STRATEGY ALTERNATIVES FOR OXIDANT CONTROL IN THE LOS ANGELES REGION

PREPARED FOR THE ENVIRONMENTAL PROTECTION AGENCY

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PREFACE

Near the beginning of 1973, the U.S. Environmental Protection Agency (EPA) announced that meeting the national primary Air Quality Standard for oxidant in the Los Angeles Air Quality Control Region might require vehicle mileage reductions in excess of 80 percent, which would be achieved by massive gasoline rationing. Since the announcement was based upon a preliminary analysis, a special task force was formed at EPA headquarters in Washington, D.C., to perform an in-depth analysis of the problem and to search for alternative strategies that might cause smaller economic and social disruptions in the region than massive gas rationing would. All this was to be accomplished within a few months.

In support of this effort, The Rand Corporation undertook a study to assist the EPA task force in screening strategy alternatives, identifying superior strategies, and investigating the sensitivity of the superior strategies to various assumptions.

The results of that study were transmitted quickly and informally to the EPA task force by means of progress reports and briefings. After completion of the study, Rand issued informal working notes describing the policy results and the methodology. Rand’s contract with the EPA required only that the results of the study be documented informally for the task force’s use; it did not provide resources for the formal publication and widespread distribution of a project report. Because considerable outside interest has been expressed in the study, however, Rand has used its own resources to expand, refine, and integrate these informal notes and to publish the present report. Its purpose is to summarize the policy results of the study and to present an overview of the analysis methodology. The analysis is based upon the state of knowledge in spring 1973. The results should therefore be viewed in that context, although the report is being published and distributed somewhat later.

It should be noted that our study of alternative oxidant-control strategies for Los Angeles benefited considerably from tools and results previously developed as part of the San Diego Clean Air Project. Indeed, not only were some of the tools developed in San Diego successfully transferred and applied in the context of the Los Angeles study, but some examples and text from the San Diego project’s summary report have been incorporated in this report to help amplify and clarify the discussion of methodology and assumptions.

1 The work upon which this publication is based was performed in whole or in part under Contract No. 68-01-0475 with the Office of Research and Development, Environmental Protection Agency.

2 A joint venture of San Diego County and The Rand Corporation, the Clean Air Project sought strategies for meeting the national Air Quality Standard in San Diego as specified by the 1970 Amendments to the Clean Air Act. It represented a pioneering effort to analyze a comprehensive menu of alternative strategies in terms of their many impacts on the quality of life in a region. The Clean Air Project was supported by a grant to San Diego County from the EPA and by contributions from local sources.
SUMMARY

BACKGROUND AND GOALS OF THE STUDY

In January 1973, the U.S. Environmental Protection Agency (EPA) announced a strategy for meeting the national primary Air Quality Standard for oxidant in the Los Angeles Air Quality Control Region; that strategy included massive gas rationing to reduce vehicle mileage by more than 80 percent. Soon afterward, in the spring of 1973, a special task force was formed at EPA headquarters, Washington, D.C., to search for alternative strategies that might cause smaller economic and social disruptions to the region than massive gas rationing would. This investigation was to be accomplished in just a few months.

Building upon relevant tools and results developed in the San Diego Clean Air Project, The Rand Corporation undertook a study to assist the EPA task force in screening strategy alternatives, identifying superior strategies, and investigating the sensitivity of the superior strategies to various assumptions.

In this study, Rand had several specific tasks: Task One was to evaluate alternative strategies for meeting the national standard for oxidant in the Los Angeles Air Quality Control Region by 1975 or 1977. This included developing preliminary estimates of all the relevant input data; modifying them as more complete or up-to-date data became available from studies being conducted within the EPA; screening the many strategies available to control emissions of hydrocarbons and nitrogen oxides (NO₂); and identifying the superior strategy (or strategies), using the criteria of cost and effectiveness.

Task Two was to investigate the sensitivity of the superior strategies identified in Task One to alternative values of input data (e.g., emission factors or air-quality models). The input data were developed from the results of concurrent studies being conducted within the EPA and made available by the EPA Project Officer.

This report summarizes the policy results of the Rand study—i.e., the superior strategies and their sensitivity to key assumptions—and provides an overview of the analysis methodology.

PRINCIPAL ASSUMPTIONS

A number of basic assumptions must be made to estimate the emissions from various sources, the effectiveness of various control strategies, and the air quality that results from various emission levels. It should be noted that we use the amount of reactive hydrocarbon emissions as a proxy for oxidant to predict air quality, as is common practice.

Alternative Sets of Technical Assumptions

Two sets of technical assumptions are used to calculate reactive hydrocarbon emission levels under various control strategies: a reference set and a pessimistic set. The reference technical assumptions reflect our judgment as to the most realistic values for Los Angeles that were available at the time of the study (mid-April 1973). The pessimistic technical assumptions essentially correspond to those being used by the EPA-headquarters task force at that time; we term them "pessimistic" because
they combine several individually conservative assumptions in a way that makes it
very costly and difficult to meet the oxidant standard.

Although both sets of assumptions use the same set of composite\(^1\) hydrocarbon
reactivity fractions,\(^2\) they use different emission factors (amount of emissions per
vehicle mile) for light-duty motor vehicles and different values for catalytic-converter
effectiveness, as a retrofit device, in removing reactive hydrocarbon emissions from
vehicle exhaust.

**Alternative Air-Quality Models**

In addition to the alternative sets of technical assumptions, we also considered
several alternative air-quality models in the sensitivity analysis. (These determine
the maximum allowable reactive hydrocarbon emissions if a particular oxidant
standard is to be met.) First, to have a basis for comparison, we used the linear-
rollback model, although it is widely believed by many investigators to underesti-
mate the reactive hydrocarbon reductions required in the Los Angeles region. As an
alternative, the EPA provided the EPA-Medium model for predicting oxidant air
quality in Los Angeles. The EPA-Medium model requires greater amounts of control
than the linear-rollback model does; for example, to meet the present national
primary standard for oxidant, the linear-rollback model requires an 87-percent
reduction from 1970 reactive hydrocarbon emission levels, whereas the EPA-Medi-
um model requires 93 percent. The EPA-Medium model was used most consistently
in this study because it was considered more realistic; the results presented in this
summary are based on this model.

**Alternative Concentration Levels for the Oxidant Standard**

In the sensitivity analysis of superior strategies, we considered the following five
values as alternative concentration levels for the oxidant standard:\(^3\) 0.08 ppm (the
present national primary standard), 0.10 ppm (the present California standard), 0.15
ppm, 0.20 ppm (the health-advisory-alert level of the California Air Resources
Board), and 0.25 ppm maximum one-hour concentration levels. Although both 1975
and 1977 were considered as mandate years for the standard, only the 1977 results
are presented in this report; it would be extraordinarily difficult, even under favorable
assumptions, to meet the standards by 1975. A somewhat relaxed concentration
level is considerably easier to meet, and a somewhat postponed mandate year lessens
lead-time problems and allows the natural replacement of older, dirtier vehicles by
newer, cleaner ones.

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1 "Composite" in the sense that some were developed by the EPA using one definition of reactivity,
while others were developed by the California Air Resources Board and the Los Angeles Air Pollution
Control District using other reactivity definitions.

2 Conventionally, only total hydrocarbons are measured in the atmosphere or in emissions. Yet it is
reactive hydrocarbons rather than total hydrocarbons that are used as a proxy for oxidant. Thus, for each
primary source of hydrocarbon emissions, we must specify a reactivity fraction, i.e., a factor which
expresses the fraction of the total hydrocarbon emissions that might react under certain conditions. This
fraction is used to estimate the amount of reactive hydrocarbon emissions contained in the total hydrocar-
on emissions measured or predicted for each source.

3 In determining the air quality for a given species, the concentration levels considered are not
instantaneous values but rather average values for some interval of time (one hour, say) specified by the
standard and termed the averaging time. For oxidant, as an example, the standard is a maximum
concentration of 0.08 ppm for a one-hour averaging time. A particular standard is violated for a region
if any point in the region exceeds the standard. Thus Los Angeles would exceed the oxidant standard if
the maximum concentration exceeded 0.08 ppm anywhere in the region for more than one hour during
the year.
PROMISING COMPONENTS FOR CONSTRUCTING OVERALL STRATEGIES

Pollutant emissions come from both mobile sources, such as automobiles, and fixed sources, such as smokestacks. (Aircraft, although mobile, are included in the fixed-sources category because their significant emissions occur at or near the various regional airports.)

In this study, an overall strategy for the region is considered to be made up of strategy components, each applying a certain class of controls to a particular class of sources:

1. **Fixed-Source Controls.** These controls are applied to stationary sources and to aircraft.
2. **Retrofit-I/M.** These involve applying retrofit control devices and inspection/maintenance (I/M) policies to in-use vehicles—light-duty motor vehicles (LDMVs) such as automobiles and light trucks, heavy-duty vehicles (HDVs) such as trucks and diesel buses, and motorcycles.
3. **Transportation Management.** These controls are primarily concerned with reducing either LDMV miles (the origin of most mobile-source emissions) or congestion. They include such tactics as bus-system improvements, mileage surcharges or limitations (e.g., added gasoline taxes or rationing), incentives to carpool, and traffic controls (e.g., ramp metering).

Our goal is to identify superior strategies for oxidant control in Los Angeles, using the criteria of cost and effectiveness. But, given both fixed and mobile sources, potential strategies involve such a vast array of controls that it becomes impractical to evaluate all feasible combinations. It is possible only to identify a reasonable number of the most promising component strategies to apply to the different sources, and to evaluate and compare possible combinations of them.

The process of identifying the most promising component strategies is called screening. For each class of sources, the screening criterion used here is the ratio of the annualized cost (for procurement and operation) of the strategy to its effectiveness in reducing emissions, i.e., a cost-effectiveness criterion of dollars per ton of reactive hydrocarbon removed.

The results of the screening process are summarized below.

**Promising Strategies for Fixed Sources, Including Aircraft**

Two promising fixed-source control strategies are identified: a *nominal strategy* and a *maximal strategy*. The nominal strategy reflects only the controls proposed by the EPA (in the January 1973 announcement); no additional controls are added.

Additional reactive hydrocarbon controls have been proposed by Rand for certain fixed-source categories. These could produce additional reactive hydrocarbon reductions for the nominal 1977 levels of 50 percent for surface-coating and miscellaneous-solvent users, and 78 percent for aircraft. Overall, these additional reactive hydrocarbon controls could reduce fixed-source reactive hydrocarbon emissions 45 percent from the nominal 1977 levels, for an annual cost of $25 million\(^4\) (about $630 annually per ton of reactive hydrocarbons removed).

Additional NO\(_x\) controls have been proposed by Rand for petroleum production, marketing, and refining facilities, for power plants, and for other industrial combus-

\(^4\) All costs, whether for fixed sources or other controls, are annual costs; they include the incremental operating expenditures plus the investment and installation expenditures annualized by means of a capital recovery factor.
tion. The additional controls produce a 36-percent NO\textsubscript{x} reduction from the nominal fixed-source levels, for an annual cost of $32 million (about $647 annually per ton of NO\textsubscript{x} removed).

The effects of additional reactive hydrocarbon and NO\textsubscript{x} controls are independent. Thus, a maximal strategy for fixed-source controls can be defined which includes the nominal strategy along with both the additional reactive hydrocarbon and NO\textsubscript{x} controls; it provides the maximum practical reduction in these emissions from fixed sources, for an annual cost of over $57 million.

Promising Strategies for Heavy-Duty Vehicles and Motorcycles

Under the nominal strategy for HDVs and motorcycles, emissions of all species except NO\textsubscript{x} will be lower than their 1970 levels, despite mileage growth. This improvement is the result of emission standards, to be operative by 1975, for new heavy-duty gasoline and diesel engines. No controls are scheduled for motorcycles or ships and railroads.

Under the maximal strategy for these vehicles, motorcycles with two-cycle engines are replaced with four-cycle-engine motorcycles. This produces a 12-percent reduction in the nominal reactive hydrocarbon emissions from HDVs and motorcycles. (It should be noted that the number of bus miles and their associated emissions will vary with the transportation-management strategy; these effects are dealt with as part of those strategies.)

In this study, the maximal strategy for HDVs and motorcycles is always used in conjunction with the maximal strategy for fixed sources, while the nominal strategy for these vehicles is always used in conjunction with the nominal strategy for fixed sources.

Promising Retrofit-Inspection/Maintenance Strategies for Light-Duty Motor Vehicles

Many different retrofit control devices and mandatory I/M programs have been proposed to reduce the emissions from LDMVs. But the possibility of applying different combinations of these retrofit devices to different mixes of model years makes the number of possible retrofit-I/M strategies very large. To find the most cost-effective strategies, we calculated the costs and the emission reductions that would result from applying different combinations of devices to different mixes of model years. On this basis, we identified 28 promising LDMV retrofit-I/M strategies, which we identify by the 26 letters of the alphabet and the numerals 0 and 1. Each reflects a combination of retrofit devices and an I/M program applied to vehicles in specified age classes. In general, these strategies are labeled in increasing order of extensiveness, cost, and effectiveness, from A to Z, 0, and 1.\textsuperscript{5}

At an annualized cost of roughly $600 million, the maximum retrofit-I/M strategy could reduce 1977 LDMV emissions by about 74 percent under the reference technical assumptions and 60 percent under the pessimistic assumptions.

Air-Quality Improvements Possible Without Mileage Reductions

Substantial improvements in air quality can be achieved without any reductions

\textsuperscript{5} Among the individual items included in these strategies are crankcase blowby controls, evaporative-loss controls, vacuum spark-advance disconnect, catalytic exhaust-gas converters, and alternate I/M programs.
in vehicle mileage traveled (VMT), i.e., they can be achieved solely by means of added fixed-source controls and retrofit-I/M strategies.

Under the reference technical assumptions, an oxidant standard of 0.20 ppm or less could be achieved in the late 1970s in Los Angeles solely by means of fixed-source controls and extensive retrofit-I/M. The 0.20-ppm level represents a more-than-threefold improvement over the 1970 worst-day level, and an even greater decrease in the number of high-concentration days.

Under the pessimistic technical assumptions, an oxidant standard of 0.20 ppm or less could be achieved in the mid-1980s in Los Angeles in the same way. Significantly, the 0.20-ppm level, which corresponds to the health-advisory-alert level, should occur for a maximum of only one hour during the year, and that at only the worst location in the Los Angeles basin.

**Promising Transportation-Management Strategies**

In Los Angeles, 70 percent of the trips taken are short (8 miles or less) and represent only 30 percent of the total VMT. Conversely, 30 percent of the trips (those of 8 miles or more) contain 70 percent of the total VMT. Thus, our transportation-management strategies are designed primarily to reduce LDMV mileage in long trips, since these are responsible for most of the mobile-source emissions. By imposing penalties to make automobiles relatively less attractive and by improving the bus service to make buses relatively more attractive, these strategies are designed to cause people to form car pools, to switch from automobile to bus, or to forgo less essential trips. They may also result in less congestion and thus could improve average trip speed and related emissions.

On the basis of an auxiliary sensitivity analysis, the following transportation-management tactics appeared most promising:

1. Imposing a mileage surcharge or limitation (added gas tax or rationing).
2. Inducing changes in occupancy (car pooling for home-work trips).
3. Improving the bus system by
   - Reducing headways by running buses more frequently
   - Increasing area coverage to make more people bus-eligible
   - Reducing fares to zero by making the ride free.

A promising strategy will involve a particular mixture of these tactics. Since they are defined in relatively general terms, we shall now try to define them operationally.

For an automobile penalty, we impose an *LDMV mileage surcharge*. This penalty would make LDMV miles less attractive and provide incentives to carpool, to switch to buses, or to forgo trips entirely. It is a policy lever that may be interpreted as an added local gasoline tax or as a proxy used to simulate gasoline rationing. The strategy is defined by surcharge rate in cents per mile driven.

For bus-system improvements, different strategies primarily represent different bus headways (frequencies). The *peak and off-peak headways* indicate the average time between buses during these two periods; these determine the frequency of service and influence the average wait and bus-system capacity. (As a point of reference, the Southern California Rapid Transit District (SCRTD) has recently been providing bus headways of 20 minutes during the peak period and 30 minutes during the rest of the day.)

Two other bus-system improvements have been made in all bus strategies considered: First, the *bus fare* has been set to zero—i.e., providing free bus transportation to make bus travel relatively less expensive than auto, particularly for long
trips. Second, in determining the bus-eligible population, we have limited the bus-system improvements to Los Angeles and Orange Counties: The bus-service area has been chosen so that 90 percent of the population in these counties would be bus-eligible, i.e., within a half-mile of a bus stop. (The nominal service in these counties in 1971-72 made only 80 percent of the population bus-eligible.) For the entire region, the improvements make 80 percent of the population bus-eligible.

Other strategies such as improving traffic flow by ramp metering, dedicating bus and carpool lanes, and imposing parking limitations were found considerably less cost-effective.

Because our transportation-management strategies are designed to affect primarily long trips, they minimize the trip reductions necessary to achieve a particular air-quality standard: a 95-percent VMT reduction can be achieved by a 50-percent trip reduction; an 80-percent VMT reduction by only a 20-percent trip reduction; a 50-percent VMT reduction by only 5 percent; a 20-percent VMT reduction by about 2 percent; and 10-percent VMT reduction for negligible trip reduction. Other transportation-management strategies generally require much greater trip reductions for a given VMT reduction.

THE "TOTAL COST" OF MEETING DIFFERENT OXIDANT STANDARDS

Our primary goal, as stated above, is to identify superior strategies, under different assumptions, where the criteria of superiority are cost and effectiveness in meeting the oxidant standard. However, since all strategies meeting a particular assumed value of that standard have the same effectiveness, the superior strategies are those with the minimum cost. The question then arises, How do we define the cost of prospective strategies, which are made up of quite dissimilar components, in order to determine superiority? We need to broaden our concept of cost to include an additional cost of transportation-management strategies.

When people are forced to alter their normal behavior by forgoing trips or switching to less desirable modes, they experience a social cost; this social cost of forgone travel reflects the loss in benefits, convenience, and time that results from forgoing trips or from switching from low-occupancy auto to alternatives such as bus or carpool. We believe that the best simple proxy (easy to compute, easy to understand) for this social cost is the number of trips forgone because of a particular strategy.

Since many strategies greatly reduce the quantity and quality of regional travel, it is essential that the measure we use for the cost of a strategy include the social cost of forgone travel as well as the expenditures for the strategy components; otherwise a strategy that produced a large amount of forgone travel could seem unrealistically attractive if the actual strategy expenditures were relatively small. We shall term this measure the total-cost proxy (TCP); it consists of the net expenditures for strategy components and the monetary proxy for the social cost of forgone travel.

In order to combine the proxy for the social cost of forgone travel, which is trips forgone, with the strategy expenditures, we must have them in common units. We shall monetize the social-cost proxy by multiplying the number of trips forgone by the dollar value of a trip forgone; we call the result the monetary proxy for the social

* Massive rationing, for example, could seem unrealistically attractive if the costs to print, distribute, and administer the ration books were small.
cost of forgone travel. In calculating our monetary proxy, we have consistently used $1 as the value of a forgone trip, as estimated early in the study. (This is an estimate of the loss in social value per forgone trip, the value of the trip in excess of its average cost.)

In determining the net expenditures for strategy components, we allow the revenue collected from the surcharge, if any, to be used to offset the cost of the bus improvements. Thus we define the net expenditure for strategy components as the sum of the annualized expenditures on fixed-source controls, retrofit, and either the mileage surcharge or the cost of the bus improvements, whichever is larger.

We emphasize the fact that the TCP is merely a slight generalization of the cost-effectiveness concept, an artifice to help us identify superior mixed strategies. It does not purport to represent the total cost to the region of a strategy, that is, the net of all the benefits and disbenefits—many of which are not easily measured or monetized. But, having identified superior strategies on the basis of this TCP, we can then evaluate their detailed impacts on the region.7

Using this concept of the TCP and a menu of promising pure strategies, we have identified a manageable number of superior mixed strategies. To illustrate the variation in TCP with the desired concentration level of oxidant for the superior mixed strategies, an oxidant standard of 0.20 ppm could be met in 1977 for a TCP of about $500 million under the reference assumptions and $600 million under the pessimistic assumptions by strategies that include maximal fixed-source controls. Without maximal fixed-source controls, an additional $1.3 billion annually in TCP would be required to meet this standard under the pessimistic assumptions. (Of this, about $700 million would be unallocated income from surcharges.) Clearly, the additional fixed-source controls greatly increase the cost-effectiveness of meeting the standard. Indeed, under the pessimistic technical assumptions, standards tighter than 0.20 ppm cannot be met if nominal fixed-source controls are used because the fixed-source emissions alone exceed the standard.

An oxidant standard of 0.10 ppm could be achieved in 1977 for a TCP of $2.6 billion annually under the reference assumptions. Under the pessimistic assumptions, the TCP is increased by about $2.4 billion annually. (There would be about $800 million and $1600 million unallocated income from surcharges, respectively.)

An oxidant standard of 0.08 ppm could be achieved in 1977 for a TCP of about $5 billion annually under the reference assumptions. Using the pessimistic assumptions increases the TCP almost $4 billion annually. (There would be about $1.8 billion and $2.9 billion in unallocated income from surcharges, respectively.)

For a given standard level, these enormous differences in TCP are due to the difference in technical assumptions. Clearly, the uncertainty about the relative validity of the reference and pessimistic technical assumptions should be resolved before any stringent strategy is chosen. Using unduly pessimistic assumptions greatly multiplies the monetary and social cost of meeting relatively tight standards.

The above discussion also suggests the need for marginal analysis in setting the oxidant standards for a region such as Los Angeles. Are the additional benefits from more stringent oxidant standards worth the additional monetary and social costs of the controls? For example, if the oxidant standard were set at 0.20 ppm in Los

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7 This dependence reflects the fact that whenever the cost of the bus improvements is greater than the income available from the mileage surcharge, then the entire surcharge, if any, is used and the remaining improvement cost included in the net expenditures; whenever the surcharge is greater than the improvement cost, then part of the mileage surcharge collected will be unallocated. This unallocated surcharge may eventually be used to offset some other cost or to purchase some partially offsetting benefit. It is nonetheless part of transportation-management expenditures and is therefore included when calculating net expenditures. When superior strategies are evaluated in terms of detailed impacts, unallocated surcharge income is explicitly considered as a benefit.
Angeles, the health-advisory-alert situation (when persons with respiratory and coronary problems—about 10 percent of the population—would be warned to take precautionary measures, and school students would be asked to curtail strenuous activity) should obtain for one hour not more than once per year at the worst location in the region. Tightening the standard to 0.08 ppm increases the net expenditure by about $2.5 billion and the social-cost proxy by about $2.2 billion, under the reference assumptions. But the questions arise, Are the corresponding health and other savings for Los Angeles worth this? Is it possible to obtain larger benefits by spending the $2.5 billion net expenditures on some alternative social policy such as the establishment of preventive-medicine clinics, the search for a cancer cure, and so forth?

**COMPOSITION AND IMPACTS OF SUPERIOR STRATEGIES**

The composition and selected impacts of superior strategies under three alternative oxidant standards are summarized below.

### Superior Strategies for Meeting a 0.20-ppm Oxidant Standard

For a 0.20-ppm oxidant standard, the superior strategies under the reference and pessimistic assumptions are very similar. They both include the maximal fixed-source controls and the nominal bus system (about 1800 buses), and they involve no mileage surcharge. They differ only in the amount of retrofit, with the reference assumptions requiring less retrofit (about $290 million annually and about 6000 man-years of labor for installation) than the pessimistic (about $390 million annually and over 15,000 man-years).

### Superior Strategies for Meeting a 0.10-ppm Oxidant Standard

To meet a 0.10-ppm oxidant standard, the superior strategies under the reference and pessimistic assumptions both use maximal fixed-source control, maximal retrofit (requiring over 16,000 man-years of labor for installation), and the biggest bus system considered (over 7000 buses and over 45,000 employees) to make buses available to 90 percent of the Los Angeles and Orange County populations about every 5 minutes in the peak and 7 minutes in the off-peak period.

The two assumption sets differ only in the surcharge: 5.6¢ per mile for the reference and 20¢ per mile for the pessimistic. These are roughly equivalent to added gasoline taxes of 73¢ and $2.60 per gallon, respectively.\(^9\)

Under the reference assumptions, 5 percent of the uncontrolled trips are forgone, with a social-cost proxy of about $500 million annually. Of the remaining trips, about 20 percent of the total are by bus and about 16 percent of the home-work trips are by carpool.

Under the pessimistic assumptions, about 22 percent of the uncontrolled trips are forgone, with an associated social-cost proxy of over $2 billion annually. Of the

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\(^9\) This increases gasoline prices in the Los Angeles basin to a level roughly comparable with European prices in mid-April 1973.

\(^9\) Note that although the surcharge may seem relatively high on a per-vehicle-mile basis, it is considerably lower on the per-person-mile basis that affects trip-making behavior. The 20¢-per-mile surcharge amounts to 10¢ per person-mile, roughly comparable to the nominal cost per person-mile; thus the total cost per person-mile is not quite doubled by the 20¢-per-mile surcharge.
remaining trips, about 27 percent of all trips are by bus and about 60 percent of the home-work trips are by carpool.

Superior Strategies for Meeting a 0.08-ppm Oxidant Standard

To meet a 0.08-ppm oxidant standard under either set of technical assumptions requires not only the maximal fixed-source and retrofit controls and the biggest bus system allowed, but also substantial surcharges to produce massive VMT reductions.

The reference assumptions require a 214-per-mile surcharge. (Significantly, this strategy is essentially the same as that for meeting the 0.10-ppm oxidant standard under the pessimistic assumptions.) Under the reference assumptions, 22 percent of the uncontrolled trips are forgone, with an associated social-cost proxy of over $2.1 billion. Of the remaining trips, almost 28 percent are taken by bus and more than 60 percent of the home-work trips are by carpool.

The pessimistic assumptions require a $1.28-per-mile surcharge\(^\text{10}\) to produce an almost 95-percent VMT reduction. Nearly 50 percent of the uncontrolled trips are forgone, with an associated social-cost proxy of nearly $5 billion. Of the remaining trips, almost 50 percent of the total trips are by bus, and essentially 100 percent of the home-work trips are by carpool.

Trends in Superior-Strategy Composition

As the oxidant standard is tightened, both sets of assumptions exhibit the same trend in the order in which strategy components are applied, but the pessimistic assumptions cause each component to be added about 0.05 ppm sooner. In both cases, LDMV retrofit-I/M is applied first and increases in extensiveness as the standard is tightened. When this strategy becomes insufficient to meet the standard, a combination of an LDMV mileage surcharge and improved bus system are used to induce people to reduce their low-occupancy LDMV mileage by carpooling or riding the bus.\(^\text{11}\) As the standard is tightened still further, the largest bus-system improvement considered becomes insufficient, so the LDMV mileage surcharge (the only remaining lever) is increased further to induce people to forgo trips.\(^\text{12}\)

Oxidant Standards Achievable with Small Reductions in Trip-Making

Using the superior strategies identified, a 20-percent reduction in the number of trips (about 80 percent of the VMT) could achieve an oxidant standard of 0.08 ppm in 1977 under the reference assumptions and 0.10 ppm under the pessimistic assumptions.

As the standard is loosened, a negligible reduction in the number of trips (and a resulting 10-percent VMT reduction) could permit an oxidant standard better than 0.15 ppm to be achieved in 1977 under the reference assumptions and 0.20 ppm under the pessimistic assumptions.

\(^{10}\) Although a $1.28-per-vehicle-mile surcharge may seem surprisingly high, the reader should again recall that tripmaking behavior is on a person-mile basis. This surcharge amounts to 32% per person-mile, roughly a fourfold increase over the nominal.

\(^{11}\) Significantly, we have found that the bus-system improvements alone do not provide a sufficient incentive to induce substantial modifications in the use of low-occupancy LDMVs. Inducing such modifications requires both the carrot (improved bus system) and the stick (mileage surcharge).

\(^{12}\) In this discussion, we have assumed that maximal fixed-source controls, which are generally more cost-effective than other strategy components, have already been applied.
NEED TO REEXAMINE TECHNICAL ASSUMPTIONS

Our sensitivity analysis clearly shows that combining many individually conservative assumptions into a jointly pessimistic set will greatly increase the monetary and social costs of achieving a given air-quality standard. Although the "true values" of these assumptions remain uncertain, those in the reference set are, in our judgment, more realistic for Los Angeles than the pessimistic assumptions, which we consider unduly pessimistic. The pessimistic assumptions essentially correspond to those being used by the EPA-headquarters task force studying Los Angeles in mid-April 1973.13

There are at least two serious implications of using unduly pessimistic assumptions. First, regions with only a moderate air-quality problem, such as San Diego, may be forced into an unnecessarily costly control strategy. More important, regions with very severe air-quality problems, such as Los Angeles, may find that the standards cannot be attained without economic and social chaos; this, in turn, could lead to an unnecessary loosening of the standards. The data we have accumulated from the EPA and the California Air Resources Board sources and our experience with sensitivity analyses lead us to suggest strongly that the pessimistic (EPA) assumptions about LDMV emission factors, catalytic-converter effectiveness, and hydrocarbon reactivity fractions should be critically reexamined.

It should be noted that a particular technical assumption will often have a seemingly counterintuitive effect on meeting the standards; assuming relatively "clean" vehicles rather than "dirty" ones, for example, may make it harder to meet the standards, which is certainly counterintuitive. Such counterintuitive effects generally result from the rollback paradox, which arises because assumptions made for some analysis year also affect the emission calculations for the base year that determine the allowable emissions for a given oxidant standard. The rollback paradox's significance depends on the relative magnitude of fixed-source and mobile-source emissions and the relative effect of assumptions on emissions in the base and analysis years.

13 Since that time, several modifications have been made to the assumptions by various components of the EPA; some of these are less pessimistic and others are more pessimistic.
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1. INTRODUCTION

AIR POLLUTION IN LOS ANGELES

Air pollution is a significant problem in the Los Angeles basin. In 1970, the oxidant concentration exceeded the National Primary Air Quality Standard on about 250 days; on the worst day, the concentration exceeded the standard by nearly 800 percent. In 1975, even after the new controls presently legislated for new cars and other sources have been implemented, the oxidant concentration is expected to exceed the standard on about 220 days and, on the worst day, by about 600 percent. Although oxidant is the most troublesome air-pollutant species in Los Angeles, it is not the only species exceeding the standards in 1970 and 1975.

THE NEED FOR ANALYSIS

In 1970, Congress passed the Clean Air Act Amendments requiring all air basins to meet various air-quality standards by 1975. Unfortunately, these cannot be met in Los Angeles by presently legislated controls on new cars and other pollutant sources. Under the Clean Air Act Amendments, the California Air Resources Board (CARB) and the U.S. Environmental Protection Agency (EPA) are required to prepare and promulgate air-quality implementation plans for each region to meet the standards. This legislation provides that states will be penalized by stiff fines for failing to meet the standards.

Implementing control strategies to meet the standards, however, may produce substantial impacts affecting the quality of life in the Los Angeles basin. These impacts would include not only improvements in air quality and expenditures for control devices but also changes in travel volumes, times, and costs; in taxes; in energy consumption; in employment; and in the distribution of such effects among different locations and social groups (such as the poor). Different control strategies will produce quite different regional impacts: Rationing gasoline, for example, reduces vehicle miles and auto-related employment but produces savings in energy consumption; adding retrofit devices to used cars increases costs and energy consumption but produces employment opportunities for mechanics; improving bus usage increases average travel times but produces energy savings, employment, and travel opportunities for those without cars.

The overall impact on the Los Angeles basin of meeting the air-quality standards may be relatively large or small, relatively favorable or unfavorable, depending on the control strategy selected. Without sufficient analysis of alternative strategies, unnecessarily large monetary and social costs may be incurred if unnecessarily drastic measures—such as, perhaps, massive gasoline rationing—are applied.

1 For simplicity, we shall usually use the term "Los Angeles basin" to represent the region that the Environmental Protection Agency calls "The Los Angeles Intrastate Air Quality Control Region" and the California Air Resources Board calls "The South Coast Air Basin."

2 In determining the air quality for a given species, the concentration levels considered are not instantaneous values but rather average values for some interval of time (one hour, say) specified by the standard and termed the averaging time. For oxidant, as an example, the standard is a maximum concentration of 0.08 ppm for a one-hour averaging time. A particular standard is violated for a region if it is exceeded at any point in the region. Thus the Los Angeles basin would exceed the oxidant standard if the maximum concentration exceeded 0.08 ppm in the region for more than one hour during the year.
PROJECT TASKS AND GOALS

Near the beginning of 1973, the EPA announced that meeting the national primary Air Quality Standard for oxidant in the Los Angeles basin might require vehicle mileage reductions in excess of 80 percent, which would have to be achieved by massive gasoline rationing. Since the announcement was based upon a preliminary analysis, a special EPA-headquarters task force was formed to perform an in-depth analysis of the problem and to search for alternative strategies that might cause smaller economic and social disruptions in the region than massive gas rationing would. All this was to be accomplished within a few months.

Building upon its previous work in the San Diego Clean Air Project [1], The Rand Corporation undertook a study to assist the EPA task force in screening strategy alternatives, identifying superior strategies, and investigating the sensitivity to assumptions of the superior strategies.

In this study, Rand had several specific tasks: Task One was to evaluate strategy alternatives for reaching the national oxidant standard in the Los Angeles Air Quality Control Region by 1975 or 1977. This evaluation involved developing preliminary estimates of all the relevant input data, modifying the estimates as more complete or up-to-date data became available from studies being conducted within the EPA; screening the many strategies available to control emissions of hydrocarbons and nitrogen oxides (NOx) in order to meet the national oxidant standard; and identifying the superior strategy, or strategies, using the criteria of cost and effectiveness.

Task Two was to investigate the sensitivity of the superior strategies identified in Task One to alternative values of input data (e.g., emission factors or air-quality models). The input data were developed from the results of concurrent studies being conducted within the EPA and made available by the EPA Project Officer.

The results of this study were to be quickly and informally transmitted to the EPA for inclusion in their strategy selection process. A preliminary description of the symbols and equations used in the models was submitted 30 days after the start of work. A technical progress report containing considerable analysis was submitted after 45 days. A briefing on the final results of the original study, with handout copies of the briefing charts and essays describing the assumptions, was delivered after 60 days.

At the request of the EPA, Rand undertook further analysis beyond that envisioned in the original contract plan and budget. This consisted primarily of rerunning the analysis with newly derived data values for several assumptions and with a newly modified transportation model that accounted for the hitherto neglected effects of carpooling. Preliminary results from the added analysis were transmitted over the telephone after a few days, with informal briefing charts following soon by mail. Ninety days after the original study began, a final briefing was given in Washington, D.C., on the results of the extended analysis.

This report presents a summary of the policy results of the Rand study, i.e., it describes the superior strategies and their sensitivity to key assumptions. It is a summary in the sense that it does not report all the sensitivity analyses done in the study but concentrates on important policy results. Some of the analyses that are not reported here were intermediate steps in identifying superior strategies, while others involved assumptions which became obsolete during the study; many of these were included in earlier transmittals, progress reports, or briefings.

Before presenting the policy results, we shall first briefly describe the strategies and assumptions considered and the organization of the rest of the report.
THE COMPONENTS OF A REGIONAL STRATEGY

Pollutant emissions come from both mobile sources such as automobiles and fixed sources such as smokestacks. (Aircraft, although mobile, are included with fixed sources because their significant emissions occur at or near the various regional airports.) We define a control tactic to be any single action for improving air quality. Tactics are either technological, such as adding some control device to automobiles, or managerial, such as providing incentives to carpool. We define a strategy to be a mix of tactics.

It is convenient, analytically and expositionsally, to consider an overall strategy for the region as made up of three components, termed pure strategies, where each applies a certain class of controls to a particular class of sources:

1. Fixed-source controls. These are both managerial and technological and are applied to stationary sources and to aircraft.

2. Retrofit-I/M. These involve applying retrofit control devices and inspection/maintenance (I/M) policies to in-use vehicles; these vehicles are either (a) light-duty motor vehicles (LDMVs)—under 6000 pounds unladen weight—such as automobiles and light trucks, (b) heavy-duty vehicles (HDVs) such as trucks and diesel buses, or (c) motorcycles.

3. Transportation management. These controls are primarily concerned with either reducing LDMV miles (the origin of most mobile-source emissions) or reducing congestion. These include such tactics as bus-system improvements, mileage surcharges or limitations (e.g., added gasoline taxes or rationing), incentives to carpool, and traffic controls (e.g., ramp metering).

An overall strategy for the region, involving a particular mixture of pure strategies, is therefore termed a mixed strategy.

ANALYTICAL APPROACH

Given both fixed and mobile sources of pollution, potential strategies involve a multitudinous array of tactics—so vast that it becomes impractical to evaluate, in terms of detailed impacts, all feasible combinations. We were thus compelled to identify a manageable number of the most promising strategies for subsequent evaluation. The first stage in our analysis therefore consisted of screening—reducing the number of feasible strategies that merit further evaluation—to identify the superior strategies. The criterion we have used for screening is the cost-effectiveness of a strategy in reducing emissions; in this context, cost is the annualized cost (for procurement and operation) of a strategy, and its effectiveness is the amount by which it reduces emissions, primarily of reactive hydrocarbons, the most troublesome pollutant in Los Angeles.²

After screening, we undertook the evaluation of the most promising strategies. This required us to make detailed predictions of the various impacts of alternative superior strategies on the Los Angeles basin. Such impacts have been grouped as follows:

² The reader may be puzzled by the seeming contradiction between this statement that the most troublesome pollutant is reactive hydrocarbons and an earlier statement that the most troublesome air-quality species is oxidant. Oxidant is in fact Los Angeles' most serious air-quality problem. Oxidant, however, is not emitted by sources on the earth but rather is produced by photochemical reactions in the atmosphere that involve reactive hydrocarbon emissions. Thus, the amount of reactive hydrocarbon that is emitted into the atmosphere is commonly used as a proxy for the amount of oxidant that will be produced. (This is discussed in Section 6 and Appendix H.)
- Environmental impacts, such as air quality and energy consumption.
- Transportation-service impacts, such as travel times and volumes.
- Economic impacts, such as investment costs, taxes, and employment.
- Distributional impacts, or how selected impacts are distributed by social group (e.g., costs by income group) or by location (e.g., air quality by sections of the county).

Superior strategies were evaluated in the context of specific cases, where each case corresponds to a particular set of technical assumptions about emission factors and other variables\(^4\) in combination with a particular air-quality model for relating emission levels to air-quality levels. By defining alternative sets of technical assumptions, alternative air-quality models, and alternative concentration levels for the oxidant standard and then using these in the evaluation process, we have been able to show how the composition and impacts (costs, transportation service, employment, etc.) of superior strategies vary with these factors. The alternative sets of technical assumptions considered in our analysis are discussed below. (Several other assumptions of lesser importance will be mentioned, in context, in the main text of this report.)

**ALTERNATIVE SETS OF TECHNICAL ASSUMPTIONS**

A number of technical assumptions must be made to estimate the emissions from various sources, the effectiveness of various control strategies, and the air quality resulting from various emission levels. Our analysis has shown that the three most crucial factors in these assumptions are the following:

1. **LDMV emission factors.** For each pollutant species, these express the emissions per mile of driving for an average vehicle in each model year.

2. **Catalytic-converter effectiveness.** Although essential agreement exists as to the approximate effectiveness of most pollution-control devices for new and used vehicles, there is disagreement about the catalytic-converter retrofit-device effectiveness in removing reactive hydrocarbon emissions from motor-vehicle exhausts. Since reactive hydrocarbon is the proxy for oxidant, and since catalytic converters may remove between 50 and 80 percent of the reactive hydrocarbon emissions from motor vehicles, this effectiveness is a salient factor.

3. **Hydrocarbon reactivity fractions.** Conventionally, only total hydrocarbons are measured in the atmosphere or in emissions. Yet it is reactive hydrocarbons rather than total hydrocarbons that are used as a proxy for oxidant. Thus, for each primary source of hydrocarbon emissions, we must specify a reactivity fraction, i.e., a factor which expresses the fraction of the total hydrocarbon emissions that might react under certain conditions. This fraction is used to estimate the amount of reactive hydrocarbon emissions contained in the total hydrocarbon emissions measured or predicted for each source.

\(^4\) Although we evaluated a comprehensive and extensive menu of impacts, we did not evaluate all conceivable impacts. Among the impacts we have neglected are (1) the costs of not meeting the standards (health, etc.), (2) employment impacts occurring outside Los Angeles or in the far future, (3) the long-term effects of strategy costs and benefits, such as improved air quality, on the regional pattern and rate of growth (e.g., locational choices and migration), (4) various economic impacts distributed by location, and (5) various impacts distributed by racial group. These impacts were neglected primarily because of methodological limitations. Because of time and data limitations, we also neglected certain distributional impacts—transportation-service by income group and air-quality by location—that we had successfully estimated in the San Diego Clean Air Project.
From the best information available as of mid-April 1973, we assumed for these three factors those values we considered to be most realistic for the Los Angeles basin. We have termed them the reference technical assumptions. Just prior to April 1973, the EPA-headquarters task force studying Los Angeles defined an alternative set of values by combining several individually more conservative assumptions. (These essentially correspond to the values that were subsequently specified for use in Los Angeles by EPA Region IX in July 1973.) Since these values make it much more difficult and costly to meet the standards, we have termed them the pessimistic technical assumptions. (Section 6 presents a summary and critical evaluations of the reference and pessimistic values.)

ALTERNATIVE AIR-QUALITY MODELS

The air-quality model determines the percentage reduction in base-year emissions required to meet each air-quality standard. (The base year is one for which there are detailed air-quality measurements and sufficient information for compiling a total-emissions inventory.) This percentage is then multiplied by the total emissions in the base year to determine the allowable emissions under that standard for any year.

In our study, we used several air-quality models for relating reactive hydrocarbon emissions to oxidant air quality in the Los Angeles basin. First, to have a basis of comparison, we used the linear-rollback model. This model has been used to prepare the implementation plans for most other air basins but is generally considered to underestimate the required reductions in reactive hydrocarbon emissions for Los Angeles. We also used three alternative models provided by the EPA. These we termed the EPA-Low, EPA-Medium, and EPA-High models, depending on the relative severity of the required reactive hydrocarbon reduction. Each of these models required greater amounts of control than did the linear-rollback model; to meet the national primary oxidant standard of 0.08 ppm, for example, the EPA-Medium model required a 93-percent reduction from the 1970 emission levels, whereas linear rollback required only an 87-percent reduction. The EPA-Medium model was used most consistently in this study because it was considered the most realistic; the EPA-Low and EPA-High models were used in some of the early sensitivity analyses whose results were transmitted informally to the EPA but are not summarized in this report. (Appendix I discusses the alternative air-quality models.)

ALTERNATIVE CONCENTRATION LEVELS AND MANDATE YEARS FOR THE OXIDANT STANDARD

In the 1970 Amendments to the Clean Air Act, a maximum concentration level of 0.08 ppm is specified as the national primary standard for oxidant; the mandate year by which this concentration level is to be obtained in each region has been set at 1975, unless a postponement to 1977 is granted, on a regional basis, by the EPA Administrator. But there is some controversy as to whether the 0.08 ppm maximum concentration level is excessively stringent (e.g., the California standard is 0.10 ppm) and whether the 1975 mandate year is feasible for a region with an oxidant problem as severe as that in Los Angeles. A somewhat relaxed concentration level would be considerably easier to meet, and a somewhat postponed mandate year would lessen lead-time problems and allow the natural replacement of older, dirtier vehicles by newer, cleaner ones.
In our sensitivity analysis, we considered the following five values as alternative concentration levels for the oxidant standard:

- The national primary standard for oxidant, 0.08 ppm, is meant to protect, with a safety margin, persons with serious respiratory problems from adverse effects.
- The California standard for oxidant, 0.10 ppm, is meant to prevent serious eye irritation and possible impairment of lung function in persons with chronic pulmonary disease and also to prevent damage to vegetation.
- The Stage-1 or health-advisory-alert level of the Air Pollution Emergency Contingency Plan, adopted by the CARB, is 0.20 ppm. At this concentration level, persons with respiratory and coronary problems would be warned to take precautionary measures, and school students would be asked to curtail strenuous activity.
- Concentration levels of 0.15 and 0.25 ppm were also used to fill out the range considered.

Although both 1975 and 1977 were considered as alternative mandate years for the oxidant standard, only the 1977 results are presented in this report. It was generally found extraordinarily difficult, even under favorable assumptions, to meet the oxidant standard by 1975.

**ORGANIZATION OF THIS REPORT**

Sections 2 through 4 identify promising pure strategies: controls for fixed sources (including aircraft) in Sec. 2, retrofit-I/M in Sec. 3, and transportation-management strategies in Sec. 4. Section 5 identifies superior (i.e., cost-effective) combinations of these pure strategies and evaluates them in terms of various cost, transportation-service, employment, and other impacts on the basin. The evaluations include different combinations of the alternative technical assumptions, air-quality models, and oxidant-standard concentration levels mentioned above, thereby showing how the composition and impacts of superior strategies vary with these assumptions. Section 6 presents a critical evaluation of the technical assumptions. And, finally, Sec. 7 describes the overall study methodology.

Various appendices support the main text: Appendix A describes the candidate retrofit devices; Appendix B discusses why a number of hitherto highly regarded transportation-management strategies seem less promising than those we recommend; Appendix C presents supporting data on fixed-source strategies; Appendix D summarizes strategies for HDVs and motorcycles; Appendix E presents an inventory of motor vehicles and mileage, by type of vehicle, for the Los Angeles basin; Appendix F summarizes the composition of promising retrofit strategies for 1977; Appendix G relates the land area covered by bus to the population eligible to use it; Appendix H details the technical assumptions concerning vehicle emission factors and hydrocarbon reactivities; Appendix I provides a summary description of the various analytical models; Appendix J presents emission inventories for the basin; and, finally, Appendix K summarizes population forecasts for the basin.
Reference for Section 1

2. PROMISING STRATEGIES FOR FIXED SOURCES, INCLUDING AIRCRAFT

1970 EMISSIONS FROM FIXED SOURCES

Our starting point for developing the inventories for all fixed sources, including aircraft, was the State Implementation Plan[1] of the CARB. Verification of the 1970 base inventory reported in that plan consisted of comparisons with inventories for the portions of individual counties in the Los Angeles basin published in the same report and with the more detailed inventory published by the Los Angeles Air Pollution Control District (APCD) [2], and application of the test of reasonableness.1 However, in developing the 1970 base inventory for this study, shown in Table 2.1, the emissions of reactive hydrocarbons were adjusted to reflect new EPA reactivity-fraction estimates;2 these reactivity fractions are generally much higher than those used by the CARB in preparing the inventories in the Implementation Plan and thus yield a much larger inventory for reactive hydrocarbons for the same inventory of total hydrocarbons. The EPA did not specify new reactivity fractions for petroleum production or refining, aircraft, agriculture, and other minor sources, so we left these at the CARB levels in the inventories; for consistency, however, these reactivity fractions—and the resulting inventory levels—should be reevaluated. (The effects on the inventories of different reactivity fractions are illustrated later in Sec. 6 and Appendix H.)

THE 1975 NOMINAL STRATEGY

The 1975 nominal strategy embodies the expected conditions for fixed sources in the Los Angeles region in 1975. It also shows the effects of controls expected to be implemented by 1975 under existing or planned regulations, and it reflects estimates of population and industrial growth and technological changes. (This nominal strategy closely approximates the EPA Region IX strategy of January 1973. Subsequent EPA strategies have introduced most of the additional controls for reactive hydrocarbons we recommend later in this section.)

Table 2.2 summarizes the effects of the 1975 nominal strategy for fixed-source emissions on pollutant levels. (A detailed breakdown of the emissions by source is given at the beginning of Appendix C.) The slight increase over the 1970 levels shown for NOx and carbon monoxide results from the effect of controls being slightly overshadowed by growth.

The starting point for developing the 1975 nominal-strategy estimates was again the CARB plan [1]. The CARB plan estimates the changes due to growth for each

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1 We should mention that the original data supplied by the individual Air Pollution Control Districts has been examined and processed by a number of analysts in different organizations without their noting gross omissions of sources. These independent checks include the original CARB compilation [1]; examination (primarily for the Los Angeles APCD, which includes most of the emissions in the basin) by an investigator at the California Institute of Technology [3]; review by EPA Region IX [4]; and evaluation by the investigators in the present study who had recent experience in constructing such inventories [5]. This is not to say that employment of different sampling methods or definitions of pollutants (e.g., reactive hydrocarbons) would not yield different values, however, as discussed in Sec. 6 and Appendix H.

2 Personal communication with Mr. P. Downing, EPA, April 18, 1973.
Table 2.1

ESTIMATED DAILY EMISSIONS FROM FIXED SOURCES: 1970 BASE INVENTORY
(tons/day)\(^a\)

<table>
<thead>
<tr>
<th>Emission Source</th>
<th>Hydrocarbons</th>
<th>Oxides of Nitrogen</th>
<th>Sulfur Dioxide</th>
<th>Carbon Monoxide</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
<td>Reactive</td>
<td>Particulates</td>
<td>Total</td>
</tr>
<tr>
<td>Petroleum</td>
<td>114.0</td>
<td>---</td>
<td>0.4</td>
<td>27.9</td>
</tr>
<tr>
<td>Production</td>
<td>45.0</td>
<td>5.0</td>
<td>5.0</td>
<td>22.0</td>
</tr>
<tr>
<td>Refining</td>
<td>148.0</td>
<td>138.0</td>
<td>---</td>
<td>11.0</td>
</tr>
<tr>
<td>Total</td>
<td>307.0</td>
<td>143.0</td>
<td>5.4</td>
<td>60.9</td>
</tr>
<tr>
<td>Organic-solvent users</td>
<td>250.0</td>
<td>200.0</td>
<td>15.0</td>
<td>---</td>
</tr>
<tr>
<td>Surface coating</td>
<td>32.2</td>
<td>25.7</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Dry cleaning</td>
<td>105.0</td>
<td>84.0</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Degreasing</td>
<td>173.0</td>
<td>138.4</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Total</td>
<td>560.2</td>
<td>448.1</td>
<td>21.0</td>
<td>---</td>
</tr>
<tr>
<td>Chemical</td>
<td>---</td>
<td>---</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>Metallurgical</td>
<td>---</td>
<td>---</td>
<td>21.3</td>
<td>3.0</td>
</tr>
<tr>
<td>Mineral</td>
<td>1.0</td>
<td>---</td>
<td>26.5</td>
<td>5.5</td>
</tr>
<tr>
<td>Incineration</td>
<td>22.4</td>
<td>1.9</td>
<td>16.8</td>
<td>6.2</td>
</tr>
<tr>
<td>Combustion of fuels</td>
<td>7.0</td>
<td>0.2</td>
<td>7.8</td>
<td>135.0</td>
</tr>
<tr>
<td>Steam power plants</td>
<td>6.8</td>
<td>0.1</td>
<td>9.8</td>
<td>88.8</td>
</tr>
<tr>
<td>Other industrial</td>
<td>0.4</td>
<td>0.2</td>
<td>9.8</td>
<td>60.1</td>
</tr>
<tr>
<td>Domestic &amp; commercial</td>
<td>14.2</td>
<td>6.3</td>
<td>27.4</td>
<td>284.0</td>
</tr>
<tr>
<td>Total</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Lumber</td>
<td>22.4</td>
<td>9.8</td>
<td>9.3</td>
<td>0.5</td>
</tr>
<tr>
<td>Agriculture</td>
<td>85.9</td>
<td>33.0</td>
<td>24.0</td>
<td>20.4</td>
</tr>
<tr>
<td>Aircraft</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Total</td>
<td>1,012.9</td>
<td>636.3</td>
<td>152.2</td>
<td>380.7</td>
</tr>
</tbody>
</table>

SOURCE: CARB State Implementation Plan [1], adjusted per EPA recommendations (personal communication with P. Downing, EPA, April 18, 1973).

\(^a\)The various totals shown may differ slightly from the sum of their components as shown, due to rounding.

Table 2.2

POLLUTANT LEVELS UNDER 1975 NOMINAL STRATEGY

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>1975 Value (percent of 1970 level)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total HC</td>
<td>54</td>
</tr>
<tr>
<td>Reactive HC</td>
<td>38</td>
</tr>
<tr>
<td>Particulates</td>
<td>87</td>
</tr>
<tr>
<td>NO(_2)</td>
<td>100</td>
</tr>
<tr>
<td>SO(_2)</td>
<td>62</td>
</tr>
<tr>
<td>CO(^*)</td>
<td>102</td>
</tr>
</tbody>
</table>
pollutant but does not distribute them by emission source. It also estimates reductions for each pollutant, by major categories of emission sources, but does not consider certain controls planned by the EPA. Accordingly, the CARB estimates were used for all pollutants except reactive hydrocarbons, and all sources except aircraft. The reactive hydrocarbon estimates were derived from EPA calculations to reflect EPA extensions to the CARB control tactics. The aircraft data were extrapolated from the results of a similar investigation for the San Diego Air Basin; this extrapolation was appropriate because the ratios of aircraft-emission reactive hydrocarbon to total hydrocarbons for the two basins are similar, and similar growth trends are expected.

We shall now discuss the effects of the 1975 nominal strategy on each pollutant; the numbers cited have been selected from the first table in Appendix C, which presents a detailed inventory of the emissions from all categories of fixed sources under the nominal strategy.

**Reactive Hydrocarbon**

Measures scheduled (or expected) to be implemented by 1975 should reduce the reactive hydrocarbon emissions from the petroleum (production, marketing, refining), organic-solvent users, and aircraft categories, resulting in a 62-percent reduction from the 1970 reactive hydrocarbon level for fixed sources. It is estimated that controls on the emissions from gasoline service-station tanks and from automobile tank-filling operations, which will require new regulations, could reduce reactive hydrocarbons from petroleum marketing activities by up to 85 percent. Emissions from the service-station tanks could be reduced by using concentric fill-hoses when loading from tank trucks and by using submerged-fill procedures; emissions from automobile tank-filling operations could be reduced by using a vapor recovery system (with special nozzles) in conjunction with a piping system for recycling the displaced vapors. (See Refs. 5 and 6 for further discussion of methods and their effectiveness.)

Dry cleaners and degreasers, which are now covered by Rule 66 in Los Angeles and comparable rules in the other counties, would, by EPA proposals for 1975, be virtually cleaned up, the former by introduction of activated-carbon adsorption devices and the latter by substitution of nonreactive 1,1,1-trichloroethylene. Implicit in the EPA proposals is a tightening of the rules governing use and disposal of organic solvents to include small operators. The EPA also suggests that emissions from surface coating and miscellaneous-solvent users (these categories include food-processing, printing, and pharmaceuticals activities, for example) could be cut in half by tightening Rule 66 and its equivalents. Control methods available for coatings unaffected by heat include further substitution of nonreactive solvents and substitution of water-based coatings. For coatings affected by heat, alternatives include substitution of water-based coatings, use of powdered coatings, and use of high-solids coatings. Independent estimates, which are discussed more fully below in the section on additional reactive hydrocarbon controls, confirm the feasibility of reducing surface-coating emissions.

The reactive hydrocarbon emissions from aircraft are expected to be cut by

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* See discussion in Appendix C, under “Some Practical Aspects of Adsorption Systems for Air Pollution Control.”
* Personal communication from Mr. J. Hayes, former Air Pollution Coordinator, American Can Company, March 8, 1973, and Dr. E. E. McSweeney, Technical Director, Union Camp Corporation, March 12 and 19, 1973.
modification of the JT-8D engines used in medium-range aircraft such as the Boeing 727, according to an agreement between the air carriers and the EPA.

Particulates

Particulate matter is expected to drop to 87 percent of the 1970 level. Several emission categories will be affected [1]. Emissions from petroleum operations are expected to be reduced by about 1 ton per day as a result of more stringent visible-emission regulations. Reductions of 6 tons per day should occur in surface-coating activities, principally spray-booth-type operations, because of stricter grain-loading and visible-emission regulations. These regulations plus more stringent restrictions on process weights should effect daily reductions of 6 tons and 7 tons, respectively, in the metallurgical and minerals industries. Finally, additional restrictions on incinerators and bans on open burning of solid waste and backyard burning are expected to reduce particulates from the incineration category by 6 tons per day.

Oxides of Nitrogen

The 1975 nominal NO\textsubscript{x} level is expected to be essentially unchanged from the 1970 level because reductions from controls in some categories will be offset by increases due to growth in others. In the petroleum industry, reductions should occur because of the replacement of internal combustion engines by electric motors for oil-well-pump engines; this replacement is expected to be two-thirds completed by 1975 [3]. The restrictions on incineration noted above should reduce NO\textsubscript{x} emissions to about 60 percent of the 1970 level. In the combustion-of-fuels category, all of the larger fossil-fuel electric generating plants are expected to be modified by 1975 to meet NO\textsubscript{x} emission standards like those in Los Angeles APCD Rule 68.\footnote{It is projected that the ratio of oil to gas for all power plants by 1975 will be substantially higher than in 1970. This will result in higher NO\textsubscript{x} emissions because the Rule 68 allowances are more generous for oil than for gas [2].} There are no plans to modify either the smaller power-plant boilers or the other industrial boilers and heaters to reduce present NO\textsubscript{x} emissions.

Sulfur Dioxide

A 40-percent reduction in the SO\textsubscript{2} level is anticipated by 1975 [1]. Most of the decrease will result from adoption of rules directed at controlling chemical-plant emissions (sulfur recovery and sulfuric acid plants), which should remove nearly 100 tons per day. Regulations limiting SO\textsubscript{2} emissions should also result in a 10-ton daily reduction from petroleum refinery operations and a 6-ton daily reduction from power plants and other fuel-burning equipment.

Carbon Monoxide

Total emissions of carbon monoxide are expected to increase slightly. Significant reductions resulting from controls on incineration activities (discussed above) and from regulation of agricultural burning will be countered by increases in emissions from aircraft which will be caused by changes in aircraft mix and operation levels.

Since reactive hydrocarbons and NO\textsubscript{x} loom as the most critical pollutants in the Los Angeles region\footnote{Of course, sulfur dioxide could become a serious problem if low-sulfur oil ceases to be available in adequate quantities.} and their rollback might cause serious transportation disrup-
tions and imply high monetary and social costs for control, we investigated the possibility of applying additional controls to further reduce fixed-source emissions of these agents. The potentially promising additional controls for reactive hydrocarbons are essentially independent of those for NOx, so it has been practical to investigate them independently, and they are described separately below. Then we shall consider their costs and effects when combined into a maximal control strategy.

ADDITIONAL REACTIVE HYDROCARBON CONTROLS FOR 1975

Only two source categories seemed promising areas for additional controls in 1975: organic-solvent users and aircraft. Controls applied to the other categories under the nominal strategy would reduce their emissions to very low levels or would push existing technical limits.

Organic-Solvent Users

Potential controls for surface coating and miscellaneous-solvent users were specified above under the 1975 nominal strategy. The EPA estimates that these controls could reduce reactive hydrocarbon emissions by 50 percent. However, based on conversations with persons in the industry (both solvent producers and solvent users), we estimate that the nominal emission level for reactive hydrocarbons, under optimistic conditions, could be halved again.7 The substitution of nonreactive solvents has been stretched about as far as possible, according to industry sources, but the technologies of the other controls (e.g., coating substitution and vapor adsorption) are largely well understood, and the products could probably be made available by 1975, with the proper motivation. The major hindrance to effecting such reductions (or even those cited under the nominal strategy) appears to be the shortage of and long delivery times for the equipment required to implement the new coatings in production-line operations.

Relatively little data is available for estimating the cost of achieving this greatly reduced emission level. By adjusting data from Ref. 3 to reflect differences in reactivity fractions, however, we made a rough estimate that the annualized cost for such reductions in Los Angeles County would be $82 a year for each ton of reactive hydrocarbon removed.8

Our judgments on the possibilities for substituting coatings and other products having nonreactive characteristics are based on the following explicit examples obtained from the literature and from conversations with knowledgeable individuals.

The American Can Company has been using water-based enamels for the outside

---

7 Personal communication with Mr. J. Hayes, formerly Air Pollution Coordinator, American Can Company, March 8, 1973; Dr. E. E. McSweeten, Technical Director, Union Camp Corporation, March 12 and 19, 1973; Mr. W. Shoum, Dow Chemical Company, March 8, 1973; and Mr. W. Hart, J. B. Mitchell Company, March 8, 1973.

8 To establish the annualized cost of these (and other) additional controls, we estimated the incremental investment, which covers purchase and installation of controls, and the annual operating and maintenance expenses. For nongovernment activities, these investment costs were annualized with a gross discount rate of 15 percent (which is equivalent to approximately 7.5 percent after allowing for taxes on corporate profits). For government activities not subject to taxes, a discount rate of 7.5 percent was used. These rates appear to be appropriate for the types of processes involved and present circumstances. Estimates of useful lives for the type of equipment used in the various control tactics were employed in the annualizing computations.
of cans in production for two years with little difficulty. Similar inner coatings for cans have not yet been developed; these are quite special and require approval by the Food and Drug Administration. In the meantime, of course, reactive emissions from such special coating operations can be largely controlled by adsorption or by incineration.

The General Motors assembly plant in South Gate, California, is now operating completely with nonpolluting coatings, most of them water-based, and their Van Nuys, California, plant will soon be in production with similar coatings. These include both primer and finish coats for car bodies. Results so far have been highly satisfactory. Five additional cases of the production use of such coatings are described in Ref. 7. These include manufacture of trailers, automotive parts, welded assemblies, and metal furniture. The coatings are available in a wide range of glosses and pigmentation, and they are being adapted for the entire range of application techniques [8].

The dry-powder-type paints present some difficulties in changing colors frequently and in keeping separate and reusing the surplus powder, and they require new application equipment. The resulting coatings, however, are eminently satisfactory. Advantages of these new coatings over the older types include elimination of fire hazards, as well as air pollution, and greatly simplified maintenance. Industrial health problems are also reduced. It is estimated by the Los Angeles APCD that the larger manufacturers can adjust to these new coating techniques and that they alone contribute at least 75 percent of the emissions from surface coating. Small operators may experience some difficulties because of lack of technical know-how and because of the financial costs for new equipment. There are some special applications, such as high-gloss lacquers for fine furniture, for which alternative coatings having exactly similar characteristics may not yet exist. Until such substitutes are available, coatings having somewhat different characteristics might be used, or close control could be applied to the use of conventional lacquers.

Printing inks loom large in the category of “other” solvent users, and at least one water-based printing ink is developed and ready for production testing. Rubber manufacturers (tires) are also experimenting successfully with the use of nonpolluting solvents in the Los Angeles basin, and where these are not feasible (as in certain spraying operations), additional controls such as incineration are being installed. This latter tactic is frequently feasible for cases where nonpolluting coatings cannot readily be adopted. Other applications of these new coatings are described in Refs. 9 through 14.

We sought information on coatings for Los Angeles County by type of application, to use in preparing a detailed list of substitutes and the amounts of reactive hydrocarbon they would remove. Such data, however, were unavailable. A 1963 survey of organic-solvents users (before Rule 66 was in effect) provided, by general industry group, only the amounts consumed in terms of the chemical constituents of solvents. Data from a recently completed APCD survey of nearly 8000 users and suppliers are not yet available for analysis, and current plans, unfortunately, do not provide for the data to be processed in a form that would allow analysis by class of solvent or application [6].

9 Personal communication with Mr. J. Hayes, March 8, 1973.
10 Personal communication with Mr. N. Shaffer, Los Angeles APCD, April 1973.
11 Personal communication with Mr. C. Finnegan, Ameritone Paint Company, April 19, 1973.
12 Personal communication with Dr. E. E. McSweeney, Union Camp Corporation, March 12 and 19, 1973.
Aircraft

We have identified two tactics as further alternatives for reducing the emissions from aircraft: (1) piston-engine modification in combination with jet-aircraft towing, and (2) piston-engine modification in combination with jet-engine modification.

In the first tactic, which we shall hereafter term the “piston modification,” catalytic afterburners would be installed on piston-engine aircraft and low-lead gasoline would be used. The annual cost of this modification would be about $500 per general aviation aircraft [5]. If tractor towing of jet aircraft during ground movements was also implemented at the major civil and military airports, significant reductions could be achieved for carbon monoxide and particulates in addition to reactive hydrocarbons. The expected reductions and the basis of extrapolation from the San Diego Air Basin data are given in Table 2.3. We justify this extrapolation by the similarity of the 1970 aircraft-emission reactive hydrocarbon/total hydrocarbon ratios and expected growth trends for the two basins: The 1970 reactive hydrocarbon/total hydrocarbon ratio for San Diego was 0.349; for Los Angeles, it was 0.384. These ratios imply similar mixes of jet and piston aircraft (because each type has a distinctive reactive hydrocarbon/total hydrocarbon ratio) and similar types of operations in the two areas.¹³ Thus, the proportional reduction in each pollutant realized by introducing a control tactic in San Diego—as shown by the improvement ratios in Table 2.3—can be applied directly to the Los Angeles case. The first tactic (piston modification and jet towing), which would reduce the aircraft reactive hydrocarbon emissions to 30 percent of the nominal level for 1975, is estimated to cost $1551 for each ton removed, or an annualized total cost of $11.6 million beginning in 1975.

If the minor combustor redesign of the JT-8D engine called for in the nominal strategy were extended to all jet engines (air carrier and military) except business jets, which are low emitters for their class, and combined with the piston-engine modification, the decrease in emissions would be as shown in Table 2.3. The annualized total cost for these aircraft controls is estimated to be $22.7 million in 1975, based on $2820 per ton of reactive hydrocarbons [5].

The safety implications of the jet-towing operation require investigation, as does the designing and installation of exhaust devices for aircraft piston engines. Moreover, installation of such devices may exceed the services available if it is to be accomplished by 1975.

The administrative advantage of the first tactic is that it appears to be within the purview of the local APCDs. In view of the critical need to reduce reactive hydrocarbons, however, the second tactic, which would achieve greater reductions in emissions, might receive the necessary Federal action for implementation.

Other Reactive Hydrocarbon Reductions

A source of significant reactive hydrocarbon emissions which bears further examination is agriculture. In 1970, about 9 tons of reactive hydrocarbon were being emitted per day in the Ventura County portion of the Los Angeles basin by agricul-

¹³ This Los Angeles basin ratio is based upon the CARB-based inventory, Table 2.1, which apparently assumes somewhat different jet- and piston-engine reactivity definitions (which vary among component counties) than the San Diego inventory. The question of different reactivity definitions will be treated later. If we reestimate the Los Angeles basin ratio using San Diego reactivities, it is 0.428, and Los Angeles County is 0.386. This ratio is still quite similar to the San Diego ratio alone, given the approximations of the inventories, and we feel the extrapolation from San Diego is justified. The higher ratio for the entire Los Angeles basin reflects the greater fraction of general-aviation piston-engine operations that exists there than in Los Angeles County.
### Table 2.3
EXTRAPOLATION OF AIRCRAFT EMISSIONS: SAN DIEGO AIR BASIN TO LOS ANGELES AIR BASIN

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>San Diego Air Basin (tons per year)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total HC</td>
<td>5,329</td>
<td>4,297</td>
<td>0.806</td>
<td>1,061</td>
<td>0.247</td>
<td>847</td>
<td>0.197</td>
</tr>
<tr>
<td>Reactive HC</td>
<td>1,862</td>
<td>1,584</td>
<td>0.851</td>
<td>433</td>
<td>0.273</td>
<td>342</td>
<td>0.216</td>
</tr>
<tr>
<td>NOₓ</td>
<td>1,314</td>
<td>1,522</td>
<td>1.158</td>
<td>1,522</td>
<td>1.000</td>
<td>1,522</td>
<td>1.000</td>
</tr>
<tr>
<td>CO</td>
<td>12,702</td>
<td>15,476</td>
<td>1.218</td>
<td>3,045</td>
<td>0.197</td>
<td>3,010</td>
<td>0.194</td>
</tr>
<tr>
<td>SO₂</td>
<td>511</td>
<td>602</td>
<td>1.178</td>
<td>602</td>
<td>1.000</td>
<td>602</td>
<td>1.000</td>
</tr>
<tr>
<td>Particulates</td>
<td>2,409</td>
<td>2,672</td>
<td>1.109</td>
<td>848</td>
<td>0.317</td>
<td>287</td>
<td>0.107</td>
</tr>
<tr>
<td>Los Angeles Basin (tons per day)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total HC</td>
<td>85.9</td>
<td>69.2</td>
<td>---</td>
<td>17.1</td>
<td>---</td>
<td>13.6</td>
<td>---</td>
</tr>
<tr>
<td>Reactive HC</td>
<td>33.0</td>
<td>28.1</td>
<td>---</td>
<td>7.7</td>
<td>---</td>
<td>6.1</td>
<td>---</td>
</tr>
<tr>
<td>NOₓ</td>
<td>20.4</td>
<td>23.6</td>
<td>---</td>
<td>23.6</td>
<td>---</td>
<td>23.6</td>
<td>---</td>
</tr>
<tr>
<td>CO</td>
<td>199.0</td>
<td>242.0</td>
<td>---</td>
<td>47.7</td>
<td>---</td>
<td>47.0</td>
<td>---</td>
</tr>
<tr>
<td>SO₂</td>
<td>4.0</td>
<td>4.7</td>
<td>---</td>
<td>4.7</td>
<td>---</td>
<td>4.7</td>
<td>---</td>
</tr>
<tr>
<td>Particulates</td>
<td>24.0</td>
<td>26.6</td>
<td>---</td>
<td>8.4</td>
<td>---</td>
<td>2.8</td>
<td>---</td>
</tr>
</tbody>
</table>

*a* Piston-engine modification and jet towing at major airports.  
*b* Piston-engine and jet-engine modification.  
*c* Data from Ref. 5.  
*d* Data for 1970 from ARB State Implementation Plan [1].  
*e* The reactive hydrocarbon/total hydrocarbon ratios for emissions in San Diego and in the Los Angeles basin are similar for 1970, implying similar mix and type of operations, and expected growth trends are similar. Accordingly, the 1975 values were extrapolated from the 1970 Los Angeles Air Resources Board values by applying the San Diego ratios of 1975 nominal to 1970. The proportionate reductions expected from applications of Tactics 1 and 2 in San Diego were likewise applied to the Los Angeles basin.

Additional processing plants. We do not know what the processes are, but we speculate that they involve meat smoking or deep-fat frying, the emissions from which are highly reactive. Such activities are presently controlled in Los Angeles County.

### ADDITIONAL NOₓ CONTROLS FOR 1975

Reactive hydrocarbons are not the only pollution problem in the Los Angeles region. Oxides of nitrogen, which are formed (along with other nitrogen and oxygen compounds) when air is exposed to high temperatures, are not only injurious in themselves, in concentrations above certain levels, they also contribute to the formation of photochemical smog. Through control of different aspects of the combustion process in different types of combustors, the amount of total NOₓ can be held to relatively low levels. The control tactics include limiting the amount of excess air in the combustion process, recirculating flue or exhaust gases, introducing two-stage combustion processes, and substituting natural gas for oil.

Because NOₓ controls were not treated by the EPA in their study of Los Angeles [4] and were treated only lightly by Rand in their study of San Diego [5], where NOₓ
is not a major problem, a relatively full description of the problems and means of NO$_x$ controls is appropriate. That discussion is presented in the latter part of Appendix C, since it is too voluminous to be consistent with the level of detail in this section. The costs and effects of additional NO$_x$ controls are presented immediately below, however, as part of the description of how additional NO$_x$ and reactive hydrocarbon controls can be combined together into a maximal control strategy for fixed sources.

A 1975 MAXIMAL CONTROL STRATEGY

The candidate methods for reducing NO$_x$ emissions are essentially independent from those for reducing reactive hydrocarbon emissions. Thus a maximal strategy for fixed sources can be formed from the candidates without further evaluation. For only one source category—aircraft—did we identify more than one candidate. In constructing the maximal strategy, we selected the tactic of combining piston- and jet-engine modifications because it provided a greater reduction in reactive hydrocarbon emissions than did the other tactic. For all the other sources, we merely used the unique candidates previously identified.

Table 2.4 summarizes, by source category, the additional controls that we have combined with those in the nominal strategy to form the 1975 maximal strategy for fixed sources.

This maximal strategy is intended to represent the maximum practical reduction in the reactive hydrocarbon and NO$_x$ emissions from fixed sources, given the expected state of the art in the mid-1970s. (Although the measures were selected specifically to reduce these pollutants, some reduce other contaminants too.) Under the maximal strategy, reactive hydrocarbon emissions would be reduced to about 20 percent of their 1970 level, a 45-percent reduction from their 1975 nominal-strategy level; NO$_x$ emissions would be reduced to about 64 percent of their 1970 level, due solely to the maximal-strategy tactics, since the nominal strategy, in effect, merely counterbalances growth. There would also be some reduction in particulates and carbon monoxide, although the additional controls were not directed at these pollutants. (Table C-2, in Appendix C, presents a detailed inventory of emissions, by source category and species, under the 1975 maximal strategy.)

Table 2.5 shows the estimated financial costs$^{14}$ of the additional controls in the 1975 maximal strategy; these are incremental to the cost of the nominal strategy, which we did not estimate. For the Los Angeles region, the total bill would be $57 million annually. Of this amount, about $25 million, somewhat less than half, would be spent on hydrocarbon controls, mainly on aircraft, while about $32 million would be required for NO$_x$ controls, mainly on large boilers.

Figure 2.1 shows the relation between reactive hydrocarbon reduction (from the nominal 1975 level) and cost as the control tactics in the maximal strategy are successively introduced in order of increasing cost per ton. Figure 2.2 shows a similar relation for NO$_x$ reduction.

EXTRAPOLATING STRATEGY EFFECTS TO 1977

To estimate the level of pollutants and costs of reduction in 1977, corresponding

$^{14}$ Financial costs as distinct from the various social and other costs which the table does not treat.
Table 2.4  
ADDITIONAL CONTROLS IN THE 1975 MAXIMAL STRATEGY

<table>
<thead>
<tr>
<th>Source Category</th>
<th>Controls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Pollutant:</td>
<td>Reactive Hydrocarbons</td>
</tr>
<tr>
<td>Surface coating</td>
<td>Introduction of water-based and nonreactive coatings; control of reactive emissions through adsorption and incineration</td>
</tr>
<tr>
<td>Miscellaneous-solvent users</td>
<td>Substitution of nonreactive solvents; introduction of water-based solvents; adsorption and incineration</td>
</tr>
<tr>
<td>Aircraft</td>
<td>Piston-engine and jet-engine modifications</td>
</tr>
</tbody>
</table>

Primary Pollutant: NO_x

<table>
<thead>
<tr>
<th>Emission Source</th>
<th>Annual Cost ($)</th>
<th>Tons Removed Per Year</th>
<th>Total Annual Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface coating</td>
<td>82</td>
<td>19,272</td>
<td>1,590</td>
</tr>
<tr>
<td>Miscellaneous-solvent users</td>
<td>82</td>
<td>12,848</td>
<td>1,066</td>
</tr>
<tr>
<td>Aircraft (piston &amp; jet modifications)</td>
<td>2,820</td>
<td>8,030</td>
<td>22,664</td>
</tr>
<tr>
<td>Totals</td>
<td>631</td>
<td>40,150</td>
<td>25,320</td>
</tr>
</tbody>
</table>

---

In addition to those in the 1975 nominal strategy.

Table 2.5  
ESTIMATED FINANCIAL COSTS OF 1975 MAXIMAL STRATEGY

<table>
<thead>
<tr>
<th>Emission Source</th>
<th>Annual Cost ($)</th>
<th>Tons Removed Per Year</th>
<th>Total Annual Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactive Hydrocarbon Controls</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface coating</td>
<td>13</td>
<td>3,832</td>
<td>50</td>
</tr>
<tr>
<td>Petroleum refining (large compressors)</td>
<td>13</td>
<td>3,504</td>
<td>46</td>
</tr>
<tr>
<td>Petroleum marketing (small compressors)</td>
<td>37</td>
<td>3,504</td>
<td>130</td>
</tr>
<tr>
<td>Power Plants</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gas for oil</td>
<td>0</td>
<td>12,337</td>
<td>0</td>
</tr>
<tr>
<td>Small boilers</td>
<td>450</td>
<td>5,439</td>
<td>2,448</td>
</tr>
<tr>
<td>Other industrial combustion of fuel</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large boilers</td>
<td>195</td>
<td>7,264</td>
<td>1,416</td>
</tr>
<tr>
<td>Medium boilers</td>
<td>2,700</td>
<td>10,243</td>
<td>27,636</td>
</tr>
<tr>
<td>Large refinery heaters a</td>
<td>27</td>
<td>2,008</td>
<td>54</td>
</tr>
<tr>
<td>Small refinery heaters a</td>
<td>226</td>
<td>1,605</td>
<td>363</td>
</tr>
<tr>
<td>Totals</td>
<td>647</td>
<td>49,736</td>
<td>32,163</td>
</tr>
</tbody>
</table>

---

Placed in this category in the CARB 1970 inventory.
Fig. 2.1—Relations between reduction of reactive hydrocarbons and cost as control tactics are successively introduced.

Note: Piston-engine aircraft modification and jet towing is an alternative tactic to piston-engine and jet-engine modification.

Fig. 2.2—Relations between reduction of NO$_x$ and cost as control tactics are successively introduced.
values for 1975 can be inflated by 2.5 percent, the expected growth due to population increase and increases in real income, as estimated using data from Ref. 1.

References for Section 2

1. Implementation Plan for Air Pollution Control; South Coastal Basin, California Air Resources Board, 1971.
2. Profile of Air Pollution Control, Air Pollution Control District, County of Los Angeles, 1971.
6. Transportation Control Strategy Development for the Metropolitan Los Angeles Region, TRW, January 1973; see especially Appendix L, "Evaporative Losses from Service Station Fueling Operations."
3. PROMISING STRATEGIES FOR VEHICLE RETROFIT

RETROFIT STRATEGIES FOR LIGHT-DUTY MOTOR VEHICLES (LDMVs)

Technological controls for mobile sources involved emission-control retrofit devices and mandatory inspection/maintenance (I/M) programs for in-use vehicles. Only LDMVs, which produce 90 percent of all mobile-source emissions, are considered eligible for these controls. Heavy-duty trucks and diesel buses are not considered eligible because (1) no practical retrofit device has been demonstrated for these vehicles, and (2) they receive better maintenance than LDMVs, since virtually all are commercial vehicles. Motorcycles are also considered ineligible for retrofit; however, because their reactive hydrocarbon emission rates are very high (particularly for two-cycle engines), we recommend formulation and enforcement of appropriate emission standards.¹

In this section, we discuss potential LDMV emission-control tactics and describe the screening process leading to 28 promising retrofit-I/M strategies (hereafter referred to simply as retrofit strategies). See Ref. 1 for details on the various tactics, costs, and effectiveness.

CANDIDATE RETROFIT DEVICES

In recent years, many retrofit emission-control devices for LDMVs have been proposed. Some possible devices and the model years for which each may be applicable are listed below:

- Crankcase-blowby control (1960-55)
- Evaporative-loss control² (1969-55)
- Vacuum-spark-advance disconnect (VSAD) (1970-55)
- NOₓ control kit (e.g., exhaust-gas recirculation) (1970-55)
- Pre-1966 retrofit kit (1965-55)
- Catalytic exhaust-gas converter³ (1974-55)

Here we exclude 1975 and later models from retrofit on the assumption that they will meet the stringent Federal emission standards for hydrocarbons and carbon monoxide and the California standards for NOₓ with original equipment. We ex-

¹ Appendix D discusses the emissions from the strategies for heavy-duty vehicles and motorcycles (as well as ships and railroads). A nominal strategy for these other types of vehicles is defined that reflects the new-vehicle emission standards for heavy-duty vehicles and diesel-powered buses. A maximal strategy is also defined for them; it replaces all two-cycle-engine motorcycles (which have high reactive hydrocarbon emission rates) with four-cycle-engine motorcycles. These strategies are always applied in conjunction with the corresponding nominal and maximal strategies for fixed sources.

² Although the EPA employed evaporative control in early 1973 strategies for San Diego and Los Angeles, they have since questioned its practicality. However, a very recent study at the California Institute of Technology Environmental Quality Laboratory concluded that evaporative control is entirely practical and cost-effective [2].

³ The controversy about the range of applicable years for the catalytic converter, as well as its effectiveness, is discussed in Sec. 6. In accord with statements by the manufacturer, we assume that virtually all pre-1971 vehicles can use the unleaded fuel required by the converter, most by modification to operate on low-octane unleaded fuel, the rest by the use of high-octane fuel that raises the octane rating with compounds other than lead.
clude pre-1955 vehicles because they will account for less than 0.1 percent of vehicle miles traveled in 1975.

Appendix A briefly describes the purpose, operation, and problems of these devices. Two additional tactics, the thermal afterburner and gaseous-fuel conversion, were also considered but were rejected for the reasons discussed there.

CANDIDATE INSPECTION/MAINTENANCE TACTICS

Many different I/M programs have been proposed. In our analysis, we consider two alternative programs as candidate tactics.

State I/M Program

This tactic corresponds to Option II of the program recommended by the governor's task force [3]. It includes (1) mandatory annual inspection (at idle) of all vehicles (resulting in 25 percent being repaired according to a prescribed maintenance schedule), (2) random roadside inspection (at idle) testing 20 percent of all vehicles annually (again with a 25-percent rejection rate), and (3) regulated tune-up procedures for vehicles normally receiving commercial maintenance. This tactic represents a medium-effort I/M program yielding moderate emission reductions.

Mandatory Maintenance to Minimum Pollution Capability (MPC)

This tactic requires an annual tune-up (with replacement of essential parts), which reduces emissions to the engine's MPC. We feel that this tactic represents the maximum emission reduction that could be attained with a maintenance program but at a substantial cost. Thus, the MPC maintenance program is more effective but significantly less cost-effective than the state I/M program. To insure more complete compliance, the MPC program also includes a random roadside inspection, equivalent to that in the state I/M program.

DEVISING CANDIDATE LDMV RETROFIT STRATEGIES

Retrofit control strategies for LDMVs are composed of various combinations of the tactics described above. The effects of the crankcase-blowby and evaporative-loss control tactics are each assumed independent of other retrofit devices. The exhaust devices are not necessarily independent, however. When several exhaust devices operate together, their joint effectiveness must be considered. Since essentially all vehicles have crankcase blowby after 1970, we form promising retrofit strategies by first screening exhaust strategies, then screening evaporative-loss strategies, and finally forming superior combinations of the survivors.

Exhaust Strategies

Our analysis of exhaust-control tactics revealed a definite hierarchy of practicality and cost-effectiveness. This hierarchy and the assumption that each tactic is applied to all eligible vehicles form the foundation for the set of basic exhaust-control strategies presented in Table 3.1.

Henceforth, we will assume that exhaust-control tactics are always applied to
Table 3.1

EXHAUST-CONTROL STRATEGY

<table>
<thead>
<tr>
<th>Exhaust Strategy</th>
<th>Tactics</th>
<th>Eligible Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>NOx control kit</td>
<td>1970-66</td>
</tr>
<tr>
<td></td>
<td>VSAD disconnect</td>
<td>1965-55</td>
</tr>
<tr>
<td>II</td>
<td>NOx control kit</td>
<td>1970-66</td>
</tr>
<tr>
<td></td>
<td>Pre-1966 retrofit kit</td>
<td>1965-55</td>
</tr>
<tr>
<td>III</td>
<td>State I/M program</td>
<td>All</td>
</tr>
<tr>
<td></td>
<td>NOx control kit</td>
<td>1970-66</td>
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<tr>
<td></td>
<td>Pre-1966 retrofit kit</td>
<td>1965-55</td>
</tr>
<tr>
<td>IV</td>
<td>State I/M program</td>
<td>All</td>
</tr>
<tr>
<td></td>
<td>Catalytic exhaust-gas converter</td>
<td>1974-55</td>
</tr>
<tr>
<td></td>
<td>NOx control kit</td>
<td>1970-66</td>
</tr>
<tr>
<td></td>
<td>Pre-1966 retrofit kit</td>
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<tr>
<td>V</td>
<td>Mandatory maintenance to MPC</td>
<td>All</td>
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<tr>
<td></td>
<td>Catalytic exhaust-gas converter</td>
<td>1974-55</td>
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<td>NOx control kit</td>
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<tr>
<td></td>
<td>Pre-1966 retrofit kit</td>
<td>1965-55</td>
</tr>
</tbody>
</table>

a particular model year in one of the combinations in Table 3.1, thereby allowing us to easily specify and apply a joint effectiveness.

Each of the above strategies need not, however, be applied to all the eligible model years. Strategy IV, as an example, might be modified by applying the catalytic-converter retrofit to 1974-71 vehicles only. The possibility of applying these strategies to different mixes of model years greatly enlarges the number of possible strategies. To identify the most cost-effective exhaust-control strategies, we calculated the costs and emission reductions of different basic exhaust strategies applied to different mixes of model years. (These calculations were greatly facilitated by the Motor Vehicle Emission and Cost (MOVEC) model, initially developed for this purpose but applied extensively to other phases of the project, as described in Sec. 7.) We eliminated the combinations that were more expensive without being more effective than another alternative and retained the more cost-effective mixes of controls and applicable years as the exhaust-control strategies.

Evaporative-Loss Control Strategies

Evaporative-loss control devices can also be applied to different mixes of model years, yielding many possible evaporative-loss control strategies. We formed candidate strategies by applying the tactic first to the most cost-effective year (e.g., 1969), then to the two most cost-effective years (e.g., 1969 and 1968), and so forth. The tactic becomes less cost-effective as it is applied to increasingly older vehicles, for two reasons: First, since older vehicles have shorter remaining lives, the investment costs are annualized over a shorter period, making control appear more expensive for them than for newer vehicles. Second, since older vehicles are driven fewer miles per year, the yearly emission reduction is smaller, making evaporative control appear less effective than it is for newer vehicles.
The evaporative-loss control strategies obtained in this way are thereby ranked in order of cost-effectiveness.

THE 28 PROMISING RETROFIT STRATEGIES

Many different combinations can be created from the exhaust-control and evaporative-loss control strategies discussed above, for these classes are independent. The question is, What are the most cost-effective combinations? The following rule guided us in devising the most cost-effective overall retrofit strategies. Each exhaust-control strategy was combined only with an evaporative-loss control strategy having the same or better cost-effectiveness for reactive hydrocarbon emissions. The resulting 28 promising retrofit strategies are labeled A through Z, 0, and 1. (In general, the level of control increases from A to 1.) Several strategies are noteworthy:

- Strategy A corresponds to no LDMV retrofit (i.e., uncontrolled emissions).
- Strategy D corresponds to the current control program mandated by the CARB.
- Strategy Z corresponds to maximum retrofit combined with the state I/M program.
- Strategy 1 corresponds to maximum retrofit combined with maximum I/M (i.e., maintenance to MPC).

(The detailed composition of these 28 retrofit strategies is shown in Appendix F, along with the applicable model years for each tactic for a 1977 implementation.)

SENSITIVITY OF LDMV EMISSIONS TO RETROFIT-I/M STRATEGY AND TECHNICAL ASSUMPTIONS

Figures 3.1 and 3.2 depict the reactive hydrocarbon emissions from LDMVs under each of the 28 promising retrofit strategies versus the annualized strategy cost. Figure 3.1 is based on the reference technical assumptions, however, whereas Fig. 3.2 is based on the pessimistic assumptions. (The emissions are for 1977 and assume no reductions in vehicle miles traveled (VMT).)

Figure 3.1 indicates that LDMVs produce about 490 tons per day of reactive hydrocarbon emissions under Strategy A (no retrofit) at a zero annualized cost; about 430 tons per day under Strategy D (the CARB-mandated retrofit strategy) at a $60 million annualized cost; and about 130 tons per day under Strategy 1 (the maximum-retrofit strategy) at a $640 million annualized cost.

4 Crankcase-blowby control is assumed present, since by 1970 essentially all vehicles will have it either as retrofit or original equipment.

5 Discarding a few with relatively low cost-effectiveness, and inserting a few composite strategies where there was a major gap.

6 The annualized cost of retrofit is made up of two components: an investment cost for the procurement and installation of the devices and an operating cost for the increase in fuel consumption and maintenance. The investment cost is annualized by means of a capital-recovery factor at a 7.5-percent discount rate. The operating-cost component included here assumes no reduction in vehicle miles traveled from the uncontrolled levels. Note that once the investment has been made, any reduction in vehicle miles will produce a corresponding decrease in the operating cost—and in total annualized cost as well.
Fig. 3.1—Reactive hydrocarbon emissions from LDMVs under the reference technical assumptions versus annualized cost of retrofit-1/M strategy

Fig. 3.2—Reactive hydrocarbon emissions from LDMVs under the pessimistic technical assumptions versus annualized cost of retrofit-1/M strategy

Figure 3.2, using the pessimistic assumptions, shows that about 450 tons per day of reactive hydrocarbon emissions would be produced by LDMVs under Strategy A at zero annualized cost; about 425 tons per day under Strategy D at a $60 million annualized cost; and about 180 tons per day under Strategy 1 at a $610 million annualized cost.

Comparing these two figures, we note that the emissions are higher under the reference assumptions for Strategy A but lower under Strategy 1. This difference occurs because the cleaner emission factors of the pessimistic assumptions dominate the emission level at low levels of control, but the greater effectiveness of the catalytic converter in the reference assumptions becomes dominant at high levels of control. (Incidentally, the higher annualized cost of Strategy 1 under the reference assumptions reflects the costs of more frequent replacement of the catalytic element to help insure durability and maintain effectiveness, as discussed in Sec. 6.)

The air-quality implications of the emission differences shown in Figs. 3.1 and 3.2 will be discussed in Sec. 5. The reader is cautioned against making casual attempts to relate the relative differences in emission levels shown in the two figures to relative differences in air quality. The same amount of total emissions in some future year will generally imply different air quality under different technical assumptions. This is a consequence of the rollback paradox discussed in Sec. 6.
SENSITIVITY TO YEAR, AUTO-EMISSION STANDARDS, AND AIR-QUALITY MODEL

Figure 3.3 shows the sensitivity of total regional reactive hydrocarbon emissions to changes in calendar year and in auto-emission standards for two important strategies. What we term the EPA IX strategy approximates the strategy proposed for the Los Angeles basin by EPA Region IX in January 1973; it essentially consists of nominal fixed-source control plus a retrofit strategy involving the CARB-mandated retrofit program for 1955-70 vehicles, the state I/M program (defined earlier), catalytic-converter retrofit on 1966-74 vehicles, and evaporative-loss control retrofit on 1966-69 vehicles. The Rand (MAX) strategy consists of maximal fixed-source control plus maximum retrofit, Strategy 1. In this discussion, neither strategy involves any reduction in VMT.

The reference technical assumptions, used in Fig. 3.3, assume that vehicle miles grow 1.8 percent compounded annually,7 that fixed sources grow 1 percent compounded annually,8 and that technology improvements are introduced in 1985 that reduce reactive hydrocarbon emissions from a post-1985 vehicle to half the 1977-vehicle level. The reactive hydrocarbon level shown for each year assumes that implementation occurred no later than that year. Significantly, the curves may be interpreted as showing the effect of delaying the mandate year for the standard as well as the time history after implementation.

The dashed curves represent the emissions under the original auto-emission standards. The solid curves represent the emissions under the revised auto-emission standards, i.e., where the emission factors for 1975 vehicles have been modified to reflect the "1975 California Interim Standards" for auto emissions announced by the EPA on April 11, 1973. The difference between the corresponding dashed and solid curves indicates that the primary effect of the revision to the auto-emission standards would be to delay the attainment of various oxidant levels by at most six months. (It should be noted that we consistently assume the revised auto-emission standard everywhere else in our analysis and discussion.)

The lines in Fig. 3.3 labeled A, B, and C illustrate the sensitivity of the oxidant-standard value attainable to the air-quality model used and the year. These lines represent three different reactive hydrocarbon emission goals for the region, each of which corresponds to a pair of oxidant-standard values, with the appropriate value depending on which air-quality model is used (rollback or EPA-Medium); the pair of oxidant-standard values is indicated on each line.

Line A corresponds to an oxidant standard of 0.20 ppm under the EPA-Medium model and 0.18 ppm under rollback. With no VMT reduction, the Rand (MAX) strategy can achieve this by 1975, the EPA IX strategy by 1978.

Line B corresponds to an oxidant standard of 0.18 ppm under the EPA-Medium model and 0.10 ppm (the existing California standard) under rollback. With no VMT reductions, the Rand (MAX) strategy can achieve this by 1976, the EPA IX strategy by 1980.

Line C corresponds to an oxidant standard of 0.16 under the EPA-Medium model and 0.08 under rollback. We see that this cannot be met without a substantial VMT reduction, even with technology improvements introduced in 1985.

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7 This growth rate is assumed by the EPA, based on California Department of Finance forecasts.
8 This assumes that fixed sources grow at the same rate as population.
OBSERVATIONS

Under the reference technical assumptions, an oxidant standard of no worse than 0.20 ppm could be achieved in the late 1970s in Los Angeles solely by means of fixed-source controls and extensive retrofit—with no VMT reduction. The 0.20-ppm level represents a more-than-threefold improvement over the 1970 worst-day level, and an even greater improvement in the number of high-concentration days.

Moreover, a large reduction in emissions under the EPA-Medium model produces only a very small reduction in oxidant. Therefore, enormous reductions in VMT will clearly be necessary to achieve a 0.08-ppm oxidant standard using that model. It is extraordinarily difficult to go below the level of 0.18 ppm using EPA-Medium or 0.10 ppm using rollback, but relatively easy to achieve these levels with no VMT reduction.

In a similar analysis, not discussed here, we found that under the pessimistic technical assumptions, an oxidant standard of no worse than 0.20 ppm could be achieved in the mid-1980s in Los Angeles solely by means of fixed-source controls and extensive retrofit—with no VMT reduction.
References for Section 3


4. PROMISING STRATEGIES FOR TRANSPORTATION MANAGEMENT

Transportation-management strategies are primarily concerned with reducing LDMV miles, since these account for most mobile-source emissions. Such strategies generally reduce LDMV mileage by lessening the number or length of LDMV trips that would occur in the uncontrolled situation.

Many different tactics have been proposed for constructing transportation-management strategies. These include a variety of bus-system improvements that would cause trips to be switched from LDMVs to the less-polluting bus mode, carpooling incentives that would reduce the number of LDMV trips by increasing the occupancy rate, automobile penalties that would cause some trips to be forgone entirely by making them seem too difficult to be worthwhile, and congestion improvements—direct and indirect—that would improve average trip speed and the associated vehicle emissions. Before we can identify the most cost-effective tactics, we must first examine certain characteristics of travel patterns and decisionmaking in Los Angeles, for these have implications that will largely determine strategy effectiveness.

TRAVEL IN LOS ANGELES

Figure 4.1 shows the cumulative percentage of total trips and VMT in Los Angeles as a function of trip length (derived from data in Ref. 1); these data represent the uncontrolled situation where control strategies have not altered normal patterns. The shortest 70 percent of trips (those of 8 miles or less) account for only 32 percent of the total VMT. Conversely, the longest 30 percent of the trips (8 miles or more) account for 68 percent of the total VMT. (Indeed, the longest 20 percent of the trips—those of 11 miles or more—contain 55 percent of the total VMT.)

This implies that our transportation-management strategies should be designed primarily to reduce LDMV mileage in long trips, since these are responsible for most of the mobile-source emissions. Furthermore, VMT-reduction strategies that emphasize long trips would cause far less disruption in the normal travel patterns than would strategies that emphasize short trips.

Since people travel for a variety of purposes, their choice of mode, elasticity of demand, and willingness to forgo trips will differ according to those purposes. In our analysis, we shall separate trips into two types:

- **Home-work trips**, whose total number will remain constant (inelastic demand) as service quality varies, although their modal split between auto and bus will change.
- **Other trips**, whose total number will vary (elastic demand) with service quality.

Home-work trips include intermediate stops; they are considered absolutely essential and have their number held constant to provide a sharp lower bound on the number of trips necessary to maintain regional viability. Other trips include all those taken for other purposes, such as shopping and recreation; they are considered less essential.
In the uncontrolled situation for Los Angeles, the average trip length is 7 miles for all trips, 10 miles for home-work trips, and 6 miles for other trips (derived from Ref. 1).

In Los Angeles, the occupancy rate (number of people per vehicle) for LDMVs is quite low. The average occupancy rate is about 1.2 for all trips, about 1.1 for home-work trips, and about 1.3 for other trips. Increasing the occupancy rate (carpooling) could substantially reduce vehicle miles without eliminating trips, particularly home-work trips.

**FACTORS INFLUENCING TRAVEL DECISIONS**

People make travel decisions—whether to take a trip or not and whether to use low-occupancy auto, bus, or carpool—primarily on the basis of the perceived cost of the service quality available for that trip. In the transportation models calibrated to Los Angeles, this perceived cost is represented by a weighted combination of four service characteristics:

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1. It is true that LDMV emissions result from LDMV miles. But the decisions that generate those miles are made on the basis of trips, not miles. Trips are the goods people consume to fulfill some social need—the miles themselves are not the goal of travel. Thus, transportation-management strategies are designed to influence trip-making behavior, and their characteristics must be viewed on a per-trip basis, not on the per-mile basis that has often been used, mistakenly, in environmental studies.

2. This is true for both the Voorhees modal-split model [2] and the Los Angeles version of the policy-oriented urban transportation model [3]. The latter model, employed in this study, was originally developed for San Diego and then transferred to and recalibrated for Los Angeles, as described in Appendix H. Hereafter, when we refer to the policy-oriented urban transportation model we shall mean the Los Angeles version rather than the San Diego version; the logical structure of the two versions, as described in Ref. 3, is essentially the same, although they differ in a variety of data values.
1. The excess time—the time spent walking or waiting.
2. The line-haul time—the time spent in the vehicle.
3. The cost per mile—either the auto operating cost or the distance-dependent component of bus fare.
4. The fixed cost—either the auto parking cost (or some other fee) or the distance-independent component of bus fare.

It should be noted that in Los Angeles the perceived cost of one minute of excess time is nearly twice that of one minute of line-haul time [2]. This implies that strategies that reduce the waiting time or headway for buses a certain number of minutes (by running buses more frequently) will be considerably more effective in making the bus attractive than strategies that reduce the riding time on the bus (by increasing its speed) the same number of minutes.

THE COMPOSITION OF PROMISING STRATEGIES FOR TRANSPORTATION MANAGEMENT

On the basis of an auxiliary sensitivity analysis, the following transportation-management tactics appeared most promising:

1. Imposing a mileage surcharge or limitation (added gas tax or rationing).
2. Inducing changes in occupancy (carpooling for home-work trips).
3. Improving the bus system by
   • Reducing headways by running buses more frequently
   • Increasing area coverage to make more people bus-eligible
   • Reducing fares to zero by making the ride free.

A promising strategy will involve a particular mixture of these tactics. Since they are defined in relatively general terms, we shall now try to define them operationally, describing how they affect travel in Los Angeles and indicating, where possible, what values are most appropriate for promising strategies. (Other strategies such as improving traffic flow by ramp-metering, dedicating bus and carpool lanes, and limiting parking availability were found to be considerably less promising, for the reasons given in Appendix B; many had minimal effectiveness, while some merely had much lower cost-effectiveness.)

The LDMV mileage surcharge is a penalty that is imposed on LDMV miles to make them less attractive; it provides incentives to carpool, to switch to bus, or to forgo trips. It is a policy lever that may be interpreted as an added local gasoline tax or as a proxy used to simulate gasoline rationing. The surcharge rate in cents per mile driven is indicated as the strategy.

To understand the effect of the surcharge, the reader must note this important distinction: Trip-making behavior depends on the cost per person-trip, not per vehicle-mile. The surcharge has several complementary effects, which we shall discuss in turn.

First, the surcharge makes bus much cheaper than auto for the longer trips. Since longer trips account for most of the VMT, these are precisely the ones we wish to switch to bus.\(^3\)

Second, the surcharge also provides an incentive for people to carpool. (A carpool

\(^3\) The cost of the auto trip increases in proportion to distance; the surcharge magnifies this. In contrast, the cost per bus trip either remains constant (a fixed fare per trip) or increases only very gradually with distance (a fixed fare plus an added fare per zone).
is defined as three or more people in an LDMV.) By making vehicle miles considerably more expensive, the surcharge causes people to increase the vehicle occupancy rate in order to reduce their individual trip cost. There are, of course, time penalties associated with picking up various carpools; these are considered in our analysis, but they are generally small compared with the cost savings of carpooling when a substantial surcharge is imposed. We consider the effect of carpooling incentives only on home-work trips; these are relatively longer and have relatively closer synchronization of origin, destination, and desired departure time among potential carpoolers than do trips for other purposes.

Third, the surcharge induces people to forgo some trips they normally would make; the trips become sufficiently expensive that they no longer seem worthwhile.

For bus, the peak and off-peak headways show the average time between buses during these two periods; these determine the frequency of service and influence the average wait and bus-system capacity. As a point of reference, the Southern California Rapid Transit District (SCRTD) was reportedly providing bus headways of 20 minutes in the peak and 30 minutes in the off-peak period during 1971-72, the most recent years for which complete data are available. We have assumed these headways in the nominal bus system (i.e., existing trends) forecast for the mid-1970s. For bus-system improvements, we have identified peak-period headways of 5, 10, and 15 minutes as promising candidates, in addition to the nominal 20 minutes; the off-peak-period headway has been given a maximum value of 40 minutes (the nominal), with its preferred value being determined by the transportation model [3].

The bus-eligible population shows the percentage of total Los Angeles basin population within a half-mile of a bus stop. For the nominal bus system, we estimated that 70 percent of the population would be bus-eligible, based upon the service area of the 1971-72 bus system. As an improvement, we identified a service area making 80 percent of the population bus-eligible; it includes the most densely populated part of the total populated area. We used this service area for all bus systems considered in this study. Increases in bus-eligible population beyond 80 percent are probably not cost-effective; the low density causes the service area—and hence the bus-system costs—to increase much faster than the eligible population [3,4]. The bus-system service-area improvement has been limited to Los Angeles and Orange Counties, where it makes 90 percent of their population bus-eligible (only 80 percent were eligible in the nominal 1971-72 situation). We have chosen to limit the service-area improvements to these counties because they generate about 83 percent of the total vehicle mileage in the basin and possess a relatively high and regular population density that is favorable to bus.

The bus fares show the average fare per trip. In all other bus systems considered, we have set the bus fare equal to zero (free ride), making bus relatively less expensive than auto, particularly for long trips.

References for Section 4


5. SUPERIOR STRATEGIES: THEIR COMPOSITION, IMPACTS, AND SENSITIVITY TO ASSUMPTIONS

PERSPECTIVE

In the previous sections, cost-effective pure strategies were identified for fixed sources, LDMV retrofit, and transportation management. In this section we attempt to identify cost-effective combinations of those pure strategies—i.e., superior mixed strategies—and to evaluate them in terms of various impacts. Specifically, we shall show how the composition, cost, and impacts of superior strategies vary with the choice of technical assumptions, air-quality model, and oxidant-standard concentration level. Before attempting to identify superior strategies, however, we shall first review the components of a strategy and then generalize, somewhat, the concept of their cost.

Strategy Components

The fixed-source control strategy may be either nominal or maximal, as defined in Sec. 2. The nominal strategy assumes that previously mandated rules—circa January 1973—will be carried out and no more will be added. The maximal places additional reactive hydrocarbon controls on organic-solvent users and aircraft and additional NO, controls on various sources. These two fixed-source control strategies include the corresponding nominal and maximal strategies for HDVs and motorcycles as defined in Appendix D.

The LDMV retrofit strategy may be any one of the 28 strategies discussed in Sec. 3. These are labeled A through Z, 0, and 1 in increasing order of extensiveness, cost, and effectiveness.

The LDMV mileage surcharge is a penalty imposed on LDMV miles to make them less attractive; it provides incentives to carpool, to switch to bus, or to forgo trips. It is a policy lever that may be interpreted as an added local gasoline tax or as a proxy used to simulate gasoline rationing. The surcharge rate in cents per mile driven is indicated as the strategy.\(^1\)

The bus-eligible population shows the percent of total population within a half-mile maximum walking distance of a bus stop; it reflects the area actually served by the bus system. The peak and off-peak headways show the average time between buses during these two periods; these determine the frequency of service and influence the average wait and bus-system capacity. The bus fares show the out-of-pocket cost of an average bus trip.

Costs

Our primary goal, as the reader will recall, is to identify superior strategies, under different assumptions, where the criteria of superiority are cost and effective-

\(^1\) Trip-making behavior will reflect the total cost of driving, the nominal (uncontrolled) cost plus additional costs due to retrofit and surcharge. At the time we analyzed transportation-management strategies (spring 1973), the average price of gasoline in Los Angeles was about $0.40 per gallon; this, along with other expenses of owning an auto such as insurance and depreciation, suitably annualized, yields a nominal cost of 0.67 per mile for LDMVs. Should a large increase in gasoline price raise this cost per mile, the surcharge necessary to yield a particular mileage reduction would decrease by the same amount.
ness in meeting the oxidant standard. For a particular assumed value of the oxidant standard, however, all strategies meeting that standard have the same effectiveness; the superior strategies are therefore those with the minimum cost. But the question then arises, How do we define the cost of prospective strategies, which are made up of quite dissimilar components? We need to broaden our concept of cost to include an additional, social cost of transportation-management strategies.

**The Social Cost of Forgone Travel.** In the absence of transportation-management strategies to alter their normal travel behavior, people would make a certain number of trips with a certain modal split, most of them by low-occupancy auto. Transportation-management strategies, however, would cause people to alter their normal travel behavior; a mileage surcharge, for example, would cause some trips to be forgone and other trips to be switched from low-occupancy auto to “less desirable” alternatives such as bus or carpool. These behavioral changes we term forgone travel; they reflect the loss in mobility.

When people are forced to alter their normal behavior by forgoing trips or switching to less desirable modes, they experience a social cost; this social cost of forgone travel reflects the loss in benefits, convenience, and time that results from forgoing trips and switching to alternative modes. Since “social-cost meters” have not yet been invented and general welfare functions have not yet been developed sufficiently, no one really knows how to measure this social cost explicitly and exactly. We believe that the best simple proxy (easy to compute, easy to understand) for it is the number of trips forgone because of a particular strategy.

**The Total-Cost Proxy for Mixed Strategies.** Since many strategies greatly reduce the quantity and quality of regional travel, it is essential that the measure we use for the cost of a strategy include the social cost of forgone travel as well as the expenditures for the strategy components; otherwise (1) a strategy that produced a large amount of forgone travel could seem unrealistically attractive if the actual strategy expenditures were relatively small, and (2) a strategy that produced a particular mileage reduction with a large social cost could erroneously seem as attractive as another strategy that produced the same mileage reduction with a small social cost. We shall term this measure the total-cost proxy (TCP); it consists of the net expenditures for strategy components and the monetary proxy for the social cost of forgone travel.

In order to combine the proxy for the social cost of forgone travel (i.e., trips forgone) with the strategy expenditures, we must have them in common units. We shall monetize the social-cost proxy by multiplying the number of trips forgone by the dollar value of a trip forgone (suitably derived, as discussed below); we call the result the monetary proxy for the social cost of forgone travel.

In determining the net expenditures for strategy components, we shall allow the revenue collected from the surcharge, if any, to be used to offset the cost of the bus improvements. Thus we define the net expenditure for strategy components as the sum of the annualized expenditures on fixed-source controls, retrofit, and either the mileage surcharge or the cost of bus improvements, whichever is larger.

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2 Massive rationing, for example, could seem unrealistically attractive if the costs to print, distribute, and administer the ration books were small.

3 For example, one strategy might produce a certain mileage reduction by causing many trips to be forgone, with a large social cost, while another might produce the same reduction by causing many trips to switch to bus, with a small social cost.

4 If the amount of surcharge that has been collected, which depends on the necessary mileage reduction, exceeds the cost of bus improvements, then there will be unallocated surcharge income. Although this unallocated surcharge may eventually be used to offset some other cost or to purchase some partially offsetting benefit, it is nonetheless part of the transportation-management expenditures and will be considered here in calculating their cost-effectiveness. When transportation-management strate-
It should be noted that the TCP, in effect, provides a "snapshot" of the costs from the perspective of the implementation year, assuming that all components of the strategy would be implemented in that year. While providing a consistent framework for comparison, a snapshot of costs from this perspective is meant to be conservative; under a particular strategy, the amount of forgone travel (reflecting the mileage reduction necessary to meet the standards), for example, should be largest in the implementation year and smaller in subsequent years (in the near term) as the older, dirtier vehicles are gradually replaced with newer, cleaner ones. (The emission reduction due to cleaner vehicles is expected to surpass the increase due to regional growth.) We emphasize the fact that the TCP is merely a slight generalization of the cost-effectiveness concept, an artifact to help us identify superior mixed strategies. It does not purport to represent the total cost to the region of a strategy, that is, the net of all the benefits and disbenefits—many of which are not easily measured or monetized. But, having identified superior strategies on the basis of this TCP, we can then evaluate their detailed impacts on the region.\(^5\)

Using this concept of the TCP and the menu of promising pure strategies from Secs. 2 through 4, we have identified a manageable number of superior mixed strategies; these will be described, evaluated, and compared in the subsections below.

The process of identifying superior mixed strategies by means of the TCP was made practical by the tradeoff model [1], which is described briefly in Sec. 7 and in detail in Appendix 1. In calculating the monetary proxy for the social cost of forgone travel, we have consistently used $1 as the value of a forgone trip. (This is an estimate of the loss in social value per forgone trip, the value of the trip in excess of its average cost.) That value was estimated early in the study. After the analysis phase of the study concluded, we devised a more sophisticated technique for estimating this value that employs the tradeoff model.\(^6\) Using that technique, we have found that al-

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\(^5\) The TCP is meant to focus on the local decisionmaker—to view costs from his perspective. But what are considered "costs" depends very much on perspective. From the viewpoint of a local decisionmaker, a tax that was levied in Los Angeles and spent in some other region would probably be considered a cost; from the viewpoint of a national decisionmaker, it would probably be considered a transfer payment. From the viewpoint of an accountant, the surcharge collected would probably be considered a transfer payment, since it is a payment made by car users to the government and involves no use of real resources. Our choice of this particular form of the TCP (and our subsequent treatment of certain detailed impacts) reflects our belief that local decisionmakers tend to view costs more like accountants than economists and the local economy more like a closed than an open system (the latter being the perspective of the national decisionmaker).

\(^6\) As a highly simplified description of technique, the number of trips forgone is estimated for various values of the surcharge rate. By comparing a particular change in the number of trips being taken with the change in the amount being paid to take them, the social value of the forgone travel (in excess of the cost of the travel under the nominal price structure) corresponding to a certain number of forgone trips can be inferred (see Ref. 1). In terms of economic theory, the approach is an extension of the technique whereby the economic value of a given change in travel is approximated by the change in the associated "consumer surplus." The theoretical relation of consumer surplus to the value of travel is discussed in Refs. 2 and 3; it has been applied, for example, by the Federal Department of Transportation in the Transportation Research Allocation Study (TRANS) [4]. Reference 1 describes the TCP concept as used in this study, the modifications necessary to extend it to transportation-service-improvement or energy-conservation problems, and various techniques for estimating a monetary value for social cost with the tradeoff model.
though $1 is an appropriate value when a moderate number of trips are forgone (and, indeed, is a lower bound), a somewhat smaller value is more appropriate when less than a few percent are forgone [1]. We have verified, however, that essentially the same mixed strategies would have been identified if the smaller value had been used when appropriate.

The Concept of Cases

We shall evaluate our mixed strategies in the context of cases. A case consists of a set of superior strategies, selected and evaluated for a particular combination of technical assumptions and air-quality model. Each of the different strategies in the case corresponds to an alternative level for the oxidant standard and represents the combination of strategy components meeting that level for the minimum value of the TCP.

In the remainder of this section, four different cases will be compared: The nominal case incorporates the nominal fixed-source controls, the pessimistic technical assumptions, and the EPA-Medium air-quality model; it is similar to strategies and assumptions being used by EPA Region IX in early 1973. Case A introduces maximal fixed-source control instead of nominal; in terms of assumptions and fixed-source control, it is similar to EPA plans of mid-1973. Case B replaces the pessimistic technical assumptions of Case A with the reference technical assumptions. Case C replaces the EPA air-quality model of Case B with the rollback air-quality model; this case is included primarily for comparison purposes, since it is widely believed that the rollback model considerably underestimates the necessary emission reductions for the Los Angeles basin.

Preview of Results

Having defined these cases, which reflect different assumptions, we shall discuss in succession how the TCP, the strategy composition (as reflected in component expenditures), the travel reduction, and the various impacts (e.g., transportation service, employment) of superior strategies vary with the concentration level assumed for the oxidant standard. To put these results in perspective, we shall conclude with some brief comments on the cost and health implications of not meeting various levels of the standard.

TOTAL-COST PROXY FOR SUPERIOR STRATEGIES VERSUS ASSUMPTIONS

For each of the four cases defined above, Fig. 5.1 depicts how the TCP\(^7\) for superior strategies varies with the concentration level assumed for the oxidant standard. (Since the cases reflect different choices of technical assumptions and air-quality model, they also illustrate the sensitivity of the TCP to these factors.)

For an oxidant standard of 0.25 ppm, all cases have relatively low TCP, about $200 million annually. For an oxidant standard of 0.20 ppm (corresponding to the CARB's Stage-1 alert), the nominal-case TCP is about $1.5 billion more than that of

\(^7\) As originally defined and used to identify superior strategies, the TCP included the cost of bus improvements. Hereafter, it will be more convenient to display values of the TCP and bus-system expenditure that reflect the annualized expenditures for the entire bus system, not merely the improvements. The difference is about $65 million annually.
Fig. 5.1—Sensitivity of the TCP of superior strategies to technical assumptions, air-quality model, and oxidant standard

the other cases; its larger residual of fixed-source emissions must be counterbalanced by larger reductions in other emissions, which are less cost-effective. The nominal case cannot meet oxidant-standard levels tighter than 0.20 ppm because the emissions from fixed sources alone exceed those levels. Thus, all other cases replace the nominal with maximal fixed-source controls.

When the EPA air-quality model is used, both Case A and Case B are able to meet even the most stringent oxidant standard proposed. The only difference between the two is the choice of technical assumptions—and the size of the TCP. Notice that for an oxidant standard of 0.08 ppm, the pessimistic technical assumptions increase the TCP almost $4 billion per year. For a 0.10-ppm standard, the difference is about $2.5 billion per year, and for 0.15 ppm, over $1 billion per year. These TCP differences strongly suggest that the uncertainty about the relative validity of the reference versus the pessimistic technical assumptions should be resolved before any strategy is chosen. Using unduly pessimistic assumptions will greatly multiply the monetary and social cost of meeting relatively tight standards.

\* Case C differs from Case B in that the rollback air-quality model is used instead of the EPA’s. Case C meets the oxidant standard at all levels, but at 0.08 ppm the TCP is lower than that for Case B by a factor greater than 3. The use of the rollback model makes Case C seem unrealistic to those who consider the rollback model unduly optimistic for the Los Angeles region.

\* An alternate approach to waiting for this resolution is to develop and implement an adaptive strategy to hedge against uncertainty, as illustrated in Ref. 5; a strategy from Case B, assuming the reference assumptions, could be implemented initially and then augmented subsequently if its performance proved inadequate because the pessimistic assumptions actually obtained.
Additional insights into the possible implications of a choice between Case A and Case B can be gained by looking at the major cost components of each, as represented by expenditures.

THE COMPOSITION OF SUPERIOR STRATEGIES UNDER DIFFERENT ASSUMPTIONS

For Case A, Fig. 5.2 shows how the component-strategy expenditures behave as the oxidant standard is varied; Fig. 5.3 provides similar information for Case B. With an oxidant standard of 0.20 ppm, neither case requires a mileage surcharge and both use a minimal bus system and the same fixed-source controls (maximal), but Case A, with the pessimistic technical assumptions, requires a more extensive LDMV retrofit-I/M strategy.

When the oxidant standard is tightened to 0.15 ppm, Case A requires a significant LDMV mileage surcharge and a substantially improved bus system to reduce LDMV miles. Case B (with the reference technical assumptions), on the other hand, requires a very small LDMV mileage surcharge and still uses the smallest bus system. Both cases use the same LDMV retrofit-I/M strategy—the maximum.

As the oxidant standard is tightened, the differential effect of the pessimistic technical assumptions becomes even greater. In fact, at 0.10 ppm, both cases have gone to the same large bus system that was employed by Case A when the standard was 0.15 ppm. However, Case A requires a significantly higher LDMV mileage surcharge than does Case B—$2.5 billion versus $1.5 billion annually. The higher mileage surcharge in Case A causes a relatively greater reduction in LDMV miles,

![Graph showing component-strategy expenditures of Case A as a function of oxidant standard](image-url)
so that while both cases employ the same maximum retrofit-I/M strategy, the operating cost of this retrofit strategy is less in Case A than in Case B (fewer LDMV miles are driven in Case A than in Case B), and so is its annualized cost.\textsuperscript{10}

Meeting the 0.08-ppm oxidant standard requires further increase in the LDMV mileage surcharge but a much greater one in Case A than in Case B—$3.6 billion versus $2.5 billion annually. As was done for the 0.10-ppm standard, the maximum LDMV retrofit-I/M strategy is employed in both cases, but due to the greater reduction in LDMV miles, the annual cost of retrofit is less than it was at 0.10 ppm but still more costly in Case A than in Case B.

In summary, as the oxidant standard is tightened, both cases behave similarly, but Case A, with the pessimistic technical assumptions, shows each effect much sooner (about 0.05 ppm) than does Case B. In both cases, LDMV retrofit-I/M is applied first and increases in extensiveness as the standard is tightened. When this strategy becomes insufficient to meet the standard, a combination of an LDMV mileage surcharge and improved bus are used to induce people to reduce their low-occupancy LDMV mileage by carpooling or riding the bus. As the standard is tightened still further, the largest bus improvement becomes insufficient, so the LDMV mileage surcharge (the only remaining lever) is increased further to induce the forgoing of trips; this reduces the VMT further and also causes the operating cost of LDMV retrofit to decrease.

\textsuperscript{10} The cost of LDMV retrofit is made up of two components: an investment in the devices themselves and a mileage cost that derives from loss of engine efficiency and increased fuel and maintenance cost. Once the maximum investment has been made, increases in the mileage surcharge produce decreases in the miles driven, with commensurate decreases in the mileage-related operating cost—and hence in the annualized total cost as well.
Since these strategy components are, in essence, applied in order of decreasing cost-effectiveness, the general trend deserves reiteration: As the standard is tightened, the order of application of strategy components is as follows: (1) increase fixed-source control to maximum, (2) increase retrofit-I/M to maximum, (3) increase bus system in combination with increasing mileage surcharge, and (4) further increase mileage surcharge.\(^{11}\)

Significantly, we have found that bus-system improvements alone are not sufficient incentive to induce substantial modifications in the use of low-occupancy LDVMs. Inducing such modifications requires both the carrot (improved bus) and the stick (mileage surcharge).

REDUCTIONS IN TRAVEL UNDER DIFFERENT ASSUMPTIONS

Figure 5.4 indicates the required reduction in vehicle miles and person-trips for Cases A and B as a function of the oxidant standard. It is clear that the required

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\(^{11}\) Reference 5 discusses the relative cost-effectiveness of fixed-source, retrofit, and transportation-management strategies. For San Diego, measuring cost-effectiveness in terms of dollars per ton of reactive hydrocarbon emissions removed, it was found that the maximal fixed-source control strategy is 29 times more cost-effective than maximum retrofit and between 130 and 350 times more cost-effective than a massive transportation-management strategy.
reduction in LDMV miles and person-trips is extremely sensitive to both the required oxidant standard and the technical assumptions.

Because our transportation-management strategies emphasize long trips, they can produce large VMT reductions for moderate trip reductions: a 95-percent VMT reduction for eliminating 50 percent of the trips, an 80-percent VMT reduction for 20 percent of the trips, a 50-percent VMT reduction for 5 percent of the trips, a 20-percent VMT reduction for about 2 percent of the trips, and a 10-percent VMT reduction for negligible trips.

At an oxidant standard of 0.08 ppm, Case A requires a VMT reduction of 95 percent but only a 50-percent trip reduction; Case B requires a reduction of 78 percent of VMT but only 22 percent of trips. Under the pessimistic assumptions, VMT are almost completely eliminated, but at a cost of only about 50 percent of the trips.

Relaxing the oxidant standard slightly, from 0.08 ppm to 0.10 ppm, has a significant impact on the necessary travel reductions. For Case B, the necessary reduction is 47 percent in VMT but only 5 percent in trips; for Case A, the necessary reduction is 78 percent in VMT but only 22 percent in trips. Case A at 0.10 ppm is comparable to Case B at 0.08 ppm. Using the superior strategies identified, a 20-percent reduction in the number of trips (about 80 percent VMT) could, in 1977, achieve an oxidant standard of 0.08 ppm under the reference assumptions and 0.10 ppm under the pessimistic assumptions.

As the standard is loosened, a negligible reduction in the number of trips (a 10-percent VMT reduction) could, in 1977, permit an oxidant standard more stringent than 0.15 ppm to be achieved under the reference assumptions and 0.20 under the pessimistic assumptions.

THE IMPACTS OF SUPERIOR STRATEGIES FOR MEETING ALTERNATIVE OXIDANT LEVELS

Thus far, we have compared superior strategies, embodied in cases, in terms of how their component costs and travel reductions varied with assumptions such as the oxidant standard or air-quality model. For three alternative oxidant standards (the CARB Stage-1 alert level of 0.20 ppm, the California standard of 0.10 ppm, and the national primary of 0.08 ppm), we shall now compare the same superior strategies in terms of various impacts on the region—environmental, transportation-service, economic, and employment impacts.

Some Definitions

Some of these impacts have been defined previously, and most of them are intuitive and obvious. For some, however, we shall provide capsule definitions.

The amount of carpooling shows the percent of home-work trips by LDMVs occupied by three or more persons. The occupancy for home-work trips, which are individual-oriented, is assumed to increase with the surcharge, whereas the occupancy for other trips, which are family-oriented, is assumed to remain constant.

The annual strategy expenditures for fixed-source controls, retrofit, LDMV mileage surcharge, and the bus system are the annualized values defined earlier. We remind the reader that the annualized cost of retrofit includes both procurement and operating cost. Thus the same retrofit strategy may sometimes have somewhat different costs in two different cases; if the LDMV mileage differs between the cases,
then the operating costs will differ and so will the overall costs. However, the
bus-system expenditures shown here are the expenditures for the entire system, not
merely the expenditures for the improvements over the existing bus system. We
have chosen to use total-system expenditures in order to show the full financial
implications of the cases considered; when one compares cases, the costs of the
existing bus system "net out," in effect, because they are contained in all cases.

The number of buses is an indicator of the investment in equipment required by
the particular bus service provided. It also gives some indication of possible procurement
lead times and hence strategy feasibility. Annual bus miles and passenger
miles are shown as indices of bus activity and usage.

Recurring employment includes bus-system personnel, auto-maintenance per-
sonnel required to handle the additional auto maintenance that results from the
installation of retrofit devices and to operate legislated vehicle-inspection programs,
and the reduction in gasoline service-station personnel due to reductions in auto
miles driven (which we did not estimate). Additional recurring employment would
be considered a long-run benefit to the community, although obtaining sufficient
numbers of the required people may present some lead-time problems. The
mechanics necessary to perform the initial installation of retrofit devices are included
as nonrecurring employment. Unlike recurring employment, nonrecurring employ-
ment is a relatively short-term phenomenon and hence a potentially disruptive
influence on the local economy, since it may require more skilled people than are
easily available.

We shall discuss in detail the expenditure impacts of the various LDMV retrofit
strategies. First, the total cost of purchasing and installing devices will be shown—
unannualized.

Next, the recurring annual costs associated with the various cases will be shown.
These costs reflect added maintenance and increased fuel consumption due to opera-
tion with the retrofit devices. (Significantly, the catalytic converter allows the en-
gine to be tuned to maximize fuel economy instead of to minimize reactive hydrocar-
bon emissions; thus the catalytic converter partially offsets the increased fuel con-
sumption of other retrofit devices.) The annual gasoline consumption reflects reduc-
tions both in fuel economy and in annual LDMV mileage.

In all of the mixed strategies considered, a pure strategy for retrofit was among
the components selected. However, whenever an intermediate amount of retrofit is
required, a linear combination of two pure strategies—a hybrid retrofit strategy
—will often have the same effectiveness as the pure strategy selected, but at lower
annualized cost. (The tradeoff model, which searches for the superior mixed strate-
gies as described in Sec. 7 and Appendix I, automatically finds the hybrid retrofit
strategies.) The composition of these hybrid retrofit strategies and the prospective
savings are also shown.

For Case B in Table 5.1, as an example, the strategy composition is shown as
63E/37W; this means that under the hybrid strategy, 63 percent of the vehicles
receiving retrofit would be subjected to retrofit Strategy E and the remainder to
Strategy W. The annualized savings from applying this hybrid strategy (instead of
pure Strategy J) are shown as $58.4 million, almost 20 percent of the net expendi-
tures for Case B when retrofit Strategy J is included.

The problem with the hybrid strategy—and the reason that its cost was not used
in calculating the net expenditure—is its implementation. The hybrid strategy must

12 Additional recurring employment is mildly beneficial when there is appreciable unemployment in
the local economy. When there is full employment in the local economy, on the other hand, it would be
mildly inflationary.
be applied only to groups of vehicles with identical age distributions; that is, the age distribution of the vehicles receiving retrofit Strategy E must be identical with those receiving retrofit Strategy W. (This is a consequence of the mathematical technique by which the hybrid strategies are determined.) This requirement raises implementation problems; it means that some form of lottery or similar selection technique would have to be used to assign the vehicles to groups (after all, most people will want less retrofit rather than more, particularly under the user-pays financing scheme). However, the potential savings are sufficiently large that techniques for implementing hybrid strategies should be sought assiduously during implementation planning. (The desired fraction of the vehicles may fortuitously be found incompatible with the more extensive Strategy W and could thus receive Strategy E through natural selection.)

The impacts we present below are neither mutually exclusive nor exhaustive. That is, we may neglect some of the strategy's effects on Los Angeles (e.g., distributional effects by race, as mentioned in the Introduction), and we may doublecount some others to provide different perspectives on the same effect.\(^\text{13}\) The choice and presentation of the impacts reflect the intent of the study: to provide a snapshot of impacts, from the perspective of a particular implementation year that will help decisionmakers choose the preferred strategy for eventual implementation.

We shall now compare superior strategies, embodied in the previously defined cases, in terms of their impacts for oxidant-standard values of 0.20, 0.10, and 0.08 ppm. (Although we shall show the impacts of Case C for comparison purposes, we shall not discuss them, since they are based on the rollback model.)

**Superior-Strategy Impacts for 0.20-ppm Oxidant Standard**

Table 5.1 compares superior strategies for meeting an oxidant standard of 0.20 ppm. Comparing the strategy components, we see that Cases A and B involve maximal rather than nominal fixed-source control and that the nominal case requires maximum retrofit (Strategy 1), whereas Case A with the pessimistic assumptions requires nearly the maximum (Strategy 0) and Case B an intermediate amount (Strategy J). Cases A and B have the existing bus-system headways, 20/30, but the nominal case has those corresponding to the biggest bus system considered, 5/7. Only the nominal case requires a mileage surcharge; its value of 4.6\(^2\) per mile corresponds to an added gasoline tax of about 60\(^2\) per gallon, which would yield an overall price of about 1 per gallon, a bit below European prices in 1973.

In terms of transportation-service impacts, the nominal case requires a 41.7-percent mileage reduction to meet even this relatively relaxed oxidant standard. This reduction would be accomplished by increasing the percentage of bus trips to 19 percent of all trips, by carpooling for 20 percent of the home-work trips, and by forgoing 4 percent of the uncontrolled number of trips entirely. The transportation-service impacts of the other cases are similar to each other but markedly less disruptive than those of the nominal case; in fact, their negative percentages of trips forgone means that these cases induce between 1 and 2 percent new trips.

With respect to the TCP, the pessimistic assumptions of Case A require somewhat more retrofit than do the reference assumptions of Case B; thus the TCP is

\(^{13}\) From the standpoint of an economist, we are doublecounting, for example, when we present incremental recurring employment, which includes the additional bus drivers resulting from bus-system improvements, as well as expenditures, which include the wages paid the additional bus drivers. From the standpoint of the local decisionmakers, however, we believe this dual perspective may be useful; it shows the extent that revenue the region must raise to finance a strategy, which includes the bus subsidy, will be counterbalanced by employment gains within the region.
### Table 5.1
**IMPACTS OF SUPERIOR STRATEGIES FOR MEETING A 0.20-ppm OXIDANT STANDARD**

<table>
<thead>
<tr>
<th>Item</th>
<th>Nominal Case</th>
<th>Case A</th>
<th>Case B</th>
<th>Case C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Principal Assumptions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technical-assumption set</td>
<td>Pessimistic</td>
<td>Nominal</td>
<td>Pessimistic</td>
<td>Nominal</td>
</tr>
<tr>
<td>Air-quality model</td>
<td>EPA-Medium</td>
<td>EPA-Medium</td>
<td>EPA-Medium</td>
<td>EPA-Medium</td>
</tr>
<tr>
<td><strong>Strategy Components</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fixed source</td>
<td>Nominal</td>
<td>Maximal</td>
<td>Maximal</td>
<td>Maximal</td>
</tr>
<tr>
<td>Retrofit&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1</td>
<td>0</td>
<td>J</td>
<td>A</td>
</tr>
<tr>
<td>Mileage surcharge, c/mt</td>
<td>4.6</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bus headways, &lt;sup&gt;b&lt;/sup&gt; peak/off-peak, min</td>
<td>5/7</td>
<td>20/29</td>
<td>20/29</td>
<td>20/30</td>
</tr>
<tr>
<td>Bus fare, c/trip</td>
<td>Free</td>
<td>Free</td>
<td>Free</td>
<td>Free</td>
</tr>
<tr>
<td><strong>Impacts</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transportation-service impacts</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LDMV mileage reduction, % of uncontrolled</td>
<td>41.7</td>
<td>5.4</td>
<td>5.5</td>
<td>2.6</td>
</tr>
<tr>
<td>Trips forgone, % of uncontrolled</td>
<td>3.6</td>
<td>-1.0</td>
<td>-1.0</td>
<td>-1.9</td>
</tr>
<tr>
<td>Trips by bus, % of all trips</td>
<td>19.4</td>
<td>4.8</td>
<td>4.8</td>
<td>4.8</td>
</tr>
<tr>
<td>Carpooling, % of home-work trips</td>
<td>20</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Monetary proxy for social cost,&lt;sup&gt;c&lt;/sup&gt; $ millions</td>
<td>351.2</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Financial impacts</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual strategy expenditures, $ millions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fixed-source controls</td>
<td>0</td>
<td>58.9</td>
<td>58.9</td>
<td>58.9</td>
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<tr>
<td>Retrofit</td>
<td>473.2</td>
<td>392.6</td>
<td>290.1</td>
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</tr>
<tr>
<td>Mileage surcharge</td>
<td>1,420.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Bus</td>
<td>719.0</td>
<td>143.0</td>
<td>143.0</td>
<td>140.0</td>
</tr>
<tr>
<td>Net expenditures after transfers,&lt;sup&gt;d&lt;/sup&gt; $ millions</td>
<td>1,893.2</td>
<td>594.5</td>
<td>492.0</td>
<td>198.9</td>
</tr>
<tr>
<td><strong>Total cost, $ millions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total-cost proxy</td>
<td>2,244.4</td>
<td>594.5</td>
<td>492.0</td>
<td>198.9</td>
</tr>
<tr>
<td>Unallocated income from surcharge</td>
<td>701.0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Bus-system impacts</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of buses</td>
<td>7,254</td>
<td>1,813</td>
<td>1,813</td>
<td>1,813</td>
</tr>
<tr>
<td>Annual bus miles, millions</td>
<td>485</td>
<td>121</td>
<td>121</td>
<td>119</td>
</tr>
<tr>
<td>Annual passenger miles, millions</td>
<td>17,147</td>
<td>5,035</td>
<td>5,044</td>
<td>4,809</td>
</tr>
<tr>
<td>Recurring employment</td>
<td>45,237</td>
<td>8,413</td>
<td>8,422</td>
<td>8,244</td>
</tr>
<tr>
<td><strong>Retrofit impacts</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Purchase and installation of devices</td>
<td>1,087</td>
<td>859</td>
<td>414</td>
<td>0</td>
</tr>
<tr>
<td>Nonrecurring employment</td>
<td>16,443</td>
<td>15,831</td>
<td>5,833</td>
<td>0</td>
</tr>
<tr>
<td>Inspection and maintenance</td>
<td>329</td>
<td>207</td>
<td>171</td>
<td>0</td>
</tr>
<tr>
<td>Annual cost, $ millions</td>
<td>10,688</td>
<td>6,726</td>
<td>5,569</td>
<td>0</td>
</tr>
<tr>
<td>Recurring employment</td>
<td>None</td>
<td>None</td>
<td>632/374</td>
<td>None</td>
</tr>
<tr>
<td>Hybrid retrofit strategy</td>
<td>None</td>
<td>None</td>
<td>632/374</td>
<td>None</td>
</tr>
<tr>
<td>Annualized savings, $ millions</td>
<td>0</td>
<td>0</td>
<td>39</td>
<td>0</td>
</tr>
<tr>
<td><strong>Energy impacts</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual gasoline consumption, million gal</td>
<td>2,372</td>
<td>3,925</td>
<td>3,888</td>
<td>3,861</td>
</tr>
<tr>
<td>Annual diesel-fuel consumption, million gal</td>
<td>97</td>
<td>24</td>
<td>24</td>
<td>24</td>
</tr>
</tbody>
</table>

<sup>a</sup>See Appendix F for detailed composition.

<sup>b</sup>60 percent of Los Angeles basin population bus-eligible (90 percent of Los Angeles and Orange Counties population).

<sup>c</sup>Monetary proxy for social cost of forgone travel assumes $1 as the value per forgone trip.

<sup>d</sup>Surchargé income used to offset bus subsidy to whatever extent possible.
about $100 million higher for Case A, $595 million versus $492 million. The nominal case has by far the largest TCP, $2.2 billion, of which about $700 million is unallocated income from the surcharge. The nominal case’s “biggest” bus system requires more than 7000 buses versus about 1800 in the other cases; its maximum retrofit strategy requires over 16,000 semiskilled mechanics for installation and over 10,000 mechanics annually for inspection and maintenance. The less-extensive retrofit strategies of the other cases imply proportionately less employment.

We note that Case B may save $59 million annually by implementing a hybrid retrofit strategy consisting of a mixture of 63 percent Strategy E and 37 percent Strategy W instead of pure Strategy J.

**Superior-Strategy Impacts for 0.10-ppm Oxidant Standard**

Table 5.2 compares superior strategies for meeting an oxidant standard of 0.10 ppm. The nominal case cannot meet this standard, as the emissions from fixed sources alone exceed 0.10 ppm. Comparing their strategy components, Cases A and B differ only in surcharge, 20¢ per mile for Case A and 5.6¢ per mile for Case B, which roughly correspond to added gasoline taxes of $2.60 and 73¢ per gallon, respectively.

Neither Case A nor Case B has very favorable transportation-service impacts: Case B requires over 50 percent of trips to be forgone, with a social-cost proxy of $514 million, while Case A requires over 21 percent of trips to be forgone, with a social-cost proxy of over $2 billion. In Case B, over 20 percent of trips are by bus; in Case A, 27 percent. Case B has about 35-percent carpooling for home-work trips versus 83-percent for Case A. Case B is certainly preferred over A in terms of its impacts on transportation service.

Case B is also preferred in terms of TCP: The $2.6 billion for B is approximately half the $5 billion for A, but there is unallocated income from surcharge in each case, amounting to about $860 million and $1700 million, respectively. In terms of other impacts shown, the two cases come off equally well. (Both cases require over 16,000 semiskilled mechanics initially for retrofit installation and over 10,000 mechanics annually for retrofit inspection and maintenance. Both cases require about 45,000 bus-system personnel.) Case B emerges as the superior strategy if one accepts the reference technical assumptions.

**Superior-Strategy Impacts for 0.08-ppm Oxidant Standard**

Table 5.3 compares superior strategies for meeting an 0.08-ppm oxidant standard. To meet this stringent standard, Cases A and B both require not only the maximal fixed-source and retrofit controls and the biggest bus system, but also a substantial surcharge to produce massive VMT reductions.

Case B requires a 21¢-per-mile surcharge (an added gasoline tax of over $2.70 per gallon) to produce a 77-percent mileage reduction. For Case B, 22 percent of the nominal trips are forgone, with a social-cost proxy of over $2.1 billion. Of the remaining trips, almost 28 percent are taken by bus, with more than 84 percent of the home-work trips by carpool.

---

14 Note that although the surcharge may seem relatively high on a per-vehicle-mile basis, it is considerably lower on the per-person-mile basis that affects trip-making behavior. The 20¢ per mile surcharge amounts to 10¢ per person-mile, roughly comparable to the nominal cost per person-mile; thus the total cost per person-mile is not quite doubled by the 20¢-per-mile surcharge. The $2.60-per-gallon surcharge corresponds to a gasoline price of $3 per gallon. This is roughly one-third higher than the prices prevailing in certain European countries (e.g., Portugal) in spring 1974.
Table 5.2
IMPACTS OF SUPERIOR STRATEGIES FOR MEETING A 0.10-ppm OXIDANT STANDARD

<table>
<thead>
<tr>
<th>Item</th>
<th>Nominal Case</th>
<th>Case A</th>
<th>Case B</th>
<th>Case C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Principal Assumptions</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technical-assumption set</td>
<td>Pessimistic</td>
<td>EPA-Medium</td>
<td>Pessimistic</td>
<td>EPA-Medium</td>
</tr>
<tr>
<td>Air-quality model</td>
<td>EPA-Medium</td>
<td>EPA-Medium</td>
<td>EPA-Medium</td>
<td></td>
</tr>
<tr>
<td><strong>Strategy Components</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fixed source</td>
<td>Nominal 1</td>
<td>Maximal 1</td>
<td>Maximal 1</td>
<td>Maximal R</td>
</tr>
<tr>
<td>Retrofit</td>
<td>---</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mileage surcharge, c/mi</td>
<td>20.0</td>
<td>5.6</td>
<td>0.2</td>
<td></td>
</tr>
<tr>
<td>Bus headways, peak/off-peak, min</td>
<td>5/8</td>
<td>5/7</td>
<td>20/29</td>
<td></td>
</tr>
<tr>
<td>Bus fare, c/trip</td>
<td>Free</td>
<td>Free</td>
<td>Free</td>
<td></td>
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<tr>
<td><strong>Impacts</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Transportation-service impacts</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low mileage reduction, % of uncontrolled</td>
<td>---</td>
<td>76.3</td>
<td>46.5</td>
<td>7.7</td>
</tr>
<tr>
<td>Trips forgone, % of uncontrolled</td>
<td>---</td>
<td>21.5</td>
<td>5.3</td>
<td>-0.3</td>
</tr>
<tr>
<td>Trips by bus, % of all trips</td>
<td>---</td>
<td>27.2</td>
<td>20.3</td>
<td>5.2</td>
</tr>
<tr>
<td>Carpooling, % of home-work trips</td>
<td>---</td>
<td>83</td>
<td>35</td>
<td>5</td>
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<tr>
<td>Monetary proxy for social cost, $ millions</td>
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<td>2,092.6</td>
<td>516.0</td>
<td>0</td>
</tr>
<tr>
<td>Financial impacts</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual strategy expenditures, $ millions</td>
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<td>58.9</td>
<td>58.9</td>
<td>58.9</td>
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<td>Fixed-source controls</td>
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<td>367.6</td>
<td>480.7</td>
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<td>117.3</td>
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<td>724.0</td>
<td>143.0</td>
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<td>Bus</td>
<td>---</td>
<td>2,923.7</td>
<td>2,125.2</td>
<td>665.2</td>
</tr>
<tr>
<td>Net expenditures after transfers, $ millions</td>
<td>---</td>
<td>5,016.3</td>
<td>2,639.2</td>
<td>665.2</td>
</tr>
<tr>
<td>Total cost, $ millions</td>
<td>---</td>
<td>5,016.3</td>
<td>2,639.2</td>
<td>665.2</td>
</tr>
<tr>
<td>Unallocated income from surcharge</td>
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<td>0</td>
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<tr>
<td>Bus-system impacts</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of buses</td>
<td>---</td>
<td>7,221</td>
<td>7,254</td>
<td>1,813</td>
</tr>
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<td>Annual bus miles, millions</td>
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<td>488</td>
<td>122</td>
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<td>17,871</td>
<td>5,218</td>
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<td>70,668</td>
<td>61,342</td>
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<tr>
<td>Retrofit impacts</td>
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</tr>
<tr>
<td>Purchase and installation of devices</td>
<td>---</td>
<td>1,087</td>
<td>1,087</td>
<td>975</td>
</tr>
<tr>
<td>Total cost, $ millions</td>
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<td>16,443</td>
<td>16,611</td>
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<td>Nonrecurring employment</td>
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<td>16,443</td>
<td>16,611</td>
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<tr>
<td>Inspection and maintenance</td>
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<td>253</td>
<td>202</td>
</tr>
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<td>Annual cost, $ millions</td>
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<td>10,688</td>
<td>6,564</td>
</tr>
<tr>
<td>Recurring employment</td>
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<td>10,688</td>
<td>6,564</td>
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<td>None</td>
<td>3E/97W</td>
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<td>0</td>
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<td>None</td>
<td>3E/97W</td>
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<td>Energy impacts</td>
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<td></td>
</tr>
<tr>
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<td>964</td>
<td>2,177</td>
<td>3,826</td>
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<td>Annual diesel-fuel consumption, million gal</td>
<td>---</td>
<td>95</td>
<td>98</td>
<td>24</td>
</tr>
</tbody>
</table>

a See Appendix F for detailed composition.

b 20 percent of Los Angeles basin population bus-eligible (90 percent of Los Angeles and Orange Counties population).

Monetary proxy for social cost of forgone travel assumes $1 as the value per forgone trip.

d Surcharge income used to offset bus subsidy to whatever extent possible.
### Table 5.3
**IMPACTS OF SUPERIOR STRATEGIES FOR MEETING A 0.08-ppm OXIDANT STANDARD**

<table>
<thead>
<tr>
<th>Item</th>
<th>Nominal Case</th>
<th>Case A</th>
<th>Case B</th>
<th>Case C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Principal Assumptions</td>
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<td></td>
<td></td>
</tr>
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<td>Pessimistic</td>
<td>Reference</td>
<td>Reference</td>
</tr>
<tr>
<td>Air-quality model</td>
<td>EPA-Medium</td>
<td>EPA-Medium</td>
<td>Rollback</td>
<td>Rollback</td>
</tr>
<tr>
<td>Strategy Components</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fixed source</td>
<td>Nominal</td>
<td>Maximal</td>
<td>Maximal</td>
<td>Maximal</td>
</tr>
<tr>
<td>Retrofit</td>
<td>---</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Mileage surcharge, c/ml</td>
<td>---</td>
<td>128.0</td>
<td>21.0</td>
<td>21.0</td>
</tr>
<tr>
<td>Bus headways,(^b) peak/off-peak, min</td>
<td>---</td>
<td>5/7</td>
<td>5/7</td>
<td>5/6</td>
</tr>
<tr>
<td>Bus fare, c/trip</td>
<td>---</td>
<td>Free</td>
<td>Free</td>
<td>Free</td>
</tr>
<tr>
<td>Transportation-service impacts</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low mileage reduction, % of uncontrolled trips</td>
<td>---</td>
<td>94.6</td>
<td>77.5</td>
<td>29.7</td>
</tr>
<tr>
<td>Trips forgone, % of uncontrolled trips</td>
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<td>49.8</td>
<td>22.3</td>
<td>-1.6</td>
</tr>
<tr>
<td>Trips by bus, % of all trips</td>
<td>---</td>
<td>48.5</td>
<td>27.9</td>
<td>18.5</td>
</tr>
<tr>
<td>Carpooling, % of home-work trips</td>
<td>---</td>
<td>100</td>
<td>84</td>
<td>20</td>
</tr>
<tr>
<td>Monetary proxy for social cost,(^c) $ millions</td>
<td>---</td>
<td>4,644.5</td>
<td>2,167.6</td>
<td>0</td>
</tr>
<tr>
<td>Financial impacts</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>Annual strategy expenditures, $ millions</td>
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<td>58.9</td>
<td>58.9</td>
<td>58.9</td>
</tr>
<tr>
<td>Retrofit</td>
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<td>311.9</td>
<td>373.5</td>
<td>538.7</td>
</tr>
<tr>
<td>Mileage surcharge</td>
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<td>2,493.1</td>
<td>786.4</td>
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<td>708.0</td>
<td>849.0</td>
</tr>
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<td>Net expenditures after transfers,(^d) $ millions</td>
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<td>4,017.9</td>
<td>2,925.5</td>
<td>1,446.6</td>
</tr>
<tr>
<td>Total cost, $ millions</td>
<td>---</td>
<td>8,862.4</td>
<td>5,093.1</td>
<td>1,446.6</td>
</tr>
<tr>
<td>Unallocated income from surcharge</td>
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<td>2,930.1</td>
<td>1,785.1</td>
<td>0</td>
</tr>
<tr>
<td>Bus-system impacts</td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Number of buses</td>
<td>---</td>
<td>7,221</td>
<td>7,221</td>
<td>7,254</td>
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<tr>
<td>Annual bus miles, millions</td>
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<td>479</td>
<td>564</td>
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<tr>
<td>Annual passenger miles, millions</td>
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<td>22,466</td>
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<td>Recurring employment</td>
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<td>44,465</td>
<td>54,601</td>
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<td>Retrofit impacts</td>
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<tr>
<td>Purchase and installation of devices</td>
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<td>1,087</td>
<td>1,087</td>
<td>1,087</td>
</tr>
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<td>16,443</td>
<td>16,443</td>
</tr>
<tr>
<td>Inspection and maintenance</td>
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<td>329</td>
<td>329</td>
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<td>10,688</td>
<td>10,688</td>
<td>10,688</td>
</tr>
<tr>
<td>Recurring employment</td>
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<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Hybrid retrofit strategy</td>
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<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Strategy composition, $/VY</td>
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<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Annualized savings, $ millions</td>
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<td>220</td>
<td>915</td>
<td>2,840</td>
</tr>
<tr>
<td>Energy impacts</td>
<td>---</td>
<td>97</td>
<td>96</td>
<td>113</td>
</tr>
</tbody>
</table>

\(^a\)See Appendix F for detailed composition.

\(^b\)80 percent of Los Angeles basin population bus-eligible (90 percent of Los Angeles and Orange Counties population).

\(^c\)Monetary proxy for social cost of forgone travel assumes $1 as the value per forgone trip.

\(^d\)Surcharge income used to offset bus subsidy to whatever extent possible.
Case C requires a $1.28-per-mile surcharge\textsuperscript{15} to produce an almost 95-percent VMT reduction. For Case C, nearly 50 percent of the nominal trips are forgone; of the remaining trips, almost 50 percent are by bus, with essentially 100 percent of the home-work trips by carpool.

Both cases require over 16,000 semiskilled mechanics for retrofit installation and over 10,000 mechanics for annual retrofit inspection and maintenance. Both cases require about 45,000 bus-system employees (the same numbers as required for the 0.10-ppm standard).

The TCP is about $5 billion for Case B (with $1.8 billion being unallocated surcharge) and $8.9 billion for Case A (with $2.9 billion being unallocated surcharge). Although the reference technical assumptions make it considerably easier for Case B, the monetary and social costs of meeting the 0.08-ppm oxidant standard are nonetheless enormous. To put these costs—and those for meeting the lesser standards—in perspective, we shall briefly discuss the health and monetary costs of not meeting these three alternative standards.

THE HEALTH AND ECONOMIC COSTS OF NOT MEETING THE STANDARDS

Although we can estimate the costs of strategies for meeting the standards, we cannot really estimate the health and economic costs of not meeting them. Thus we cannot really show the tradeoffs between coming close to the standard with a moderately costly strategy and meeting the standard with a considerably more costly strategy. To put such tradeoffs in perspective, however, several comments can be made.

The national primary standard for oxidant, 0.08 ppm, is meant to protect, with a safety margin, persons with serious respiratory problems from adverse effects. The California standard for oxidant, 0.10 ppm, is meant to prevent eye irritation and possible impairment of lung function in persons with chronic pulmonary disease and also to prevent damage to vegetation [6,7].

As reported in the \textit{Los Angeles Times}, November 14, 1973, the Air Pollution Emergency Contingency Plan adopted by the CARB, effective April 1, 1974, provides that an APCD "would call a Stage 1 or health advisory alert when oxidants reach a level of 0.20 ppm. A CARB medical committee determined that persons with respiratory and coronary problems, about 10 percent of the population, are adversely affected when pollutants reach the Stage 1 level. These persons would be warned to take precautionary measures and school students would be asked to curtail strenuous activity." (Note that if an oxidant standard of 0.20 ppm prevailed, the situation described above should obtain no more than one hour per year at the worst location in the region.)

Our knowledge of the chronic effects on humans of repeated low-level exposures to various pollutants is incomplete and inconclusive, being based on statistical studies of persons exposed to the mixtures of pollutants that occur in urban areas [7]. An EPA study [8] reports that "The national health costs of air pollution in 1968 were estimated to be $6.06 million. Studies by Ridker and by Lave and Seskin related health effects to particulate and sulfur oxide pollutants. Until better evidence is forthcoming, it is assumed that the health costs of pollution stem from particulates and sulfur oxides." These health costs include both medical costs and lost earnings.

\textsuperscript{15} Although a $1.28-per-vehicle-mile surcharge may seem surprisingly high, the reader should again recall that trip-making behavior is on a person-mile basis. This surcharge amounts to $2 per person-mile, roughly a fourfold increase over the nominal.
The study also reports that "The total national cost in 1968 of damage resulting from air pollution was $16.1 billion, which includes $5.2 billion for residential property, $4.7 billion for materials, $6.1 billion for health, and $0.1 billion for vegetation. ... The $16.1 figure is considered to be a reasonable, conservative estimate." The same report also attributes most of these costs to SO₂ and particulates. Only about $1.2 billion are attributed to oxidant (and about $0.8 billion to NOₓ), nearly all for damage to materials.

In considering these costs, it should be noted that they represent savings that might accrue from a 100-percent reduction in all emissions; estimating the savings from smaller reductions involves problems of scaling, since the functional relationship between the amount of damage and the level of emissions is basically unknown.

The above discussion is suggestive rather than definitive, but it clearly indicates the need for marginal analysis in the setting of standards: Are the additional benefits from more stringent oxidant standards worth the additional monetary and social costs of the controls? For example, if the oxidant standard were set at 0.20 ppm in Los Angeles, the health-advisory-alert situation described above should obtain for one hour no more than once per year at the worst location in the region. Tightening the standard to 0.08 ppm increases the net expenditure by about $2.5 billion and the social-cost proxy by about $2.2 billion, using Case B as an example. The questions arise, Are the corresponding health and other benefits for Los Angeles worth the costs? Can larger benefits be obtained by spending the $2.5 billion net expenditure on some alternative social policy such as the establishment of preventive-medicine clinics, the search for a cancer cure, and so forth?

References for Section 5

6. CRITICAL EVALUATION OF TECHNICAL ASSUMPTIONS

We have seen that the impacts of a given strategy are extremely sensitive to the choice of technical assumptions. Indeed, the TCP for meeting the present national primary standard for oxidant increases more than $4 billion yearly if the pessimistic assumptions are chosen instead of the reference assumptions. Considerable analysis has shown the following technical assumptions to be most important:

- Catalytic-converter effectiveness in removing reactive hydrocarbon emissions.
- LDMV emission factors (low-mileage (new-car) emission factors, age-deterioration factors).
- Hydrocarbon reactivity fractions.

Unfortunately, the "true values" for most of these technical assumptions remain uncertain. From the best information available as of mid-April 1973, we selected what seemed to be the most realistic values for Los Angeles and termed them the reference assumptions. Just prior to that time, the EPA-headquarters task force studying Los Angeles defined an alternative set combining a number of individually more conservative assumptions; these essentially correspond to the values being specified for Los Angeles by EPA Region IX in July 1973. Since they make it much more difficult and costly to meet the standards, we have termed them the pessimistic assumptions.

The remainder of this section will briefly discuss each of the important technical assumptions. (Considerable supplemental detail can be found in Appendix H.) For each assumption where there is a difference, we will critically compare the reference and pessimistic values and their sources. Table 6.1 summarizes the two sets of values. Note that the emphasis throughout is on reactive hydrocarbon emissions (and oxidant concentration), which are the primary focus of the study.

THE ROLLBACK PARADOX

Often, a particular technical assumption will have a seemingly counterintuitive effect on meeting the standards; assuming relatively "clean" vehicles rather than "dirty" ones, for example, may make it harder to meet the standards, which is certainly counterintuitive. Such counterintuitive effects generally result from the rollback paradox. Therefore, we shall discuss this concept before considering the various technical assumptions.

The paradox can best be illustrated by a hypothetical example. Suppose we are considering two alternative reactivity assumptions for mobile sources; the "low-reactivity" assumption says that there is only half as much reactive hydrocarbon in a given amount of mobile-source emissions as the "high-reactivity" assumption says there is. Intuitively, we would expect the low-reactivity assumption to make the oxidant standard easier to meet in some analysis year because it implies that cars are cleaner than under the high-reactivity assumption. But the rollback paradox reverses this. The rollback paradox arises because assumptions made for some analysis year also affect the emission calculations for the base year that determine
Table 6.1

COMPARISON OF VALUES UNDER REFERENCE AND PESSIMISTIC TECHNICAL ASSUMPTIONS

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Reference</td>
<td>Pessimistic</td>
</tr>
<tr>
<td>LIMV emission factors</td>
<td>CVS-2A\textsuperscript{a}</td>
<td>CVS-2</td>
</tr>
<tr>
<td>Catalytic-converter effectiveness, Z</td>
<td>70</td>
<td>50</td>
</tr>
<tr>
<td>Hydrocarbon reactivity, fraction of total</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motor-vehicle exhaust</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>Motor-vehicle evaporative/blowby losses</td>
<td>0.67</td>
<td>0.67</td>
</tr>
<tr>
<td>Gasoline marketing</td>
<td>0.90</td>
<td>0.93</td>
</tr>
<tr>
<td>Petroleum storage</td>
<td>0.93</td>
<td>0.93</td>
</tr>
<tr>
<td>Petroleum production and refining</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Organic solvents</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>Power plants</td>
<td>0.28</td>
<td>0.28</td>
</tr>
<tr>
<td>Diesel Exhaust</td>
<td>0.99</td>
<td>0.99</td>
</tr>
<tr>
<td>Aircraft</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jet</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td>Piston</td>
<td>0.70</td>
<td>0.70</td>
</tr>
<tr>
<td>Agriculture</td>
<td>0-0.95</td>
<td>0-0.95</td>
</tr>
</tbody>
</table>

\textsuperscript{a}Adjusted CVS-2 values.
\textsuperscript{b}Based on CARB data (see Appendix H).
\textsuperscript{c}Personal communication from Project Monitor Paul Dowling, EPA, April 18, 1973. In the case of gasoline marketing, the reactivity fraction was not furnished directly but was calculated from the EPA-furnished value of 138 daily tons of reactive hydrocarbons in 1970.

The allowable emissions to meet the oxidant standard: Consider two cases (low and high) which represent different inventories of reactive hydrocarbon emissions for the same region in a given base year. Assume that the fixed-source emissions are identical in both cases, but that, although vehicle miles are the same, the mobile-source emissions are markedly different because they were calculated with the low- and high-reactivity assumptions, respectively. The resulting base-year emission inventories might be those in Table 6.2. Assume that the maximum oxidant concentration recorded in the region in the base year was 0.40 ppm and that the oxidant standard is 0.08 ppm. The rollback technique thus requires an 80-percent reduction in reactive hydrocarbon emissions to achieve the standard in the analysis year. Further assume that fixed-source emissions in the analysis year are reduced by 50 percent from the base year, to 100 tons per day in the analysis year, with the result shown in Table 6.3.

Now assume that technological controls are available that can reduce mobile-source emissions in the analysis year by 90 percent from the base-year level. Any additional mobile-source emission reduction will be achieved by a vehicle mileage reduction, as shown in Table 6.4. Thus, the counterintuitive result is that assumptions which lead to greater mobile-source emissions being calculated for the analysis year may make it easier to meet the air-quality standards. The rollback paradox's significance depends on the relative magnitude of fixed-source and mobile-source emissions and the relative effect of assumptions on emissions in the base and analysis years.\textsuperscript{1}

\textsuperscript{1} The implications of the rollback paradox are applicable to any air-quality prediction technique that requires a percentage reduction in emissions from the amount computed in some base year.
Table 6.2
ILLUSTRATIVE BASE-YEAR EMISSION INVENTORIES

<table>
<thead>
<tr>
<th>Type</th>
<th>Reactive Hydrocarbon Emissions (tons/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Case</td>
</tr>
<tr>
<td>Fixed source</td>
<td>200</td>
</tr>
<tr>
<td>Mobile source</td>
<td>400</td>
</tr>
<tr>
<td>Total</td>
<td>600</td>
</tr>
</tbody>
</table>

Table 6.3
ILLUSTRATIVE ALLOWABLE EMISSIONS

<table>
<thead>
<tr>
<th>Item</th>
<th>Reactive Hydrocarbon Emissions (tons/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Case</td>
</tr>
<tr>
<td>Allowable total</td>
<td>120(^a)</td>
</tr>
<tr>
<td>Minus fixed-source</td>
<td>-100</td>
</tr>
<tr>
<td>Allowable mobile-source</td>
<td>20</td>
</tr>
</tbody>
</table>

\(^a\)Rollback calculation: \((0.08/0.40)600\).
\(^b\)Rollback calculation: \((0.08/0.40)1000\).

Table 6.4
ILLUSTRATIVE MILEAGE REDUCTION REQUIRED

<table>
<thead>
<tr>
<th>Item</th>
<th>Reactive Hydrocarbon Emissions (tons/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Low Case</td>
</tr>
<tr>
<td>Mobile-source with controls</td>
<td>40</td>
</tr>
<tr>
<td>Amount above allowable</td>
<td>20</td>
</tr>
<tr>
<td>Vehicle mileage reduction required,</td>
<td>50</td>
</tr>
</tbody>
</table>
CATALYTIC-CONVERTER EFFECTIVENESS

A preliminary sensitivity analysis clearly demonstrated that the success of any retrofit strategy that requires large emission reductions is strongly dependent on the assumed effectiveness of the catalytic-converter retrofit. Published EPA data [1] give a 50-percent effectiveness value for removing total hydrocarbons. (However, recent unpublished data from EPA indicate that the converter will reduce the reactivity of the exhaust gas by approximately 20 percent. Assuming the 50-percent effectiveness of total hydrocarbon removal, this implies a 60-percent reduction in reactive hydrocarbon emissions [2].) The 50-percent effectiveness value, used in the pessimistic assumptions, probably represents a lower limit, but it may be unduly pessimistic. In contrast, the value of 80 percent, based upon data from Universal Oil Products [3], the manufacturer of one such device, probably represents a practical upper limit for catalytic converters installed as a retrofit. (The device effectiveness in our discussion is for the converter only—that is, not in conjunction with any other device—although it includes an air pump if one has not already been installed.)

To improve estimates of converter effectiveness, the CARB is currently conducting an evaluation of the Universal Oil Products catalytic-converter retrofit on a 100-vehicle fleet. The reference effectiveness value of 70 percent is largely based upon the preliminary results of this project and appears to be reasonable. Indeed, in the recent revision to the state implementation plan, the CARB postulated a 73-percent reduction in reactive hydrocarbon for the retrofit.

It must be noted, however, that the CARB assumed that only 80 percent of the pre-1971 vehicles would be able to use the unleaded gasoline required by the catalyst because such fuel is low-octane. In contrast, our analysis has presumed, in accord with statements by the manufacturers, that virtually all vehicles can use the unleaded fuel required by the converter, most by modification to operate on low-octane fuel, the rest by the use of high-octane fuel that raises the octane rating with compounds other than lead.

---

1 The CARB project is intended to evaluate the effectiveness of the device on vehicles in the state fleet for a one-year period. Because of the preliminary nature of the results obtained to date, the CARB has not published any of their findings. Hence, the material presented in this section is the result of an analysis performed by the Rand staff using CARB preliminary data and should not be interpreted as representing the CARB position. Somewhat later data yielding almost identical results appear in a CARB staff report [4].

2 The CARB evaluation is being conducted with the CVS-1 test cycle (cold start only). As such, it is a stringent test of the device, since the majority of emissions (with the device installed) occur before the catalytic element has reached its normal operating temperature. (If the CVS-2 test cycle were used, which adds a hot start and additional driving at normal operating temperature, one would anticipate a higher effectiveness.) Furthermore, although it does not reflect the official position of the EPA, it should be noted that a 68-percent effectiveness (on total hydrocarbons) was assumed in a recent article by Joel Horowitz, senior staff member of the EPA Office of Air and Water Programs [5].

3 Currently, the EPA estimates [6] that only 75 percent of the 1971-74 and 20 percent of the pre-1971 model years are "capable of running adequately and without excessive engine wear on a commercially available lead-free gasoline."

4 The primary question here is the octane rating of lead-free gasoline. The commercial grades of unleaded gasoline presently being sold in California are approximately 91/92 octane [7], whereas some vehicles with high-compression engines (particularly pre-1971 models) require at least 100-octane fuel (research octane number). Some of these vehicles can be modified to use a lower-octane gasoline simply by retarding the timing a few degrees. For the remaining vehicles that still require a higher-octane gasoline, there is another solution. A lead-free gasoline with an octane rating of 101/102, AMOCO Premium (has been marketed by a major oil company (primarily in the East) for many years, and the gasoline does not poison the catalyst. Thus the real issue is whether it is practical for this brand of gasoline or its equivalent to be refined in larger quantities and distributed for use in regions requiring massive emission reductions. A secondary question is engine wear; however, a two-year test of 340 vehicles by the California Division of Highways has conclusively shown that unleaded gasoline does not result in excessive engine wear. (Information based on personal communications with the following...
The durability (nondeteriorative effectiveness) of the catalytic-converter retrofit during actual vehicle operation by the general public has yet to be adequately demonstrated. The evaluation of retrofit durability is, of course, one of the primary objectives of the CARB project, and hence more definitive data will soon be available. However, to reduce concern regarding the deterioration of the catalytic element, the incremental maintenance cost for the reference assumption includes the cost of catalyst replacement every 12,000 miles. (The platinum catalytic element can be recycled.) This requirement is practical, since our hierarchy of control retrofit strategies requires all vehicles to undergo some annual I/M scheme before the catalytic converter can be introduced as a tactic.

LIGHT-DUTY MOTOR-VEHICLE EMISSION FACTORS

The calculation of mass emissions requires the specification of emission factors. These are generally expressed in terms of mass emissions per vehicle mile and are, of course, a function of both the model year and the age of the vehicle.

The EPA has provided low-mileage (new-car) emission factors, age-deterioration factors, and average vehicle-speed correction factors based on a specific test procedure called CVS-2. The EPA requires that these CVS-2 factors be used in the preparation of implementation plans [1].

After an evaluation of the CVS-2 factors for hydrocarbons, we decided that some adjustment was necessary for the following reasons:

- The factors showed dissimilar trends with model year when compared with CARB field surveillance data.
- They are based on a relatively small sample.
- Their predicted values for 1972-74 vehicles disagree with existing California emission standards that vehicles sold in the state must meet.

The main objective of the adjustments we have made to the CVS-2 emission factors and age-deterioration factors is to reflect the model-year emission trends observed in the CARB field surveillance of more than 16,000 vehicles. We call our adjusted values CVS-2A. (See Appendix H for details.) After the CVS-2A values used in this study were developed they were revised slightly when some added data became available into a set termed CVS-2B. Since the two sets are nearly identical, we shall often discuss them generically as CVS-2B.

A discussion of the sensitivity of LDMV emission control to assumptions was given in Sec. 3. To illustrate the extreme sensitivity of results to assumptions concerning hydrocarbon emission factors, let us consider the effect of changing just one factor, using an example from the San Diego region: Suppose maximal fixed-source


\[\text{In the CARB preliminary results, device effectiveness appears to deteriorate and then to stabilize after 3000 to 4000 miles of operation. But the base-line (without the device installed) vehicle-emission measurements were performed immediately after a tune-up. Hence the deterioration of the effectiveness in the first 4000 miles is attributable not only to the device itself but to the normal deterioration in emission levels that generally occurs in time after an engine tune-up. Indeed, UOP has presented evidence [3] that such lessened effectiveness can be wholly attributed to this "normal deterioration."}\]

\[\text{In 1975, CVS-2 will become the Federal Test Procedure. It consists of a cold start and a 23-minute driving cycle, followed by a hot start and a repeat of the first 8 minutes and 25 seconds of the driving cycle. A constant-volume sample of exhaust gas is collected during the test, and mass emissions are then determined by forming weighted combinations of the cold-start and hot-start data to reflect typical urban driving patterns.}\]
control has been implemented. With application of the CVS-2B emission factors, along with the rest of the reference assumptions, an annual retrofit expenditure of $75 million could achieve the oxidant standard in San Diego County without a reduction in vehicle miles. But simply replacing the CVS-2B factor for pre-1966 vehicles with the CVS-2 value would require a 20-percent reduction in vehicle miles to meet the standard, which could also be met by increasing the annual retrofit expenditure to $102 million. (This extreme sensitivity is a direct consequence of the rollback paradox.)

HYDROCARBON REACTIVITY FRACTIONS

Hydrocarbons represent a huge class of organic substances containing carbon, hydrogen, oxygen, and sometimes substituted elements such as nitrogen, sulfur, and halogens. Few, if any, are toxic in themselves at the levels existing in even highly polluted atmospheres. But photochemical reactions occurring between some hydrocarbons and other substances in the atmosphere produce oxidants, a mixture of oxidizing substances that does cause undesirable physiological and aesthetic effects at low concentrations. Because of the complexity of oxidant photochemistry, the concentration of hydrocarbons is commonly used as a proxy to estimate the concentration of oxidants that will be produced. (It should be recognized that the use of hydrocarbons as a proxy for oxidant formation involves a large number of chemical and meteorological assumptions.)

Conventionally, what are measured in the atmosphere or in emissions are total hydrocarbons, but it is reactive rather than total hydrocarbons that are used as a proxy for oxidant. Thus, for each primary source of hydrocarbon emissions, we must specify a reactivity fraction—a factor that expresses the fraction of the total hydrocarbon emissions that might react under certain conditions to produce oxidants. This fraction is used to estimate the reactive amount contained in the total hydrocarbon emissions measured or predicted for each source.

Determining the amount of reactive hydrocarbons among the total hydrocarbons is difficult; even measurements of total hydrocarbons will vary, depending upon the analytical method used. The EPA has developed fractions, based on tests, for evaluating the reactivity of hydrocarbons from different sources, but many of their reactivity fractions are different from those (also based on tests) used by the Los Angeles APCD and the CARB. The question is, What fractions are most appropriate for conditions in Los Angeles?

We have identified three general definitions of reactivity: limit, worst-day, and legal. Limit reactivity is the maximum fraction of total hydrocarbon that could react in any region under limit conditions, given sufficient time. Worst-day reactivity is the fraction that does react in a given region under its worst conditions. Legal reactivity is the fraction set by the local APCD for reasons of administrative and technical practicality. Although legal reactivities are often the basis of administrative and technical practicality. Although legal reactivities are often the basis of regional emission inventories, they usually do not include all substances that might be chemically reactive on the worst day or at the limit. Worst-day reactivities may approximate the limit values in a region with a severe smog problem such as Los Angeles; in another region, they may be much less.

The same hydrocarbon reactivity fractions are used in both the reference and pessimistic technical assumptions, as shown in Table 6.1. But the values themselves come from different sources and thus, although they are the best available at the time, they reflect different definitions of reactivity and interpretations of experimental results. Many of the reactivity fractions employed in this study are limit reactivi-
ties that were developed by the EPA for use in Los Angeles. However, such fractions were not available for all the source categories considered. For these, we used the best available estimates from the CARB and the Los Angeles APCD and from our previous work in San Diego; these are generally lower than the limit values, some being legal reactivities and others being worst-day reactivities based upon interpretations of earlier experiments. The hydrocarbon reactivity fractions used in this study are therefore a composite, reflecting partially inconsistent interpretations of reactivity. We do not believe this composite set of reactivities is the most appropriate one for Los Angeles; it was, however, the best set available to us at the time of the analysis.

To illustrate the sensitivity of results to reactivity assumptions, we prepared two additional fixed-source inventories: the CARB/LAPCD inventory is based upon the lower reactivity fractions employed by these organizations; the Consistent EPA inventory is based upon our reevaluation of the reactivities of other substances to make them consistent with the values developed by the EPA for gasoline marketing and organic solvents. Under the Consistent EPA reactivities, the reactive hydrocarbon level from fixed sources was 876 tons daily in 1970; under the composite fractions used in this study, it was 636 tons, 73 percent of the Consistent EPA value; and, under the CARB/LAPCD fractions, it was 228 tons, only 26 percent of the Consistent EPA value. When additional controls are added, relative differences become more pronounced because the controls imposed on the gasoline marketing activities and organic-solvent users cause these sources to decline in influence with respect to the remaining sources, which show a greater variation in reactivity fraction under the different interpretations.

The use of the Consistent EPA inventory, based on limit reactivities, would make it harder to meet the standards in Los Angeles. Despite the fact that worst-day reactivities probably are close to limit reactivity values in Los Angeles, an inventory based upon limit reactivities may nevertheless be somewhat too large when compared to one based, ideally, upon a consistent set of worst-day reactivities. (See Appendix H for details.)

CONCLUDING OBSERVATIONS

Our sensitivity analysis has clearly shown that combining many individually conservative assumptions into a jointly pessimistic set will greatly increase the monetary and social costs of achieving a given air-quality standard. Although the "true values" of these assumptions remain uncertain, those in the reference set are, in our judgment, more realistic for Los Angeles than the pessimistic assumptions, which we consider unduly pessimistic. (The pessimistic assumptions essentially correspond to those being used by the EPA-headquarters task force studying Los Angeles in mid-April 1973.)

The use of unduly pessimistic assumptions has at least two serious implications. First, regions with only a moderate air-quality problem, such as San Diego, may be forced into a control strategy that is far more costly than need be. More important, regions with very severe air-quality problems, such as Los Angeles, may find that the standards cannot be attained without economic and social chaos; this, in turn, could lead to an unnecessary loosening of the standards. The data we have accumulated from EPA and CARB sources and our experience with sensitivity analyses lead us to suggest firmly that the pessimistic (EPA) assumptions should be critically reexamined.

In our analysis, we have considered EPA assumption values which were current
as of spring 1973. Since that time, however, several modifications have been made to the assumptions by various components of the EPA; some of these are less pessimistic and others are more pessimistic. Reference 8 considers the EPA assumption values as of winter 1974 and shows their influence on strategy composition and impacts.

References for Section 6

3. Price, W. R., Jr., *The UOP Miniventer: An Effective and Feasible Short Term Control Option*, statement at a special meeting on short-term control options called by the California Air Resources Board at Los Angeles, California, on October 30, 1972.
7. DESCRIPTION OF OVERALL STUDY METHODOLOGY

This section describes the overall study methodology that was used in evaluating alternative air-quality control strategies for the Los Angeles basin. This methodology, which reflects the policy orientation of the study, was designed to assist in the evaluation of a large number of conceptual strategies defined in relatively gross terms, and to emphasize breadth of scope rather than depth of detail. We will first discuss the methodology components, then interactions and data flows between them, and finally our general analytical approach.

METHODOLOGY COMPONENTS

All of the models and methods have been tailored to Los Angeles’ particular characteristics, but at the same time they have purposely been made general enough to be easily adapted for use in similar studies of other regions.¹ To provide flexibility, the inputs necessary to describe a strategy have been held to a minimum. They have been carefully selected to capture the most important characteristics of the alternative strategies and to be useful in estimating the full range of impacts. The methodology includes the following major components:

- The fixed-source analysis techniques [1] evaluate the cost and effectiveness of controls on fixed sources, which include aircraft. They also estimate the distribution of costs among various civilian industries and the military.
- The motor-vehicle emission and cost (MOVEC) model [2] evaluates the cost and effectiveness of retrofit and I/M strategies for in-use vehicles. MOVEC also reports detailed impacts for each retrofit strategy considered, including the increase in fuel consumption and the distribution of retrofit costs among different income groups.
- The transportation model [3] evaluates the costs and effects of transportation-management strategies such as added gasoline taxes or improved bus service. Unlike other models, it considers induced changes in the number of trips, amount of carpooling, and degree of congestion. It reports detailed transportation-service impacts, both in the aggregate and as distributed among income groups and travel purposes, and also various economic impacts.
- The bus-system cost model [4] is used to estimate the annualized costs of providing a particular quantity and quality of bus service to a region. Another form of the model (the aggregate bus cost model) is incorporated in the overall transportation model where it is used to estimate total annualized cost for each bus system considered. The full model, run separately, estimates not only the detailed costs of each promising bus alternative but also a variety of economic and financial impacts such as employment, fuel consumption, and taxes.
- The tradeoff model [5] is used to find the best combination, i.e., the superior strategy, given a fixed-source control strategy, a menu of vehicle retrofit strategies, and a menu of transportation-management strategies. The best combina-

¹ To illustrate, the tools were originally developed in the San Diego Clean Air Project and tailored to the San Diego region. They were adapted and applied to the Los Angeles region in just a few weeks to study oxidant control strategies for Los Angeles.
tion is defined as the one that meets the desired air-quality standard for the
minimum value of the total-cost proxy (TCP), where this proxy includes both the
net expenditure for strategy components and the monetary proxy for the social
cost of forgone travel.\footnote{All expenditures and costs are expressed as annual values; the investment costs have been annual-
ized by means of a capital-recovery factor. The "net expenditures" reflect the transfer of mileage sur-
charge revenue to offset the cost of bus improvements to whatever extent possible. When people are forced
to alter their normal behavior by forgoing trips or switching to less desirable modes, they experience a
loss in social value—the social cost of forgone travel. We use the number of forgone trips as a proxy for
this social cost and monetize it by multiplying this number by the dollar value of a forgone trip (suitably
derived). This is discussed in Sec. 5.} The tradeoff model reports a variety of economic, environ-
mental, and transportation-service impacts for the superior strategy it selects;
most of the transportation-service impacts come directly from the transporta-
tion model, which operates within the tradeoff model as a subroutine. The
tradeoff model also performs sensitivity analyses automatically for certain fac-
tors; for example, if alternative air-quality standard levels are specified for a
particular species, then the model will automatically select the superior strategy
for each level from the given menu, thereby showing how superior-strategy
composition and cost vary with the level of the standard.

- The \textit{air-quality model} determines the percentage reduction in base-year em-
issions required to meet each air-quality standard. This percentage is then multi-
plied by the total emissions in some base year\footnote{The base year is one for which there are detailed air-quality measurements and sufficient informa-
tion for compiling a total-emissions inventory.} to determine the allowable
emissions under that standard for any year.

- \textit{Techniques for the calculation of total base-year emissions} are described in Ref.
2.

Summary descriptions of the important analytical models are presented in Ap-
pendix I.

INTERACTIONS AND DATA FLOWS BETWEEN
METHODOLOGY COMPONENTS

Figure 7.1 is a system flow chart of the Rand-developed methodology used to
analyze the impacts of regional air-quality control strategies. This flow chart shows
the primary interactions and data flows between the major methodology compo-
nents. Many of these components (e.g., the MOVEC and bus-system cost models) are
useful as freestanding analytical tools. However, since it serves as the hub of the
overall methodology, as indicated in the flow chart, we shall describe the data flows
from the perspective of the tradeoff model.

The initial inputs (upper right-hand corner of the flow chart) to the tradeoff
model are the case description, the dollar value of a trip forgone, and the bus-system
coverage (in terms of area and population served); the case description includes
items such as the analysis year, regional population, and basic transportation infor-
mation.

The next inputs to the tradeoff model (moving from right to left on the flow chart)
are coefficients for the aggregate bus cost model, which are generated by the bus-
system cost model from parameters describing the institutional characteristics and
cost situation of the local bus company. The transportation model uses these coeffi-
cients to estimate the cost of the bus system in terms of the number of buses, annual
bus mileage, etc. Various strategy components are input next: (1) A menu of bus
Fig. 7.1—Methodology components: interactions and data flows
systems is described in terms of alternative combinations of headways and fares. (2) The allowable range of LDMV mileage surcharge is specified. (3) An analysis of fixed sources (including aircraft) is made. The cost of a specific fixed-source control strategy is then input directly to the tradeoff model, while the corresponding fixed-source emissions are input to the MOVEC model and subsequently passed to the tradeoff model, along with emissions from all sources other than LDMVs (e.g., heavy-duty trucks) previously input to MOVEC. (4) Composite cost and effectiveness parameters for each of the LDMV retrofit strategies being considered are input to the tradeoff model for use in calculating the effects of retrofit strategies; these parameters are calculated by MOVEC from a menu of retrofit strategies and a semipermanent data set that includes a particular choice of technical assumptions, as well as the vehicle use characteristics, etc. The total emissions in the base year, which were calculated in a separate analysis and provided to MOVEC, are input to the tradeoff model, which then determines the allowable emissions under a particular standard by multiplying the base-year emissions by the percentage reduction required to meet that standard.

This required percentage reduction in base-year emissions is the final input to the tradeoff model. The air-quality model calculates one such percentage for each quality standard being considered.\(^\text{4}\)

Using all the above information, the tradeoff model calculates the costs and emissions for all possible combinations from a given menu of strategy components and then selects the best combination, i.e., the superior strategy. This selection process, as defined earlier, involves meeting the standards while minimizing the TCP. The effects of transportation-management strategies—including the amount of forgone travel, carpooling, and congestion—are calculated by the transportation model operating as a subroutine. The emissions that the tradeoff model calculates for each combination, with vehicle emissions corrected for speed, are compared with the allowable emissions under a particular air-quality standard to determine whether or not it meets that standard. Along with various economic, environmental, and transportation-service impacts for the superior strategy selected, the tradeoff model also outputs the actual percentage reduction in emissions.

**GENERAL ANALYTICAL APPROACH**

The primary goal of this study is to help decisionmakers identify superior strategies for air-pollution control in Los Angeles. But, given both fixed and mobile sources, potential strategies involve a multitudinous array of controls so vast that it becomes impractical to evaluate all feasible combinations. It is therefore necessary to use a three-step process in the search for a preferred strategy.

**Identifying Promising Component Strategies**

First, we identify a reasonable number of the most promising component strategies for fixed-source (including aircraft) controls, retrofit, and transportation management. The most promising component strategies are those that are most cost-effective in reducing emissions. By using a cost-effectiveness criterion, we screen feasible combinations of control tactics so as to obtain a manageable number of

\(^\text{4}\) To automatically investigate the sensitivity of results to the choice of standard and air-quality model, the tradeoff model can, in one run, consider five alternative standard levels for a particular species and employ three alternative air-quality models besides linear rollback.
promising component strategies to be subjected to further analysis. The screening process for fixed-source strategies employs the fixed-source analysis techniques, that for retrofit strategies employs the MOVEC model, and that for transportation-management strategies employs both the transportation and tradeoff models. In this context, the cost of a component strategy is its annualized cost (for procurement and operation), and its effectiveness is the amount by which it reduces emissions, primarily of reactive hydrocarbons, the most troublesome pollutant in Los Angeles.

**Identifying Superior Strategies**

Second, as an adjunct to screening, superior combinations of the promising component strategies are identified by using the tradeoff model. Given a specific fixed-source strategy, a specific menu of retrofit strategies, and a specific menu of transportation-management strategies, the tradeoff model finds the best combination of what it was given—a superior strategy. Generally, a set of tradeoff runs must be made in order to consider a full menu of fixed-source strategies, since the model can consider only one per run, and to refine the original menu of transportation-management strategies with experience, since their effectiveness is partially dependent on the effectiveness of the retrofit strategies. From this set of tradeoff runs comes a set of superior strategies for further evaluation.\(^5\)

Here, the criterion for identifying superior strategies—meeting the air-quality standards while minimizing the TCP—has been more comprehensive than the cost-effectiveness criterion that was used to identify promising component strategies. But this is still not a sufficiently comprehensive criterion for selecting the preferred strategy for implementation.

**Evaluating and Comparing Superior Strategies**

Finally, the set of superior strategies is evaluated and compared in terms of their many impacts on the region. These impacts—transportation-service, economic, environmental, distributional—are estimated for each superior strategy and then presented to decisionmakers for the comparison of alternatives. The various impacts may be shown on a "scorecard"—a table that shows, by color code, the ranking of each strategy for a particular impact. The decisionmakers can then add to this factual knowledge their feeling for human and societal values—the intangibles necessary for humane decisionmaking. (Reference 6 describes the scorecard concept and general approach.)

Most of the impacts for the scorecard are calculated directly by the various methodology components discussed previously. A few other impacts, primarily various kinds of employment, are calculated by applying ad hoc techniques to certain outputs from the methodology components. For example, the cost estimates that MOVEC provides for the installation and maintenance of retrofit devices are used to calculate the nonrecurring and recurring direct employment for mechanics.\(^6\) Similarly, the reduction in annual miles, estimated by the transportation model, can be used to calculate the reduction in direct employment for service-station attend-

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\(^5\) Indeed, there will usually be several sets generated for purposes of sensitivity analysis: one set of strategies may be made for one year and certain technical assumptions, a second set for another year, and a third set for another set of assumptions.

\(^6\) The nonrecurring and recurring direct employment are estimated by taking the total annual labor cost for retrofit installation and maintenance, respectively, and dividing them by an estimate of the average salary (including overhead) of a semiskilled mechanic in Los Angeles.
In turn, changes in the direct employment of one sector of the regional economy produce changes in the employment of interrelated sectors, and this is called indirect employment; e.g., an increase in mechanics should increase employment for their local suppliers. A regional input/output model similar to that in Ref. 7 can be used to estimate these indirect employment effects.

References for Section 7


Reductions in service-station employment are estimated by assuming that such employment is proportional to miles driven annually.
Appendix A

DESCRIPTION OF CANDIDATE RETROFIT DEVICES

Crankcase-Blowby Control. This tactic consists of installing a positive crankcase ventilation system to reduce blowby emissions. We assume that all vehicles operating after calendar year 1969 have the device for the following reasons. In 1961, most new vehicles were voluntarily equipped with the device; it became mandatory for domestically produced new vehicles in 1961 and for foreign ones in 1964. Beginning in 1964, most California counties (including Los Angeles) have required installation of this system on cars not so equipped upon initial registration in California or upon transfer of ownership. Hence, we assume that all 1960-55 vehicles have had this system retrofitted by 1970, and newer vehicles have it from retrofit or original equipment. The effect of this control tactic is assumed to be independent of any other retrofit control that may be installed.

Evaporative-Loss Control. This retrofit system is intended to reduce gasoline evaporative losses from the vehicle storage tank and other elements of the fuel system. In principle, it is much the same as evaporative controls required on all light-duty vehicles sold in California beginning in 1970. The Environmental Quality Laboratory at California Institute of Technology recently completed a study [1] of the feasibility of this control tactic. They concluded that it is an entirely practical and effective retrofit for reducing hydrocarbon evaporative emissions. The effect of the evaporative-loss control tactic is assumed to be independent of any other retrofit control that may be installed.

Vacuum-Spark-Advance Disconnect [2]. This tactic consists simply of disconnecting and plugging the vacuum-spark-advance line. (Only those vehicles equipped with both a centrifugal spark advance and a vacuum spark advance are eligible.) The result is a significant reduction in NOx emissions accompanied by small reduction in hydrocarbon emissions. Vehicles using this tactic generally experience temperature increases in both the exhaust gas and the radiator coolant. To ensure adequate drivability, the engine timing and carburetor settings should be adjusted at the time of the disconnect.

Control Kit for Oxides of Nitrogen [3-7]. In November 1971, the State of California enacted legislation permitting the CARB to approve retrofit devices that would reduce emissions of NOx on 1970-66 vehicles while conforming to statutory criteria for cost and effectiveness. Devices approved by the CARB to date utilize an exhaust-gas recirculation system, vacuum-spark-advance disconnect, or both. We represent these different devices by a single tactic with a given cost-effectiveness.

Pre-1966 Retrofit Kit [8,9]. California law also provides for accreditation by the CARB of retrofit devices for 1965-55 vehicles that reduce emissions of hydrocarbon, carbon monoxide, and NOx while conforming to statutory criteria. Two such devices have thus far been approved, both requiring a tune-up to low-emissions specifications and a vacuum-spark-advance disconnect with either a thermal override switch (to prevent overheating) or an electronically controlled speed sensor for reconnecting the vacuum advance under certain driving conditions. Again, we consider these devices to represent a single tactic.

Catalytic Converter [10-12]. A catalytic converter is a muffler-type device that accelerates the oxidation of hydrocarbons and carbon monoxide in exhaust gas
to water and carbon dioxide. Large emission reductions are thus made possible, and most new vehicles in 1975 will be equipped with catalytic converters so that stringent 1975 Federal emissions standards can be attained. All catalysts developed to date require the use of lead-free gasoline to prevent poisoning of the catalytic element.

The CARB is presently evaluating a catalytic converter developed as a retrofit device for 1974-55 vehicles. Preliminary results of this evaluation indicate that the device is a practical means of achieving substantial reductions in total hydrocarbon and carbon monoxide emissions.\(^1\) Even more substantial reductions in reactive hydrocarbon emissions have been observed. Furthermore, tests to date show that the catalyst should remain effective for at least 12,000 miles. The effectiveness of the device beyond 12,000 miles has not yet been adequately demonstrated, and hence to insure its durability, we have assumed that the catalytic element is replaced once each year and we have included this cost in our calculations. The platinum catalyst used in this retrofit device can be recycled.

**Thermal Afterburner—Rejected [13-14]**. A thermal afterburner oxidizes exhaust gases by introducing additional air into a manifold (as near the engine as possible) in an attempt to complete the combustion process. Current indications are that an afterburner would be more costly but no more effective than the catalytic converter. The afterburner can, however, use ordinary fuel, unlike the catalytic converter, which requires unleaded fuel. Unfortunately, a commercially viable afterburner has not been developed. Hence, we rejected the afterburner as a practical retrofit tactic for the 1975-77 time frame.\(^2\)

**Gaseous-Fuel Conversion—Rejected [14-16]**. A number of gaseous-fuel conversion kits (liquid natural gas, compressed natural gas, and liquid propane gas) are commercially available. However, because of the large initial investment required, the limited range of the converted vehicles, and the sparseness of fuel distribution facilities, the conversion appears more practical for fleet vehicles than ordinary vehicles. When compared with the competing catalytic-converter retrofit, the gaseous-fuel conversion is more expensive (assuming all costs are annualized and then expressed in terms of cost per mile) but no more effective in reducing emissions.

The gaseous fuel causes some loss in peak power and its tanks occupy a substantial fraction of vehicle trunk space. Moreover, with the currently developing energy crisis, there is uncertainty about the gaseous-fuel supply. For these reasons, we have rejected gaseous-fuel conversion as a generally applicable LDMV retrofit tactic. Furthermore, even for fleet vehicles, gaseous-fuel conversion may not be the most cost-effective tactic.

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\(^1\) Personal communication with A. Donnelly, California Air Resources Board, Vehicle Test Facility, El Monte, California, December 1972 to August 1973.

\(^2\) The necessity of using unleaded gasoline may restrict the applicability of the catalytic-converter retrofit. (In our view, however, whether or not the oil companies can produce sufficient amounts of unleaded gasoline is the more critical question.) If subsequent research shows the limitation to be significant, then the thermal afterburner should be reconsidered as an alternative to the catalytic converter.
PREFACE

Near the beginning of 1973, the U.S. Environmental Protection Agency (EPA) announced that meeting the national primary Air Quality Standard for oxidant in the Los Angeles Air Quality Control Region might require vehicle mileage reductions in excess of 80 percent, which would be achieved by massive gasoline rationing. Since the announcement was based upon a preliminary analysis, a special task force was formed at EPA headquarters in Washington, D.C., to perform an in-depth analysis of the problem and to search for alternative strategies that might cause smaller economic and social disruptions in the region than massive gas rationing would. All this was to be accomplished within a few months.

In support of this effort, The Rand Corporation undertook a study to assist the EPA task force in screening strategy alternatives, identifying superior strategies, and investigating the sensitivity of the superior strategies to various assumptions.

The results of that study were transmitted quickly and informally to the EPA task force by means of progress reports and briefings. After completion of the study, Rand issued informal working notes describing the policy results and the methodology. Rand's contract with the EPA\(^1\) required only that the results of the study be documented informally for the task force's use; it did not provide resources for the formal publication and widespread distribution of a project report. Because considerable outside interest has been expressed in the study, however, Rand has used its own resources to expand, refine, and integrate these informal notes and to publish the present report. Its purpose is to summarize the policy results of the study and to present an overview of the analysis methodology. The analysis is based upon the state of knowledge in spring 1973. The results should therefore be viewed in that context, although the report is being published and distributed somewhat later.

It should be noted that our study of alternative oxidant-control strategies for Los Angeles benefited considerably from tools and results previously developed as part of the San Diego Clean Air Project.\(^2\) Indeed, not only were some of the tools developed in San Diego successfully transferred and applied in the context of the Los Angeles study, but some examples and text from the San Diego project's summary report have been incorporated in this report to help amplify and clarify the discussion of methodology and assumptions.

\(^1\) The work upon which this publication is based was performed in whole or in part under Contract No. 68-01-0475 with the Office of Research and Development, Environmental Protection Agency.

\(^2\) A joint venture of San Diego County and The Rand Corporation, the Clean Air Project sought strategies for meeting the national Air Quality Standard in San Diego as specified by the 1970 Amendments to the Clean Air Act. It represented a pioneering effort to analyze a comprehensive menu of alternative strategies in terms of their many impacts on the quality of life in a region. The Clean Air Project was supported by a grant to San Diego County from the EPA and by contributions from local sources.
References for Appendix A


Appendix B

COMMENTS ON LESS PROMISING TRANSPORTATION-MANAGEMENT STRATEGIES

In addition to the most promising transportation-management strategies listed in Sec. 4, several other strategies were considered in an auxiliary sensitivity analysis. These were found to be considerably less promising, however, and were not used in constructing superior strategies. Here we shall briefly list some of these strategies and discuss why they seem less promising. Only the final one appears to offer appreciable hydrocarbon reductions.

Traffic-Flow Improvements. Various policies such as metering freeway ramps or removing bottlenecks have been proposed to improve vehicle speeds and thereby reduce the emission rate per vehicle mile. These tactics are generally ineffective for the following reasons: First, only small improvements in average trip speed can be expected from such tactics because most miles on most trips are driven on residential streets and on the parts of the arterial and freeway network that would be unaffected by these tactics. Second, when there is extensive vehicle retrofit (which is very likely if the standards are to be met), then even extreme improvements in speed cannot achieve significant emission reductions. We elaborate on the reasons below.

The influence of average trip speed on LDMV emissions is well established. Increasing the average speed decreases hydrocarbon and carbon monoxide emissions but increases NOx. But, as speed increases, what will be the net effect of the opposing changes in reactive hydrocarbon and carbon monoxide emissions on the one hand, and NOx emissions on the other? Although NOx emissions may meet their own air-quality standard, they can nevertheless exacerbate the oxidant problem because they react with reactive hydrocarbon to produce photochemical smog and its oxidant component. Clearly, we need a measure of the relative importance of both kinds of emissions in forming photochemical smog. One such measure is reactive emissions, developed by the Technical Advisory Committee to the CARB.1

Figure B-1 compares the effectiveness of various tactics that improve average trip speed, using a San Diego example. Specifically, we compare, for two extremes of average speed, the reactive emissions from LDMVs as the amount of retrofit increases through the 28 promising strategies. The two average speeds considered—25 and 45 mph—are extremes in that the former corresponds to the average trip speed experienced in most major urban areas [2], whereas the latter represents a much greater speed improvement than appears possible in San Diego—or Los Angeles (as will be shown). Figure B-1 indicates that once a large amount of retrofit has been implemented—which is likely to occur if the clean-air standards are to be met—then even extreme improvements in speed can produce essentially no additional emission reductions. The potential for appreciable improvements in average trip speed is scant. Trips take place on a mixture of residential streets, arterials, and freeways. The average speed for a trip is thus a weighted combination of the trip times on the various streets. Since speeds on residential streets and arterials depend heavily on speed limits and stops, and since a substantial fraction of all trips—long

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1 Reactive emissions consist of 100 percent of the reactive hydrocarbon plus 50 percent of the NOx. This measure and its correlation with photochemical smog are discussed in Ref. 1.
and short—are driven on such streets, it can be seen that even substantial improvements in freeway speed could produce only small improvements in average trip speed for the region.

For these reasons, we conclude that tactics explicitly designed to improve average speed offer little promise for significant emission reductions in Los Angeles. Nevertheless, in examining other tactics (e.g., reducing vehicle miles), we do consider their indirect influence on average trip speed and its effect on emissions, as discussed in Sec. 7.

Traffic Priorities to Buses and Carpooling. Various priority policies have been proposed for dedicating certain freeway (and arterial) lanes for use solely by buses and carpooling. The intent of these policies is to reduce the bus and carpool trip times so as to provide time incentives for people to switch from the low-occupancy auto mode. Unfortunately, these policies do not produce sufficient time savings to cause many people to alter their normal (i.e., uncontrolled) trip-making behavior. With respect to carpooling, consider this example: An average work trip is 10 miles long, of which 2 miles are spent on residential streets at an average speed of 15 mph, 4 miles on arterials at an average speed of 25 mph, and 4 miles on freeways. If the speed on the freeway portion of the trip is 35 mph—the peak-period average on congested freeway lanes—then the trip time is 28 minutes, of which 14.4 minutes were spent on surface streets. Yet if the freeway speed were doubled to 70 miles an hour, this would only reduce the trip time to 24 minutes—a saving of at most 4 minutes. A time saving of this magnitude seems unlikely to cause most travelers to alter their trip-making behavior in favor of carpooling, particularly when the time penalty for picking up the carpoolers would generally exceed 4 minutes. Fur-

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2 See the discussion in Ref. 3 of the "street mix usage function" in Sec. II and "network loading" in Sec. V.
thermore, these policies would not offer perceptible time savings for the substantial fraction of trips and vehicle miles generated in the off-peak period.\(^3\)

With respect to buses, similar arguments hold. Local bus speeds and hence travel times are dominated by the number of stops, not the congestion; hence these policies would be ineffective. Express bus travel times would not improve substantially compared to auto travel times for the same reason as is given above for carpools—the time savings of the priority policies are small compared to the trip time spent traveling on other streets, stopping, etc.

**Parking Policies.** Policies that increase parking charges are considerably less effective than mileage surcharges; a parking charge is a fixed cost and thus has its greatest effect on the shortest trips, which contain a small fraction of vehicle miles, whereas the mileage surcharge has its greatest effect on the longest trips, which contain most of the VMT.\(^4\) Policies that reduce the availability of parking places can be analyzed similarly. Reducing the availability of parking places in an area can be thought of as creating a time penalty while searching for a parking place; this time penalty is a fixed penalty and hence is most effective against the shorter trips, which contain only a small fraction of the total VMT.

**Land-Use Changes.** The length (and hence vehicle mileage) of trips can be reduced by bringing origins and destinations closer together. Such locational changes may result from the implementation of long-term land-use/transportation plans, but they cannot happen to any practical extent in the near term (i.e., the 1970s).

**Bicycle Policies.** Various policies of dedicated bikeways, preferential treatment for bikes on highways, bicycle parking by or piggybacking on buses, and so forth, have been proposed to make bicycles more attractive and thus provide incentives to switch from automobile travel. Unfortunately, the shortest auto trips are the ones that are most likely to be switched, and these contain only a small fraction of the miles traveled. Consider an optimistic example: Trips whose length is 4 miles or less constitute about 45 percent of all trips but only about 12 percent of the miles traveled, as shown in Sec. 4. Making an optimistic assumption, suppose that 10 percent of these short trips are switched to bicycle (i.e., that bicycle gets a 10-percent modal split of these trips). The resulting mileage reduction would be only 1.2 percent. Note also that most of these are not commuter trips but shopping and school trips where bundles and children must be carried; such trips may not be fully compatible with the bicycle or be appreciably influenced by the policies proposed.

**Four-Day Workweek.** The four-day workweek has been proposed as a means to reduce emissions, with implementation by a variety of policies. Although it is difficult to calculate the economic and social costs of converting to a four-day workweek, it is easy to estimate the range of potential emission reductions. For the

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\(^3\) However, the choice of a carpool over a low-occupancy auto (or, indeed, bus over auto) reflects not only the overall trip time (including any carpool pick-up time) but also the overall trip cost, where both are on a per-person rather than per-vehicle basis. Thus, if substantial increases in the price of gasoline occur (which give the same kind of cost incentives as a mileage surcharge) and if carpool-matching schemes become widely available, it is possible that these priority policies could influence an appreciable fraction of the longest trips in the region. This could make priority policies seem unexpectedly effective, since, although few in number, these trips contain a high percentage of the total regional VMT. We were precluded from considering this possibility in the present study by time and resource limitations.

\(^4\) The EPA Final Implementation Plan of October 15, 1973, specifies a parking surcharge of 25\(^a\) per hour. For a typical work trip involving 8 hours of parking, this amounts to a surcharge of $2 per trip. Since the average work trip in Los Angeles is 20 miles round trip, this would be approximately equivalent to a surcharge of 10\(^b\) per mile. This mileage surcharge, however, should produce considerably greater mileage reductions than the parking surcharge. Indeed, we have found that when appreciable changes in travel behavior are desired, it may cost the region at least three times as much to produce the change by parking surcharge as it would by mileage surcharge.
present five-day workweek, the typical vehicle averages 33.8 miles per day during the workweek and 27.6 miles per day during the weekend [2]. Assuming these same rates hold for a four-day workweek, then a 3-percent emission reduction should result. On the other hand, it is possible that the amount of driving on a regularly occurring three-day weekend could approximate that on a present two-day weekend if most weekend mileage should prove independent of weekend duration (e.g., if the number of church and shopping trips remained constant and if these contained most of the miles). From this optimistic viewpoint, the four-day workweek could produce emission reductions approaching 15 percent.

References for Appendix B

Appendix C

SUPPORTING DATA FOR FIXED-SOURCE STRATEGIES

This appendix provides four sets of supporting data for the fixed-source strategies: (1) a detailed emission inventory for fixed sources under the 1975 nominal strategy; (2) a discussion of the practical aspects of vapor-adsorption systems, which are promising but controversial, as a pollution-control device; (3) a description of additional NOx controls; and (4) a detailed emission inventory for fixed sources under the 1975 maximal strategy.

DETAILED EMISSIONS INVENTORY FOR THE 1975 NOMINAL STRATEGY

Table C-1 shows the estimated daily emissions under the 1975 nominal strategy, broken down by source category, for each pollutant. The controls and their effects were discussed, pollutant by pollutant, in Sec. 2.

SOME PRACTICAL ASPECTS OF VAPOR- ADSORPTION SYSTEMS FOR AIR-POLLUTION CONTROL

In theory, vapor-adsorption systems have considerable promise as pollution-control devices, primarily for controlling reactive hydrocarbon emissions from organic-solvent users. Vapor-adsorption systems exist and are routinely applied in various industrial applications. But the question arises, Are they now—or with what modifications could they become—practical for pollution-control applications?

Background

The industrial use of adsorption of vapors on finely dispersed, activated solid surfaces for various purposes dates back to 1922. The process was an outgrowth of knowledge gained from gas-mask technology during WWI. Activated charcoal was the original—and is still the most widely used—adsorption material, although many other substances are available for special purposes [4]. The adsorption process works best for vapors having molecular weights somewhat higher than air and is especially useful where concentrations of vapors lie between one part in one hundred and one part in one million of air—a concentration range where incineration becomes more costly for air-pollution control. Equipment in a wide range of sizes and adsorption characteristics is available off-the-shelf, and the state of the art is highly developed.

Until quite recently, adsorption was primarily used to recover valuable solvents from industrial-process equipment vents rather than for air-pollution control. Adsorption for solvent recovery has been less widely used in the more recent decades because capital-equipment costs have risen with respect to solvent costs. Solvent costs in general have decreased in comparison with those of other commodities, so there has been less motivation to install adsorption equipment for solvent-recovery purposes [4]. Solvent recovery in this context appears to become marginal at a
### Table C-1

**ESTIMATED DAILY EMISSIONS FROM FIXED SOURCES: 1975 NOMINAL STRATEGY**

(tons/day)\(^a\)

<table>
<thead>
<tr>
<th>Emission Source</th>
<th>THC</th>
<th>RHC</th>
<th>Particulates</th>
<th>NO(_2)</th>
<th>SO(_2)</th>
<th>CO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petroleum</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production b</td>
<td>122.8</td>
<td>--</td>
<td>0.4</td>
<td>19.8</td>
<td>5.8</td>
<td>--</td>
</tr>
<tr>
<td>Refining</td>
<td>48.5</td>
<td>5.4</td>
<td>4.3</td>
<td>23.5</td>
<td>42.9</td>
<td>5.3</td>
</tr>
<tr>
<td>Marketing</td>
<td>17.4</td>
<td>16.2</td>
<td>--</td>
<td>11.8</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>188.7</td>
<td>21.6</td>
<td>4.7</td>
<td>55.1</td>
<td>48.7</td>
<td>5.3</td>
</tr>
<tr>
<td>Organic-solvent users</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface coating</td>
<td>132.5</td>
<td>106.0</td>
<td>9.9</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Dry cleaning</td>
<td>0.4</td>
<td>0.3</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Degreasing</td>
<td>6.0</td>
<td>0.0</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Other</td>
<td>88.5</td>
<td>70.8</td>
<td>6.6</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>227.4</td>
<td>177.1</td>
<td>16.3</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Chemical</td>
<td>--</td>
<td>--</td>
<td>0.5</td>
<td>0.2</td>
<td>21.7</td>
<td>--</td>
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<tr>
<td>Metallurgical</td>
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<td>16.6</td>
<td>3.2</td>
<td>34.8</td>
<td>3.2</td>
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<tr>
<td>Mineral</td>
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<td>--</td>
<td>21.2</td>
<td>5.9</td>
<td>0.8</td>
<td>--</td>
</tr>
<tr>
<td>Incineration</td>
<td>24.1</td>
<td>2.0</td>
<td>11.9</td>
<td>3.6</td>
<td>0.3</td>
<td>34.4</td>
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<td>Combustion of fuels</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Steam power plants</td>
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<td>0.2</td>
<td>4.3</td>
<td>129.6</td>
<td>38.3</td>
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<td>Other industrial</td>
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<td>0.1</td>
<td>9.4</td>
<td>94.9</td>
<td>9.1</td>
<td>1.2</td>
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<tr>
<td>Domestic &amp; commercial</td>
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<td>0.2</td>
<td>10.4</td>
<td>64.2</td>
<td>0.6</td>
<td>0.4</td>
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<tr>
<td><strong>Total</strong></td>
<td>15.3</td>
<td>0.5</td>
<td>24.1</td>
<td>288.7</td>
<td>48.0</td>
<td>1.6</td>
</tr>
<tr>
<td>Lumber</td>
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<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Agriculture</td>
<td>24.1</td>
<td>10.6</td>
<td>9.9</td>
<td>0.5</td>
<td>1.7</td>
<td>20.7</td>
</tr>
<tr>
<td>Aircraft</td>
<td>69.2</td>
<td>28.1</td>
<td>26.6</td>
<td>23.6</td>
<td>4.7</td>
<td>242.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>549.9</td>
<td>239.9</td>
<td>131.8</td>
<td>380.8</td>
<td>161.7</td>
<td>307.2</td>
</tr>
</tbody>
</table>

**Total/1970 level, %**

<table>
<thead>
<tr>
<th>THC</th>
<th>RHC</th>
<th>Particulates</th>
<th>NO(_2)</th>
<th>SO(_2)</th>
<th>CO</th>
</tr>
</thead>
<tbody>
<tr>
<td>54.3</td>
<td>37.7</td>
<td>86.6</td>
<td>100.0</td>
<td>61.6</td>
<td>101.6</td>
</tr>
</tbody>
</table>

**SOURCE:** Growth factors and reductions in pollutants other than hydrocarbons from CARB Implementation Plan [1]; reduction in hydrocarbons and reactivity fractions from EPA ([2] and personal communication with Mr. P. Downing, April 18, 1973).

\(^a\)The various totals may differ slightly from the sum of their components as shown, due to rounding.

\(^b\)Adjusted to account for replacement of internal combustion oil-pump engines by electrical engines [3].
solvent cost of about 50¢ per gallon, although this break-even point varies depending upon the concentration of the vapors in the vented air, the adsorption characteristics of the vapors, and the investment policy of the company. Adsorption for solvent recovery loses much of its value if different solvents are employed in the same venting system. The mixture of solvents then recovered from the absorbent upon regeneration is almost useless.

Regeneration equipment for the individual user is commonly available. However, adsorption-system manufacturers will pick up saturated adsorbers and deliver reactivated ones if desired.

Manufacturers of equipment support our findings in San Diego [5] that many users of expensive solvents—e.g., dry cleaners employing halogenated solvents, degreasers, and other specialty-solvent users—would save money by adding adsorption equipment for solvent recovery. On the other hand, users of inexpensive petroleum solvents—e.g., petroleum-solvent dry cleaners—cannot gain by recovering the cheap solvent. The vapors are usually widely dispersed in such plants, so that much air must be moved through a recovery system, thus increasing equipment and operating costs. As an indication of these costs, in our study of air pollution in San Diego we assumed the vapors to be uniformly distributed; to move sufficient air (and vapor) to maintain the health standard (less than 500 ppm solvent vapor) would require an annual cost of about $2700 per average-size plant to remove 18.6 tons. Inasmuch as at least 50 percent of the vapors removed are somewhat reactive, the cost per ton of removing this reactive material is $290, given the emissions from this source in San Diego. According to manufacturers, because of these costs, no petroleum-solvent users in this country remove vapors by adsorption; however, there is no known technical obstacle to this practice. Presently, petroleum-solvent users vent their vapors to the atmosphere. The solvents are slightly modified to meet rules similar to the Los Angeles APCD’s Rule 66, but they still contain photochemically reactive materials.

In addition to the mixed-solvents problem, adsorption systems present another operational difficulty: Adsorbers can selectively remove deterioration inhibitors added to certain, more costly, halogenated solvents. Without inhibitors, the solvents can break down, become less effective in doing their job, and become more photochemically reactive [4]. This adsorption characteristic weighs particularly heavily on the use of 1,1,1-trichloroethane, a very effective, nonreactive solvent for degreasing. This solvent can be recovered by condensation (95 percent), but the difference between this recovery and the 98 to 99 percent realizable by adsorption is a significant financial loss.

It appears that an immediate solution to this difficulty would be to add (automatically, if necessary) new inhibitor to the regenerated solvent. However, it is allegedly against the marketing policy of the Dow Chemical Company, the principal manufacturer of 1,1,1-trichloroethane, to sell the inhibitor separately, unmixed.

1 Personal communication from R. Wollman, Barnaby-Cheney Company, Los Angeles.
2 Personal communication from J. G. Hayes, formerly of American Can Company, now an independent consultant.
3 Personal communication from R. Wollman, Barnaby-Cheney Company; and W. Hart, J. B. Mitchell Company, Inglewood, California.
4 The expected life of equipment is assumed to be 10 years, in conjunction with a 15-percent gross discount rate. The uniform-distribution assumption is conservative with regard to equipment sizes required. More detailed analysis by individual plants would probably yield lower costs.
5 W. Hart (see note #3) said that there was, however, a large petroleum dry cleaning firm in Australia that successfully removes vapors by adsorption.
6 1,1,1-trichloroethane now sells for $1.35 per gallon in 4000-gallon lots, up to $2.00 per gallon in one-gallon lots (personal communication from W. Shoum, Dow Chemical Company).
with the solvent. Dow realizes the importance of making 1,1,1-trichloroethane compatible with absorption systems and is giving high priority to finding a solution to the problem.

References 6 through 10 present discussions of the theoretical basis of adsorption and criteria for the engineering design of systems for specific purposes. References 4 and 9 contain information from which costs for adsorption systems may be determined.

Evaluation of Vapor Adsorption in the Context of Air-Pollution Control

Increasing stringency of rules for control of vapors emitted from industries and commerce using organic solvents should reactivate the previously lagging use of adsorption systems for this purpose. When the social values of the controlled emissions are added to the reuse values of the regenerated solvents, adsorption should show an advantage over other methods such as incineration for controlling a range of concentrations of organic vapors. In addition, adsorption has an advantage over incineration in not creating emissions of other pollutants (e.g., NOx). There appear to be no insurmountable technological barriers to the application of adsorption systems for organic-vapor control.

A major problem, one common to many vapor-control systems besides adsorption, is that of vapors not reaching the venting system. For example, if operator negligence causes solvent to be dragged out from the system on processed parts and emitted vapors do not reach the control system, then the performance of the system may be degraded. Sometimes, dragout may result from improper design, as when wooden racks are used and, saturated with solvent, are allowed to dry in the room atmosphere. This overall problem is not unique to adsorption and merges with problems of industrial hygiene. One solution is to treat all of the room air to maintain industrial health standards. Recycling of treated air is sometimes feasible and, in some instances, results in reduced costs.

ADDITIONAL NOx CONTROLS FOR 1975

Mixtures of compounds of nitrogen and oxygen (principally NOx and NO) are formed when air is exposed to high temperatures. Not only are these compounds physiologically injurious in themselves above certain concentrations in ambient air, they also contribute to the formation of photochemical smog. By controlling different aspects of the combustion process in combustors, the amounts of total NOx can be held to relatively low levels. Principal control measures produce these effects in one or a combination of ways: reducing peak combustion temperatures; reducing excess air in the mixture; providing a time, temperature, composition profile for the gas stream that minimizes NOx formation and encourages its decomposition back to the elemental nitrogen and oxygen [10].

Low excess air (LEA) in the combustion mixture may be assured by special control devices added to the system. Care must be taken to prevent the mixture from becoming too fuel-rich and thus increasing the emissions of carbon monoxide and possibly reactive hydrocarbons. New combustion systems are available with this LEA control, as are retrofits for many operating systems. On the average, LEA results in about a 40-percent reduction in NOx emissions for commercial and industrial boilers [3].
Two-stage combustion (TSC) to achieve the desired conditions has proved effective for large utility boilers but is limited in applicability to other types and sizes [3]. Recycling a portion (10 to 20 percent) of the flue gas into the primary combustion zone has the combined effects of reducing the peak combustion temperature and diluting the combustion air [10]. The process is analogous in effects to exhaust-gas recirculation in internal combustion engines. Used alone, flue-gas recycling (FGR) can yield a 30- to 60-percent reduction in NOx over uncontrolled systems. And FGR may be combined with LEA to yield up to 75-percent reductions in NOx emissions [3,10].

Some fuels, such as natural gas, produce lower NOx emissions than oil or coal. Converting a combustor from oil to gas can reduce emissions by one-third [3], even on controlled units.

Increasing numbers of gas-turbine engines are employed as stationary engines by the utility and other industries. These engines initially have low NOx emission levels, but they may be further reduced by techniques such as water injection. Industrial internal combustion engines are amenable to NOx control by techniques similar to those used in mobile sources—primarily by exhaust-gas recirculation [10].

Other processes for NOx control are less well developed and are unlikely to be available for large-scale application by 1975. These include methods for removing NOx from flue gas, fluidized-bed combustion, catalysts to speed the decomposition of NOx to the elements, and inhibitors to reduce the initial formation of NOx from the elements.

The tactics expected to be implemented by 1975 were discussed under the nominal strategy in Sec. 2. However, there are several technological possibilities for the further reduction of NOx emissions from the above sources. From the menu of technological possibilities, we selected the following set that appeared sufficiently well developed to permit their application for control by the end of 1975.

**Large and Medium Industrial Boilers**

This category represents steam boilers used for industrial processes other than the generation of electricity. The tactic selected here for maximal control is to apply LEA plus FGR to both classes of boilers. For the large boilers, this control is assumed to result in an average reduction per average boiler from 0.20 tons per day to 0.06 tons per day, at an estimated annual cost of $195 per ton reduced [3]. For medium boilers, the control is assumed to result in a reduction from 0.0068 tons per day to 0.0021 tons per day for the average boiler; the cost has been estimated at $2700 per ton [3]. We recognize that difficult problems may be encountered in applications of this retrofit to some installations [3]. Also, the lack of equipment and knowledgeable skills may prevent implementation of this application by the end of 1975 without a major, emergency effort.

**Large and Small Refinery Heaters**

We propose that LEA be installed in large and small refinery heaters, which are largely uncontrolled at present [3]. The large heaters (larger than $90 \times 10^4$ Btu/hr) are assumed to have an average present emission factor of 0.24 ton per day, and the small heaters, an average of 0.06 ton per day. Assuming a 40-percent reduction of NOx emissions through LEA, the controlled emissions should be about 0.14 ton per day and 0.036 ton per day, respectively. Costs per ton reduced are estimated to be $27 for the large heaters and about $226 for the small heaters [3].
Large Power Plants Operating on Low-Sulfur Oil

A number of the large fossil-fuel power plants operating in the Los Angeles basin already have extensive, installed controls for NOx. We assume, based upon Ref. 1, that the remaining such plants in the basin will be controlled to meet the equivalent of Los Angeles APCD Rule 68 by 1975. An additional control suggested in Ref. 3 would be to operate these plants on natural gas instead of the planned major use of low-sulfur oil. Gas operation can reduce NOx emissions by one-third, even in these controlled plants and at what should be negligible cost. It is particularly important to operate these plants on gas during the summer smog season. Gas may be more available during this season when the demand for residential heating is low. Since the average presently controlled boiler emits 3.8 tons per day, this tactic can reduce NOx emissions for this class to 2.5 tons per day. For the presently uncontrolled boilers, we estimate a reduction of 5.8 tons per day for FGR only to 3.8 tons per day for gas substitution.

Small Power-Plant Boilers (Under 175-Mw Capacity)

No NOx controls are employed on small power-plant boilers except the use of gas and low-sulfur oil. Most were originally expected to be phased out of operation during the 1970s [3]. Recent delays in finding suitable sites for and constructing new types of power plants may require that a number of the older plants continue operation. On these we propose the installation of LEA plus FGR for maximal control. At present, these boilers are estimated to emit an average of 0.62 ton per day of NOx. The suggested controls should reduce emissions to 0.31 ton per day, at an annual cost of approximately $450 per ton [3].

Large and Small Stationary Internal Combustion Engines

These engines are located mostly in the oil and gas industry and are used primarily for driving pumps and compressors. Neither are controlled for NOx emissions [3]. The control tactic proposed is the use of exhaust-gas recirculation or water injection to reduce NOx emissions. These are analogous to devices developed to control NOx in motor-vehicle engines. The average large engine (greater than 300 hp) is estimated to emit 0.18 ton per day of NOx. Controls should reduce this to a level of 0.04 ton per day, at a cost of about $13 per year [3].

Small engines (less than 300 hp and exclusive of 30-hp oil-well pump engines) are estimated to emit an average of 0.019 ton per day of NOx, and control should reduce this to 0.005 ton per day [10]. The estimated annual cost per ton reduced is $37.

Other Sources

Appropriate modifications for small residential and commercial burners to reduce their NOx emissions are probably not feasible within the time period considered here. Premixed burners may have some applicability for these small burners in the future, as well as LEA and FGR for new combustors.

The chemical, mineral, and metallurgical industries and incineration have not increased their NOx emissions in the Los Angeles basin since 1961 and are not likely to increase in the future [3].

We must reiterate that although the technology appears to be developed to the extent necessary to accomplish these control tactics, questions still exist as to whether these controls could be installed and operating by the end of 1975 short of a major,
emergency-type effort. Bottlenecks will appear for most instances because of special-equipment shortages and the lack of skilled, knowledgeable personnel. For many of the fixed-source categories described above, almost every unit is unique in some manner that may require special design considerations before controls can be successfully (and safely) applied.

DETAILED EMISSIONS INVENTORY FOR THE 1975 MAXIMAL STRATEGY

Table C-2 shows the estimated daily emissions under the 1975 maximal strategy, broken down by source category, for each pollutant. The controls and their effects were discussed, pollutant by pollutant, in Sec. 2.

Table C-2

ESTIMATED DAILY EMISSIONS FROM FIXED SOURCES:
1975 MAXIMAL STRATEGY
(tons/day)\textsuperscript{a}

<table>
<thead>
<tr>
<th>Emission Source</th>
<th>THC</th>
<th>RHC</th>
<th>Particulates</th>
<th>NO\textsubscript{2}</th>
<th>SO\textsubscript{2}</th>
<th>CO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Petroleum</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Production</td>
<td>122.8</td>
<td>--</td>
<td>0.4</td>
<td>8.2</td>
<td>5.8</td>
<td>--</td>
</tr>
<tr>
<td>Refining</td>
<td>48.5</td>
<td>5.4</td>
<td>4.3</td>
<td>14.4</td>
<td>42.9</td>
<td>5.3</td>
</tr>
<tr>
<td>Marketing</td>
<td>17.4</td>
<td>16.2</td>
<td>--</td>
<td>2.6</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Total</td>
<td>188.7</td>
<td>21.6</td>
<td>4.7</td>
<td>25.2</td>
<td>48.7</td>
<td>5.3</td>
</tr>
<tr>
<td>Organic-solvent users</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface coating</td>
<td>66.5</td>
<td>53.2</td>
<td>9.9</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Dry cleaning</td>
<td>0.4</td>
<td>0.3</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Degreasing</td>
<td>6.0</td>
<td>0.0</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Other</td>
<td>44.5</td>
<td>35.6</td>
<td>6.4</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Total</td>
<td>117.4</td>
<td>89.1</td>
<td>16.3</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Chemical</td>
<td>--</td>
<td></td>
<td>0.5</td>
<td>0.2</td>
<td>21.7</td>
<td>--</td>
</tr>
<tr>
<td>Metallurgical</td>
<td>--</td>
<td></td>
<td>16.6</td>
<td>3.2</td>
<td>34.8</td>
<td>3.2</td>
</tr>
<tr>
<td>Mineral</td>
<td>1.1</td>
<td>--</td>
<td>21.2</td>
<td>5.9</td>
<td>0.8</td>
<td>--</td>
</tr>
<tr>
<td>Incineration</td>
<td>24.1</td>
<td>2.0</td>
<td>11.9</td>
<td>3.6</td>
<td>0.3</td>
<td>34.4</td>
</tr>
<tr>
<td>Combustion of fuels</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steam power plants</td>
<td>7.5</td>
<td>0.2</td>
<td>4.3</td>
<td>79.6</td>
<td>38.3</td>
<td>--</td>
</tr>
<tr>
<td>Other industrial</td>
<td>7.3</td>
<td>0.1</td>
<td>9.4</td>
<td>36.5</td>
<td>9.1</td>
<td>1.2</td>
</tr>
<tr>
<td>Domestic &amp; commercial</td>
<td>0.4</td>
<td>0.2</td>
<td>10.4</td>
<td>64.2</td>
<td>0.6</td>
<td>0.4</td>
</tr>
<tr>
<td>Total</td>
<td>15.3</td>
<td>0.5</td>
<td>24.1</td>
<td>180.3</td>
<td>48.0</td>
<td>1.6</td>
</tr>
<tr>
<td>Lumber</td>
<td>--</td>
<td></td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Agriculture</td>
<td>24.1</td>
<td>10.6</td>
<td>9.9</td>
<td>0.5</td>
<td>1.7</td>
<td>20.7</td>
</tr>
<tr>
<td>Aircraft (piston and jet mod)</td>
<td>13.1</td>
<td>6.1</td>
<td>8.4</td>
<td>23.6</td>
<td>4.7</td>
<td>47.7</td>
</tr>
<tr>
<td>Total</td>
<td>383.8</td>
<td>129.9</td>
<td>113.6</td>
<td>242.5</td>
<td>161.7</td>
<td>112.9</td>
</tr>
</tbody>
</table>

| Total/1970 level, %    | 37.9 | 20.4 | 74.6 | 63.7  | 61.7  | 37.4 |
| Total/1975 nominal, %  | 69.8 | 54.2 | 86.2 | 63.7  | 100.0 | 36.8 |

\textsuperscript{a}Source: Calculations by the Rand staff, based upon data in Sec. 2 and Appendix C.

\textsuperscript{a}The various totals may differ slightly from the sum of their components as shown, due to rounding.
References for Appendix C

1. Implementation Plan for Air Pollution Control, South Coastal Basin, California Air Resources Board, 1971.
Appendix D

STRATEGIES FOR HEAVY-DUTY VEHICLES AND MOTORCYCLES

Mobile sources include light-duty motor vehicles (LDMVs) and five other types of vehicles, termed non-LDMVs. Control strategies for LDMVs are discussed extensively in Sec. 3. This appendix describes the 1970 emissions from non-LDMVs and presents estimates of their 1975 emissions under the nominal and maximal control strategies.

1970 NON-LDMV EMISSIONS

The five types of non-LDMVs are (1) heavy-duty gasoline trucks, (2) heavy-duty diesel trucks, (3) diesel-powered buses, (4) motorcycles, and (5) ships and railroads. Their emissions in 1970 are shown in Table D-1. The major source of reactive hydrocarbon, carbon monoxide, and NOx emissions was heavy-duty gasoline trucks; motorcycles and diesel trucks also were significant polluters. The data for ships and railroads are taken from the CARB State Implementation Plan[1]; emissions of the remainder were calculated using estimates, by type, of the numbers of vehicles, the number of miles driven yearly, and the age distributions of the vehicles. The first two are described in Appendix E; the third is discussed below.

Table D-1

<table>
<thead>
<tr>
<th>Emission Source</th>
<th>THC</th>
<th>RHC</th>
<th>CO</th>
<th>NOx</th>
<th>SO2</th>
<th>Lead</th>
<th>Particulates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heavy-duty gasoline trucks</td>
<td>117.7</td>
<td>90.3</td>
<td>718.5</td>
<td>42.6</td>
<td>0.9</td>
<td>2.5</td>
<td>1.6</td>
</tr>
<tr>
<td>Heavy-duty diesel trucks</td>
<td>11.3</td>
<td>11.2</td>
<td>46.4</td>
<td>43.4</td>
<td>6.2</td>
<td>---</td>
<td>3.7</td>
</tr>
<tr>
<td>Diesel-powered buses</td>
<td>1.4</td>
<td>1.4</td>
<td>5.8</td>
<td>5.4</td>
<td>0.8</td>
<td>---</td>
<td>0.5</td>
</tr>
<tr>
<td>Motorcycles</td>
<td>23.4</td>
<td>18.5</td>
<td>88.5</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.6</td>
</tr>
<tr>
<td>Ships and railroads</td>
<td>5.4</td>
<td>---</td>
<td>9.2</td>
<td>6.2</td>
<td>1.1</td>
<td>---</td>
<td>3.6</td>
</tr>
<tr>
<td>Total</td>
<td>159.2</td>
<td>121.4</td>
<td>868.4</td>
<td>97.7</td>
<td>9.1</td>
<td>2.6</td>
<td>10.0</td>
</tr>
</tbody>
</table>

SOURCE: CARB State Implementation Plan[1] and calculations by the Rand staff.

*Diesel emissions are calculated from a reactivity of 0.99, based on personal communication from P. Downing, EPA.

NON-LDMV AGE DISTRIBUTION

The emission factors for motorcycles are independent of age. We estimated that engines in diesel-powered trucks have a five-year life span, and that the ages of truck
engines are equally distributed over this period. We treated diesel-powered buses in the same way. Because heavy-duty gasoline-powered trucks are less likely to be used for long-haul trips, we estimated a seven-year engine life. The total number of trucks was distributed 16 percent in each of the first five years and 10 percent each in the sixth and seventh years.

1975 NOMINAL STRATEGY FOR NON-LDMVs

The expected emissions of our five non-LDMV mobile sources in 1975 are shown in Table D-2, based upon the non-LDMV vehicle and mileage forecasts of Appendix E and the age distribution described above. Despite expected growth, emissions of all species except NO$_x$ are estimated to be lower in 1975. This results from the emission standards, to be operative by 1975, for new heavy-duty gasoline and diesel engines. No controls are scheduled for motorcycles or ships and railroads.

Table D-2

<table>
<thead>
<tr>
<th>Emission Source</th>
<th>Pollutant (tons/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>THC</td>
</tr>
<tr>
<td>Heavy-duty gasoline trucks</td>
<td>74.4</td>
</tr>
<tr>
<td>Heavy-duty diesel trucks*</td>
<td>5.8</td>
</tr>
<tr>
<td>Diesel-powered buses*</td>
<td>0.7</td>
</tr>
<tr>
<td>Motorcycles</td>
<td>24.9</td>
</tr>
<tr>
<td>Ships and railroads</td>
<td>5.4</td>
</tr>
<tr>
<td>Total</td>
<td>111.2</td>
</tr>
</tbody>
</table>

Percent of 1970 total

<table>
<thead>
<tr>
<th>Pollutant (tons/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>THC</td>
</tr>
<tr>
<td>69.9</td>
</tr>
</tbody>
</table>

SOURCE: Calculations by the Rand staff.

*Diesel emissions are calculated from a reactivity of 0.99, based on personal communication from P. Downing, EPA.

1975 MAXIMAL STRATEGY FOR NON-LDMVs

Transportation-management strategies could substantially affect the numbers of buses in service and, therefore, the total bus emissions. These types of strategies are discussed at length in the text and are not treated here. It might be noted, however, that they assume that any additional intracity buses would satisfy the 1975 emission standards for diesel engines.

A maximal-strategy tactic for motorcycles would be to ban those with two-cycle engines. If all motorcycles with two-cycle engines were replaced by motorcycles with four-cycle engines, the resulting non-LDMV emissions (assuming that bus miles remain constant at the nominal amount) would be as shown in Table D-3. Emissions
of reactive hydrocarbon would decline by about 12 percent; carbon monoxide and lead would increase slightly. We have not calculated the monetary or social cost of such replacement.

In our calculations, the maximal strategy for non-LDMVs is always used in conjunction with the maximal strategy for fixed sources, and the nominal strategy is used with the nominal strategy for fixed sources. As noted before, the number of bus miles and their associated emissions may vary with the transportation-management strategy for buses; this is considered in assessing the effects of those strategies. However, since buses added in 1975 or later must meet the diesel emission standards, large increases in bus miles would produce only moderate increases in reactive hydrocarbon and NOx emissions.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>1975 Maximal Emissions (tons/day)</th>
<th>Percent of 1975 Nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total HC</td>
<td>99.1</td>
<td>89.1</td>
</tr>
<tr>
<td>Reactive HC</td>
<td>74.4</td>
<td>88.4</td>
</tr>
<tr>
<td>CO</td>
<td>698.2</td>
<td>101.9</td>
</tr>
<tr>
<td>NOx</td>
<td>101.5</td>
<td>100.0</td>
</tr>
<tr>
<td>SO2</td>
<td>6.5</td>
<td>100.0</td>
</tr>
<tr>
<td>Lead</td>
<td>2.2</td>
<td>104.7</td>
</tr>
<tr>
<td>Particulates</td>
<td>8.1</td>
<td>97.6</td>
</tr>
</tbody>
</table>

Reference for Appendix D

Appendix E


NUMBER OF VEHICLES

The number of vehicles, including commercial vehicles and motorcycles, registered in each of the counties in the Los Angeles basin in 1970 is given in Table E-1.

In 1970, 15.7 percent of all commercial vehicles in the area were heavy-duty (6001 lb and over unladen weight) and 3.9 percent of all commercial vehicles were powered by diesel engines. These figures yield the breakdown shown in Table E-2 by vehicle class for the six-county region.

With the aid of the following data, we estimated the proportions of these vehicles registered in the Los Angeles basin in 1970 and projected estimates for 1975 and 1977. Emission inventories in Ref. 1 show that 93.84 percent of the emissions from gasoline-powered vehicles in the six-county region occurred in the Los Angeles basin. The corresponding figure for heavy-duty diesel emissions is 96.04 percent. We assumed this latter figure also applies to heavy-duty gasoline-powered trucks. Data from the American Transit Association [2] indicate that there are 1820 diesel-powered buses operating in the basin. Finally, we assumed that 38 percent of the motorcycles have two-cycle engines, the remainder having four-cycle engines. Combining these facts and estimates, we arrived at the figures shown in Table E-3 for 1970; multipliers of 1.065 and 1.104 were used to estimate the 1975 and 1977 numbers, respectively [1].

As a check on the validity of the estimates in Table E-3, we used the same technique to estimate the number of automobiles in the basin. This result was within 0.4 percent of an independent approximation made at the University of California, Riverside [3].

VEHICLE MILES TRAVELED

Emission factors from the State Implementation Plan [1] were used to infer the average daily fuel consumption of motor vehicles in the Los Angeles basin. (These emission factors, in pounds per gallon, were derived from the total state gasoline tax paid in the basin.) We found that gasoline-powered vehicles used an average of 11,442,553 gallons per day in 1970.

Some additional data were required before we could determine the vehicle miles traveled (VMT) by vehicle class. First, American Transit Association data show 62,938 million intracity bus miles in the basin in 1971 [2]; we used this figure as a proxy for 1970. We assumed that all heavy-duty trucks averaged 20,000 miles per year, and that motorcycles averaged 3900 miles per year. Data from the American Petroleum Institute show an average gasoline mileage of 13.22 miles per gallon for light-duty motor vehicles [4]. Mileages of 5.0 and 50.0 miles per gallon were used for

1 Personal communication with Mr. Ralph D. Cook, California Department of Motor Vehicles, November 1972.
### Table E-1

**VEHICLES REGISTERED IN THE LOS ANGELES BASIN IN 1970**

<table>
<thead>
<tr>
<th>County</th>
<th>Registration in 1970</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Passenger Vehicles</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>3,687,840</td>
</tr>
<tr>
<td>Orange</td>
<td>801,090</td>
</tr>
<tr>
<td>Riverside</td>
<td>227,110</td>
</tr>
<tr>
<td>San Bernardino</td>
<td>323,620</td>
</tr>
<tr>
<td>Santa Barbara</td>
<td>137,380</td>
</tr>
<tr>
<td>Ventura</td>
<td>182,450</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>5,359,490</strong></td>
</tr>
</tbody>
</table>


### Table E-2

**INVENTORY OF VEHICLES, BY TYPE, IN SIX SOUTHERN CALIFORNIA COUNTIES IN 1970**

<table>
<thead>
<tr>
<th>Vehicle Class</th>
<th>Number in Six-County Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light-duty passenger vehicles</td>
<td>5,359,490</td>
</tr>
<tr>
<td>Light-duty commercial vehicles</td>
<td>606,614</td>
</tr>
<tr>
<td>Heavy-duty gasoline-powered vehicles</td>
<td>84,912</td>
</tr>
<tr>
<td>Heavy-duty diesel-powered vehicles</td>
<td>28,064</td>
</tr>
<tr>
<td>Motorcycles (two-cycle and four-cycle)</td>
<td>247,510</td>
</tr>
</tbody>
</table>

### Table E-3

**ESTIMATED NUMBER OF VEHICLES, BY TYPE, IN THE LOS ANGELES BASIN IN 1970, 1975, AND 1977**

<table>
<thead>
<tr>
<th>Vehicle Class</th>
<th>Number of Vehicles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1970</td>
</tr>
<tr>
<td>Light-duty motor vehicles (passenger and commercial)</td>
<td>5,598,592</td>
</tr>
<tr>
<td>Heavy-duty gasoline-powered trucks</td>
<td>81,549</td>
</tr>
<tr>
<td>Heavy-duty diesel-powered trucks</td>
<td>25,133</td>
</tr>
<tr>
<td>Diesel-powered buses</td>
<td>1,820</td>
</tr>
<tr>
<td>Four-cycle motorcycles</td>
<td>144,001</td>
</tr>
<tr>
<td>Two-cycle motorcycles</td>
<td>88,262</td>
</tr>
</tbody>
</table>
heavy-duty trucks and motorcycles, respectively. From these figures and the numbers of vehicles shown in Table E-3, we made the estimates of VMT given in Table E-4. The totals shown in Table E-4 agree well with a simple extrapolation of the total miles calculated for 1967 in the LARTS study [5]. Furthermore, the figures are qualitatively similar to those derived by Rand for the San Diego study [6].

Table E-4

ESTIMATED DAILY VEHICLE MILES, BY VEHICLE TYPE, IN THE LOS ANGELES BASIN IN 1970, 1975, AND 1977

<table>
<thead>
<tr>
<th>Vehicle Class</th>
<th>Average Daily Vehicle Miles</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1970</td>
</tr>
<tr>
<td>Light-duty motor vehicles</td>
<td>138,797,000</td>
</tr>
<tr>
<td>(passenger and commercial)</td>
<td></td>
</tr>
<tr>
<td>Heavy-duty gasoline-powered trucks</td>
<td>4,468,400</td>
</tr>
<tr>
<td>Heavy-duty diesel-powered trucks</td>
<td>1,377,200</td>
</tr>
<tr>
<td>Diesel-powered buses</td>
<td>172,400</td>
</tr>
<tr>
<td>Four-cycle motorcycles</td>
<td>1,538,600</td>
</tr>
<tr>
<td>Two-cycle motorcycles</td>
<td>938,100</td>
</tr>
<tr>
<td>Totals</td>
<td>147,296,700</td>
</tr>
</tbody>
</table>

References for Appendix E

Appendix F

COMPOSITION OF PROMISING RETROFIT STRATEGIES IN 1977

<table>
<thead>
<tr>
<th>Strategy</th>
<th>Tactic</th>
<th>Applicable Model Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Crankcase blowby control</td>
<td>1960-55</td>
</tr>
<tr>
<td>B</td>
<td>Crankcase blowby control, NOx control kit and/or VSAD</td>
<td>1960-55, 1970-66</td>
</tr>
<tr>
<td>C</td>
<td>Crankcase blowby control, NOx control kit and/or VSAD</td>
<td>1960-55, 1970-55</td>
</tr>
<tr>
<td>D</td>
<td>Crankcase blowby control, Pre-1966 exhaust retrofit and NOx control kit and/or VSAD</td>
<td>1960-55, 1970-55</td>
</tr>
<tr>
<td>E</td>
<td>Crankcase blowby control, Evaporative-loss control, Pre-1966 exhaust retrofit kit and NOx control kit and/or VSAD</td>
<td>1960-55, 1969-66, 1970-55</td>
</tr>
<tr>
<td>F</td>
<td>Crankcase blowby control, State I/M and pre-1966 exhaust retrofit kit and NOx control kit and/or VSAD</td>
<td>1960-55, 1974-55</td>
</tr>
<tr>
<td>G</td>
<td>Crankcase blowby control, Evaporative-loss control, State I/M and pre-1966 exhaust retrofit kit and NOx control kit and/or VSAD</td>
<td>1960-55, 1969-66, 1974-55</td>
</tr>
<tr>
<td>H</td>
<td>Crankcase blowby control, Catalytic exhaust-gas converter and state I/M, State I/M and pre-1966 exhaust retrofit kit and NOx control kit and/or VSAD</td>
<td>1960-55, 1974-73, 1972-55</td>
</tr>
<tr>
<td>J</td>
<td>Crankcase blowby control, Catalytic exhaust-gas converter and state I/M, State I/M and pre-1966 exhaust retrofit kit and NOx control kit and/or VSAD</td>
<td>1960-55, 1974-71, 1970-55</td>
</tr>
<tr>
<td>L</td>
<td>Crankcase blowby control, Catalytic exhaust-gas converter and state I/M, State I/M and pre-1966 exhaust retrofit kit and NOx control kit and/or VSAD</td>
<td>1960-55, 1974-68, 1967-55</td>
</tr>
<tr>
<td>M</td>
<td>Crankcase blowby control, Evaporative-loss control, Catalytic exhaust-gas converter and state I/M, State I/M and pre-1966 exhaust retrofit kit and NOx control kit and/or VSAD</td>
<td>1960-55, 1969-68, 1974-68</td>
</tr>
</tbody>
</table>

86
<table>
<thead>
<tr>
<th>Strategy</th>
<th>Tactic</th>
<th>Applicable Model Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>Crankcase blowby control</td>
<td>1960-55</td>
</tr>
<tr>
<td></td>
<td>Catalytic exhaust-gas converter and state I/M and NOx control kit and/or VSAD</td>
<td>1974-66</td>
</tr>
<tr>
<td></td>
<td>State I/M and pre-1966 exhaust retrofit kit and NOx control kit and/or VSAD</td>
<td>1965-55</td>
</tr>
<tr>
<td>O</td>
<td>Crankcase blowby control</td>
<td>1960-55</td>
</tr>
<tr>
<td></td>
<td>Evaporative-loss control</td>
<td>1969-66</td>
</tr>
<tr>
<td></td>
<td>Catalytic exhaust-gas converter and state I/M and NOx control kit and/or VSAD</td>
<td>1974-66</td>
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<tr>
<td></td>
<td>State I/M and pre-1966 exhaust retrofit kit and NOx control kit and/or VSAD</td>
<td>1965-55</td>
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<td>P</td>
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<td>1960-55</td>
</tr>
<tr>
<td></td>
<td>Evaporative-loss control</td>
<td>1969-66</td>
</tr>
<tr>
<td></td>
<td>Catalytic exhaust-gas converter and state I/M and NOx control kit and/or VSAD</td>
<td>1974-66</td>
</tr>
<tr>
<td></td>
<td>State I/M and pre-1966 exhaust retrofit kit and NOx control kit and/or VSAD</td>
<td>1965-55</td>
</tr>
<tr>
<td>Q</td>
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<td>1960-55</td>
</tr>
<tr>
<td></td>
<td>Evaporative-loss control</td>
<td>1969-66</td>
</tr>
<tr>
<td></td>
<td>Catalytic exhaust-gas converter and state I/M and NOx control kit and/or VSAD</td>
<td>1974-64</td>
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<tr>
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<td>1963-55</td>
</tr>
<tr>
<td>R</td>
<td>Crankcase blowby control</td>
<td>1960-55</td>
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<tr>
<td></td>
<td>Evaporative-loss control</td>
<td>1969-66</td>
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<tr>
<td></td>
<td>Catalytic exhaust-gas converter and state I/M and pre-1966 exhaust retrofit kit and NOx control kit and/or VSAD</td>
<td>1974-64</td>
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<td>State I/M and pre-1966 exhaust retrofit kit and NOx control kit and/or VSAD</td>
<td>1963-55</td>
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<td>S</td>
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<td>1969-68</td>
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<td>T</td>
<td>Crankcase blowby control</td>
<td>1960-55</td>
</tr>
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<td></td>
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<td>1969-61</td>
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<td>1974-61</td>
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<td>1960-55</td>
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<td>V</td>
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<td>1960-55</td>
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<tr>
<td></td>
<td>Evaporative-loss control</td>
<td>1969-68</td>
</tr>
<tr>
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<td>1974-61</td>
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<td>State I/M and pre-1966 exhaust retrofit kit and NOx control kit and/or VSAD</td>
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<td></td>
<td>Evaporative-loss control</td>
<td>1969-66</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>State I/M and pre-1966 exhaust retrofit kit and NOx control kit and/or VSAD</td>
<td>1960-55</td>
</tr>
<tr>
<td>Strategy</td>
<td>Tactic</td>
<td>Applicable Model Years</td>
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<td>----------</td>
<td>------------------------------------------------------------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td>X</td>
<td>Crankcase blowby control</td>
<td>1960-55</td>
</tr>
<tr>
<td></td>
<td>Catalytic exhaust-gas converter and state I/M</td>
<td></td>
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<tr>
<td></td>
<td>and pre-1966 exhaust retrofit kit and NOx control kit and/or VSAD</td>
<td></td>
</tr>
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<td>Y</td>
<td>Crankcase blowby control</td>
<td>1960-55</td>
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<tr>
<td></td>
<td>Evaporative-loss control</td>
<td>1969-66</td>
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<tr>
<td></td>
<td>Catalytic exhaust-gas converter and state I/M</td>
<td></td>
</tr>
<tr>
<td></td>
<td>and pre-1966 exhaust retrofit kit and NOx control kit and/or VSAD</td>
<td>1974-55</td>
</tr>
<tr>
<td>Z</td>
<td>Crankcase blowby control</td>
<td>1960-55</td>
</tr>
<tr>
<td></td>
<td>Evaporative-loss control</td>
<td>1969-55</td>
</tr>
<tr>
<td></td>
<td>Catalytic exhaust-gas converter and state I/M</td>
<td></td>
</tr>
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<td></td>
<td>and pre-1966 exhaust retrofit kit and NOx control kit and/or VSAD</td>
<td>1974-55</td>
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<td>0</td>
<td>Crankcase blowby control</td>
<td>1960-55</td>
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<tr>
<td></td>
<td>Evaporative-loss control</td>
<td>1969-62</td>
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<tr>
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<td></td>
</tr>
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<td></td>
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<td>1974-55</td>
</tr>
<tr>
<td>1</td>
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<td>1960-55</td>
</tr>
<tr>
<td></td>
<td>Evaporative-loss control</td>
<td>1969-55</td>
</tr>
<tr>
<td></td>
<td>Maintenance to MPC</td>
<td>1975-55</td>
</tr>
<tr>
<td></td>
<td>Catalytic exhaust-gas converter and pre-1966</td>
<td></td>
</tr>
<tr>
<td></td>
<td>exhaust retrofit kit and NOx control kit and/or VSAD</td>
<td>1974-55</td>
</tr>
</tbody>
</table>
Appendix G

ESTIMATING THE BUS-ELIGIBLE POPULATION FOR THE LOS ANGELES BASIN

ASSUMPTIONS AND METHODOLOGY

The bus-system improvements considered here are limited to Los Angeles and Orange Counties, and the bus-eligible population is a function of the area covered by the bus system.

We chose to limit bus-system improvements to these two counties for several reasons. The primary reasons are (1) the major portion (approximately 84 percent) of the vehicle miles driven in the Los Angeles basin in 1970 were driven in these counties, so they are the primary candidates for vehicle-mile reductions; and (2) because of the relatively high density and regularly distributed population in this region, the bus is most likely to be cost-effective there.

Our bus routes are configured so that no one living in an area served by bus will have to walk more than one-half mile to a bus stop. With these provisions, the curve in Fig. G-1 relating fraction of population to fraction of area covered for Los Angeles and Orange Counties combined was used to estimate bus-eligible population as a function of area covered. The total area of the two counties is estimated to be 4735 square miles.

POPULATION ESTIMATES FOR LOS ANGELES AND ORANGE COUNTIES

Table G-1 presents estimates of the population in each of the six counties in the Los Angeles basin for 1975 and 1977.¹ The population forecast for Los Angeles and Orange Counties combined is shown in Table G-2. Because our bus-system improvements are limited to this region, these people make up the maximum bus-eligible population.

BUS-ELIGIBLE POPULATION VERSUS BUS-SERVICE AREA

Table G-3 presents the bus-eligible population in Los Angeles and Orange Counties for 1975 and 1977 for varying bus-service areas. The maximum area encompasses the two counties (4735 square miles), and the maximum bus-eligible population is the total population of the counties (8,738,000 and 8,890,000 persons for 1975 and 1977, respectively).

Bus-service areas have been selected so that each reduction in service area causes a 10-percent reduction in bus-eligible population. Notice that when the bus-service area covers 592 square miles (12.5 percent of the total area), 50 percent of the total population is still bus-eligible. The 1971-72, or nominal, case is approximated by a service area of 1184 square miles and a bus-eligible population of 6,990,000

¹ This table summarizes the work in Appendix K.
Fig. G-1—Relationship of population to area in five Southern California counties
Table G-1
TOTAL POPULATION IN SIX-COUNTY REGION

<table>
<thead>
<tr>
<th>County</th>
<th>Total Population(^a) (thousands)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1975</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>6,966.9</td>
</tr>
<tr>
<td>Orange</td>
<td>1,770.8</td>
</tr>
<tr>
<td>Ventura</td>
<td>455.6</td>
</tr>
<tr>
<td>Riverside</td>
<td>518.5</td>
</tr>
<tr>
<td>San Bernardino</td>
<td>725.2</td>
</tr>
<tr>
<td>Santa Barbara</td>
<td>265.0</td>
</tr>
<tr>
<td><strong>Six-county total</strong></td>
<td><strong>10,702.0</strong></td>
</tr>
<tr>
<td><strong>Los Angeles basin</strong></td>
<td><strong>10,043.0</strong></td>
</tr>
</tbody>
</table>

\(^a\)See Appendix K for population estimates.

\(^b\)Assumed proportional to motor-vehicle emissions.

Table G-2
POPULATION IN LOS ANGELES AND ORANGE COUNTIES
(maximum bus-eligible population)

<table>
<thead>
<tr>
<th>County</th>
<th>Total Population (thousands)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1975</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>6,966.9</td>
</tr>
<tr>
<td>Orange</td>
<td>1,770.8</td>
</tr>
<tr>
<td><strong>Totals</strong></td>
<td><strong>8,737.7</strong></td>
</tr>
</tbody>
</table>

(80 percent of the population). In our analysis, we generally used a service area of 1421 square miles, with 90 percent of the population bus-eligible.

WHERE SHOULD BUS ELIGIBILITY BE PROVIDED?

Of the vehicles registered in 1970 in Los Angeles, Orange, Riverside, San Bernardino, Santa Barbara, and Ventura Counties, 83 percent were in Los Angeles and
Table G-3
BUS-ELIGIBLE POPULATION VERSUS BUS-SERVICE AREA

<table>
<thead>
<tr>
<th>Bus-Service Area (sq mi)</th>
<th>Bus-Eligible Population (thousands)</th>
<th>Percent of Population Bus-Eligible</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1975</td>
<td>1977</td>
</tr>
<tr>
<td>4,735</td>
<td>8,738</td>
<td>8,890</td>
</tr>
<tr>
<td>1,421</td>
<td>7,864</td>
<td>8,001</td>
</tr>
<tr>
<td>1,384b</td>
<td>6,990b</td>
<td>7,112b</td>
</tr>
<tr>
<td>947</td>
<td>6,117</td>
<td>6,223</td>
</tr>
<tr>
<td>758</td>
<td>5,243</td>
<td>5,334</td>
</tr>
<tr>
<td>592</td>
<td>4,369</td>
<td>4,445</td>
</tr>
<tr>
<td>450</td>
<td>3,495</td>
<td>3,556</td>
</tr>
<tr>
<td>308</td>
<td>2,621</td>
<td>2,667</td>
</tr>
<tr>
<td>185</td>
<td>1,747</td>
<td>1,778</td>
</tr>
<tr>
<td>71</td>
<td>874</td>
<td>889</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

*a* Los Angeles and Orange Counties.  
*b* Nominal 1971-72 Value.

Orange Counties. Since VMT are well correlated with vehicle registrations, these two counties are the prime candidates for any attempt to reduce VMT. Further, as stated above, the relatively more dense and uniformly distributed population in these areas indicates that bus-system improvements designed to improve air quality would be most cost-effective in these counties.

BUS ELIGIBILITY IN OTHER AREAS OF THE BASIN

San Bernardino, Ventura, and perhaps other counties outside the Los Angeles/Orange County area currently have limited bus service. But the total VMT is relatively small in those counties, and hence the possibility of achieving a significant reduction in VMT by improving bus service is also relatively small. Bus VMT in these areas is presently small relative to automobile VMT, and because of the low population density any expansion of bus service or coverage promises to be very expensive. It would appear to be difficult if not economically impossible to provide a sufficiently attractive bus system to divert many people in these areas from their autos. Therefore, our calculations ignore present-level bus service in these areas, and we consider them as auto-eligible only.
Appendix H

TECHNICAL ASSUMPTIONS CONCERNING VEHICLE EMISSION FACTORS AND REACTIVITY FRACTIONS

LIGHT-DUTY MOTOR-VEHICLE EMISSION FACTORS

Light-duty motor-vehicle (LDMV) emission factors are generally expressed in terms of mass emissions per vehicle mile and are a function of both vehicle model year and the age of the vehicle. Considerable controversy exists as to which set of emission factors is the most realistic for the purpose of compiling emission inventories. This appendix presents the results of our analysis of this situation and our recommendations on the most reasonable assumptions.

Candidate Emission Factors

LDMV emission factors are generally based on one of three test procedures. The test procedures are used to specify new-vehicle emission standards and have evolved in an attempt to replicate the emissions that would be expected from a vehicle during a typical urban driving cycle. A brief description of these procedures follows.

- **7-mode.** Used in the specification of the original California exhaust-emission standards (1966) and became the Federal Test Procedure (FTP) for 1968-71 model-year vehicles. This is a cold-start test, with the average pollutant concentration in the exhaust being determined by a weighting of seven distinct driving modes.

- **CVS-1.** Used as the FTP for 1972-74 model-year vehicles. This is a cold-start test in which a constant volume of the exhaust gas is collected during a 23-minute driving cycle. Mass emissions are then determined by analyzing the contents of the collection bag.

- **CVS-2.** Will become the FTP in 1975. This is the CVS-1 cold-start test, with the first 8 minutes and 25 seconds of the driving cycle being repeated after a hot start. The average mass emissions are determined by weighting the cold-start and hot-start portions of the test.

The 7-mode emission factors may be derived from data contained in Ref. 1, the CVS-1 factors from Refs. 2 and 3, and the CVS-2 from Ref. 4.

The 7-mode factors are regarded in some quarters as inappropriate for the calculation of mass emissions. For this reason they were not included in our original sensitivity analysis. However, the analysis of the CVS-1 and CVS-2 factors showed the CVS-2 to be much more pessimistic in terms of achieving given air-quality standards. This is a result of the CVS-1 emission factors being generally dirtier than the corresponding CVS-2 values. The optimism resulting from CVS-1 is thus a direct consequence of the rollback paradox. Not all trips within a region begin with a cold start, and hence the CVS-2 factors are widely regarded as providing the most representative values for average vehicle emissions.

The EPA has provided low-mileage emission factors, age-deterioration factors, and average vehicle-speed correction factors based on the CVS-2 test procedure and requires that these data be used in the preparation of implementation plans [4]. The results of the sensitivity analysis dictated that an evaluation of these data would be
in order. On the basis of that evaluation, some adjustments to the published CVS-2 factors are recommended.

**Why Adjust CVS-2?**

Our analysis revealed that the CVS-2 low-mileage emission factors published by the EPA had certain disquieting characteristics:

- The CVS-2 factors show greatly dissimilar trends with model year (for pre-1968 vehicles) when compared with CARB field surveillance data [1]. (Although CARB data are based on a 7-mode hot-start test, and the CVS-2 on a different test, they should show similar trends.)
- They are based on data obtained from a relatively small sample.
- The predicted values for 1972-74 vehicles do not agree with existing California emission standards [5], which all vehicles sold in the state must meet.

A question also arose regarding the age-deterioration factors provided by the EPA. The results of our analysis of these factors and our adjustments to CVS-2 are presented below.

**Age-Deterioration Factors.** The EPA age-deterioration factors in Ref. 4 for pre-1975 vehicles are apparently based on CARB field surveillance data of Ref. 1 on in-use vehicles. In the EPA document, the deterioration factors are regarded as a function of model year; that is, each model year (or group of model years with similar characteristics) has a unique deterioration function for each species. In earlier work at Rand we developed a deterioration function for each species that is independent of vehicle model year. These functions are also based on CARB field surveillance data and are similar to those used in Ref. 2. It thus became necessary to compare the universal set with the EPA model-year-specific functions [6].

The results of this comparison are presented in Fig. H-1. The 1966 and 1970 model years were chosen for this comparison because their deterioration characteristics for exhaust hydrocarbon emissions are the most dissimilar of the model years for which extensive data have been accumulated. It is clear from Fig. H-1 that for this species the universal deterioration function appears to be a somewhat better approximation than the model-year-specific functions. In light of this comparison, the universal age-deterioration functions developed by Rand have been used in nearly all of our analyses. It should be noted, however, that this comparison has not been made for carbon monoxide or NOx emissions. (The carbon monoxide and NOx emission factors have not been extensively analyzed, since these species have not formed the binding constraint in the regions we have considered.) We anticipate that the universal functions will yield a less accurate approximation for these species, but the error should be small.

We have also treated the deterioration factors for 1975 and later vehicles somewhat differently than recommended by the EPA in Ref. 4. In that report, the deterioration factors for those vehicles that will probably be equipped with catalytic converters were based on some very preliminary data on catalyst deterioration, which were obtained from vehicle manufacturers by the National Academy of Science [2]. Rather than use these factors, we have based our calculations again on the universal deterioration functions. However, low-mileage emission factors were adjusted so that the average vehicle emissions over the first 50,000 miles of service would be equal to the applicable new-vehicle emission standard. This is, of course, in accordance with the Federal durability requirement for post-1974 vehicles. The treatment will result in somewhat smaller emission levels being predicted for 1975 and later vehicles, after the deterioration factors have been applied.
Adjustments to CVS-2 Emission Factors. The main objective of the adjustments we have made to the CVS-2 emission factors published by the EPA is to reflect (approximately) the relative model-year emission levels observed in CARB field surveillance. The CARB data are based on the testing of more than 16,000 in-use vehicles and, as noted earlier, serve as the primary source for the generation of age-deterioration factors. Our initial adjustments yielded a set of low-mileage emission factors that we designated CVS-2A. Since that time, more detailed data based on the latest field surveillance report [1] have been obtained from the CARB and a new adjusted set, designated CVS-2B, has evolved. Only minor differences arise in results generated with either CVS-2A or CVS-2B factors, and this will be demonstrated shortly. Hence, only the derivation of the CVS-2B emission factors will be discussed.

The CVS-2 emission factors are based on data presented in Ref. 6. We have assumed that the CVS-2 values for 1968-71 vehicles contained in that report are quantitatively accurate. The data for these model years were derived from a 360-vehicle sample. We then computed pre-1968 low-mileage emission factors, assuming that a direct proportionality exists between the CVS-2 and 7-mode test procedures. For example, the CVS-2B value for the 1967 model year was derived with the following equations:

\[
\text{CVS-2B}_{\text{67}} = \frac{7\text{-mode}_{\text{67}}}{7\text{-mode}_{\text{68}}} \times \text{CVS-2}_{\text{68}}
\]

These adjustments resulted in the low-mileage emissions given in Table H-1. Statistically, the adjustment seems most reasonable for the 1966 and 1967 model years, since only 33 such vehicles were tested in the EPA study. The pre-1966 models, on the other hand, contained 337 vehicles in the nationwide sample. But only 73 of these were tested in California, and their emissions averaged 10.96 grams per mile of total hydrocarbons, closer to the CVS-2B values.
Table H-1
TOTAL HYDROCARBON EXHAUST EMISSIONS (grams per mile)

<table>
<thead>
<tr>
<th>Model Year</th>
<th>CVS-2</th>
<th>CVS-2B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1968</td>
<td>4.5</td>
<td>4.5</td>
</tr>
<tr>
<td>1967</td>
<td>4.6</td>
<td>4.5</td>
</tr>
<tr>
<td>1966</td>
<td>6.0</td>
<td>4.8</td>
</tr>
<tr>
<td>Pre-1966</td>
<td>8.8</td>
<td>12.0</td>
</tr>
</tbody>
</table>

Adjustments to post-1971 model-year emission factors were made with the intent of reflecting the existing California new-vehicle emission standard, which all new vehicles sold in the state must meet. Also, as noted earlier, the low-mileage factors for 1975 and later vehicles were set to conform with the EPA durability criterion. Table H-2 compares CVS-2 with CVS-2B for these model years. These modifications to 1972-74 vehicles are justifiable on two counts:

- The California hydrocarbon exhaust emission standard for those model years is 3.2 grams per mile (using CVS-1), whereas the Federal standard is 3.4 grams per mile.
- The California standards include an assembly-line quality audit of the new-vehicle emission levels before the vehicle can be certified for sale in California.

It is our feeling that these facts justify the slight modification of the CVS-2 factors for the post-1971 model-year vehicles.

Table H-2
TOTAL HYDROCARBON EXHAUST EMISSIONS (grams per mile)

<table>
<thead>
<tr>
<th>Model Year</th>
<th>CVS-2</th>
<th>CVS-2B</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971</td>
<td>2.9</td>
<td>2.9</td>
</tr>
<tr>
<td>1972</td>
<td>2.7</td>
<td>2.5</td>
</tr>
<tr>
<td>1973</td>
<td>2.7</td>
<td>2.4</td>
</tr>
<tr>
<td>1974</td>
<td>2.7</td>
<td>2.4</td>
</tr>
<tr>
<td>1975</td>
<td>0.50</td>
<td>0.80</td>
</tr>
<tr>
<td>Post-1975</td>
<td>0.23</td>
<td>0.36</td>
</tr>
</tbody>
</table>

Sensitivity of Results to Emission-Factor Assumption:
San Diego Examples

Suppose maximal fixed-source control has been implemented. Applying the CVS-2B emission factors, along with the rest of the reference assumptions, we find
that an annual retrofit expenditure of $75 million could achieve the oxidant standard in San Diego County without a reduction in vehicle miles. But simply replacing the CVS-2B factor for pre-1966 vehicles (12 grams per mile) with the CVS-2 value (8.8 grams per mile) would require a 20-percent reduction in vehicle miles to meet the standard, which could also be met by increasing the annual retrofit expenditure to $102 million. (This extreme sensitivity is a direct consequence of the rollback paradox.)

Next it is instructive to compare the effect the emission-factor assumption has on the predicted peak oxidant concentration (assuming linear rollback) in 1975. Using San Diego County as an example, we make such a comparison for the CVS-2, CVS-2A, CVS-2B, and 7-mode emission factors in Table H-3. The comparison is made for various retrofit strategies, with Strategy A being the case where used-car retrofits are absent. The remaining strategies reflect varying degrees of retrofit. It should be noted that the CVS-2 column uses the pessimistic value [7] for catalytic-converter effectiveness.

Perhaps the most important observation to be made about Table H-1 is that results based on the CVS-2B emission factors (which have been corrected for average vehicle speed) are essentially identical to those based on the California 7-mode factors. The following comments are also made on the basis of Table H-1:

- The effect of the emission-factor assumption is most clearly demonstrated in Strategy A, where the difference in catalytic-converter effectiveness does not apply, since there is no retrofit. Note that the CVS-2A, CVS-2B, and 7-mode results are essentially identical, whereas the CVS-2 predicted concentration is significantly higher.
- Strategy R would achieve the 0.08-ppm oxidant standard in all cases except under CVS-2, which would require an additional emission reduction of approximately 19 percent (or, alternatively, a vehicle-mileage reduction of 38 percent).

<table>
<thead>
<tr>
<th>Retrofit Strategy (MOVEC Symbol)</th>
<th>Resulting Peak Oxidant Concentrationa (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CVS-2b</td>
</tr>
<tr>
<td>A</td>
<td>0.170</td>
</tr>
<tr>
<td>D</td>
<td>0.164</td>
</tr>
<tr>
<td>L</td>
<td>0.124</td>
</tr>
<tr>
<td>M</td>
<td>0.116</td>
</tr>
<tr>
<td>R</td>
<td>0.099</td>
</tr>
<tr>
<td>S</td>
<td>0.106</td>
</tr>
<tr>
<td>V</td>
<td>0.104</td>
</tr>
<tr>
<td>Z</td>
<td>0.092</td>
</tr>
</tbody>
</table>

aAssuming linear rollback, medium fixed-source control, and no vehicle mileage reduction.

bCorrected for an average vehicle speed of 24.5 miles per hour.
• The predicted peak oxidant concentration for a given strategy is comparable in all cases under CVS-2A, CVS-2B, or 7-mode.

In Table H-3, the CVS-2, CVS-2A, and CVS-2B emission factors have been corrected for an average vehicle speed of 24.5 miles per hour. No speed correction was made to the 7-mode factors, since they are intended to be representative of the typical driving cycle in a California city.

HYDROCARBON REACTIVITY FRACTIONS

Recent laboratory investigations and atmospheric measurements have led to the conclusion that there is a larger fraction of reactive compounds in most hydrocarbon emissions than has been previously observed.

Problems in Estimating and Applying Hydrocarbon Reactivities

Only some of the hydrocarbons in the atmosphere enter into photochemical reactions, so a correction must be made to eliminate the nonreactive substances from any calculations. Herein lies the source of many difficulties. Conventionally, only total hydrocarbons are measured in the atmosphere or in emissions, and no attempt is made routinely to evaluate those of the total that are reactive. Measurements of reactivity have been until now a research activity in which samples of the atmosphere (or of other substances) and NOx are exposed to intense illumination in special reaction chambers. The smog-forming characteristics of the atmosphere or of other hydrocarbons exposed to light in this manner are evaluated in a number of ways. These include following the rate of formation of various known irritating substances, aerosol production, and eye irritation. In the pioneering research of the Los Angeles APCD, these smog-forming attributes of various substances were compared with the known smog-forming characteristics of automobile exhaust and certain unsaturated hydrocarbons called olefins. The substances were then classed as very reactive, moderately reactive, or inert in comparison with the known references. Based on these tests, a classification by substance was prepared and used to formulate Rule 66 of the Los Angeles APCD for the control of emissions from organic solvents [8]. (Tests of this nature are also used to judge the reactivity of emissions from hydrocarbon sources other than solvents.)

The EPA has also run similar sorts of irradiation-chamber tests (as have several other organizations), but with somewhat different experimental designs, analytical procedures, and methods for evaluating smog-forming attributes. Evaluations based on the earlier of these experiments led to a scale for evaluating reactivity of hydrocarbons that produced lower attributed reactive fractions than those used by the CARB and the Los Angeles APCD [8-10].

The results of later experiments conducted under a wider range of conditions indicate that compounds previously considered to have very low photochemical reactivity can produce significant amounts of oxidants and can otherwise contribute to smog formation [11-13]. According to the Los Angeles APCD, the low and moderately reactive hydrocarbons should be included in the inventory at full weight when judging the reactivity of emissions, because of their behavior in the atmosphere, particularly during times of high oxidant levels [14]. Analysis of the atmosphere during these periods shows that all but the essentially inert hydrocarbons have

1 Even measurements of total hydrocarbons will vary, depending upon the analytical method used.
entered into the photochemical reactions. After a period of heavy smog, areas to the east of Los Angeles, like Riverside, will show only these unreactive inert substances remaining. According to the Los Angeles APCD, analysis of the composition of the hydrocarbons during such periods can be used to estimate the length of time the air parcel has been in the basin, exposed to smog-forming conditions. Recent EPA judgments reflect these findings.\textsuperscript{3}

One final point is that more recent analytical procedures sometimes provide for measuring methane content as well as total hydrocarbons. Results will be reported both as total hydrocarbons and hydrocarbons less methane. Use of the latter value to represent reactive hydrocarbons will overstate the reactive hydrocarbon content of the emission or air sample for many cases, because inert substances other than methane are frequently present that are not measured as methane and thus add inert substances to the total of what would then be labeled reactive. Information on these hydrocarbon analytical methods is contained in Ref. 15.

Alternative Definitions of Reactivity: An Interpretation

We identify three general definitions of reactivity: (1) Limit reactivity. This is the maximum fraction of total hydrocarbon that could react under limit conditions, given sufficient time; it is region-independent. (2) Worst-day reactivity. This is the fraction of total hydrocarbon that does react under the worst conditions; it varies with region, being higher in a region with unfavorable meteorology. In a basin with a severe smog problem, such as Los Angeles, the worst-day reactivity may approach the limit reactivity; in another region, it may be much less. (3) Legal reactivities. There are legally established reactivity fractions set by the local APCD. These are often the basis for regional emission inventories, although they may or may not be similar to the limit or worst-day reactivities. The legal reactivities are often set with administrative and technical practicality in mind, but they usually do not include all substances that might be chemically reactive on the worst day or at the limit.

Figure H-2 illustrates the relationship among these definitions. For a hypothetical hydrocarbon mixture, the vertical axis shows the fraction of its total hydrocarbons that react, r. The dwell time, box size, and various other meteorological conditions, represented by t, appear on the horizontal axis. As t increases, r increases to some limit r\textsuperscript{L}. In a bad smog basin, the observed reaction fraction r\textsubscript{1} is close to r\textsuperscript{L}; in another basin, the conditions on even the worst day might be substantially less severe, with a resulting lower observed fraction of r\textsubscript{2}. (A legally established reactivity fraction, r\textsubscript{L}, might fall anywhere, implying some value of t, t\textsubscript{L}.)

The distinctions among these three definitions of reactivity are not generally made or understood. (Indeed, we have coined the terms limit reactivity and worst-day reactivity ourselves to clarify the issue.) Inappropriate or inconsistent application of these reactivity definitions can yield errors in the emission inventory for a region. These, in turn, can cause error in selecting appropriate control tactics or determining the amount of control necessary (and the expense of control). Suppose, for example, that limit reactivities were used to construct the inventory for a region with a very mild smog problem; then the amount of total hydrocarbon reacting would be overstated, and overcontrol (and excessive expense) might result.

It is significant that meaningful comparisons and extrapolations between basins can be made only when worst-day reactivities are used.

\textsuperscript{2} Personal communication with M. F. Brunelle, Los Angeles APCD, April 6, 1973.
\textsuperscript{3} Personal communication with P. Downing, EPA, April 18, 1973.
Reactivity Fractions Used in This Study

The same hydrocarbon reactivity fractions are used in both the reference and pessimistic sets of technical assumptions, but the values themselves come from different sources and thus, although they are the best available at the time, they reflect different definitions of reactivity and interpretations of experimental results. Many of the reactivity fractions employed in this study are limit reactivities that were developed by the EPA for use in Los Angeles.\(^4\) However, such fractions were not available for all the source categories considered. For these, we used the best available estimates from the CARB and the Los Angeles APCD and from our earlier work in San Diego\(^5\); these are generally lower than the limit values, some being legal reactivities and others being worst-day reactivities based upon interpretations of earlier experiments. The hydrocarbon reactivity fractions used in this study are therefore a composite, reflecting partially inconsistent interpretations of reactivity.

\(^4\) Specifically, the EPA has recommended that the reactivity for legally nonreactive organic solvents be valued at the chemically and meteorologically estimated 0.80 reactivity fraction, gasoline marketing at 0.93, and diesel exhaust at 0.89 (personal communication from P. Downing, EPA, April 18, 1973). In the case of gasoline marketing, the reactivity fraction was not furnished directly but was calculated from the EPA-furnished value of 138 daily tons of reactive hydrocarbons in 1970.

\(^5\) For piston aircraft, the exhaust is assumed to have a 0.70 reactivity fraction. (This is somewhat lower than the 0.80 fraction for automobile exhausts because the aircraft generally have better ignition systems and more stringent maintenance.) Jet aircraft exhaust is assumed to have a 0.90 reactivity fraction, including both moderate- and low-reactivity substances. These reactivity fractions were derived by Rand [16] from data contained in an aircraft study done for the EPA by Northern Research and Engineering Company. [17]. It should be noted that some analyses have used higher reactivity fractions for jets than for piston aircraft; given the different characteristics of their fuels and combustion processes, this is chemically and thermodynamically counterintuitive.
We do not believe this composite set of reactivities is the most appropriate one for Los Angeles; it was, however, the best set available to us at the time of the analysis.

**Sensitivity of Fixed-Source Inventory to Alternative Reactivities**

To illustrate the sensitivity of results to reactivity assumptions, we prepared two additional fixed-source inventories: the CARB/APCD is based upon the lower reactivity fractions employed by these organizations; the Consistent EPA inventory is based upon our reevaluation of the reactivities of other substances to make them consistent with the values developed by the EPA for gasoline marketing and organic solvents.

Table H-4 shows three different sets of hydrocarbon reactivity fractions for the principal fixed sources. The first set, Consistent EPA, can be interpreted as limit reactivities, that is, they reflect the maximum reaction that could occur independent of local air-basin characteristics. In the Los Angeles basin, the worst-day reactivity values may be close to the limit values, as was pointed out above.

<table>
<thead>
<tr>
<th>Emission Source</th>
<th>Consistent EPA</th>
<th>CARB/APCD</th>
<th>Composite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline marketing</td>
<td>0.93</td>
<td>0.35-0.45</td>
<td>0.93</td>
</tr>
<tr>
<td>Petroleum storage(^d) (gasoline and other)</td>
<td>0.93</td>
<td>0.50</td>
<td>0.93</td>
</tr>
<tr>
<td>Petroleum production and refining</td>
<td>0.93</td>
<td>0-0.10</td>
<td>0-0.10</td>
</tr>
<tr>
<td>Organic-solvent users</td>
<td>0.80</td>
<td>0.20</td>
<td>0.80</td>
</tr>
<tr>
<td>Power plants</td>
<td>0.90</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Aircraft</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jet</td>
<td>0.90</td>
<td>0.37</td>
<td>0.30</td>
</tr>
<tr>
<td>Piston</td>
<td>0.70</td>
<td>0.41</td>
<td>0.70</td>
</tr>
<tr>
<td>Agriculture</td>
<td>0.90-0.95</td>
<td>0-0.95</td>
<td>0-0.95</td>
</tr>
</tbody>
</table>

\(^d\)Included in the gasoline-marketing category in the CARB inventory format.

The CARB/APCD reactivity fractions in Table H-4 are substantially lower, reflecting legal definitions of reactivity and earlier interpretations of experimental results for worst-day reactivity. For example, solvents meeting Rule 66 are legally considered to be nonreactive. There was some uncertainty in our initial contacts with the Los Angeles APCD about whether these remaining amounts were included in their inventories. We subsequently found that they were included, but at the fraction supposedly contained in solvents meeting Rule 66, i.e., at 20 percent by weight.\(^6\) The reactivity of gasoline for the marketing activity is assessed at 46 percent in 1970;\(^7\) the Los Angeles APCD judges that reactivity as 40 to 50 percent.\(^6\) They estimate that in 1975, the reactivity of gasoline will have been reduced to

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\(^6\) Personal communication with Mr. S. M. Weiss, Principal Air Pollution Engineer, Los Angeles County APCD, March 12, 1973.

\(^7\) In some of the other counties in the basin, the reactivity fractions were slightly higher. Los Angeles County, however, dominates the total.
between 30 and 40 percent; we therefore used a 35-percent reactivity for the 1975 nominal and maximal cases.

The composite reactivities shown in Table H-4 are the set generally used in this study. When compared to the other sets, they show inconsistency in the interpretation of reactivity. Again, we do not think this is the most appropriate set, but it was the best set available to us at the time of the analysis.

The sensitivity of the fixed-source inventories to the ranges of reactivity is shown in Table H-5. The control tactics applied under the nominal and maximal strategies are those described in Sec. 2.

### Table H-5

<table>
<thead>
<tr>
<th>Control Strategy</th>
<th>Reactive Hydrocarbons (tons/day)</th>
<th>Consistent EPA</th>
<th>CARB/APCD</th>
<th>Composite</th>
</tr>
</thead>
<tbody>
<tr>
<td>1970</td>
<td>876.0</td>
<td>228.3</td>
<td>636.3</td>
<td></td>
</tr>
<tr>
<td>1975 nominal</td>
<td>427.4</td>
<td>102.2</td>
<td>239.9</td>
<td></td>
</tr>
<tr>
<td>1975 maximal</td>
<td>290.6</td>
<td>57.7</td>
<td>129.9</td>
<td></td>
</tr>
</tbody>
</table>

Using the Consistent EPA reactivity assumptions, we derive a reactive hydrocarbon level from fixed sources of 876 tons daily in 1970; under the composite fractions used in this study, the level is 636 tons, 73 percent of the Consistent EPA value; and under the CARB/APCD fractions, it is 228 tons, only 26 percent of the Consistent EPA value. When additional controls are added, relative differences become more pronounced because the controls imposed on the gasoline-marketing activities and organic-solvent users cause these sources to decline in influence with respect to the remaining sources, which show a greater variation in reactivity fraction under the different interpretations.8

Use of the Consistent EPA inventory, based on limit reactivities, would make it harder to meet the standards in Los Angeles. Despite the fact that worst-day reactivities in Los Angeles probably are close to limit-reactivity values, an inventory based upon limit reactivities may nevertheless be somewhat too large when compared to one based, ideally, upon a consistent set of worst-day reactivities.

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8 The financial cost of the maximal strategy for fixed sources would remain the same; the cost per ton of reactive hydrocarbon removed by controls would vary with the reactivity fraction assumed.
References for Appendix H

Appendix I

SUMMARY DESCRIPTIONS OF ANALYTICAL MODELS

THE MOVEC MODEL

The Motor Vehicle Emission and Cost (MOVEC) model has been developed and used primarily for evaluating light-duty motor vehicle (LDMV) retrofit and inspection/maintenance (I/M) strategies. ¹ For a specific retrofit strategy in a specific calendar year, MOVEC calculates the LDMV emissions for all species, the total annualized costs (both purchase and operating) to the region, and the distribution of costs by group under three alternative payment schemes for financing the retrofit strategy. MOVEC also considers the effect of average trip speed on emissions. In addition, when emissions from other sources and the allowable regional emissions are specified, MOVEC estimates the LDMV mileage reductions (if any) necessary to meet the air-quality standard for each species.

MOVEC Operation

To analyze a selected LDMV control strategy, the MOVEC model needs only the number of LDMVs in the region, the average daily mileage, and the average trip speed. In practice, a MOVEC run has usually considered 28 different control strategies, chosen for their cost-effectiveness, to see how regional emissions vary as the cost and extent of retrofit strategies increase.

The calculation of emissions and costs is a straightforward but tedious bookkeeping operation. MOVEC uses the following basic information in making a run:

- Effectiveness and cost of the LDMV retrofit control tactics.
- Vehicle population distribution by age of vehicle.
- Vehicle mileage distribution by age of vehicle.
- New-vehicle emission factors by model year.
- Age-deterioration factors for exhaust emissions.
- Speed correction functions for exhaust emissions.
- Regional income-distribution data.
- Vehicle ownership by income group.

These data are stored in semipermanent sets; each different set of assumptions (e.g., different assumptions about device effectiveness or emission factors) is represented by a separate data set that can be recalled whenever it is wanted. The regional impacts of retrofit strategies are strongly dependent on some of the basic data assumptions. These include the vehicle emission characteristics by model year, the vehicle mileage characteristics by age of vehicle, and the assumed effectiveness and cost of the retrofit control tactics. The flexibility afforded by the semipermanent data sets permits rapid analyses of the sensitivity of the results to the various technical assumptions. The semipermanent-data concept also allows the model to be readily adapted for use in computing emissions from heavy-duty gasoline-powered or diesel-powered vehicles.

Besides the emissions of each species, the MOVEC model computes the annual-

¹ But it can be applied to other types of vehicles (e.g., heavy-duty) and other types of strategies.
ized cost to the region of the specified LDMV retrofit strategy. For each model year, it considers the following factors:

- Hardware costs of the retrofit device.
- Cost of installing the device.
- Annual increase in maintenance costs due to the strategy.
- Percentage change in fuel consumption experienced by vehicles under the strategy.

The nonrecurring costs (hardware plus installation costs) are annualized by using a capital-recovery factor based on the expected remaining life of the vehicle at the time of the retrofit. Similarly, the annual change in operating costs is determined by using the average annual miles each vehicle will be driven during its remaining life. The total annualized cost is computed on a regional basis as well as per vehicle affected.²

Finally, MOVEC calculates the distribution of retrofit-strategy costs for each of the four household-income groups—under $5000, $5000 to $10,000, $10,000 to $15,000, and over $15,000 annual income. These cost distributions are calculated under three alternative payment schemes:

- User pays.
- Uniform payment per vehicle.
- Income-proportional.

The user-pays scheme is the most regressive, with each owner paying for his own devices. Income-proportional is the most progressive, with each household in the region paying an equal proportion of its income to clean up the air they all breathe.

**MOVEC Output**

MOVEC produces printed reports, computer-generated plots, and punched-output data sets.

**Reports.** For a particular year and set of strategies, MOVEC reports the emissions by species in the following ways:

- Regional LDMV emissions.
- Regional reduction of LDMV emissions resulting from the control strategy.
- Total regional emissions from all sources.
- Total regional emissions in excess of the regional standards.

Of course, the last two parameters require additional input regarding the regional emissions form all sources other than LDMVs and an assumed set of regional emission standards (i.e., maximum allowable tons per day by species). MOVEC also reports the annualized costs (and their components) as a regional total and as distributed by income group for each of the three payment schemes.

**Plots.** MOVEC is also coupled to an S-C 4060 computer-graphics system so that it can automatically produce cost plots and time plots. That is, MOVEC plots any of the four emission parameters above (for each species) versus annualized cost of the different strategies for a given year. It also plots any of these emission parameters versus calendar year for a given strategy; that is, for a single control strategy, the model will perform the emission calculations beginning in a specified year and then in one-year increments for a specified number of years. (In this case, the model

² Note that these costs are only the direct resource costs attributable to a retrofit strategy. The associated welfare losses due to increases in the costs of owning and operating a vehicle are not included.
requires annual growth rates for both the non-LDMV emissions and the regional LDMV miles.)

**Punched Output.** For each control strategy it analyzes, MOVEC calculates an average LDMV emission factor to reflect the retrofit effectiveness, an average nonrecurring cost per vehicle to reflect retrofit procurement and installation costs, and an average recurring cost per vehicle mile to reflect retrofit increases in vehicle operating costs; these averages consider the distribution of vehicle model year and of annual mileage by age of vehicle in the LDMV population. A set of these values, one for each retrofit strategy being considered, is required by the tradeoff model. During each run, MOVEC automatically punches these data in a format suitable for immediate use by the tradeoff model.

**Comments on Speed and Flexibility**

The principal attributes of the MOVEC model are its speed and flexibility. For example, a complete run of the model (including all of the above-mentioned calculations) for 28 different retrofit control strategies requires less than 30 seconds on the IBM 360/65 computer and a modest amount of storage. Its flexibility has been demonstrated both by our San Diego analysis, in which full strategy evaluations were quickly made for six distinctly different sets of technical assumptions, and by our Los Angeles analysis, in which rapid transfer and application to another region were required.

**THE POLICY-ORIENTED URBAN TRANSPORTATION MODEL**

The transportation model is a flexible, policy-oriented tool for evaluating alternative transportation policies in an urban environment. To operate, the model requires only a few inputs, but these have been carefully selected so that a wide range of alternative technological, institutional, and pricing policies can be easily specified. For each policy considered, the model provides detailed output describing transportation-service impacts, both in the aggregate and as distributed among various income groups and travel purposes, and also various economic and environmental impacts. Both input and output have been carefully tailored to facilitate sensitivity analysis, an important policy analysis technique.

**Need for a Policy-Oriented Model**

We believe that a tool such as the one outlined above is indeed much needed. Existing models, such as the California Division of Highways model [1] and the Urban Mass Transportation Administration UTPS model [2], are intended for detailed planning. As such, they burden the user with preparing detailed road and transit networks; specifying bus lines, terminals, and schedules; and obtaining travel information on a point-to-point (or zone-to-zone) basis. Also, because these models treat the problem in such detail, the kind and number of policies and impacts that can be considered must be severely restricted, lest the computer and human costs become prohibitive.

For policy analysis this detail is not only unnecessary but undesirable. The policymaker is not interested in whether the bus routes are located along First and Third streets rather than Second and Fourth; he wants to know if the route spacing should be two blocks and how many people ride on buses. This sort of aggregate information is obscured when too much detail is presented.
On the other hand, the policymaker does want to know what effect a policy might have on average auto occupancy (the carpooling effect) and on congestion. These are just two of the impacts that previous models treat poorly or not at all. Moreover, he wants to be able to specify policies in a convenient way that is natural to him, not in terms of engineering design specifications.

Features of the Model

Our model, therefore, treats the policies and their impacts in an aggregate, regionwide manner—that is, in the terms of greatest value to the maker of overall policy. Because of its policy orientation, this model considers many more policy variables, interactive transportation effects, and impacts than previous models (e.g., it considers carpooling, congestion, and pricing).

The model predicts changes in total travel demand from changes in the quality of transportation service. In this model, for example, an increase in travel cost reduces the number of trips taken and, conversely, a decrease in travel time induces trips. Of course, changes in service quality change not only the total demand (number of person-trips) but also the distribution of trips between auto and bus (the modal split) at the same time. Thus our model simultaneously predicts the total demand and modal split, and it also considers pricing-policy effects.

Carpooling is dealt with explicitly, since changes in the quality of auto service are used to predict auto occupancy.

Realistic cost and supply models are used for each of the modes. For example, many nonlinear cost functions are used, and the quality of bus service is estimated as a function of maximum walking distance, express versus local service, street type, distance between stops, speed limits, bus acceleration characteristics, dwell time, and congestion.

The model estimates all vehicle speeds by specifically considering network capacities and speed limits, vehicle mixes on different street types, time of day, and congestion. Unlike traditional planning models, which use a physical (link-by-link) representation of the network, our model uses a statistical representation of the network supply (capacity) and the way it is used for loading the network. Using this statistical representation permits us to consider the many previously mentioned factors in determining travel times at a cost of only a few seconds of computer time. A particularly important feature of the transportation model is supply/demand bargaining. For example, the supply of buses and the design of the bus system automatically adjust to the demand for buses, while at the same time the demand for buses changes with the quality of bus service provided. Or, as another example,

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3 Such simultaneous prediction has long been urged in transportation literature, particularly by Kraft and Wohl [3], but has been hitherto unachieved. Existing transportation models generally separate demand generation from modal split. They generally predict total demand (number of trips) solely from the region's socioeconomic characteristics for a given year; thus, for a given year, they would predict the same demand under radically different transportation policies. After predicting total demand—indeed, of service quality—in one model (a demand generator), a modal-split model is used. Such models consider service quality in apportioning a constant number of trips among modes. This traditional separation of demand generation and modal split is clearly artificial and unrealistic. It postulates, in effect, that people ignore service quality in deciding whether or not to take a trip (considering only their socioeconomic characteristics), and only after having decided to take a trip do they consider service quality in choosing the mode for the trip.

4 In contrast, using the physical network burdens one with processing thousands (or tens of thousands) of network links at a cost of hours of computer time; moreover, the detail forces one to treat poorly (or not at all) the many relevant factors that the statistical representation considers. For policy-oriented analysis, we feel our technique gives better trip-time estimates. We do not, however, get link-specific assignments to the actual, physical network.
congestion changes with the amount of travel, which in turn changes as service quality changes with congestion.

In calculating the various effects of a given transportation policy, the model distinguishes two trip purposes and four income groups and estimates the transportation-service impacts for each, as well as the overall impacts.

The model is fast, inexpensive to use, and easily transferable to other regions. These features make it a very useful tool for policy analysis. It realistically highlights the important implications of a wide range of policy alternatives without requiring detailed system design.\(^5\)

**Model Approach: Not a Forecasting Model**

It should be noted that our transportation model is not a forecasting model. Rather, given a forecast of the nominal situation for some future year (the transportation policy, travel, and regional characteristics expected if existing, uncontrolled trends prevail), its purpose is to predict for that year the changes in trip demand and modal split resulting from changes in the transportation policy. Thus for each year to be analyzed, a separate, year-specific version of the model is calibrated from the regional description, nominal transportation policy, and nominal travel pattern that are forecast for that year.\(^6\) Thereafter it predicts the changes in travel from the nominal as transportation policy changes.

If the total demand for trips is assumed to remain constant in some future year, then our model operates solely as a modal-split model; indeed, for a particular transportation policy producing a particular set of service characteristics, our model will predict exactly the same number of trips and modal split (for a given trip purpose) as the existing modal-split model for the region from which it was derived. If, on the other hand, our model is given, in addition, a forecast of the potential trips for that year (the maximum number of trips that would be taken if service were improved to the limit), then our model will predict not only the change in modal split but also the change in the total demand for trips as the transportation policy changes from the nominal. We call our technique for converting a conventional modal-split model into a demand-generator/modal-split model the potential-trips approach.

**Calibration of the Model**

Although developed originally for San Diego [4], the model has been recalibrated to Los Angeles with the best available data from a variety of sources. The demand-generator/modal-split component of the model has been derived from the existing modal-split model calibrated to Los Angeles [5], augmented with data from a San Diego modal-split model [6] where necessary;\(^7\) it is from this that we get the relative

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\(^5\) With the present version of the model, the analysis of a typical policy requires less than 10 seconds on an IBM 360/65 computer, and less than 120,000 bytes of core. Since the data requirements are much less for this model than for others, it should be relatively easier to transfer to other regions. For example, the original version of this model was transferred form the San Diego region and then recalibrated to the Los Angeles region, with the best available transportation data, in just a few weeks.

\(^6\) These forecasts may be obtained by various other techniques that consider income and population growth effects, such as applying the California Division of Highways models, extrapolating past fuel consumption or demography, and utilizing the judgment of transportation or planning experts.

\(^7\) For example, the modal-split model calibrated to Los Angeles is only for home-work trips [5]. To deal with trips for other purposes, which was imperative, we had to borrow from experience in another area. San Diego appeared to be the best area to borrow from because of the many similarities in its travel and other characteristics. In the modal-split model calibrated to San Diego [6], the attractiveness of a particular trip by a particular mode for some other trip purpose is calculated as a predetermined multiple of
weighting factors of trip time versus trip cost and of waiting time versus riding time that are used in calculating the perceived cost of a trip.

The functional relationship between auto occupancy and service quality has been derived from a study of vehicle occupancy in San Diego [7], adjusted to fit Los Angeles travel as part of the recalibration process.

Information from many sources was used to prepare the required network supply and loading descriptions. Most of it was obtained by county and thus had to be recast to reflect the Los Angeles basin, which excludes large parts of Los Angeles, San Bernardino, Riverside, and Santa Barbara Counties. Considerable map work and numerous approximations had to be made. The results and some of the details of this process, as well as various other aspects of the calibration of the Los Angeles version of the transportation model, have been documented in an informal working note provided to EPA.

The model is generally applied to predict changes in the nominal travel for some particular year produced by changes in transportation policy. Given a description of the nominal transportation policy, the model is then calibrated to match the nominal travel forecast for that year—i.e., the trips and vehicle miles that would be expected in that year if the nominal policy (existing, uncontrolled trends) did not change. The forecast of nominal vehicle miles has been derived from quite reliable time series forecasting fuel consumption [8]. The forecast of nominal trips has been obtained by taking the 1967 Los Angeles Regional Transportation Study data [9] on trips and inflating it to the particular year of interest by the vehicle mileage growth rate from the time series mentioned above.

The nominal statistical representation of the network supply and loading process was obtained by analyzing network-description and average-daily-traffic data from the California Division of Highways to obtain the capacity, traffic-load, and congestion data for freeways and arterials (the freeway data were developed primarily from informal contacts, the arterial data from Ref. 10); by using residential acreage estimates from the Southern California Association of Governments (SCAG) to calculate residential street capacity and then applying factors from Ref. 10 to estimate their traffic load; and, finally, by using some Los Angeles traffic-pattern data [8] to determine the temporal distribution of traffic load among the street types.

**BUS-SYSTEM COST MODEL**

Because expanded and improved bus systems are potentially important for reducing automobile mileage and associated emissions, it is important to be able to estimate their costs. The costs of proposed bus systems cannot, however, be accurately estimated by simple linear extrapolations from the costs of existing systems; bus-system costs appear to exhibit decreasing returns to scale and extreme sensitivi-
tivity to average bus speed and load factors. Thus there is a need for a generalized bus-system cost model, one that can quickly and easily estimate the costs of many different alternatives and highly unconventional designs.

Given a relatively small number of gross design and policy inputs, the bus-system cost model developed in this project will quickly provide good estimates of the true cost of providing a particular quantity and quality of bus service to a region, show the sensitivity of cost to various changes in bus-system design and operational policy, and in addition produce estimates of a variety of economic and financial impacts, such as employment, fuel consumption, and taxes.

Cost-Analysis Methods

The approach to cost classification and estimation used in the model is quite conventional for models of this kind. Initial investment costs are estimated first and include the total costs of vehicles, yards and shops, other equipment, other facilities, and land. Recurring annual operating costs such as driver and helper wages, fuel expenses, equipment maintenance, and garage costs are then estimated; the operating-cost elements used here closely parallel those used by the American Transit Association. Initial investment costs are annualized by using a capital recovery factor, an approach fully described in Ref. 11.8

All of the above costs are then used to estimate net return on investment, depreciation, corporate-profits taxes, and bond interest if debt financing is used. The model permits the user to specify both a useful life and a salvage value at the end of that time for each asset. These are used in calculating the after-tax return on investment, depreciation, and corporate-profits taxes. For tax computations, the model applies straight-line depreciation, although it could be modified to use other methods.

The model allows the user to choose between various proportions of debt (bond) and equity (common stock) financing. When bond financing is used in some amount, it is assumed that the stipulated fraction applies equally to all assets and is the same throughout the life of the assets. Bond interest is deductible from gross income for corporate-profits tax computation and is so treated. When bonds are used, interest is a fixed annual expense, which, if not allowed by the regulating agency, will reduce after-tax return on total investment. Also, with bond financing, the return on equity investment may well be greater than the return on total investment allowed by a regulatory agency.

When we combine after-tax return on investment, corporate-profits taxes, bond interest, and depreciation with the other recurring annual costs, we arrive at total annualized costs. Because we include after-tax return on investment as a cost, we speak of annual revenue required and total annualized cost as being equivalent. If fares are insufficient to generate a revenue equal to annual cost, a subsidy is required.

All cost estimates are made by using cost-estimating relations (CERs), which are equations or functions that have cost as the dependent variable and one or more system characteristics or design specifications as the independent variables. For example, the purchase cost of a bus is estimated as a function of the number of seats.

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8 A simplified view of the capital-recovery factor is that of amortizing a loan over a given number of periods, with equal installments that include both payments on the principal and interest on the unpaid balance; this is the way one typically pays off a home mortgage or a car loan. Of course, inherent in this approach is the assumption that the bus company is a continuing business. Because there is no sinking fund providing for replacement of vehicles and structures, the annual payments would continue for the life of the company.
Development of CERs

For the most part, the generalized CERs were obtained by plotting the relevant cost against an appropriate independent variable, fitting a curve visually, and expressing the relationship mathematically. Numerous checks of reasonableness have been made, and in our judgment the CERs are thoroughly adequate for the purpose they serve. For example, costs for the Southern California Rapid Transit District were not included in the data base, yet our relationships predict them quite well. It is true, of course, that for extrapolations well beyond the range of the data base the estimates are subject to considerable uncertainty. But we have tried to minimize this uncertainty by choosing functional forms that seem physically meaningful—as well as mathematically suitable—for expressing the individual estimating relationships.

Data Sources

Data were obtained from three primary sources. Operating cost, activity, and equipment-inventory data were obtained for a cross section of approximately 100 U.S. and Canadian transit companies [12]. Data on the cost of buses were obtained from the major bus manufacturers. Data on structures, nonrevenue equipment, and parking requirements reflect an updating and modification of the pre-1965 estimates made in Ref. 13 and revised several years later in Ref. 14.

Input Examples

The inputs can conveniently be classified as (1) system design specifications, such as number of seats per bus, fuel type (gasoline, diesel, etc.), fraction of buses in maintenance, and extra buses to cover downtime for maintenance; (2) inputs related to form of ownership (e.g., public or private); (3) inputs generated in the overall transportation model, such as number of buses required, annual bus miles driven, and annual bus hours; (4) financial inputs including required after-tax return on investment, debt/equity ratio, bond interest rate, and relevant corporate-profits tax rates (Federal, state); and (5) all parameter values for the numerous cost-estimating relationships, e.g., fuel cost per gallon, fuel tax rates, land cost per square foot, useful lifetimes, and salvage values for each kind of asset.

Output Examples

Output information consists of (1) total system cost split between initial investment and annual operating costs; (2) total annualized cost which includes an annualization of the investment costs using the capital-recovery factor and both direct and indirect annual operating costs; (3) separately identifiable financial information, such as after-tax return on investment, corporate-profits taxes paid (Federal, state), bond interest paid, and subsidies if required; (4) the cost per trip and the cost per passenger mile that would need to be charged if revenue were to equal cost; (5) information required for the economic impact analyses, including the cost of labor, buses, other equipment, structures, land, fuel, interest, and fuel taxes (Federal, state, and local); and (6) the coefficients of an aggregate form of the entire model, whose use is described below.

Different Forms of the Model: Detailed Versus Aggregate

The bus-system cost model has been developed and used in two different forms: detailed and aggregate. The detailed form of the model is a separate, free-standing computer program that provides extensive cost breakdowns and also estimates a variety of economic and financial impacts for a particular bus-system alternative. The detailed model has been carefully programmed\textsuperscript{10} so that no numbers are wired in, providing maximum flexibility for change and ease of specification for the user. Indeed, the model may be thought of as a generalized transportation-system cost model. Although CERs for bus systems are presently plugged into the model, CERs representing some other mode (e.g., rail transit) could be plugged in instead, and the model would then provide cost estimates for that mode. Significantly "plug sockets" for all types of CERs that might become relevant, not merely those presently incorporated, are readily available (e.g., the model can accept CERs describing guideway construction or electricity consumption without appreciable modifications to the computer code).

The aggregate form of the model is part of the previously described policy-oriented urban-transportation model, another component of the overall analysis methodology, that is used to evaluate the effect of changes in transportation policy on the quantity, quality, and cost of transportation service. The aggregate form of the model is obtained by collapsing the full model into a single nonlinear function that gives bus-system total annualized cost (for use by the transportation model) as a function of the number of buses, bus miles, and bus hours required. The coefficients of this aggregate form are generated by running the full model with all the other variables fixed at values that represent the institutional and cost parameters of the bus company (e.g., its debt-equity ratio and its fuel cost per gallon).

THE TRADEOFF MODEL

The tradeoff model has been developed to evaluate alternative strategies for meeting regional air-quality standards, select superior strategies for further evaluation, and analyze (parametrically) the sensitivity of results to key assumptions.

Given a fixed-source control strategy, a menu of vehicle retrofit-I/M strategies, and a menu of transportation-management strategies, the tradeoff model searches for the best combination (i.e., the superior strategy). The best combination is defined as the one that meets the desired air-quality standard for the minimum value of the total-cost proxy (TCP), where this proxy includes both the net expenditure for strategy components and the monetary proxy for the social cost of forgone travel.\textsuperscript{11}

The tradeoff model reports a variety of economic, environmental, and transportation-service impacts for the superior strategy it selects; most of the transportation-service impacts come directly from the transportation model, operating as a subroutine.

The tradeoff model also helps perform sensitivity analysis, automatically for certain factors, manually for others. For example, if alternative levels of air-quality

\textsuperscript{10} In the PL/1 programming language.

\textsuperscript{11} All expenditures and costs are expressed as annual values; the investment costs have been annualized by means of a capital-recovery factor. The "net expenditures" reflect the transfer of mileage-surcharge revenue to offset the cost of bus improvements to whatever extent possible. When people are forced to alter their normal behavior by forgoing, trips or switching to less desirable modes, they experience a loss in social value—the social cost of forgone travel. We use the number of forgone trips as a proxy for this social cost and monetize it by multiplying this number by the dollar value of a forgone trip (suitably derived).
standard are specified for a particular species, then the model will automatically select the superior strategy for each level from the given menu, thereby showing how superior-strategy composition and cost vary with the level of the standard. Or, as another example, if alternative sets of technical assumptions are postulated, a separate run can be made for each set, and the model will select the superior strategy for each set of assumptions from the given menu, thereby showing how superior-strategy composition and cost vary with the choice of technical assumptions.

The tradeoff model operates in either of two modes: In the strategy-evaluation mode, all components of a combination strategy are specified uniquely in terms of a particular fixed-source strategy, retrofit strategy, bus system, and mileage surcharge (if any) for LDMVs; the model then calculates a variety of economic, transportation-service, and air-quality impacts. Alternatively, in the strategy-selection mode, a fixed-source control strategy, a menu of alternative retrofit strategies, a menu of alternative bus systems, and an allowable range of mileage surcharge for LDMVs are provided to the tradeoff model, which then selects the superior combination and calculates a variety of impacts.

**Tradeoff Operation in Strategy-Selection Mode: An Example**

Initially, the tradeoff model is given certain general descriptive information, such as the total regional population, the total area and population served by bus, the annual number of trips and vehicle miles forecast without added controls, and the dollar value of a trip forgone (for use in calculating the monetary proxy for the social cost of forgone travel). From the air-quality model, the tradeoff model also receives the reduction in daily emissions required to meet the desired air-quality standard and uses this to calculate the emissions goal—the allowable emissions if the standard is to be met.

A fixed-source control strategy is specified by the user. Its costs are input directly to the tradeoff model, for subsequent use in calculating the TCP, and its emissions are input to MOVEC (where they are used to calculate the emission reduction required of mobile sources) and then passed on to the tradeoff model. If the emissions from fixed sources alone exceed the emissions goal, as is possible even after control, the tradeoff process terminates immediately and the air quality actually achieved is printed out. If this does not occur, the process continues as follows.

A menu of up to 28 retrofit strategies, chosen in a separate analysis, is presented to the tradeoff model from MOVEC, along with their costs and effectiveness. The model orders these strategies according to their effectiveness in achieving the emissions goal. It then picks the most effective retrofit strategy as its first candidate for evaluation. Both the speed-dependent and speed-independent emission factors for the candidate strategy are recorded for subsequent use in calculating LDMV emissions, and both the investment cost and incremental operating cost per mile of the strategy are recorded for subsequent use in the TCP.

A menu of bus systems is now specified, chosen in a separate analysis; a bus system is described by a particular peak-period headway and a maximum off-peak headway, along with a fare structure. The tradeoff model now picks the bus system with the poorest peak-period headway as its first candidate for evaluation.

12 For each strategy, emissions are calculated under the assumption of no reduction in LDMV miles. The emissions are compared with the emissions goal, and the mileage reductions necessary to meet the goal, after accounting for fixed sources, are calculated. The 28 possible strategies are then ordered by necessary mileage reduction, with those requiring the least reduction in LDMV miles at the top of the list. When two or more strategies require identical mileage reduction, only the least costly is retained on the list.
At this point, the model has a fixed-source control strategy, a candidate retrofit strategy, and a candidate bus system. The headways and fare structure for the candidate bus system and the incremental operating cost per mile for the candidate retrofit strategy are now fed into the transportation model, operating as a subroutine, which uses them, along with other data, to calculate the service characteristics of auto and bus. Using these service characteristics, the transportation model estimates the total demand for trips, including the number of forgone trips, and splits this demand between auto and bus. Simultaneously, the auto service characteristics are used to estimate auto occupancy rates (carpooling); bus-load constraints are observed to limit bus travel, if necessary; and vehicle trips are assigned to the network, congestion is estimated, and average vehicle speeds are determined. After this, the transportation model provides the tradeoff model with the daily mileage and average speeds of LDMVs and buses for calculating emissions, and the annual number of trips forgone and the bus-system costs and revenue for calculating the TCP.

Given the daily LDMV and bus mileage, the tradeoff model employs the emission factors for buses and those for LDMVs under the candidate retrofit strategy, corrected for vehicle speeds, to calculate the average daily emissions. It compares the emissions under the candidate strategy with the emissions goal. If the emissions satisfy the goal, the model is ready to calculate the TCP for this combination strategy. If, on the other hand, the emissions exceed the goal, then a mileage surcharge must first be imposed on LDMVs to reduce their mileage and another cycle made through the transportation model to evaluate the surcharge effect on the number of trips either taken by carpool and bus or forgone entirely, as well as their associated mileage and emissions. Using binary search, this process is repeated for values within the allowable range of mileage surcharge until the particular mileage-surcharge value is found that reduces LDMV mileage just enough to achieve the emissions goal. If the emissions satisfy the goal, the tradeoff model is ready to calculate the TCP for this combination strategy.

The model calculates this TCP by using the fixed-source cost from the original input; the annualized retrofit investment cost originally input from MOVEC; the retrofit operating cost from the retrofit operating cost per mile and the LDMV mileage; the bus-system cost from the transportation model; the mileage surcharge from the surcharge rate and the LDMV miles driven; and the monetary proxy for the social cost of forgone travel from the transportation model's estimate of the number of forgone trips and their value, which was originally input. The TCP for this combination strategy is recorded for comparison with the proxies for the other combinations being considered in this tradeoff run.

For the same retrofit strategy, this process continues until all the remaining bus systems on the menu have been considered. The entire process is then repeated for each retrofit strategy on the ordered list. When the list is exhausted, the model compares the TCP for each combination, selects the combination with the minimum value as the superior strategy, and prepares detailed output for it.

In many cases, a linear combination of two LDMV retrofit strategies will have the same effectiveness as the selected pure strategy but a lower annualized cost. The tradeoff model includes a standard linear program that searches for these hybrid strategies. The cost of and possible savings due to these hybrid strategies are included in the output but not in used in the TCP.

**Tradeoff Output**

The output from the tradeoff model is in multiple parts.
Part one summarizes the key assumptions, the components and costs of the superior strategy, the travel reductions due to the strategy, and the makeup and savings of any hybrid retrofit strategy.

Part two describes the bus system in terms of service area, population eligible, number of buses, bus miles, bus speeds, employment, etc.

Part three provides information about how the auto and bus systems are used, including auto occupancy (carpooling); bus loads, miles, and modal split; and average trip lengths for auto and bus. Each is shown for key time periods: daily average, morning peak period, entire peak period, and off-peak.

Part four presents detailed transportation-service impacts by mode, including number of trips; vehicle and passenger miles; and trip times, speeds, and costs. Again, each is shown by key time periods.

Part five distributes these transportation-service impacts among four income groups and two travel purposes.

These data provide many of the useful impacts directly and are the primary inputs for evaluating many others.

Tradeoff Speed and Flexibility

The prime attributes of the tradeoff model are its speed in analyzing a given strategy and its modest data requirements. A typical run in the strategy-evaluation mode requires less than 15 seconds and 120,000 bytes of core on an IBM 360/65. Run times in the strategy-selection mode depend on the number of tradeoffs (e.g., alternative bus systems) that are specified by the user.

These small core and time requirements permit the economical analysis of many cases. Many alternative sets of technical assumptions may be considered, as well as many menus of strategy components. This is of particular importance to most policy studies, since many of the technical assumptions (such as LDMV emission factors) are uncertain at the present time, and it is generally desirable to perform in-depth analysis of the sensitivity of strategy composition and the resulting impacts to such assumptions.

AIR-QUALITY PREDICTION TECHNIQUES

A number of different air-quality prediction methodologies have been developed in recent years. These methodologies range in complexity from large-scale physical simulation models to simple statistical models that predict pollutant concentrations under some strategy based on concentrations observed in the past and the change in regional emissions.

We have based our air-quality analyses for the Los Angeles basin mainly on two of the less complex statistical models; the proportional rollback model and the EPA-Medium model. Here we will present a brief description of these models, including their underlying assumptions, many of which are common to both models. Finally, we will conclude with some comments on the more sophisticated statistical and physical simulation models and our reasons for omitting them in this study.

Proportional-Rollback Model

Although it is widely considered to underestimate the necessary reactive hydrocarbon emission reductions for Los Angeles, we have employed the proportional-rollback model to predict worst-day maximum pollutant concentrations for compari-
son purposes. The rollback technique assumes that a linear proportionality exists between regional emissions and observed concentrations. It is thus possible to predict concentrations under some control strategy by forecasting the emissions that would result from that strategy. For example, the maximum pollutant concentration during the analysis year at a given monitoring site under a given control strategy can be predicted by using the following equation:

\[ C^S_{\text{max}} = (E^S/E^B)C^B_{\text{max}} \]

where \( E^S \) = Average daily emissions forecast under the strategy
\( E^B \) = Average daily emissions calculated for the base year (1970 in the present analysis)
\( C^B_{\text{max}} \) = Maximum concentration observed at the monitoring site during the base year

We have assumed this equation is valid for all species and all averaging times.

The rollback model contains two implicit assumptions: first, that the spatial and diurnal variation of emissions in the analysis year are identical to that of the base year; and second, that all of the emission sources within the region are reduced by the same percentage as a result of the control strategy. An alternative interpretation of these assumptions is to regard the air basin as a large box into which all emissions are dumped. Hence, a given air-quality standard should be achieved if emission levels are rolled back by a percentage determined by the ratio of the standard concentration to the maximum observed concentration.

The EPA Models

The EPA has provided three alternative models for achieving different maximum one-hour oxidant concentrations in the Los Angeles Air Quality Control Region. These models are summarized in Table I-1. (The linear-rollback model is included for comparison, although it is generally believed that the rollback model underestimates the reactive hydrocarbon reduction required in the Los Angeles basin.)

Each of the EPA models requires greater amounts of control than does the linear-rollback model. For example, to meet the 0.08-ppm oxidant standard, the linear-rollback model requires an 87-percent reactive hydrocarbon reduction, whereas the EPA-Medium model requires 93 percent. Note, however, that the rollback paradox (discussed at the beginning of Sec. 6) applies to all the models, since they all require some percentage reduction in the emissions computed for 1970. Of the three EPA models, the EPA-Medium is used consistently in the results presented in this report. (The others were used in sensitivity analyses whose results were informally transmitted to the EPA.) Significantly, the EPA-Medium value of a 93-percent reactive hydrocarbon reduction to meet the 0.08-ppm oxidant standard in Los Angeles was used in the EPA Region IX Final Implementation Plan for Los Angeles (Nov. 12, 1973); reportedly, however, the value came from using a rollback model with a 0.03-ppm background level [15]. As an alternative for Los Angeles, the EPA 8-station-average model has since been developed by Schuck and Papetti of the EPA [15]; it requires the same 93-percent reduction.

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13 In considering the air quality for a given species, the concentration levels considered are not instantaneous values but rather average values for some interval of time (one hour, say) specified by the standard and termed the "averaging time." For oxidant, as an example, the standard is a maximum concentration of 0.08 ppm for a one-hour averaging time.
Table I-1

REQUIRED PERCENTAGE REDUCTION IN REACTIVE HYDROCARBON EMISSIONS FROM 1970 LEVELS TO ACHIEVE DIFFERENT OXIDANT STANDARDS FOR DIFFERENT AIR-QUALITY MODELS

<table>
<thead>
<tr>
<th>Model Designation</th>
<th>Max. One-Hour Oxidant Concentration (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.08</td>
</tr>
<tr>
<td>EPA-Low</td>
<td>90</td>
</tr>
<tr>
<td>EPA-Medium</td>
<td>93</td>
</tr>
<tr>
<td>EPA-High</td>
<td>96</td>
</tr>
<tr>
<td>Rollback</td>
<td>87</td>
</tr>
</tbody>
</table>


Alternative Air-Quality Models

**Frequency Versus Concentration.** The proportional-rollback and EPA-Medium models can be used to predict maximum concentrations for each species. Equally important, particularly for strategies that will not achieve the applicable air-quality standards for certain species (e.g., the 1977 nominal strategy), is the prediction of the number of days the standard concentration (or any other) will be exceeded at each monitoring site. The statistical model developed by Larsen [16] has been used for this purpose in a number of regions.14

In studying oxidant-control strategies for Los Angeles, a statistical model (Larsen's or some other) that shows the expected frequency of exceeding a particular concentration level could be very useful. Such a model may be used to investigate the tradeoffs between the number of days some concentration is exceeded and the extent and cost of the control strategy. Meeting the standard exactly might impose enormous monetary and social costs and implementation problems on a region; coming very close (e.g., by exceeding the standard concentration on just three days or by exceeding a slightly higher concentration on only one day) might be relatively easy. It is clearly desirable to have a tool that permits the region to estimate such tradeoffs and, if deemed desirable, use this information to argue for a variance from the exact standards.

**Spatial Resolution.** We realize the limitations of the air-quality prediction techniques used in our analysis. Perhaps most important is the lack of spatial resolution which, if available, would have made possible the more exact evaluation of strategies with spatially nonuniform emission reductions. Furthermore, different levels of reduction among species will surely affect the photochemistry of the reactive pollutants. Details such as these can be analyzed only by appealing to more sophisticated air-quality models.

Several large-scale physical simulation models have been developed that attempt to account for regional meteorology and topography as well as spatial and temporal emission patterns. Many of these models include such effects as pollutant transport on the macroscale, turbulent diffusion, vertical temperature gradients,

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14 Reference 17 discusses and provides examples of the application of the Larsen model in a policy context.
and atmospheric photochemistry (see Refs. 18 and 19 for typical examples). There is, at present, no general agreement in the modeling community as to which of the several available models is best suited for regional air-pollution analysis and prediction. Unfortunately, some do not treat oxidant, which is Los Angeles' problem species. Even more serious, all such physical models have two inherent shortcomings: They require exceedingly detailed inputs of regional meteorology, which are seldom readily available, as well as laboriously detailed emission inventories for each strategy, and the simulations require excessive amounts of computer time. Cost considerations (computer and human) thus virtually prohibit the use of physical simulation models in studies such as ours, where many alternative control strategies must be evaluated, usually under several sets of assumptions.

We have been developing a strategic, policy-oriented air-quality prediction methodology, under Rand-sponsored research, that is intended to be a compromise between the simple statistical and the physical simulation models, providing the speed and flexibility of the former and the spatial resolution of the latter. When such a model becomes available, it may be possible to find strategies that exploit geography and meteorology to achieve the standards at somewhat lower total cost than the ones presented.

References for Appendix I

9. Los Angeles Regional Transportation Study: Volume I—Base Year Report and Appendix to the Base Year Report, California Division of Highways, December 1963.
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**Appendix J**

**EMISSION INVENTORIES FOR THE NOMINAL CONTROL STRATEGIES: 1970 AND 1977**

<table>
<thead>
<tr>
<th>Source</th>
<th>1970 Inventory</th>
<th>1977 Inventory</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HC</td>
<td>RHC</td>
</tr>
<tr>
<td>Fixed sources (including aircraft)</td>
<td>1,012.9</td>
<td>636.3</td>
</tr>
<tr>
<td>Ships and railroads</td>
<td>5.6</td>
<td>---</td>
</tr>
<tr>
<td>Heavy-duty gasoline-powered vehicles</td>
<td>117.7</td>
<td>90.3</td>
</tr>
<tr>
<td>Heavy-duty diesel-powered vehicles</td>
<td>12.7</td>
<td>12.6</td>
</tr>
<tr>
<td>Motorcycles</td>
<td>23.4</td>
<td>18.5</td>
</tr>
<tr>
<td>Light-duty motor vehicles</td>
<td>1,834.6</td>
<td>1,406.9</td>
</tr>
<tr>
<td><strong>1970 total</strong></td>
<td>3,006.9</td>
<td>2,164.6</td>
</tr>
</tbody>
</table>

*Using reference technical assumptions.*
Appendix K

POPULATION FORECASTS FOR SIX-COUNTY SOUTHERN CALIFORNIA REGION AND SOUTH COAST AIR BASIN: 1975 AND 1977

DATA SOURCES AND BASIC ASSUMPTIONS

Table K-1 presents estimates of the compound annual population-growth rates for 1972 to 1975 in Los Angeles, Orange, Ventura, Riverside, and San Bernardino Counties. These rates were obtained informally from the Bank of America and the Security Pacific National Bank. Using this information and our best judgment, we have derived the rates shown in the last column of Table K-1 and have used these as the basis for our population forecasts for these counties. Forecasts of population for Santa Barbara County, under three different economic-growth scenarios, were developed in a recent study done by the University of California, Los Angeles. We chose to use their "normal" economic-growth scenario as the most likely forecast.

Table K-1

<table>
<thead>
<tr>
<th>County</th>
<th>Growth Rate (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B of A Estimate</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>-0.2</td>
</tr>
<tr>
<td>Orange</td>
<td>4.5</td>
</tr>
<tr>
<td>Ventura</td>
<td>3.5</td>
</tr>
<tr>
<td>Riverside</td>
<td>2.2</td>
</tr>
<tr>
<td>San Bernardino</td>
<td>1.2</td>
</tr>
</tbody>
</table>

aPersonal communication from Mr. Robert Ostrow, Economics Dept., Bank of America, Los Angeles.

bPersonal communication from Mr. Conrad C. Jamison, Security Pacific National Bank, Los Angeles. Data are given in terms of absolute changes in population.

POPULATION FORECASTS

Table K-2 presents population forecasts for each of the six counties and for the South Coast Air Basin (see Fig. K-1) for 1975 and 1977. The South Coast Air Basin
Table K-2


<table>
<thead>
<tr>
<th>County/Area</th>
<th>Population (thousands of persons)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1970</td>
</tr>
<tr>
<td>Los Angeles</td>
<td>7,036.5</td>
</tr>
<tr>
<td>Orange</td>
<td>1,408.5</td>
</tr>
<tr>
<td>Ventura</td>
<td>376.3</td>
</tr>
<tr>
<td>Riverside</td>
<td>457.0</td>
</tr>
<tr>
<td>San Bernardino</td>
<td>679.9</td>
</tr>
<tr>
<td>Santa Barbara</td>
<td>254.0</td>
</tr>
<tr>
<td><strong>Six-county total</strong></td>
<td><strong>10,212.2</strong></td>
</tr>
<tr>
<td><strong>South Coast Air Basin</strong></td>
<td><strong>9,583.1</strong></td>
</tr>
</tbody>
</table>

is estimated to contain 93.84 percent of the six-county population. This figure was derived by assuming proportionality between gasoline-powered-vehicle miles and population and between gasoline-powered-vehicle miles and emissions. (California State Implementation Plan emission inventories indicate that 93.84 percent of the emissions from gasoline-powered vehicles in the six-county region occurred in the South Coast Air Basin.) Note that most of the population growth during this time period is expected to be in Orange County.

GROWTH RATES FOR SELECTED PERIODS

Table K-3 shows the compound annual growth rates for each county, for Los Angeles and Orange Counties combined, for the aggregate of all six counties, and for three different time segments: 1970-1975, 1970-1977, and 1975-1977. Los Angeles County shows a negative growth rate between 1970 and 1977, which is largely accounted for by the shift in population from Los Angeles to Orange County that occurred between 1970 and 1972. It has been assumed that from 1972 on the population in Los Angeles County will remain relatively constant. Orange County is expected to continue to grow at about 4.5 percent per year, and the two counties together at less than 1 percent per year. The overall growth rate for all six counties is approximately 1 percent per year for the entire time period.
Table K-3

COMPOUND ANNUAL POPULATION-GROWTH RATES FOR SIX SOUTHERN CALIFORNIA COUNTIES: 1970 TO 1977

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Los Angeles</td>
<td>-0.00197</td>
<td>-0.00141</td>
<td>0.00000</td>
</tr>
<tr>
<td>Orange</td>
<td>0.04684</td>
<td>0.04546</td>
<td>0.04201</td>
</tr>
<tr>
<td>Ventura</td>
<td>0.03899</td>
<td>0.03783</td>
<td>0.03495</td>
</tr>
<tr>
<td>Riverside</td>
<td>0.02357</td>
<td>0.02440</td>
<td>0.02147</td>
</tr>
<tr>
<td>San Bernardino</td>
<td>0.01298</td>
<td>0.01270</td>
<td>0.01199</td>
</tr>
<tr>
<td>Santa Barbara</td>
<td>0.00852</td>
<td>0.01141</td>
<td>0.01870</td>
</tr>
<tr>
<td>Six-county composite</td>
<td>0.00941</td>
<td>0.00984</td>
<td>0.01091</td>
</tr>
<tr>
<td>Los Angeles and Orange</td>
<td>0.00684</td>
<td>0.00736</td>
<td>0.00865</td>
</tr>
</tbody>
</table>