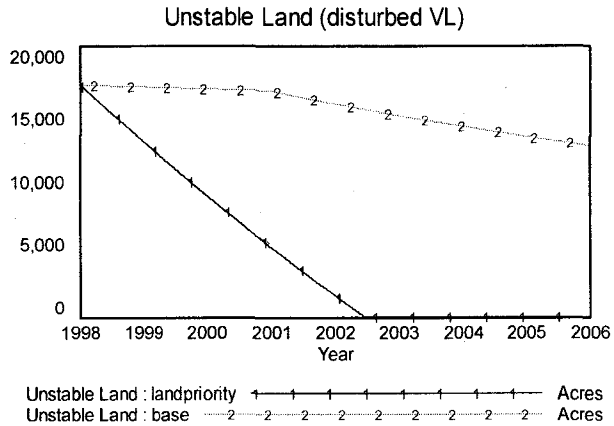
The SD model results for changing the priority of land to start on unstable land is shown in Figure 36. 75% of demanded construction allocated first to unstable lands and then split between the remaining two categories. The unstable land emissions are about 30 times greater than stable land (which is still a few factors greater than native desert emissions). Forcing more construction on this land dramatically reduces land emissions (Figure 36, a.) as disturbed or unstable vacant land acres are depleted (b.). Construction is re-allocated to other land stocks (native desert and stable land) at higher percentatges when unstable land acres are completely developed.

Figure 36 Changing priority to unstable land

a.



b.



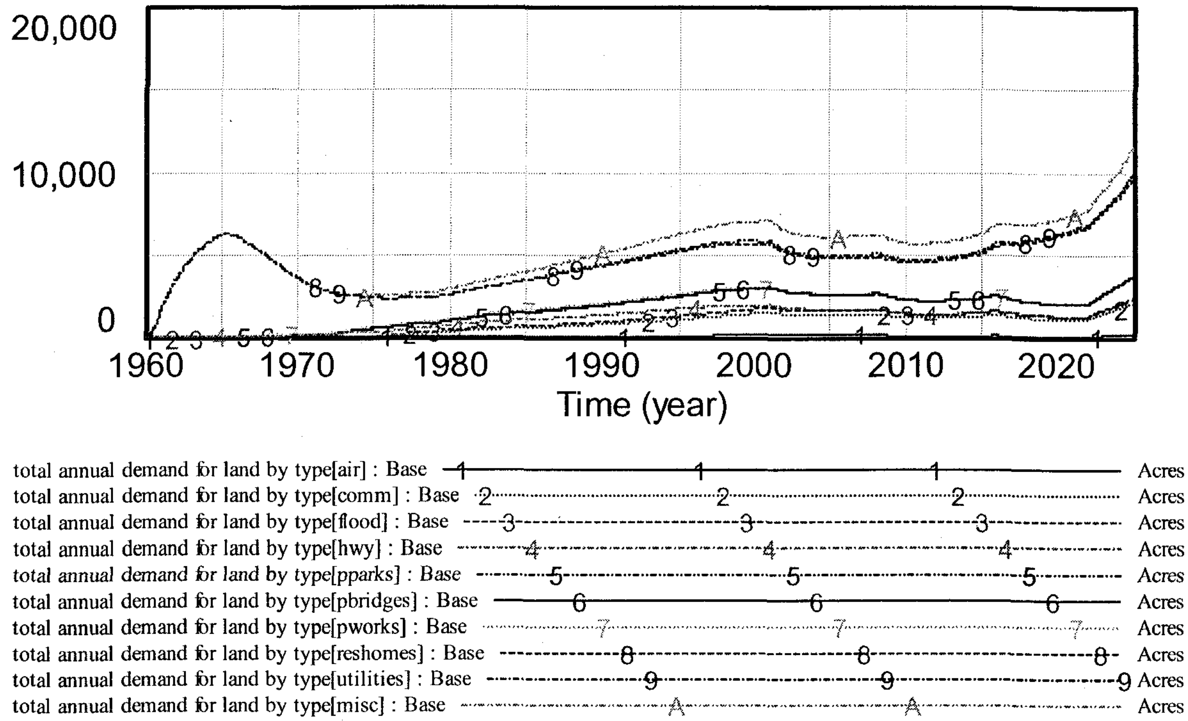
Are Boundaries Appropriate?

<u>How well does the model incorporate important drivers of PM_{10} pollution?</u>

Demand for land is based on the attractiveness of the area which changes as the area develops. Each construction project type has a calculated demand (e.g., public parks, commercial). Demanded acres are calculated using an assumed comparison of acres per person. For service project types (airports, commercial, flood detention, public parks, utilities, and miscellaneous), there is an assumed total acres of services needed per resident and then a percentage allocation which distributes the number of acres of services ordered. This demand is compared to the acres of perceived available service (which are built land and a portion what is currently under construction).

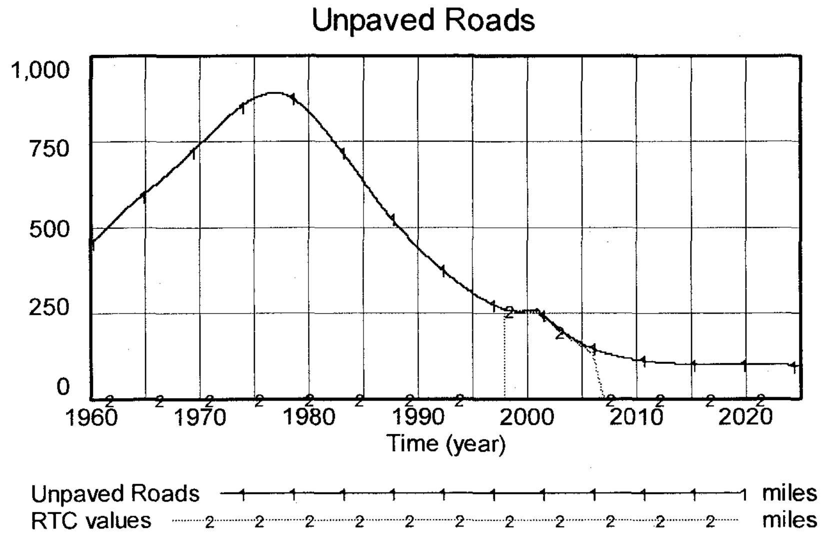
Figure 37 shows a stack graph (top line is summary total for all elements) of demand for the different project types. Demand can increase and decrease with time and, for some project types (e.g., airport demand), remain relatively low for the entire time horizon. Figure 37 shows an increase toward the end of the simulation as demand for land begins to climb when there is no more vacant land developed to satisfy it.

Figure 37 Stack graph of annual demand by project type



Another major emission source is unpaved roads. Figure 38 shows the trend for unpaved lanemiles over time. The initial creation rate is high per person but decreases with time. This is a major source of emissions that was not calculated in the PRM model (it was exogenous). Understanding this source may help understand why emissions were still high in the early years of development (despite mostly native desert land) and why emissions drop when controls were introduced. Normal paving of unpaved roads as part of development may peak after the 1980s when unpaved roads begin to drop. However, this reduction had slowed significantly by the late 1990s. At this time, a control measure of paving all unpaved roads with higher traffic volumes was instituted in a very short span, the sudden decrease in roads is evident in Figure 38. The dotted line represents the actual estimates which are only available for 1998 through 2006.

Figure 38 Unpaved road lanemiles



<u>Is there an appropriate amount of detail for the problem?</u>

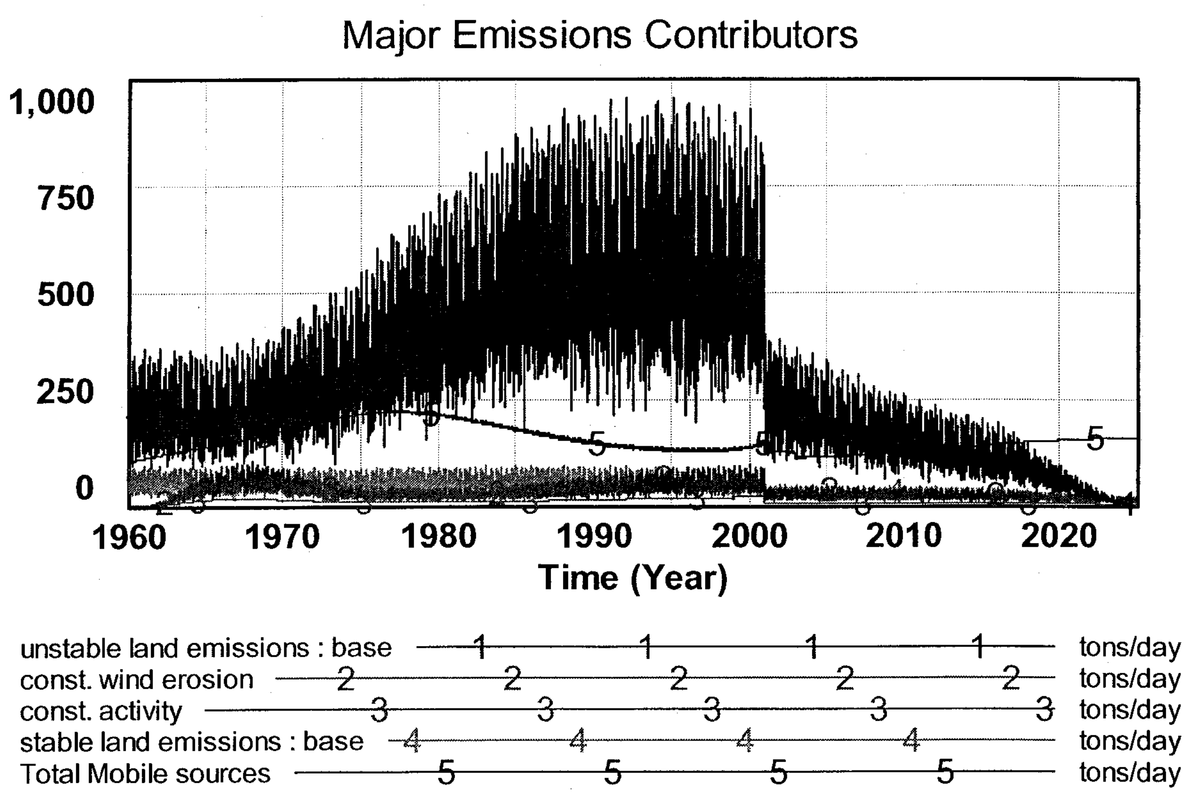
In the SD model, there are several stocks and auxiliary variables which may provide extra information but are not essential to understanding the problem. Structure describing annual tourist trends and unpaved road average daily traffic are probably more detailed than is needed. The model is capable of generating the problematic trend and showing many important details of specific emission sources. However, it is not clear whether the amount of detail is sufficient or too much. Considering the amount of output variables and that the majority of them are not often viewed during analysis, it is likely that the model could benefit from simplification.

Is the Time Horizon Sufficient and Able to Capture Long Term Impacts?

Does the Model Show How PM_{10} Became a Problem?

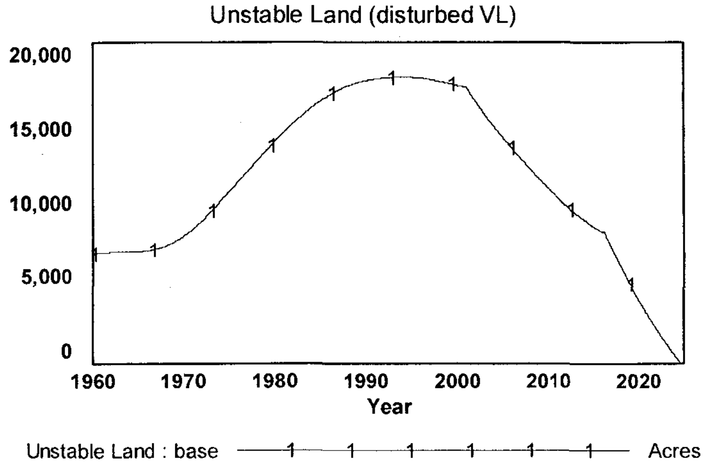
The model has a time horizon that reaches back to 1960. Some of the previous results demonstrate how development and other factors may have contributed to the PM_{10} problem. Figure 39 shows the major contributors to PM_{10} in the Las Vegas Valley on the same scale. As can be seen in the graph, unstable land emissions are by far the highest contributor for the majority of the simulation. There is a dramatic decrease in emissions when control measures are applied. In the final years of the simulation, mobile sources are the greatest contributor of emissions and are slightly rising.

Figure 39 Major contributors to PM_{10}



These results definitely indicate that unstable or disturbed land is the major reason why PM_{10} levels were so high historically. Figure 40 shows the number of unstable land acres in the Valley changing through time. Determining how this trend occurred and what could be done to avoid it would directly address the source of the PM_{10} problem. Furthermore, having a time horizon which extends back to cover this peak in emissions allows managers to perform retroactive policy analysis to determine if this peak in emissions could be reduced or possibly avoided altogether.

Figure 40 Unstable land acres

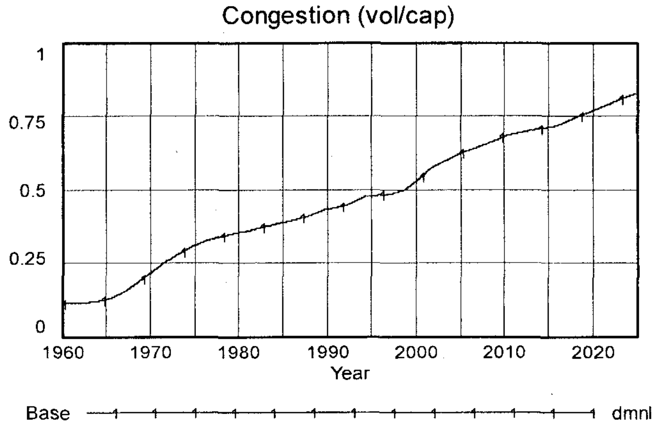


Do Models Capture Possible Future Problems With PM_{10}?

The SD model shows results out to 2025. At the most basic level, the SD model can show the projected result of the current management policies. One impact of current policies is increasing levels of congestion and therefore time in traffic. Figure 41 shows the congestion trends, defined as the volume of traffic over the capacity for traffic. The calculated results are consistent with the Regional Transportation Commission's (RTC) estimates of around 0.55 in 2000 and over 0.8 by 2025 if trends continue (Stave 2003).

Increased congestion significantly impacts other air pollutants or urban problems and so viewing this variable into the future serves as an indicator for other problems that would not be seen by either a short time horizon or a narrow model boundary. Policies which may result in worse PM_{10} levels in the future can be identified and avoided. Some policy analysis results in short term gains in variables (e.g., congestion) but then are much worse in the long run.

Figure 41 Congestion trends of current and historic policies



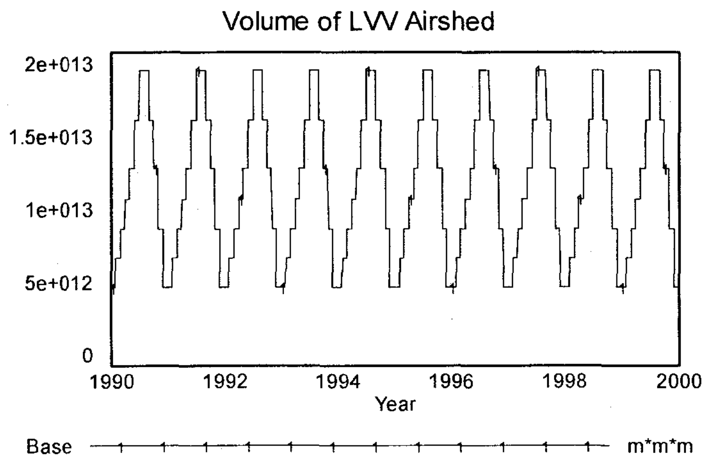
Are All Major Causal Mechanisms and Feedbacks Included?

How Well Does the Model Trace Problems Back to Their Causes?

Some of the previous policy analyses provide support for this question. The SD model includes major contributors from mobile and area emissions categories. Most changes in key components of these sectors are included in the system. Even impacts from meteorology are included which may be an important feature of the behavior of the system. Changes in the height of the boundary layer may lead to seasonal difficulties with PM_{10} even if emissions remain constant.

The model assumes an average height for the boundary layer based on the current month. Although there are daily fluctuations in the boundary layer, the seasonal impacts are easier to determine and model and may provide more useful information about the causes of spikes in concentrations. Figure 42 shows the resulting seasonal pattern in the volume of air in the Valley for a ten year period. These fluctuations cause much of the variability seen in the PM_{10} concentrations.

Figure 42 Seasonal variation in the volume of the LVV airshed

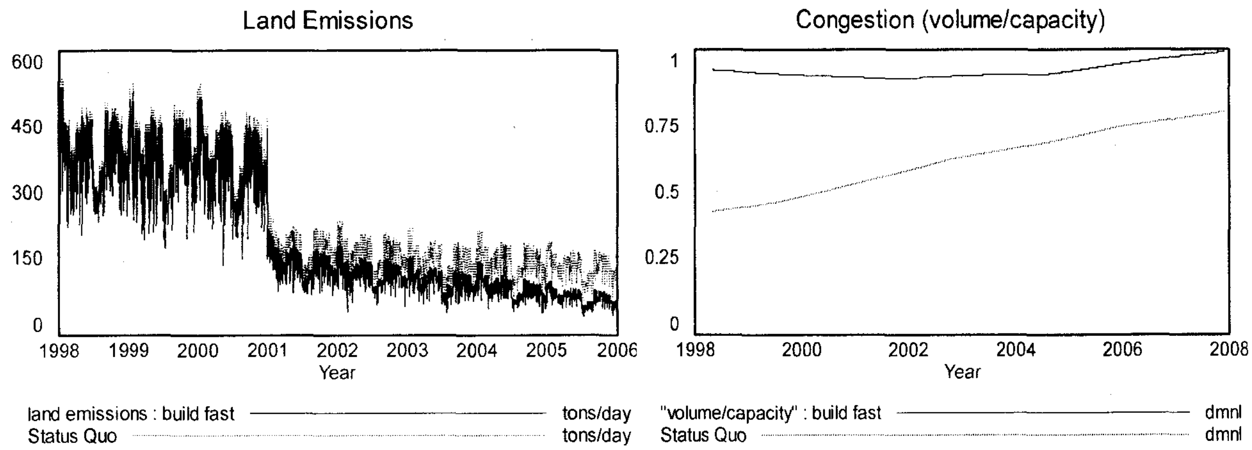


As part of the system dynamics method, variables are traced back through their causes. Therefore, in general the SD model does trace problems back through their causes and represents the major processes occurring with those causes as well.

How Well Does the Model Show Potential Side Effects from Policies?

The significance of unstable vacant land emissions to PM_{10} concentrations may lead developers to try to avoid unstable land. One approach could be attempting to maximize development to remove all vacant land, especially unstable land, as quickly as possible. Increasing the historical rate of development for Las Vegas gives the results shown in Figure 43. Developing the area more rapidly does reduce land emissions, but it subsequently causes an increase in distances traveled and the volume of traffic. Even though residents take fewer trips to compensate for increased congestion, there are still increased mobile emissions from 1998 to 2006. The effects of these changes to infrastructure result in significantly increased congestion over the base run ("Status Quo").

Figure 43 SD model results for quickly building out the area



This simulation also demonstrates that running the model for a shorter time horizon can still provide useful results (when sufficient causal mechanisms are included and the boundary uses a large enough perspective).

To What Degree Does the Model Show How the LVV Population Might Respond to Interventions?

The variable "personal trips per person" (trips taken by residents that are not obligatory or required trips) is the main place where individuals respond to changing levels of congestion and time in traffic in the model. When time in traffic increases, individuals take fewer non-essential trips. To test this response, the roadway capacity was increased by increasing the historic rate of road construction for the years 1970 to 2025. Figure 44 shows the resulting increased lane miles. As a response to extra roads, congestion is reduced, which shortens the time spent in traffic and therefore leads to individuals taking more trips. This gives the cumulative effect of increased vehicle miles traveled (VMT) as Figure 45 shows. As a result, any emissions caused by vehicles would be increased proportionally to the increase in VMT.

Figure 44 Increasing road construction

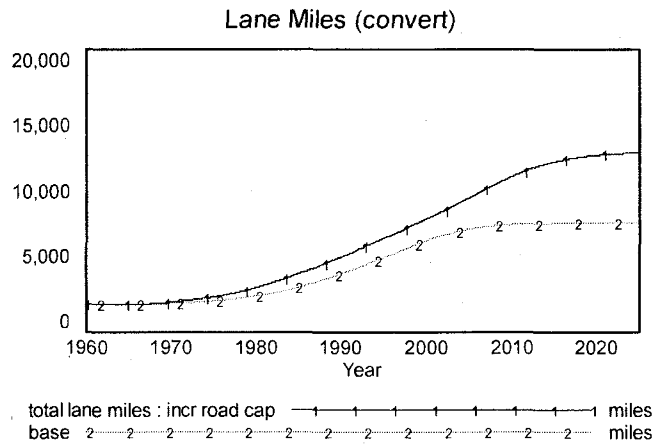
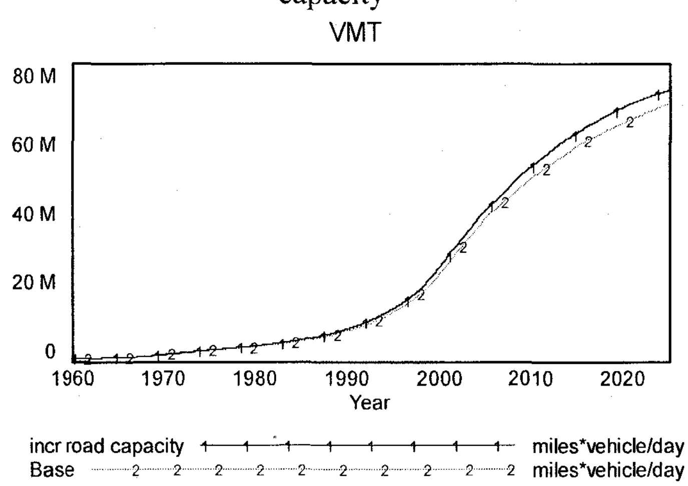


Figure 45 Vehicle miles traveled from increased capacity



The model uses an attractiveness factor to drive population. Attractiveness is based on job availability, availability of services, and time spent in traffic. Therefore, when policies influence these factors, attractiveness changes. The attractiveness drives the population that wants to move to the LVV, so this sector of the model also helps represents how people would respond to policies.

Does the Model Aid in Learning and Understanding?

Does the Models Demonstrate What Could Have Been Done to Avoid PM_{10} Problems in the LVV?

A great amount of analysis in the SD model focused on the development of the LVV and how PM_{10} problems developed as a result. Tests involved looking what could have been done to prevent or alleviate the PM_{10} problem. One major test was using the same controls that were developed and implemented in 2001. The purpose of the test was to determine the impacts of using the same control activity package, but just applying it earlier. Implementation of these controls was moved backward in time every decade until 1970 (i.e., 1990, 1980 and 1970). Figure 46 shows the concentration results from moving the same controls backward through time. Oscillations make the results difficult to see, but emissions are reduced sooner when controls are implemented earlier. Looking at the number of times in a year that the PM_{10} concentration exceeds the 150 $\mu g/m^3$ standard, as shown in Figure 47, clearly demonstrates the trend in how emissions are reduced.

Figure 46 PM10 concentrations from starting controls earlier

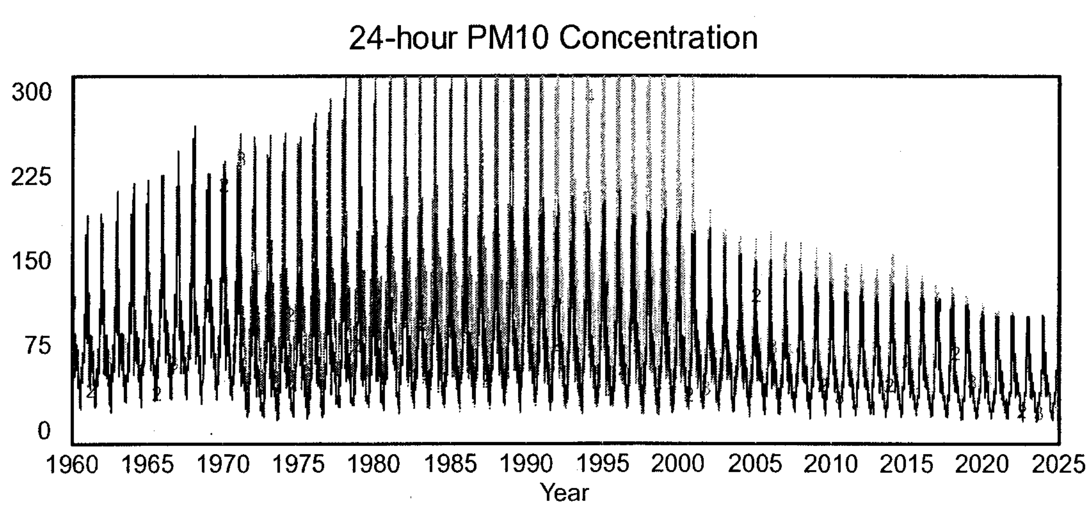
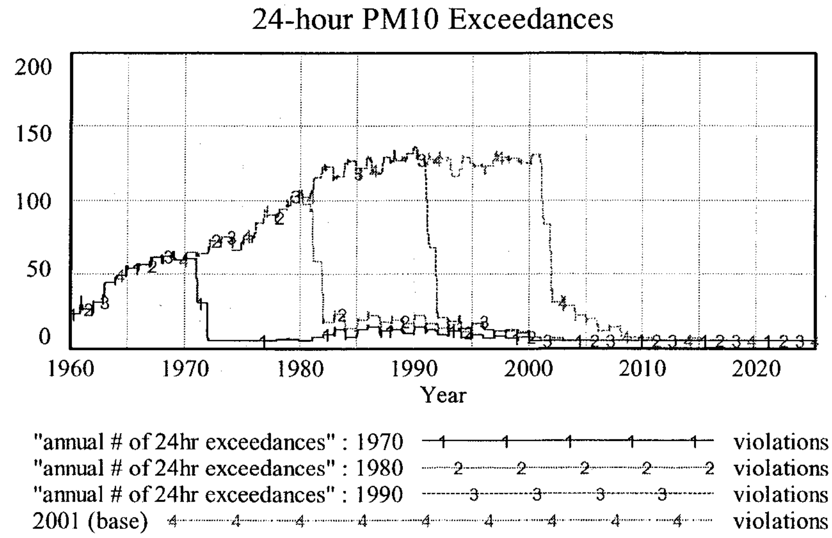


Figure 47 Exceedances resulting from changing decades

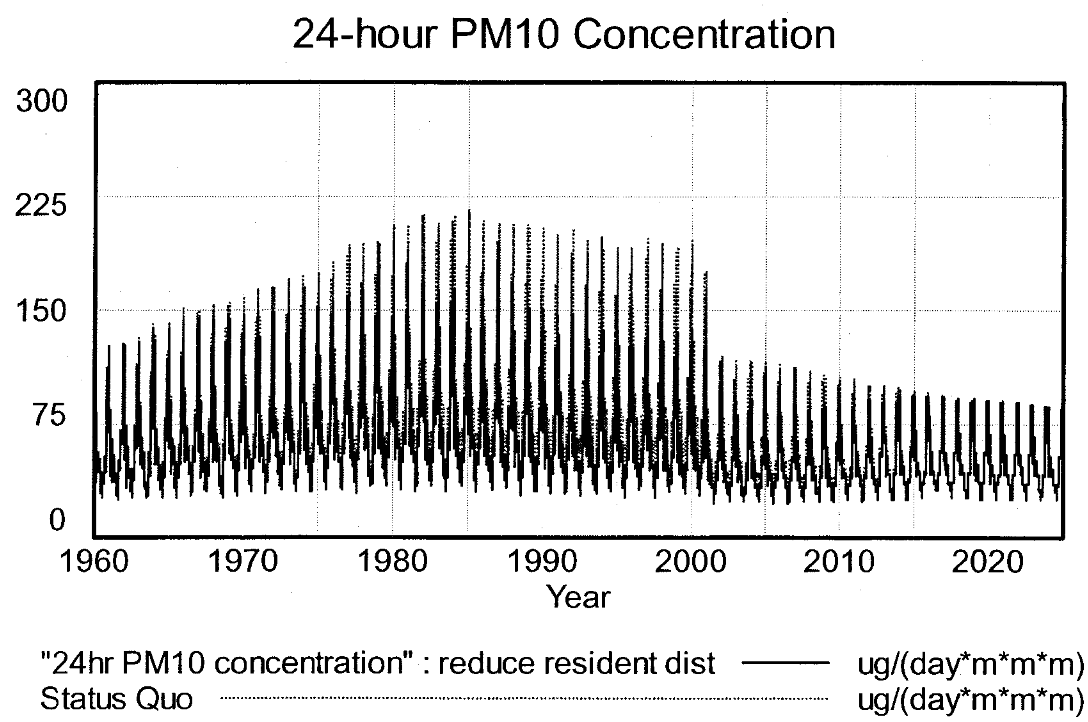


Annual costs for the earlier policies are lower than the status quo (base simulation) and remain lower until the final years when land is developed. However, cumulative costs for implementing control policies earlier are significantly higher because there is a longer duration of control application.

What Are the Major Leverage Points for Controlling PM10?

Leverage points were identified through policy analysis in the system. The rate of residential disturbance of vacant land (through off road vehicle driving and other disturbance activities) was probably the most significant leverage point. Reducing the rate by approximately half for the entire time horizon leads to the reduced emissions shown in Figure 48.

Figure 48 Reduced residential disturbance PM10 concentration



This option reduces the amount of unstable land, shown in Figure 49, which prevents a significant portion of emissions from being emitted and reduces control costs as well, shown in Figure 50.

Figure 49 Unstable land reduction

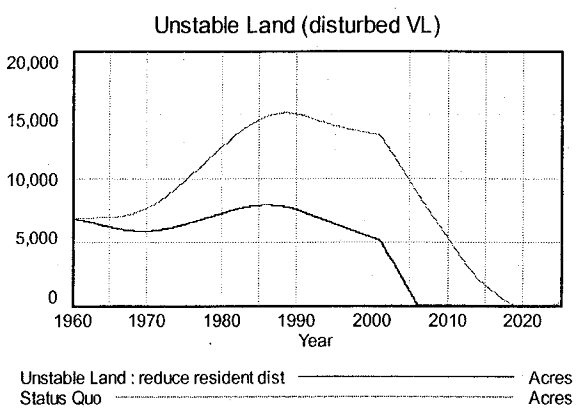
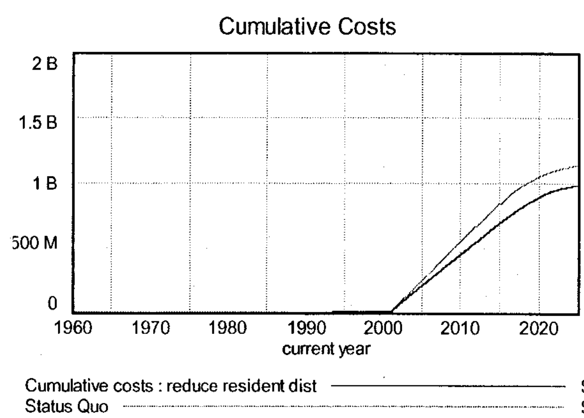


Figure 50 Cumulative cost reduction



Does the Model Provide Insights into How PM_{10} Management Could Have Been Improved?

In the simulation changing the decade when the same set of controls were applied, the control measure paralleled those actually applied in 2001. However, there are several additional policies which could be used instead. A combination policy allows the user to use a mix of policies that are both corrective (spraying water on dust) and preventative (decreasing the unpaved road rate or preventing land from becoming unstable). The following combination policy begins policies earlier (1970) and implements controls sooner (1980), sets unstable land to be the first constructed (at 40% of demand) and splits the remaining demand between the other two stocks. Many controls are also reduced since they are not expected to be necessary in the same levels. Policies also involve avoiding more unpaved shoulders (roadways which are so narrow that shoulders develop automatically) and unpaved roads begin to be paved sooner. The residential disturbance rate of land is reduced by about 20%.

This policy results in the relative concentrations given in Figure 51, which are significantly below the standard (only about two exceedances for the entire duration). This results in fewer deaths from PM_{10} exposure, shown in Figure 52 and lower annual and cumulative costs (as shown in

Figure 53). In fact, the final cumulative cost is almost $148 M less (Combo at $990.18 M and Status Quo $1.138 B).

Figure 51 Concentration of combination policy

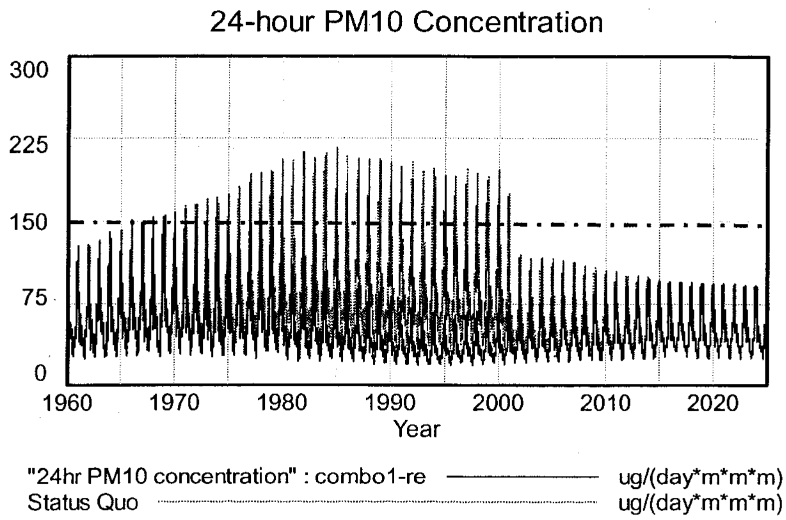


Figure 52 Cumulative Deaths Status Quo v. Combination

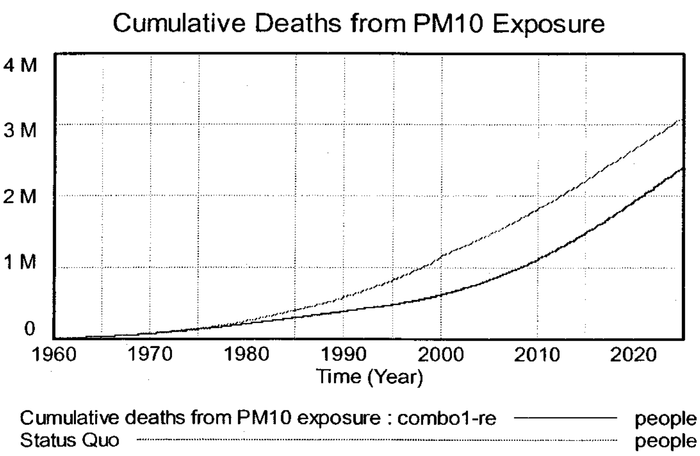
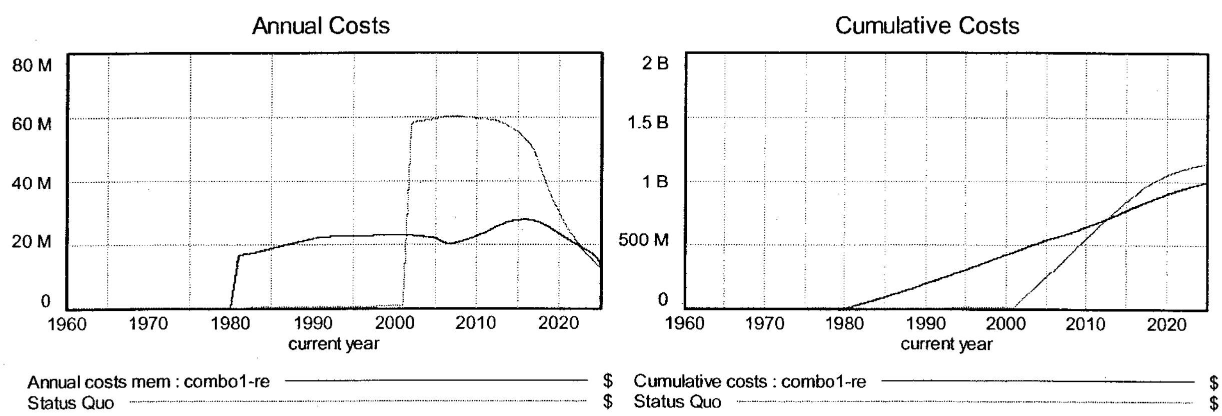


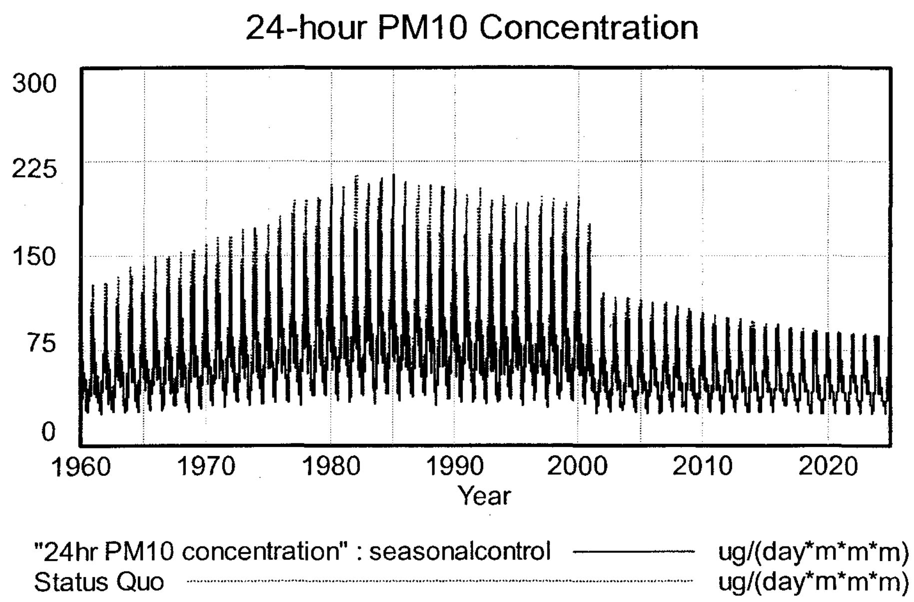
Figure 53 Annual and Cumulative Costs Comparison



Seasonal controls

Such proactive policies may serve as useful guides for other areas but they cannot help the Valley meet its current challenges. Since the boundary layer has seasonal changes, a test to better target emissions during seasonal peaks was tested. In order to evaluate this change thoroughly, major changes to model structure would have to be performed for all controls. Instead, a general seasonal control with approximately 30% more emission reductions over current policies was added. Other controls were simultaneously decreased and the difference was incorporated into the seasonal control, with slightly expanded acres and emission reduction capability. This control was only applied for the times of the year when seasonal factors combine to cause increased concentrations. Figure 54 shows the resulting reduced peaks in emissions over time, with diminishing returns as vacant land is depleted. Costs were not evaluated since the seasonal control was not properly tied to other cost calculation structure.

Figure 54 Concentration results from seasonal controls



CHAPTER FIVE

DISCUSSION

The PM_{10} Proportional Rollback Model and other decision support systems (DSS) are useful for their specific applications. However, given pervasive problems with PM_{10} management and increasing complexity, better tools for management are needed. The purpose of this thesis was to evaluate the benefits of incorporating a systems perspective into air quality management, specifically for problematic areas. The question guiding the study was whether developing a model using system dynamics would be beneficial for PM_{10} management in the Las Vegas Valley? I hypothesized that the systems perspective would have the following benefits:

- results that simulate behavior similar to what it would be in the real-world
- improved understanding of how the problem developed
- identifying harmful consequences or side effects to policies
- integration of major system components to gain a big picture perspective
- steering the focus toward long-term goals

Relating Results to the Hypotheses

What do the results show conclusively?

The SD Model Generates Real-World Behavior

The system dynamics model generates behavior close to what would be expected in the real world. This does not imply that the results are accurate or precise, but rather that the model responds in realistic ways to interventions. Recreation of the reference model and high performance on extreme behavior tests provide basic support for this claim. The model simulated values close to background levels when the state of the system was calibrated to ignore all other emissions. The system dynamics approach focuses on making causal connections between variables and capturing the major feedback mechanisms of the system. Additional structural components could be included, but as the model stands, the structure generates realistic behavior that responds reasonably to changes.

The SD Model Improves Understanding of the Problem and System

Several results demonstrate the ability of the model to explore how the PM_{10} problem developed and what could have been done to prevent it. These results improve understanding of PM_{10} and options available for managers. The model also clarifies relationships among components of the system, such as the seasonality of the boundary layer height affecting the volume of air and thus concentrations. Results point to major contributors to PM_{10} and their driving factors. Even the processes of particle addition to and removal from air can be explored.

Simulations Revealed Policy Resistance

The model was able to identify policies which may make things worse in the long run. These simulations could help avoid pitfalls that might otherwise happen as a result of well-intended policy interventions. For some tests, results indicated improvements in one area with significant deterioration in another. An example would be developing the area as fast as possible, which leads to nearly grid-locked congestion.

The Longer Time Horizon Helps Focus Users to Long-Term Consequences

Future consequences to policies enacted today are explored. Seeing the trend for nearly 20 years into the future focuses attention on what the distant effects of policies will be. Of course, this doesn't mean that managers will necessarily follow the best course of action. The model merely guides attention to the impact of interventions. In some cases, using a shorter time horizon would imply an improved situation while the longer horizon would imply the policy makes things worse.

The reverse is also true: a short-term perspective may imply a negative result while a long-term view shows the policy as beneficial. Having things get worse before they get better is another major lesson from system dynamics—counter-intuitive behavior (Forrester 1995). Examples of such behavior were mostly evidenced in the cost sector (you have to pay more now to save more in the long run) and in the transportation sector (reduce capacity or avoid developing roads and traffic is somewhat less congested in the long run).

Big Picture Perspective Improves Results

The boundary of the model was large enough that major problematic issues of policies could be discovered. Such simulations captured what would have been a side effect in another model. In fact, this may be more important than the long-term horizon. Not including the interconnectedness and essential interactions could lead to behavior which is not at all accurate, misleading, or harmful. Especially in planning situations and analysis, an integrated and more systemic view is necessary. The majority of results are insightful because they show how major components interact within a complex context.

PM_{10} Could Have Been Reduced by Applying Controls Sooner

Using the same control strategies of the historic policy, but applying them sooner would have significantly the PM_{10} exceedances. More diverse policy tests were preformed using combinations of other controls and implementation years. Several simulations and policy tests were able to avoid PM_{10} exceedances, although these policies had a range of other effects, positive and negative. Policy costs covered the spectrum of much cheaper than the status quo strategy to up to ten times more expensive. In the case shown in Chapter Four, costs were nearly $150 million less.

What do the results suggest?

The results also suggested several conclusions, but additional support would be required to demonstrate with more certainty what is only implied by this study. These findings include: that the SD model is more useful for managers, an SD perspective would lead to better-informed decisions and improves policy-making, and that anticipating problems is more effective than reacting to them.

The SD Model is Useful for Managers

Results presented above, especially for the evaluation criteria results, imply that the SD model would be more useful for managers and decision-makers than the current model. However, in order to determine this with any certainty, managers would have to test-run these two DSS and evaluate each for usefulness. All learning in this area should be useful to managers. Realizing the areas of the system where not much can be done, or where the major leverage points might be able to make managers more effective.

Additionally, the long-term perspective of the tool would mean that managers could continue using the model for years into the future. In some fields, the DSS rely heavily on technology and can quickly become obsolete. However, System Dynamics focuses on model development and process as opposed software. The earliest system dynamics models (Forrester's urban dynamics model) are still used today, not just as a basis for learning but as an actual simulation model. Managers would be able to update, expand, or connect their models through the years. Given the likelihood that regulatory changes will occur as will improved learning, it is important to have flexible tools.

Even if the SD model shows more accurate results and provides more policy options and opportunities for questions, managers may not find the structure as useful or relatable as other, more familiar, methods. The many capabilities of the SD model would have no benefit if managers could not trust in its results or would not use it. The question of how managers would respond to and use the SD model is an interesting one, but it is outside the boundary of this thesis.

An SD Perspective Leads to Better Informed Decisions and Improves Policy-Making

The implications of some policy changes are probably counter-intuitive to most managers. Using the SD model as a simulation laboratory gives managers the chance to try things that they are unable to do in the real world. Air quality models often use inputs determined by managers (or other models of other components of the system) to determine future emissions. However, the inputs that are chosen are not often determined through thorough testing of their relative effects on behavior. Knowing what policies may lead to problems beyond the key focus of the model would lead to policies that are better for the area as a whole. Of course, the model's utility comes in how it is used. Having the model will not automatically lead to improved policies. Managers must push the boundaries of the model until they are confident in its results. Confidence would hopefully lead to greater application and therefore learning. Perhaps problems in the model structure could be uncovered and the model improved. Only after policies have been implemented and their actual results have been compared to the model, would it be safe to say that the model results lead to improved policies.

Anticipating and Planning for Problems is More Effective than Reacting to Problems

Several results support that strategies of a more proactive nature may have been better for the LVV in terms of reduced pollution, costs, and health impacts. Many of the control policies are inherently more expensive and less effective compared to designing the city to avoid potentially high-emitting sources. However, there are several tradeoffs associated with these strategies. In some cases, proactive management may be more expensive. It is also founded on anticipating problems which is very difficult, especially when managers are faced with several other requirements that are mandated. However, the SD approach allows for at least some information as to the future state of the system which can make managers more effective in preparing for issues than if they occur without any prior warning.

What is Inconclusive?

Costs of Retroactive Policy Tests

The cost of strategies performed retroactively shows mixed results. In some cases, especially those involving the same kind of mitigative and reactive controls as were implemented in the LVV, costs for the more proactive strategies are much higher both annually and cumulatively. However, when policies focus more on preventative measures and planning the city to reduce emissions, costs are much lower. Several confounding factors may have caused this problem: costs include both costs to the public air quality management entities and to developers, which may be passed on to residents in both cases; no costs were offset from the income of dust permits, although this is in fact part of the DAQEM's budget (DAQEM 2007); and finally, controls do not adjust but remain fixed throughout the simulation.

Feasibility of Policy Options

A cost effectiveness of strategies could be performed using the costs of different policies, but this does not estimate the true feasibility of different policies. There may be options that are cost effective but have some other barrier (physical, technological, political) which makes them unfeasible. This was not measured in the analysis and so even if costs appear to be low for a strategy, it remains unclear whether that policy is feasible or not. Some policies seem very feasible, such as the seasonal control implementation, but the specifics of how it would work would need to be determined before such a policy could be implemented.

Identifying Harmful Policies Helps Avoid Them?

Great insight can be gained by running a simulation that causes the exact opposite of what was expected or desired to happen. However, having this information does not mean that managers will not fall into the traps. Evaluating the learning from models is difficult at best, but understanding how that learning ties into behavior is even further.

Other Findings

Outside of any direct hypothesis or question, this section explores other findings that were discovered while using the SD model to perform policy analysis. Findings include unexpected results as well as possible problems with assumptions made in the SD model.

The PRM Could Suffice for Some Purposes

For some policy questions, a non-systems based, linear model could provide relatively the same information. Of course, one might not have as much confidence in the results of the PRM which might lead to results which would not be possible. The basic questions, "Is there an exceedance?" or "Will the policy lead to concentrations below standards in 2006?" can be answered relatively easily by both models. In some cases, it may be acceptable to use a simplified, linear model. With all of the other procedural burdens faced by managers, a more comprehensive, causal model that answers questions they are not interested in asking or are unable to address is not worthwhile. However, there are several other policy scenarios where a linear model could provide an inaccurate answer to these questions (especially from lack of feedback). Additionally, as results many studies suggest (Dwyer 2007, Stave 2003, Van den Belt 2004) the process of developing a model, especially in a diverse group setting, can lead to improved understanding of the problem, causes, implications of changes, and acceptance of policies.

Unexpected Results

Residential Disturbance of Land

Residential disturbance of native desert land is a strong leverage point, controlled by the variable "disturbance rate per person." However, after the surprise of the finding, it seemed obvious why this occurs. Fugitive dust from unstable or disturbed land is one of the greatest contributors to emissions in the LVV. This rate causes land to flow from its natural state of native desert to unstable land from disturbance activities. Changes to this rate therefore have a significant impact on unstable land and therefore disturbed land emissions. Unfortunately, problems arise because this rate is quite uncertain. Although the rate used replicates the actual values for unstable land during the period of 1998 to 2001, it is unclear what happens between 1960 and 1998. Since this variable has presented itself as such an important policy lever, better information on this rate is necessary. Apart from missing data, this variable presents problems because no clear mechanism is designated in the model to show how reductions in the rate could occur and there are no associated costs for reductions in this rate since costs were limited to control strategies included in the SIP. Therefore, policy tests which focus on reducing this variable cause dramatically lower concentrations but whether the change is possible, feasible or costly remains unanswered.

Problems with Assumptions

As Sterman (1991: 11) states, "Any model is only as good as its assumptions." This section describes the major assumptions made that either seem flawed or caused abnormal behavior in model variables. Other assumptions are described in Chapter Three and a complete list is included in Appendix C, including assumptions identified below as problematic or needing improvement.

Designed Density is Exogenous

The designed density is defined as the density that developers use when constructing residences. It is commonly measured in dwelling units per some unit of area; in this model it was represented as people per acre. This variable is an exogenous input which increases with time but is not dependent on other variables in the model. During a simulation with a higher level of attractiveness to the LVV for the last twenty years, there was no increase in population values. This is because there is no feedback from the attractiveness of the area to the density that developers will construct. No matter how much attractiveness increases in later years, developers will always follow the same fixed values of density.

In reality, however, as attractiveness of the area increases, the population desiring to move to the LVV grows. A greater demand for homes would push developers to fit more people per area, increasing designed density. However, this would have some compensating feedback (Sterman 2000), because as more and more people are packed into the area, overcrowding would occur and reduce the attractiveness of the area. The assumed exogenous trend for designed density does not allow for this dynamic relationship to play out. Luckily, this is only an issue when looking the rare case of increased future attractiveness while assuming growth up until today to have occurred exactly as status quo policies. Increasing historic attractiveness does lead to a higher population projected for today and into the future.

All Land is Created Equal

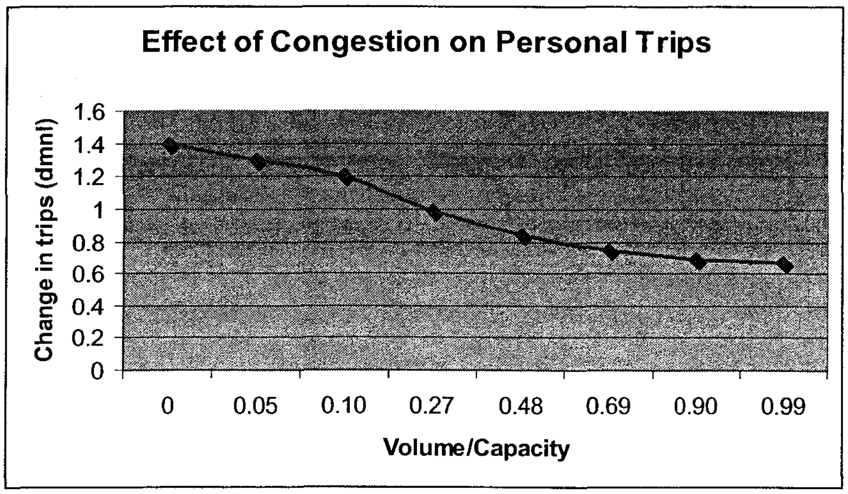
How developers choose land and what makes land attractive is not included in the model. The model assumes all "acres are created equal," which may not be a logical assumption. One policy test includes changing the priority of acres from native desert lands to unstable land. This would be an ideal strategy since it reduces one of the major contributors to PM_{10} pollution (disturbed land emissions) and by developing it first does not result in a change in costs. However, this may not be a realistic assumption, since factors such as location, ease of development and cost determine how much and of what type of land developers choose to construct. On the other hand, even if developers preferred a particular type of land, they would most likely want to develop any acres (even ones mandated by the county) as opposed to none.

Effect of Changing Road Capacity on Congestion

Increases in road capacity reduces emissions overall, even though it would be expected to lead to a greater volume of cars on the road and more congestion, offsetting any benefits of extra roads or actually making it worse (Sterman 2000, Chapter 5).

The model actually seems to imply that increasing roads would decrease congestion and increase attractiveness of the area. Although residents take more trips per person, the increase does not seem enough to counteract the effect of the increased capacity (or there are synergistic effects from the increased population which quickly saturate the available capacity). This is probably due to the assumed relationship of change in trips and congestion (=volume of cars/ road capacity). The LOOKUP table/function has a goal-seeking behavior that decreases the effect (reducing trips) as 1 is approached as Figure 55 shows. Toward the upper end, the change is less and less, as incrementally worse congestion has only a diminishing impact.

Figure 55 Effect of congestion LOOKUP table



Tests were done to make this effect more dramatic. Increasing the maximum to 2 (so that at very low congestion, individuals would take up to double the normal trip rate) and the minimum to 0.4, caused greater changes in behavior even at the higher points. This resulted in increases congestion when more roads were built as would be expected. This effect turns out to cause the difference between likely and unrealistic behavior. The net result on pollution is actually a lower PM_{10} concentration, as increasing roads removes them from an unpaved status and reduces those emissions even though VMT increases.

Emission Factors

Emission factors may not be properly calibrated. These values were brought in from the PRM for nearly all sources. The 1998 emissions inventory indicates a contribution of categories of which 90% is nearly evenly split between vacant land emissions, paved road dust, and construction emissions. However, results in the model indicate that vacant land emissions (specifically on unstable land) account for the majority of emissions.

VMT Drives Emissions

Related to the problem described above, PM_{10} emissions are based on VMT and not on time spent in traffic. Obviously, increased time driving would lead to increased emissions of particulates (perhaps just vehicular ones). The model does not capture the difference between fewer VMT at a high rate of congestion (and long time spent in traffic) and increased VMT at low levels of congestion. Many conformity models look at VMT when calculating emissions and so this is a very common and accepted practice. It does, however, leave out differences between these states in the transportation sector and how they relate to emissions. There are examples of other SD models that do base emissions off of time spent in traffic, such as the RTC3 model which calculates carbon monoxide (Stave 2002b: 152).

Controls

Control reductions were brought in from the PRM and estimated for other categories. The reductions may be overestimated because they lead to sudden, significant decreases in emissions. This may not be realistic, but it is consistent with the decreased results seen in the PRM and possibly with the reduction in exceedances.

Static Silt Loading

One assumption built into the model, reflecting the general thinking in air quality compliance documents (EPA 2003b), proposes that the silt loading factors or amount of dirt that is on the surface of a paved road is relatively constant. The EPA tracks the mechanism that directly emits particles into the air and not the ultimate source of those dust particles. This factor should be linked to the sources nearby that deposit dust on the surface so that, as vacant land develops, the overall silt loading factor throughout the valley would decrease. This feedback is important because initial disturbance could lead to greater silt loading as well.

Deaths

Deaths were not linked to PM_{10} exposure in the model. Exposure to PM seemed to cause too many deaths (see Appendix B for the section on Deaths). Even comparing mortality rates from several sources still resulted in deaths far above realistic death trends. However, this connection is an important one, especially for determining the impacts of increased air pollution. Either a new Dose-Response curve would need to be found, or population would have to be recalibrated to account for the additional deaths (by increasing birth rates). Other parameters (e.g., birth rate) come from fairly reliable sources and historic trends and averages. It was therefore assumed that the problem lay in the curve. Although the structure for this feedback was included in the model, the impact was actually turned off in a switch and deaths from PM_{10} were left out of most analysis.

Exceedances

Exceedances may be too frequent (or concentrations too high) in the current model. Actual exceedances followed the trends shown in Figure 9 on page 54. These are significantly lower than the events calculated in the model. It is important to mention that monitoring is not actually continuous and that averaging does occur throughout the day. These exceedances are considered raw exceedance amounts and the data used for comparison may have already gone through a calculation procedure. Still, the assumptions in the model seem to lead to trends which are correct, but the exceedances are not close. This would need to be further explored in order to determine if the model is over-estimating emissions, concentrations, or just exceedances.

Improving the Study

Changes in the Model

There are several technical changes that could be performed to improve the model structure and validity. However, looking at the structure from a larger perspective, the model should be changed to incorporate more of the feedback structure dealing with behaviors of human actors in the system. One example is how developers or contractors decide whether they will comply with controls. This is probably based on a combination of how well the control or site is being enforced and monitored, what the penalties for non-compliance are, and costs of implementing controls. Having these causal components determining the rate of implementation would allow for tests to determine the effectiveness of say increasing fines or spending more money on enforcement officers. Manager behavior should also be dynamic in the system instead of a one time set up defined by the inputs to the system.

The amount of money managers spend on control policies would depend on how the air quality problem is perceived (more tangibly, how far are we from the standard). Although the controls are turned on in the control implementation or policy year, the initial setting of control levels would not realistically remain constant for the entire period. For practical purposes, managers reduce control application once the desired reductions in emissions are reached. Incorporating this structure would probably lead to oscillating behavior as controls reduce emissions and then controls become lax and emissions rise, initiating the cycle once more. At the very least, the model could run in a gaming mode where managers are able to interact with the system and make policy changes every ten years or so, similar to what happens in reality. This would allow a change in the standard to be simulated to determine how management and developing agents would react to the change.

The spatial dynamics of how the area develops may be important for understanding and managing this issue. Some researchers state that hotspots are not adequately addressed in the current air quality management (NRC 2004). Looking at how policies have led to sprawl would be useful for other areas as well. Since the majority of mobile emissions are tied to the infrastructural components, some basic spatial representation of land would be useful (the model currently uses a table relationship between the size of the built environment and distances traveled).

Introducing an actual trend of emissions either for sources or as a concentration would be an important step in validating the model. Emission factors and controls may not be correctly calibrated in the model.

I would also want to generally expand control options. As it stands, not all controls are included and the estimates of how much they would reduce emissions and where was very unclear in the SIP. Adding the ability to have different levels of controls based on the season would also be a worthwhile endeavor for policy. Along these lines, costs should also be further separated by who pays (i.e., public versus developers). This would help when analyzing costs and could also be tied into the section described above for developers' decisions to implement controls.

Some variables or area of the model were included but were not fully developed and are still based on exogenous inputs. While some of these inputs come with support from other studies or are well-accepted facts, such as capacity to be added to hotel rooms, at least the basic drivers for these changes should be included in order to avoid potential problems of excluding feedback. The attractiveness of the area includes many different feedback loops (e.g., availability of jobs, time in traffic, availability of services) but not all are included. One important, but missing feedback, is the effect of overcrowding. As more people wish to move to the LVV and are not satisfied (through limited permits or time restraints needed for building land) there would be greater pressure on developers to increase the designed density of the area. This would result in increased density in many areas and at some point would become unpleasant and negatively affect attractiveness.

As described earlier, although the rate of residential disturbance to native desert land can be changed, the model presents no mechanism for causing this change. Therefore, it is unclear what a change in this variable would take in the real-world and how much this might cost. This would have to be remedied in order to perform more complete testing of policies.

Incorporating more of the mass transit sector as other models have done (Dwyer and Stave 2005, Stave 2002b) would be useful as well. Determining how more people could be convinced to take mass transit might be especially useful for policy makers (if not in air quality, then assuredly in transportation). Looking into the impact of permits more would also be useful. If significant offsets in costs can be accomplished through permits, perhaps some strategies would be a lot more feasible.

Similarly, the transportation sector was very simplified and may be more useful to managers if it were disaggregated. The type of lanes constructed (e.g., high or low speed lane miles) and the mass transit sector have the highest priority for such a change. Other SD transportation and air quality modeling projects (again, LUTAQ and RTC3) have spent significant time in these areas and shown the importance of public transportation and vehicle occupancy. Additionally, most documents from the Regional Transportation Coalition (RTC) look at emissions according to the different types of roads such as freeways and major arterials.

Ensuring the model is useful for managers is vital as is following a holistic perspective. Therefore, the level of detail in this area should be appropriate for the purpose. The current model is very detailed for some components and much simpler on others. Bringing the model to an overall even level would be an improvement.

Changes in the Study Design

Changes to the study design are also needed or recommended to strengthen support for certain arguments or explore other effects. First, the model should be used with or by air quality managers in the LVV. As emphasized in step 6 in Stave (2003), the final step of the process is using the model for public outreach. Using and developing the model has certainly improved my own understanding, it would be most beneficial if mangers were able to use it as well.

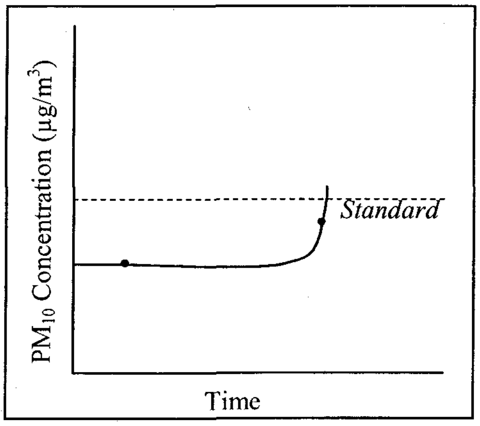
In order to better evaluate the benefits of the SD perspective, the model could be used by mangers. This would provide information on perceived benefits or measured usefulness. Identifying any barriers preventing the model from being accepted would also be useful. Furthermore, developing the model (or at least going through all of its structure and assumptions) with managers could lead to an improved tool. This would also help give managers understanding and confidence in the model to keep it from being a "black box" (Sterman 1991: 3).

Implications for Air Quality Management

One of the major insights from this study was the importance of focusing on long-term impacts and trends. Whether air quality models are overly simplified or completely data-driven, the current strategy focuses on a specific day or design value to calculate whether air quality in an area meets the federal standard. When a model seeks the best solution for an isolated point in time, it acts similar to optimization models, seeking a value and ignoring both how it is achieved and how it will change in the future (Sterman 1991: 8).

The results from the PRM were actually from discrete points in time, representing a day satisfying certain conditions. When the PRM was used to determine its ultimate results—a final PM_{10} concentration—it only used the target year of 2006 for demonstrating attainment. Any affects between the starting year and that target year were not included or even calculated. Yet, the importance of looking at trends to determine how policies are affecting emissions and concentrations cannot be over-emphasized.

Figure 56 Hypothetical case of PM_{10} concentration over time



Using only one or two points in time for comparison provides very limited information. Worse, it can mask very serious developing problematic trends. Consider a scenario where concentrations are below standards but have a rapid upward trend, as shown in Figure 56. Managers may assume a linear trajectory and that they have a while before the standard might be exceeded, which is not the case.

Of course modeling is just one component of the management process. PM_{10} pollution monitoring networks should warn managers of changes in trends. The suddenness of the upswing should send a red flag to managers of a potential problem and analysis or identification of a cause of the change may begin. At this point though, managers will be in crisis-management mode. Including trends in all modeling and automatically planning beyond demonstration deadlines might help better anticipate these problems.

Design days can be useful for air quality modeling, especially when they represent the worst case scenario. Achieving enough reductions to keep the worst case from repeating should mean that the average daily concentrations would be much lower than those peak event days. The PRM's design day does not include native desert emissions and assumes a low wind speed and so does not seem to represent a worst case scenario.

Current AQM models, as listed on the EPA's site, do not show mangers ways to develop policies. Instead, they provide technical support on how to represent particle dispersion. Managers may use other models to support the process of developing policies, but it is not specifically addressed by the EPA or required by the CAA. Requirements deal with specific control measures (e.g., best available control measures), monitoring methods, and technological advances. There are forums to aid managers, but again these typically focus on technical problems and not a big-picture perspective.

The purpose of the models recommended by the EPA and most commonly used for AQM is determining a concentration that represents a future state of the system to compare to national standards. Other important variables that change over time, such as population and VMT, are inputs to the model but usually not calculated within that model.

Models developed from the system dynamics methodology have a different purpose—increasing understanding about the system and problem at hand (Ford 1999). SD focuses on feedback and on changes over time, a good alternative to the usual discrete event analysis performed in air quality management. They are essentially management flight simulators where policies can be tested for their relative effects before being applied in the real world (Sterman 2001).

However, a word of caution is necessary. SD models do have several benefits for air quality managers but they should only be used where appropriate. The SD approach is not intended to be used for questions that do not involve dynamic problems. It is also important to place SD models in an appropriate decision-making context. Physical models have a very important role in air quality decision-making. I am not arguing that

SD models should take the place of these models. Models like the PRM also have a place. Using separate management tools that focus on different elements of the problem can also be problematic. Such isolated models provide only a small picture from a certain angle of the problem, neglecting to tie in other aspects may not represent how the system may respond to policies. SD provides a broader context to the problem that can capture many (but by no means all) of the purposes of these diverse tools. They can also point to areas or variables that need further research (Sterman 2000).

All DSS should have an appropriate application. Hopefully managers understand the limitations and purposes of these diverse tools because ultimately, it is up to the problem-solver/decision-maker to decide which tool to use. Again, system dynamics models are not suited to every situation. However, a systems dynamics model would provide a very useful supplement to the SIP process, especially for developing policies to test.

The Western Region Air Partnership was formed to address issues (develop data, tools and policies) specific to the west for improving visibility. The group is focusing more on understanding and integrating approaches in order to improve this problem area. This may be a great place to incorporate system dynamics or tools from a systems perspective. Such organizations may also indicate a change that the approach to AQM may be changing.

The SD approach is particularly applicable for growing international areas and cities, especially in cases where deterministic/predictive model data requirements are prohibitively high. The highly technical models that are the norm rely on extensive meteorological, emissions, and other data which is not only expensive and time-consuming, but often unfeasible outside of developed nations (McGranahan 2003).

Several barriers exist to the incorporation of social and physical based causal models into air pollution management. These barriers would need to be explored and addressed in order to allow wide-spread adoption of these tools. Identifying barriers would require an entire thesis, but one observation may provide a starting point. Managers are under pressure to meet regulatory requirements. Any approach which is not already widely used may require additional burdens of proof for EPA acceptance. This may make managers hesitant to try new approaches like system dynamics.

Focusing on Air Quality Improvement

Although there may be several challenges with air quality management, it is important to note that it is the regulatory framework that keeps this management style in place. Therefore, if wide-reaching changes in approach are to happen, the SIP process or other requirements may need to be changed. The regulatory framework does not specifically prevent or block the use of a SD application. Managers can use other means to develop strategies, but hopefully this thesis provides some support for the benefits of using SD or having a systems perspective.

Many air quality managers/experts criticize the over-reliance on a one-time demonstration of attainment instead of the bigger picture (NRC 2004, FOS 2004). The one time demonstration ignores many essential feedbacks and assumes an "end" to the problem instead of the dynamic nature of air quality problems. Considering the very complex dynamics of air pollutants, social and urban systems, regulatory context, and technological development, it is essential to take a more holistic perspective and look at long term impacts when looking at AQM.

Although the SD model in this thesis integrated many important sectors of the system, it still focused on PM_{10} in isolation of other pollutants. The National Research Council's Committee on Air Quality Management in the United States (2004) argues for a switch from single-pollutant SIPs to a comprehensive plan that incorporates all pollutants. Other researchers also point to the need for a holistic view regarding thinking about modeling air pollution and air pollution management, specifically a view that incorporates all pollutants and their interactions (Molina and Molina 2004).

Having multiple pollutants could show policies which may appear to reduce levels of one pollutant (and therefore solve the problem) but may actually exacerbate another pollutant. At least on results implied such a connection. Clark County currently exceeds three of the six criteria air pollutants for which NAAQS were developed: ozone, carbon monoxide and particulate matter pollution (DAQEM 2005A). PM_{10} and carbon monoxide are in serious nonattainment status (DAQEM 2005A). Although an integrated plan will require significant changes to procedures (at all levels) and may be more complicated to create, it will actually be more efficient and possibly lead to more effective strategies in the long run (NRC 2004: 298).

Rather than focusing on one time demonstrations, there needs to be more focus on tracking and follow-up measures to assure that areas are actually showing improvements in air quality (NRC 2004: 299). Air quality improvement, not attainment of standards, should be the goal. This would prevent the crisis-management situation that happens when a standard is suddenly changed. It would also give greater incentive to develop policies which support the long-term goals of the area.

Finally, while AQM has gotten very specialized through the years, it is vitally important to take a systems perspective. Other areas which may face air quality problems should use such a perspective to really identify the special conditions and interactions in their area which may help or hinder air quality improvement. AQM should still be exploratory and focused on understanding. The world is not the clean laboratory with independent variables controlled. We need tools which will incorporate the complex interplay of real systems.

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APPENDICES

On CD Rom

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Fincher, S. and K. Stave. 2007. *A Proactive Approach for Particulate Matter Air Pollution Management.* Paper to be presented (July/August 2007) at the 25th International Conference of the System Dynamics Society, Boston, MA.

Fincher, S. and K. Stave. 2006. *Managing PM_{10} in the Las Vegas Valley.* Poster presented at the 24th International Conference of the System Dynamics Society, Nijmegen, The Netherlands.

Stave, K., L. Upham, S. Fincher, and K. Barchard. 2003. *Evaluating the Effectiveness of Simulation-based Instruction about Water Resources in the Middle School Science Classroom.* Poster presented at the 21st International Conference of the System Dynamics Society, New York, NY.

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