12. THINKING ABOUT POLICY OPTIONS

We have analyzed the social costs and benefits of many policy actions planned by California air-quality regulators to reduce ozone-producing emissions from light-duty vehicles (passenger cars, light-duty trucks). We have referred to these actions collectively as "California's LDV strategy."

In this concluding section, we review and integrate our findings to consider what our analyses suggest about future directions for ozone-reduction policies. (Readers wishing to review more detailed summaries of our findings might revisit the previews of findings at the beginnings of Sections 6 through 11.) We pay special attention to policies designed to encourage development and use of zero-emission vehicles (ZEVs).

12.1 OVERVIEW OF OUR ANALYSES AND MAJOR CONCLUSIONS

To analyze California's ozone reduction strategy, we

- Developed an economic framework for identifying costs and benefits that should be considered;
- Reviewed and critiqued the most informative or influential existing studies of various elements;
- Applied standard economic principles to interpret data and estimate effects;
- Characterized ranges of reasonable disagreement about key estimates;
- Developed models to predict the costs, emission reductions, cost effectiveness, and market effects of various components of the strategy;
- Identified major sources of uncertainty.

The results of our analyses are detailed in the preceding sections. Here, for the reader's convenience, we summarize the major components of our findings in three tables. Table 12.1-1 provides an overview of our analyses, listing the key studies of costs and/or emission reductions, describing how we examined some interdependencies between elements, and
explaining how we examined market effects. Table 12.1-2 collects and explains the NCERs that we derived—in various ways—from these studies. Table 12.1-3 summarizes our findings on market-mediated effects.

Summarizing our findings in tabular form has both an advantage and a disadvantage.

The advantage is that the table facilitates a high-level view of the policy landscape. Looking across each row provides an overview of the information available for each element. Looking up and down the columns allows us to compare the kinds and quality of information available about different elements and easily identify similarities and differences in the sorts of factors that should enter the evaluation of each element.

The disadvantage is that the tables make all numbers appear to be equally reliable and comprehensive. We have used commentary in the table text and table notes to remind readers of some of the major reasons that values listed are not directly comparable. In addition, use of the tabular format obscures subtleties of meaning. To partially compensate for this limitation, we have provided a reference to the appropriate section or table in the body of this report.

Much of the analysis involved reviewing, interpreting and critiquing studies bearing on the costs and benefits of different parts of the California LDV strategy. The row headings in Table 12.1-1 list the policy elements we analyzed. The first column lists the major sources of information reviewed concerning costs, emission benefits and what we have called narrow cost-effectiveness ratios (NCERs). The effects—and especially emission benefits—of various elements depend on the effectiveness of other elements, and column (2) of the table highlights several interdependencies and describes how we analyzed them. The last column describes our analyses of market reactions to policy elements and how those reactions affect or distribute costs and benefits of the policies.
<table>
<thead>
<tr>
<th>Element of California Strategy</th>
<th>(1) Studies of Costs and/or Emission Reductions Reviewed</th>
<th>(2) Interdependencies Examined (Method)</th>
<th>(3) Market Effects Examined (Method)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ICEV Hardware</strong></td>
<td>CARB (1989a, 1990a, 1994a, b, 1995b), Sierra (1994a, c), Chrysler, Ford, GM, Honda^</td>
<td>I&amp;M (sensitivity analysis), interaction of ORVR and Stage II vapor recovery nozzles (qualitative discussion)</td>
<td>Short-run effects on prices of ICEVs, losses to buyers, and lost profits (calibrated supply and demand models); effects on fleet turnover and emissions (qualitative analysis drawing on other empirical studies)</td>
</tr>
<tr>
<td>Element of California Strategy</td>
<td>Studies of Costs and/or Emission Reductions Reviewed</td>
<td>Interdependencies Examined (Method)</td>
<td>Market Effects Examined (Method)</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>--------------------------------------------------</td>
<td>-----------------------------------</td>
<td>---------------------------------</td>
</tr>
<tr>
<td>ZEVs</td>
<td>Abacus (1994), Booz•Allen (1995), CARB (1994a,b), GAO (1994), Kalhammer et al. (1995), Moomaw et al. (1994), Sierra (1994a,c), Chrysler, Ford, GM</td>
<td>Effectiveness of ICEV emission control program; NMOG standard (sensitivity analysis)</td>
<td>Short-run gains to EV buyers, price increases of ICEVs, losses to ICEV buyers, lost profits (calibrated supply and demand models), effects on fleet turnover and emissions (qualitative analysis drawing on other empirical studies)</td>
</tr>
</tbody>
</table>

*Interviews of motor vehicle manufacturers are listed separately because they provided estimates not reported in any written study cited. We also conducted interviews with authors of many written studies, such as CARB, Sierra Research, Inc., and GAO.*
Table 12.1-2 provides information about the NCERs that we analyzed. Column (1) is a numerical summary of our information about the narrow cost-effectiveness of each element, and column (2) refers the reader to sections or tables above where details can be found. As indicated in column (3), the nature of these numbers varies a lot. In some cases, we took the NCERs directly from the studies reviewed or reexpressed them in a straightforward fashion. In others, the NCERs we report are based on adjusting NCERs that appear in other studies to make them more comparable to other NCERs or the precise concept of interest. In the case of the ZEV mandate, we used information from the studies and extensive modeling to examine important issues that no other studies address.

As we emphasize throughout the report, NCERs do not provide a complete basis for policy decisions, no matter how accurately they estimate what they set out to estimate. Thus the first step in using NCERs is being clear about what costs and benefits a particular NCER purports to estimate. Column (4) of Table 12.1-2 indicates, for each element, what costs and what benefits analysts have, in fact, attempted to account for in the NCERs they have developed.

No matter what the definition of an NCER includes, all estimated NCERs are subject to inaccuracies. In column (5) we list the major sources of uncertainty about the NCERs reported. To take two examples: Studies of the narrow cost-effectiveness of I&M programs attempt to incorporate behavioral responses such as fraud, and the accuracy with which they do so is dubious. In the case of the ZEV mandate, our sensitivity analyses highlight factors such as the magnitudes of incremental EV production and operating costs and the effectiveness of ICEV emission-control programs that dramatically affect the NCER.

For some elements, the most important reason that NCERs cannot provide a reliable guide to policy is that they don’t even attempt to account for some possibly crucial costs and benefits of a policy. Column (6) of Table 12.1-2 lists costs and benefits we believe could be very important but are simply uncounted in any way in the NCERs we report.
Table 12.1-2
Narrow Cost-Effectiveness Ratios for Elements of California’s LDV Strategy: Ranges, Sources, Definitions, Limitations

<table>
<thead>
<tr>
<th>Element</th>
<th>NCER ($1000s per ton of ROG+NOx)</th>
<th>Where Discussed in Report</th>
<th>Source</th>
<th>Costs and Benefits Included in Definition of Narrow Cost Effectiveness(^a)</th>
<th>Key Uncertainties About NCER</th>
<th>Key Uncounted Costs and Benefits(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICEV Hardware</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TLEV</td>
<td>3-40</td>
<td>Sec. 6.3</td>
<td>Derived from studies</td>
<td>Costs: R&amp;D, production, and selling costs, Benefits: emission reductions (both relative to next most stringent exhaust standard)</td>
<td>Accuracy of emission models, emission system deterioration rates, cost estimates</td>
<td>Effects on fleet turnover, location, and time of emission reductions</td>
</tr>
<tr>
<td>LEV</td>
<td>1-38</td>
<td>Table</td>
<td>reviewed</td>
<td>Costs: R&amp;D, production, and selling costs, Benefits: emission reduction relative to 1993 California vehicle</td>
<td>Accuracy of emission models, emission system deterioration rates, cost estimates</td>
<td>Location and time of emission reductions</td>
</tr>
<tr>
<td>ULEV</td>
<td>22-48</td>
<td>6.3-1</td>
<td>reviewed</td>
<td>Costs: R&amp;D, production, and selling costs, Benefits: emission reductions when Stage II vapor recovery nozzles also used</td>
<td>Interaction of ORVR and Stage II vapor recovery nozzles</td>
<td>Costs of modifications to underground storage tanks</td>
</tr>
<tr>
<td>EEE</td>
<td>0.5-3</td>
<td>Sec. 6.3</td>
<td>Derived from studies</td>
<td>Costs: R&amp;D, production, and selling costs, Benefits: emission reduction relative to 1993 California vehicle</td>
<td>Accuracy of emission models, emission system deterioration rates, cost estimates</td>
<td>Location and time of emission reductions</td>
</tr>
<tr>
<td>ORVR</td>
<td>infinite</td>
<td>Sec. 6.3</td>
<td>Derived from studies</td>
<td>Costs: R&amp;D, production, and selling costs, Benefits: emission reductions when Stage II vapor recovery nozzles also used</td>
<td>Interaction of ORVR and Stage II vapor recovery nozzles</td>
<td>Costs of modifications to underground storage tanks</td>
</tr>
<tr>
<td>Element</td>
<td>(1) NCER ($1000s per ton of ROG+NOx)</td>
<td>(2) Detailed Source</td>
<td>(3) Taken</td>
<td>(4) Costs and Benefits Included in Definition of Narrow Cost Effectiveness&lt;sup&gt;a&lt;/sup&gt;</td>
<td>(5) Key Uncertainties About NCER</td>
<td>(6) Key Uncounted Costs and Benefits&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>---------------</td>
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<td>---------------------------------------------------------------------------------</td>
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</tr>
<tr>
<td>OBD II</td>
<td>2-15&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Sec. 8.3.2</td>
<td>Taken directly from studies reviewed</td>
<td>Costs: R&amp;D, production, and selling costs. Benefits: emission reductions with enhanced I&amp;M.</td>
<td>Behavioral response to check-engine light, effectiveness of Smog Check II.</td>
<td>Repair costs, decreased time needed to diagnose malfunctions, costs and benefits of increased durability of emission-control system.</td>
</tr>
<tr>
<td>ICEV Non-Hardware</td>
<td></td>
<td></td>
<td></td>
<td>Costs: R&amp;D, production, and reduced fuel efficiency. Benefits: emission reductions given number of miles driven.</td>
<td>Effects on vehicles certified on RFG, change in effectiveness as vehicles age.</td>
<td>Reduced costs of ICEV hardware, emission reductions due to reduced driving.</td>
</tr>
<tr>
<td>CP2G</td>
<td>9-46</td>
<td>Sec. 8.1.3</td>
<td>Derived from studies reviewed</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Smog Check II</td>
<td>0.5-5.5&lt;sup&gt;c&lt;/sup&gt;</td>
<td>Sec. 8.2.3</td>
<td>Taken directly from studies reviewed</td>
<td>Costs: inspection, repair, driver time, administration. Benefits: emission reductions of repaired vehicles.</td>
<td>Extent of evasion, effectiveness of remote sensing, extent emission variability hinders identification of high emitters.</td>
<td>Driver aggravation.</td>
</tr>
</tbody>
</table>
Table 12.1-2, (Cont’d.)

<table>
<thead>
<tr>
<th>(1) NCER ($1000s per ton of ROG+NOx)</th>
<th>(2) Detailed In</th>
<th>(3) Source</th>
<th>(4) Costs and Benefits Included in Definition of Narrow Cost Effectiveness(^a)</th>
<th>(5) Key Uncertainties About NCER</th>
<th>(6) Key Uncounted Costs and Benefits(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVR 2-10(^d)</td>
<td>Sec. 8.4.3, Table 8.4-4 reviewed</td>
<td>Taken directly from studies reviewed</td>
<td>Costs: lost transportation services, program administration Benefits: emissions avoided on scrapped vehicles net of emissions from replacement transportation</td>
<td>Emissions of replacement transportation, remaining lifetimes of scrapped vehicles</td>
<td>In-migration, responses to incentives for higher emissions, reductions in Smog Check evasion</td>
</tr>
<tr>
<td>ZEV 5-1,197</td>
<td>Sec. 10.4 Table 10.4-1 based on data derived from studies reviewed</td>
<td>Modeling and sensitivity analysis</td>
<td>Costs: R&amp;D, production, and lifetime operating costs in near- and long-term Benefits: ICEV emissions directly displaced by EVs</td>
<td>Initial EV costs, decline in costs over time, effectiveness of ICEV emission control program, how manufacturers adjust ICEV fleet</td>
<td>Costs of managing reduced range, infrastructure costs, benefits of home refueling and quiet of EVs, effect on fleet turnover, ICEV mileage displaced per EV</td>
</tr>
</tbody>
</table>

\(^a\)NCER includes costs borne both inside and outside California.

\(^b\)In addition to the reductions of emissions other than ROG and NOx such as CO, air toxics, or particulates.

\(^c\)We have very little confidence that the NCER is in or near this range.

\(^d\)In contrast to other non-hardware elements of the California strategy, the NCER for AVR does not purport to incorporate behavioral effects.
### Table 12.1-3
Summary of Market-Mediated Effects, 1998 to 2002

<table>
<thead>
<tr>
<th>Element</th>
<th>Findings on Market-Mediated Effects</th>
<th>Where Discussed in Report</th>
<th>Key Sources of Uncertainty</th>
</tr>
</thead>
</table>
| ICEV hardware | ICEV prices will increase $100-$500/vehicle  
ICEV sales will fall 10K-60K vehicles/year  
ICEV buyers will lose $150M-$700M/year  
Manufacturers and dealers will lose $100M-$800M/year  
Emissions may increase in early years due to reduced fleet turnover | Table 7.2-2  
Sec. 7.4 | Effects of regulations on variable production costs  
Size of price effects |
| CP2G        | Vehicle miles traveled will fall 1.5-4 percent  
Emissions will fall by comparable amounts or more | Sec. 9.1  
Sec. 9.3 | Size of gasoline price increases  
Barriers to in-migration, elasticity of demand for older vehicles |
<p>| AVR         | In-migration, price increases of older vehicles, or both will occur; lack of price increases would be a bad sign about in-migration | Appendix 9.A |  |</p>
<table>
<thead>
<tr>
<th>Element</th>
<th>Findings on Market-Mediated Effects</th>
<th>(2) Where Discussed in Report</th>
<th>(3) Key Sources of Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZEVs</td>
<td>EV prices may be as much as $10,000 less than comparable ICEV</td>
<td>Table 11.5-1</td>
<td>Lifetime operating cost disadvantage of EVs</td>
</tr>
<tr>
<td></td>
<td>EV buyers will gain $20M-$200M/year</td>
<td>Table 11.5-2</td>
<td>Willingness of EV buyers to pay premium over ICEV prices</td>
</tr>
<tr>
<td></td>
<td>Producers may lose as much as $1.5B/year or profit as much as $350M/year in the EV market</td>
<td>Table 11.5-2</td>
<td>EV production costs, EV prices</td>
</tr>
<tr>
<td></td>
<td>ICEV prices will increase $0-$550/vehicle</td>
<td>Table 11.6-1</td>
<td>Variable costs and prices of EVs, Big 7 pricing policies</td>
</tr>
<tr>
<td></td>
<td>ICEV sales will fall 0-110K vehicles/year</td>
<td>Table 11.6-1</td>
<td>ICEV price increases, degree EV sales displace ICEV sales</td>
</tr>
<tr>
<td></td>
<td>ICEV buyers will lose $0-$800M/year in the ICEV market</td>
<td>Table 11.6-1</td>
<td>Variable costs and prices of EVs, Big 7 pricing policies</td>
</tr>
<tr>
<td></td>
<td>Big 7 will lose $100M-$800M/year in the ICEV market</td>
<td>Table 11.6-1</td>
<td>Degree EV sales displace ICEV sales</td>
</tr>
<tr>
<td></td>
<td>Other ICEV companies may lose up to $60M/year or gain $550M/year in the ICEV market</td>
<td>Table 11.6-1</td>
<td>Big 7 price increases, whether companies match Big 7 price increases</td>
</tr>
<tr>
<td></td>
<td>California consumers may gain up to $200M/year or lose up to $750M/year</td>
<td>Table 11.7-1</td>
<td>Variable costs and prices of EVs, Big 7 pricing policies</td>
</tr>
<tr>
<td></td>
<td>Emissions may increase in early years due to reduced fleet turnover</td>
<td>Sec. 11.8</td>
<td>Size of ICEV price effects</td>
</tr>
</tbody>
</table>
Studies purporting to estimate cost effectiveness for California ozone-reduction policies generally ignore how markets will react to the policy intervention. These reactions influence the actual costs of the policies, their distribution inside and outside California, and the actual emission benefits. Our analyses of the market-mediated effects of the various elements in the California strategy are summarized in Table 12.1-3. Column (1) summarizes key conclusions and column (2) indicates tables or sections where details can be found. The last column of the table indicates major sources of uncertainty about these market-mediated effects.

12.2 WHICH ELEMENTS MAKE GOOD ECONOMIC SENSE?

We have proposed economic efficiency as the policy goal of the California ozone-reduction strategy. Different policymakers have different amounts of freedom to pursue this goal. Those required to reduce emissions to comply with air-quality standards (e.g., CARB) would seek to achieve attainment in ways that are most efficient or least inefficient. Those who are free to change air-quality standards (e.g., the U.S. Congress) would seek to implement policies only if the benefits of doing so appear to exceed the costs.

We can’t tell either kind of policymaker what to decide, but we attempt to help them by clarifying existing information, developing new information, and suggesting how best to use the limited information available.

In Section 2.6, we presented some rough rules of thumb for using NCERs to decide whether a policy element promotes economic efficiency in the South Coast, given the freedom available to the policymaker. These suggestions are replicated here, for the reader’s convenience, as Table 12.2-1. The numerical values for NCERs shown in Table 12.2-1 are based on current estimates of benefits of emission reductions and are hardly definitive; we encourage policymakers to adjust them as they think appropriate.
<table>
<thead>
<tr>
<th>If you think the NCER is about:</th>
<th>And you must find more tons of reductions, then:</th>
<th>And you are free to pursue economic efficiency, then:</th>
</tr>
</thead>
<tbody>
<tr>
<td>$5,000/ton or less</td>
<td>Implement the policy unless uncounted costs appear to far outweigh uncounted benefits</td>
<td>Implement the policy unless uncounted costs appear to far outweigh uncounted benefits</td>
</tr>
<tr>
<td>$10,000/ton</td>
<td>Implement the policy unless uncounted costs appear to far outweigh uncounted benefits and alternative ways to reduce tons look even less promising</td>
<td>Implement the policy as long as uncounted costs appear not to much outweigh uncounted benefits</td>
</tr>
<tr>
<td>$25,000/ton</td>
<td>Don’t implement the policy unless uncounted benefits appear to outweigh uncounted costs or alternative ways to reduce tons look even less promising</td>
<td>Don’t implement the policy unless uncounted benefits appear to far outweigh uncounted costs</td>
</tr>
<tr>
<td>$50,000/ton or more</td>
<td>Don’t implement the policy unless uncounted benefits appear to far outweigh uncounted costs and alternative ways to reduce tons look even less promising</td>
<td>Don’t implement the policy unless uncounted benefits appear to outweigh uncounted costs by tens of thousands of dollars per ton</td>
</tr>
</tbody>
</table>
To implement these rules requires policymakers to interpret and combine the kinds of information summarized in Tables 12.1-1, 12.1-2, and 12.1-3. In our earlier discussion, we proposed three steps for proceeding systematically; here we quote the steps and suggest what we have contributed to implementing them:

Step 1: Use your beliefs about factors underlying the NCERs (based on information about the reliability of the data and methods used) to determine the narrowest range that you find plausible.

We have contributed to this step by providing the kinds of information summarized in Columns (1), (4) and (5) of Table 12.1-2. Specifically, we have clarified what particular NCERs purport to measure, pointed out potential sources of inaccuracy, and analyzed what underlying conditions would be required for a true NCER to lie in a particular part of a range reported in Table 12.1-2.

Step 2: List the potentially important costs and benefits that are not accounted for in the NCERs you have, consider what you know about them, and form as precise a judgment as you can about the relative magnitudes of uncounted costs and uncounted benefits.

We have contributed to this step by identifying uncounted costs and benefits (see column (6) of Table 12.1-2) and analyzing several of them, most notably market-mediated effects (see Table 12.1-3).

Step 3: Consult Table 12.2-1, perhaps modified to your liking, which provides some rough rules of thumb for the South Coast.

We offer the following example of how we would implement these three steps if we were considering the incremental costs and benefits of producing ULEVs rather than LEVs.

Step 1. As shown in Table 12.1-2, the information we adapted from other studies leads us to a NCER range of $22,000 to $48,000 per ton of ROG + NOx from reducing exhaust emissions from LEV to ULEV levels. Recall that the NCERs include costs borne both inside and outside California. Uncertainty about the range reflects disagreement between CARB and Sierra studies of the incremental production cost of additional hardware to upgrade LEVs to ULEVs and, perhaps more important,
uncertainties about levels of in-use emissions and the effectiveness of Smog-Check II. A policymaker who thinks the CARB cost estimates are more reliable and that ULEV deterioration rates will be lower than LEV deterioration rates might settle on a NCER near $25,000 per ton of ROG plus NOx. A policymaker who thinks the Sierra estimates are reliable and that ULEVs will deteriorate no less rapidly than LEVs might settle on a value near $50,000 per ton of ROG plus NOx as a good representation of the true NCER.

Step 2. Whatever value for the NCER you think most appropriate, consider what the NCER for the ULEV standard does not include—for example, as indicated in column (6) of Table 12.1-2, how market mediated effects could affect fleet turnover and emissions and the extent to which emission reductions will occur in non-attainment areas during times of the day and seasons when ozone levels are unlikely to cause damage. Consider how the incremental costs of ULEVs might affect prices and sales levels of ICEVs in California and the profits of manufacturers and their dealers. California policymakers are likely to emphasize the costs borne by Californians. Federal policymakers are likely to focus on costs to all Americans. Form a judgment about the factors that your NCER doesn't consider at all. Are the costs likely to outweigh the benefits, or vice versa? By a lot? A little?

Step 3. Suppose you are a California policymaker, needing to find tons of emissions to reduce, and you think that—after adjusting for costs borne outside California—$25,000 per ton is a reliable estimate of the NCER and that the price and fleet turnover effects of ULEVs rather than LEVs are very minor. Unless you have other ways to reduce the tons you think that ULEVs will provide, you may well conclude that ULEVs are an economical means of moving towards compliance. In contrast, suppose you are a federal policymaker, free to adjust the ozone standard, and you think that $50,000 per ton is a reliable estimate of the NCER and that the price and fleet turnover effects of ULEVs rather than LEVs are quite large. You might well conclude that ULEVs are economically inefficient and that if California doesn't have better options than this for achieving compliance with the federal ozone
standards in the South Coast, then perhaps the standards should be relaxed in the South Coast.

12.3 WILL THE CALIFORNIA LDV STRATEGY REALLY CONTROL ICEV EMISSIONS?

The tables and discussion above focus on individual elements of the California strategy. Let's now step back and look across all the elements aimed at ICEVs. How far can we expect them to take us toward the state's ozone-reduction goals?

The key to getting benefits from our inevitably costly LDV strategy is controlling emissions in actual use. Historically, much of the emission problem from LDVs is attributable to vehicles whose emission control systems are not functioning properly and hence emit pollutants at very high rates. Is history "bunk" or are we "doomed to repeat it"?

As highlighted in our analyses and in Table 12.1-2, considerable uncertainty surrounds estimates of the future emission benefits of all of the elements of the strategy aimed at controlling emissions from ICEVs. For the regulations aimed at new vehicles, critical issues are the degree to which they will deteriorate and how much they will emit under driving conditions not reflected in certification tests. For the regulations aimed at vehicles already on the road, the critical issues are whether high emissions will be detected, whether owners will attempt to repair problems, and whether repairs will be effective.

**Tailpipe and evaporative emission standards for new vehicles.** New vehicles may or may not turn out to deteriorate much less than their predecessors. It is highly uncertain whether the rates of deterioration of new California LDVs will come close to those required to meet certification standards over the 50,000 and 100,000 miles required by the regulations, or what their emission rates might be beyond these mileage levels. We believe that the recall program, and perhaps the warranty regulations, provide companies with major incentives to produce very durable emission-control systems. Whether companies will succeed in making such systems and especially whether deterioration due to tampering or poor maintenance will be effectively reduced, are open questions. It is also uncertain how well new emission systems will
control emissions under driving conditions not reflected in certification tests.

**OBD II.** The goal of OBD II—to detect malfunctioning emission-control systems and spur action to repair them—is crucial.

The extent to which OBD II will advance this goal is uncertain. Much of the technology is new, and the performance of new technologies generally disappoints optimists. There is also the crucial question of the behavior of drivers and mechanics when the system detects an emission problem (i.e., what happens after the light goes on?) The actual emission benefits of OBD II might be enhanced greatly by detailed attention to behavioral issues.

We view OBD II as an investment that could pay enormous dividends, but only if the behavioral issues are addressed successfully and perhaps only after the technology matures. Perhaps the most valuable payoff from OBD II will be the knowledge gained about the performance of early-generation on-board emission monitoring equipment in on-road use.

**Smog Check II and AVR programs.** If next-generation LDVs deteriorate much less than their predecessors, the regulations just discussed could make an enormous difference to aggregate emission levels once most existing vehicles are retired. But even if deterioration is not a problem for the next-generation vehicles, Californians will do a lot of breathing before these vehicles dominate the fleet. Reformulated gasoline seems to be part of the solution; what about inspection and maintenance and accelerated vehicle-retirement programs?

To date, California’s experience with vehicle inspection and maintenance programs—like experience elsewhere—has been very disappointing. Smog-Check II is an aggressive attempt to identify and clean up vehicles with high emissions or get them off the road. The program could make a real difference. However, dramatic success of Smog-Check II is hardly assured. Past difficulties with I&M programs are indicative of major challenges to effectively implementing the new program.

Reducing emissions from existing high-emitters is such a high priority that Herculean efforts to make smog check work are warranted, but we should recognize that even Herculean efforts may fail. If Smog-
Check II does fail, policymakers should be mindful of the difference between tons of reductions projected in the State Implementation Plan—which by themselves provide legal benefits but no health benefits—and actual emission reductions. The costs of Smog-Check II—including substantial time costs, enforcement costs, and inconvenience for motorists—will be real even if the emissions benefits are only theoretical.

Much of the design of the AVR program planned for the South Coast has yet to be done. Depending on the design, such programs could be a great success or a great failure. We have emphasized two serious pitfalls—in-migration and incentives for owners of vehicles to delay scrapping dirty vehicles, to keep vehicles dirty, or to tamper with them to make them dirtier. The program should be designed, implemented and enforced with potential pitfalls in mind. This will take substantial ingenuity, and efforts to achieve too much could backfire. If the AVR program is eviscerated by perverse incentives or in-migration, NCERS of less than $10,000 per ton (which ignore behavioral and market responses) will be of little consolation.

Our discussion, analyses, and conclusions pose a dilemma for California policymakers who must find a way to reduce emissions:

- Part of the emission reductions must come from LDVs;
- Vehicles with unusually high emissions are a key part of the problem;
- Efforts to control in-use emissions have not nearly eliminated emissions due to deterioration and aggressive driving;
- Dramatic future reduction in emissions from these sources is far from assured.

A dilemma like this calls for consideration of radical alternatives. One such alternative is mandating the commercialization of vehicles that don’t emit directly. The ZEV mandate—which will lead to substantial sales of battery-powered electric vehicles in California starting in 1998—places California on such a course.
12.4 IMPROVING THE QUALITY OF THE DISCUSSION OF THE ZEV MANDATE

Like many high-stakes, polarized policy debates, the debate over the ZEV mandate includes many rallying cries that are more dramatic than insightful. Before we consider what economic analysis of the ZEV mandate tells policymakers, we think it is useful to discard this distracting rhetoric.

"Californians will pay the entire cost" or "Someone else will pay."
When social costs are generated, someone must pay. Some people assert that all of the social costs of the California strategy will be borne by Californians. Others assert that the costs will be borne by others, e.g., automobile and oil companies, residents of other states. As our analyses of market-mediated effects illustrate, neither of these extreme views is plausible. Substantial portions of the costs of producing ICEVs with upgraded hardware or producing EVs can be expected to fall on both California consumers and on vehicle manufacturers and their California dealers.

"The market has spoken." Some argue that if EVs were a good idea then the market would reveal that fact in the form of numerous buyers willing to pay the cost of producing them. This argument should not be taken seriously. Current market-based incentives to abate pollution are well below the social benefits of reducing pollution. The environmental benefits of EVs would accrue almost entirely to people other than EV buyers, who would have to pay the price. The market that has been and is currently speaking cannot be relied upon to deliver economically efficient outcomes.

"We must do anything that will move us towards attainment." Some argue that at the rate we are going we will never achieve attainment in the South Coast and therefore that we must do anything that would move us along faster. This argument is also not to be taken seriously. Attainment would not be hard to achieve if we didn’t care about costs. For example, we could ban LDVs from use in the South Coast or tax gasoline at $100 per gallon. Thus we have choices. The real issue is how to choose intelligently.

"We mustn’t do anything that is very costly." This argument makes sense only if there are ways to achieve our air pollution goals that
aren't very costly or if there aren't major benefits to improving air quality. We are skeptical of both propositions and think the burden of proof lies with those who want Californians to accept one of them. The real challenge is discovering and implementing approaches that achieve real benefits at costs that are worth the benefits.

"Technology is the solution." This statement ignores an uncomfortable fact that we have met several times in our analysis: technology alone is unlikely to do the job, and human behavior is often the key to getting the benefits out of a technology that "works." We are inclined to believe that California will not make major progress in reducing ozone without both improvements in technology and changes in behavior. Moreover, looking to technology doesn't get us very far unless we have a way to analyze: What technology is the solution? When will that technology be the solution? Who can best develop that technology? What can we do to make sure that the technology will be used if it is developed?

12.5 WHAT DOES ECONOMIC ANALYSIS OF THE ZEV MANDATE TELL POLICYMAKERS?

As our analyses of the social costs and benefits of the ZEV mandate make abundantly clear, its actual economic effects cannot be pinned down at all precisely. The long-term NCERs we developed under various assumptions are as low as $5,000 and as high as $850,000 per ton of ROG plus NOx removed. Estimated NCERs depend on several controversial factors: production and operating costs of EVs between now and 2002, how quickly these costs could decline, the eventual fleet penetration of EVs, and the effectiveness of policies to reduce emissions from ICEVs. The narrow cost-effectiveness of the ZEV mandate could turn out to be very low or very high. The market-mediated effects of the ZEV mandate could be beneficial to Californians, but they could also be very detrimental. In short, the ZEV mandate could turn out to be a great success or a great failure.

This does not imply, however, that California policymakers should forget about ZEVs; without ZEVs California might also face very undesirable policy choices. To highlight this possibility consider the
following pessimistic—but not inconceivable—scenario as 2010 approaches.

Suppose California were to repeal the mandate and, as a-- plausible, yet not inevitable--consequence, ZEV technology stagnates. Suppose further that the ICEV components of the current ozone-reduction strategy don't work very well, new cost-effective emission control options have not been discovered and that, a few years before 2010, California finds itself far short of meeting the current federal ozone standards. To make matters worse, suppose also that the health effects of ozone are found to be much worse than currently thought and as a result relaxing air quality standards appears reasonable to almost no one. Under these circumstances, and perhaps even some less extreme ones, California would find itself desperately seeking ways to reduce emissions of ozone precursors and finding only additional measures that are very expensive, such as very aggressive transportation control measures or even restrictions on industrial activity. In sum, there are great risks both to proceeding with the ZEV mandate in its current form and to repealing it and doing nothing else to encourage ZEV development.

How might we protect ourselves from such a situation?

It is crucial to recognize that now, in 1996, we need only decide how to proceed over the near term, until a few years into the next century, say. We need not decide whether or how California policy will address ZEVs beyond such a time horizon. We also think it crucial to proceed in ways that accommodate the realities: the environmental and economic stakes for Californians are high, the future is very uncertain, and we will learn more as time passes.

The uncertainties and risks involving ZEVs suggest that, in considering modifications to the ZEV mandate, we should be searching for near-term ZEV policies with three key characteristics.

- **Learning.** Policy should be designed with learning as an interim objective. As new information becomes available, the most promising set of policies should become better defined.

- **Robustness.** Near-term policy should be formulated while recognizing that very undesirable outcomes--economic, environmental, or both--are possible. Thus, policy should be
formulated with specific attention to worst-case scenarios and policy paths that avoid the worst of the worst. Such policies are often referred to as "robust" policies.

• **Adaptability.** As we learn about various factors, we want to be in a position to use this information to improve policy. Policies that can be tailored as new information arrives are often referred to as "adaptive." In thinking about adaptation, it is important to recognize that flexibility in future policymaking brings with it costs of uncertainty to those who must anticipate future policy when they plan and invest.

We conclude by suggesting four principles that could help to shape ZEV policies along the lines suggested here. Strategically, policymakers should seek to improve the prospects of developing electric-drive technology; learning about, while at the same time preserving, its prospects; and avoiding unnecessarily large short-term costs.

**First, ZEV policy should aim to determine whether EVs are a promising cornerstone of California’s long-term ozone control strategy.** Determining this requires learning about many different things, including:

• Performance, cost, and availability of EV technology;
• Consumer valuation of EV performance;
• Effectiveness of current ICEV control measures;
• Cost and effectiveness of alternative LDV emission control measures such as new transportation control measures or taxes aimed at vehicle-specific emission levels; and
• Cost and effectiveness of policies aimed at sources of emissions other than LDVs, such as heavy-duty vehicles and stationary sources.

**Second, ZEV policy should protect the long-run prospects for ZEVs.** While we are agnostic about whether EVs should be a cornerstone of California’s LDV strategy, we think it very important to protect the long-run prospects for EVs. EVs may turn out to be attractive on cost and performance grounds, and for this reason it is critical to avoid
near-term developments that would constrain our ability to rely on them in the long term. Both market and political factors are relevant here.

On the market side, we need to be concerned about how the mandate or its modification could affect behavior of both consumers and innovators over the long term.

ZEV policy should consider the potential for consumer disappointment with EVs due to limited range, reliability, or infrastructure. Such disappointment could give EVs a bad name and create long-term difficulties in marketing even EVs that would not disappoint consumers. If EVs do turn out to be economical, higher market penetration rates could be the key to getting large quantities of emission reductions from them. This underscores the importance of preserving the long-run marketability of EVs, and making sure they don’t become the Edsel of the 1990s.

ZEV policy should also consider the impact of possible revisions in the mandate on the future willingness of innovators to invest. This calls for striking a careful balance between flexibility and predictability in policy formulation. For example, whatever the outcome of the current review of the mandate, it would be helpful if CARB would announce future times at which the policy will be reviewed and indicate the major factors that will be considered.

On the political front, it is also important to consider how the mandate might affect CARB’s ability to adopt innovative policies in the future. If CARB promotes a policy now that turns out to be wasteful, it may not be able, for example, to promote EVs in the future even if technological developments make EVs a good bet.

Third, ZEV policy should also accommodate a broad range of vehicles and innovators because the most promising path to widespread EV use is far from clear. We should beware of policies that unduly emphasize one type of vehicle or one type of innovator. For example, some believe that the most promising path to major emission reductions from EVs involves important roles for small EVs (e.g., niche vehicles such as neighborhood electric vehicles). Apparently, these are not the type of vehicles that will be produced by the Big 7 in the early years of the mandate, however. While the right to sell EV credits will make non-Big
7 EVs more viable, other things equal, the mandate itself may stifle demand for non-Big 7 EVs by inducing the Big 7 to market very high-quality EVs at very low prices. The current mandate may thus give us little insight into what electric-drive transportation alternatives are most viable in the near term or the long-term viability of electric drive transportation generally.

Finally, ZEV policy should look for ways to lower the cost of achieving these objectives. For example, how can we learn more about the potential of advanced batteries while avoiding costs associated with commercialization of lead-acid batteries? What can we learn about consumer use of EVs and requirements for range without fielding a large fleet of EVs before the turn of the century? If the mandate is scaled back or delayed, are there cost-effective ways to make up any lost emission reductions? In view of potential market-mediated effects on fleet turnover and emissions, would there be any lost emission reductions?

Of course, such principles—if accepted—must be translated into policy actions. Doing so will require wisdom, energy, creativity, and cooperation.
Appendix

1.A NON-ECONOMIC UNCERTAINTIES

The following are examples of the non-economic uncertainties that permeate the search for policies that will achieve California's air quality goals most economically.

Links between emissions levels and ozone levels. The atmospheric chemistry of ozone formation is very complicated. Estimates of combinations of ROG and NOx emissions that would achieve the ozone standards are based on complex atmospheric models that are calibrated to current emission estimates and ozone readings. No one knows at all precisely which combinations of emission levels of ROG and NOx would achieve compliance with ozone standards.\(^{325}\)

Current level of emissions. There is considerable uncertainty about the levels of emissions, especially from some sources. Emission levels from large stationary sources such as power plants are measured, and thus total emissions from these sources are reasonably accurately known. However, there is considerable uncertainty about the levels of emissions from mobile sources and from tens of thousand of small stationary sources. As Table 1.2-1 (in Section 1) shows, mobile sources are estimated to account for 56 percent of ROG emissions in the South Coast Basin and 82 percent of NOx emissions.

Proportionate emission reductions needed for compliance. Policy makers often think in terms of the proportionate reductions in emissions that appear to be necessary to attain our air-quality goals because doing so seems to ameliorate difficulties due to the uncertainties in

\(^{325}\)In fact, some policies that reduce one precursor or the other might have no ozone-reduction benefits whatever. For example, how reducing ROG or NOx emissions affects ozone depends on the ratio of ROG and NOx present in the atmosphere. If the ratio of ROG to NOx is high, reducing ROG alone will have little impact on ozone. If the ratio is low, reducing NOx alone may even increase ozone (National Research Council, 1991, pp. 163-173). However, ambient measurements suggest that the ROG-NOx ratio in the South Coast basin is in an intermediate range where reductions in either ROG or NOx will reduce ozone (National Research Council, 1991, p. 301).
carrying capacities and emissions inventories.\textsuperscript{326} However much thinking in proportionate terms helps, there is still substantial uncertainty about the proportionate reductions in emissions required for achieving our air quality goals.

\textsuperscript{326}Air-quality models are calibrated using measurements of actual ozone levels, and it is believed that this gives analysts a reasonably good fix on how far from required emission levels we are in proportionate terms.
2. A ESTIMATES OF EFFICIENT TAXES FOR DIFFERENT VEHICLES

We calculated the size of incentives that would encourage those who create pollution to make economically efficient decisions regarding the amount of pollution they generated. These emissions taxes would cause vehicle owners to pay the full social cost of their pollution and as a result lead them to give auto and oil companies efficient incentives to help them reduce their pollution.

There are many choices that drivers make that could affect the emissions, including what vehicle to use, how many miles to drive, and what gasoline to use. Thus, tax rates might be expressed in terms of the annual use of a vehicle (e.g., implemented with a surcharge upon registering the vehicle), cents per mile of driving, or a tax per gallon of gasoline used. We calculate efficient tax rates expressed in all three ways.

Tables 2.A-1, 2.A-2, and 2.A-3 compute efficient levels of taxes for different vehicles based on different assumed rates of emissions of ROG and NOx. Columns in the table pertain to vehicles with different emissions rates (g/ml) and rows to different estimates of pollution costs ($/ton) detailed in Table 2.B-1 in Appendix 2.B.

The different vehicles (and associated emissions rates) considered are as follows.

- The first five emissions rates are the certification emissions rates for ZEVs, \textsuperscript{327} ULEVs, LEVs, TLEVs, and Tier 1 vehicles.
- The next two columns are based on 1992 and 2000 fleet-average emissions rates for gasoline vehicles in California based on EMFAC7F as adjusted and reported in Small and Kazimi (1995, Table 4).\textsuperscript{328}

\textsuperscript{327}We use a figure of .004 g/mi of HC emissions for ZEVs to represent one estimate of the emissions required to generate the electricity used to power an electric vehicle.
\textsuperscript{328}After reviewing several studies suggesting that EMFAC7F underestimates ROG emission rates, Small and Kazimi multiply ROG emission rates in EMFAC7F by 2.1.
• The last two columns represent especially high emitters. The emissions rates are the average and maximum tailpipe emissions test results—as adjusted and reported in Hsu and Sperling (1994, Table 2)—for 74 vehicles scrapped as part of the 1990 UNOCAL scrappage program.

Using estimates of pollution costs ($/ton) and emissions rates (g/mi) for ROG and NOx, it is a matter of arithmetic to express emissions in terms of dollars per mile, per year (assuming 12,000 miles driven), or per gallon (assuming fuel economy of 23 miles per gallon), as we do in Tables 2.A-1, 2.A-2, and 2.A-3 respectively.\(^{329}\)

To illustrate the construction of the tables, consider a vehicle that emits at the average rate of the California fleet in 1992: 3.76 g/mi of ROG and 1.26 g/mi of NOx. The tables show that efficient taxes for such a vehicle operated in the South Coast would be of the order of: 2 to 13 cents per mile (Table 2.A-1), or $230 to over $1500 per year assuming 12,000 miles driven (Table 2.A-2), or 45 cents to almost $3 per gallon of gasoline assuming fuel efficiency of 23 miles per gallon.

Note especially that efficient taxes in the South Coast vary enormously—from almost trivial to almost astounding levels—over vehicles with different emissions rates. Compare, for example, ULEVs to the 1992 fleet average to the worst emitters tested in the UNOCAL program based on damage-cost estimates. In terms of dollars per year (Table 2.A-2), for example, the taxes are less than $50 (ULEVs), roughly $235 to $675 (1992 fleet average), and $4000 to $15,000 (highest emitters tested by UNOCAL).

\(^{329}\)The damage estimates from Table 2.A-1 were also adjusted for inflation—to a constant 1992 dollar basis—using the implicit price deflator for the Gross Domestic Product. (The estimates in Table 2.B-1, which are expressed as they were reported by the sources detailed, are re-expressed in 1992 dollars as detailed in Tables 2.A-1, 2.A-2 and 2.A-3.)
## Table 2.A-1

Estimates of Efficient Emission Tax Rates Expressed in Dollars (1992) per Mile

<table>
<thead>
<tr>
<th>Emission rates of ozone precursors:</th>
<th>ZEV</th>
<th>ULEV</th>
<th>LEV</th>
<th>TLEV</th>
<th>Conv</th>
<th>92avg</th>
<th>00avg</th>
<th>UnocalAvg</th>
<th>UnocalMax</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROG g/m</td>
<td>0.04</td>
<td>0.04</td>
<td>0.075</td>
<td>0.125</td>
<td>0.25</td>
<td>3.76</td>
<td>1.8</td>
<td>16.6</td>
<td>85.4</td>
</tr>
<tr>
<td>NOx g/m</td>
<td>0</td>
<td>0.2</td>
<td>0.2</td>
<td>0.4</td>
<td>0.4</td>
<td>1.26</td>
<td>0.69</td>
<td>2.4</td>
<td>9</td>
</tr>
</tbody>
</table>

**Cost ($/ton) estimates:**

<table>
<thead>
<tr>
<th>South Coast:</th>
<th>ROG $/ton</th>
<th>NOx$/ton</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Damage cost estimates:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NERA</td>
<td>2940</td>
<td>5192</td>
</tr>
<tr>
<td>Small and Kazimi</td>
<td>2920</td>
<td>10670</td>
</tr>
<tr>
<td>CEC</td>
<td>7701</td>
<td>16138</td>
</tr>
<tr>
<td>Sierra--overall</td>
<td>4862</td>
<td>0</td>
</tr>
<tr>
<td>Sierra--marginal</td>
<td>13565</td>
<td>0</td>
</tr>
<tr>
<td><strong>Control cost estimates:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CAPUC</td>
<td>20374</td>
<td>28524</td>
</tr>
<tr>
<td>SCAQMD</td>
<td>9471</td>
<td>33429</td>
</tr>
<tr>
<td>CEC</td>
<td>21060</td>
<td>29417</td>
</tr>
</tbody>
</table>

**Other air basins--CEC**

| Damage cost estimates:              |           |          |
| Ventura                             | 319       | 1835     |
| Sacramento                          | 4601      | 6785     |
| Bay Area                            | 100       | 8184     |
| San Diego                           | 109       | 6194     |

<p>| Control cost estimates:             |           |          |
| Ventura                             | 23511     | 18386    |
| Sacramento                          | 10140     | 10140    |
| Bay Area                            | 11366     | 11589    |
| San Diego                           | 19500     | 20391    |</p>
<table>
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<tr>
<th>Emission rates of ozone precursors:</th>
<th>ZEV</th>
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<th>UnocalAvg</th>
<th>UnocalMax</th>
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<tr>
<td>ROG g/m</td>
<td>0.004</td>
<td>0.04</td>
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<td>0.125</td>
<td>0.25</td>
<td>3.76</td>
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<td>0.4</td>
<td>1.26</td>
<td>0.69</td>
<td>2.4</td>
<td>9</td>
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Cost ($/ton) estimates:

<table>
<thead>
<tr>
<th>ROG $/ton NOx$/ton</th>
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South Coast:

<table>
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<td>2940</td>
</tr>
<tr>
<td>Small and Kazimi</td>
<td>2920</td>
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<tr>
<td>CEC</td>
<td>7701</td>
</tr>
<tr>
<td>Sierra--overall</td>
<td>4862</td>
</tr>
<tr>
<td>Sierra--marginal</td>
<td>13565</td>
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<tr>
<td>CEC</td>
<td>21060</td>
<td>29417</td>
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Other air basins--CEC

<table>
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</thead>
<tbody>
<tr>
<td>Ventura</td>
<td>319</td>
</tr>
<tr>
<td>Sacramento</td>
<td>4601</td>
</tr>
<tr>
<td>Bay Area</td>
<td>100</td>
</tr>
<tr>
<td>San Diego</td>
<td>109</td>
</tr>
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</table>

Control cost estimates:

<table>
<thead>
<tr>
<th>Ventura</th>
<th>23511</th>
<th>18386</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sacramento</td>
<td>10140</td>
<td>10140</td>
</tr>
<tr>
<td>Bay Area</td>
<td>11366</td>
<td>11589</td>
</tr>
<tr>
<td>San Diego</td>
<td>19500</td>
<td>20391</td>
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</table>
Table 2.A-3
Estimates of Efficient Emission Tax Rates Expressed in Dollars (1992) per Gallon
(Assumes 23 mpg)

<table>
<thead>
<tr>
<th>Emission rates of ozone precursors:</th>
<th>ZEV</th>
<th>ULEV</th>
<th>LEV</th>
<th>TLEV</th>
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<tr>
<td>SCAQMD</td>
</tr>
<tr>
<td>CEC</td>
</tr>
</tbody>
</table>

Other air basins--CEC Damage cost estimates:

| Ventura  | 319 | 1835 | 0.00 | 0.01 | 0.01 | 0.02 | 0.02 | 0.09 | 0.05 | 0.25 | 1.11 |
| Sacramento | 4601 | 6785 | 0.00 | 0.04 | 0.04 | 0.08 | 0.10 | 0.65 | 0.33 | 2.35 | 11.50 |
| Bay Area   | 100 | 8184 | 0.00 | 0.04 | 0.04 | 0.08 | 0.08 | 0.27 | 0.15 | 0.54 | 2.08 |
| San Diego  | 109 | 6194 | 0.00 | 0.03 | 0.03 | 0.06 | 0.06 | 0.21 | 0.11 | 0.42 | 1.65 |
| Control cost estimates: |
| Ventura  | 23511| 18386| 0.00 | 0.12 | 0.14 | 0.26 | 0.34 | 2.83 | 1.39 | 11.00 | 55.05|
| Sacramento | 10140| 10140| 0.00 | 0.06 | 0.07 | 0.13 | 0.17 | 1.29 | 0.64 | 4.88 | 24.25|
| Bay Area   | 11366| 11589| 0.00 | 0.07 | 0.08 | 0.15 | 0.19 | 1.45 | 0.72 | 5.48 | 27.23|
| San Diego  | 19500| 20391| 0.00 | 0.12 | 0.14 | 0.27 | 0.33 | 2.51 | 1.25 | 9.44 | 46.83|
2.8 ESTIMATES OF SOCIAL BENEFITS OF REDUCING EMISSIONS

Table 2.8-1 summarizes several estimates of the social costs of ozone-precursor emissions—or, equivalently, the social benefits of reducing those emissions—in the South Coast and other non-attainment areas in California. The estimates are expressed in terms of dollars per ton of emissions of ozone precursors.\footnote{Some important studies on the economic costs of air pollution in California are not listed in the table because they don’t report their results in dollars per ton. Especially notable examples are extensive studies summarized in Krupnick and Portney (1991) and Hall et al. (1992a), which estimate the annual dollar damages of prevailing air pollution levels relative to NAAQS. The estimates of Krupnick and Portney (1991) and Hall et al. (1992a) are, however, implicitly represented in Table 2.8-1, because this work is drawn upon in studies listed in the table. For example, Small and Kazimi (1995) use results from both Krupnick and Portney (1991) and Hall et al. (1992), and Sierra (1995b) draws heavily on the work summarized in Hall et al. (1992).}

The sources of the estimates in Table 2.8-1 are detailed at the bottom of the table. The estimates are based on two general approaches to estimating the dollar benefits of reducing air pollution:

- Damage-cost estimates are based on linking emissions to the damage they cause—for example, damage to human health (e.g., coughing spells, asthma, eye irritation, etc., due to ozone, premature deaths due to PM) and vegetation (ornamental and agricultural), and putting a dollar figure on health and vegetation damage per unit of damage.

- Control-cost estimates are developed under the theory that we can infer the value of reducing pollution from the costs we incur to avoid pollution. This theory is quite problematic, as discussed by CEC (1993, pp. 52-3), under the name of "revealed preference" (of regulatory authorities).

Conceptually damage-cost estimation is much more promising. In practice, however, it has several limitations, not the least of which is inability to apply it to all of the potentially significant sources of
damage. The damage estimates presented in Table 2.B-1 include only the following damage components:

- NERA: damage from ozone due to morbidity, and damage to materials and crops; damage from particulate matter due to mortality and morbidity, damage to materials, reduced visibility (Hahn, 1995, p. 228)
- Small and Kazimi: morbidity from ozone, morbidity and mortality from particulate matter
- CEC: damage to human health (not including chronic health effects of long-term ozone exposure), materials, plants and animals (not including effects of acid)
- Sierra: acute health effects of ozone, health effects of photochemically generated PM and benzene

**Damage-Cost Estimates Compared with Control-Cost Estimates**

Damage-cost estimates are generally substantially lower than control-cost estimates for the same regions. This is hardly surprising given the concepts and methods underlying the two types of estimates. Damage-cost estimates will tend to underestimate actual pollution costs because some types of damage are not included in the estimates (often because of lack of sufficient information). Moreover, control costs— even if well measured—may substantially overestimate the social benefits of the pollution reduced by the controls. This is because the pollution controls that are instituted result from regulatory goals and procedures driven by the federal Clean Air Act, which emphasizes reduction of pollution without consideration of cost. Thus, costs of controls may rationally—from a legal, but not economic point of view—exceed the social benefits of the controls.

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Sierra develops its estimates under the assumption that all of damage it quantifies is attributable to ROG. It seems this assumption is used to avoid underestimation of benefits of controls on refueling and evaporative (i.e., ROG) emissions, the application for which the Sierra benefit estimates were developed. This assumption tends to overestimate the pollution costs of ROG and (implicitly) underestimate damage due to NOx emissions. In using the Sierra results, we apply their estimates of ROG damage and assume that NOx damage is zero.
<table>
<thead>
<tr>
<th>Air Basin Estimation Approach</th>
<th>Source of Estimate*</th>
<th>ROG cost estimate ($/ton)</th>
<th>NOx cost estimate ($/ton)</th>
<th>Current dollar basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>South Coast:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Damage cost</td>
<td>NERA</td>
<td>2,860</td>
<td>5,050</td>
<td>$1991</td>
</tr>
<tr>
<td>Damage cost</td>
<td>Small and Kazimi</td>
<td>2,920</td>
<td>10,670</td>
<td>$1992</td>
</tr>
<tr>
<td>Damage cost</td>
<td>CEC</td>
<td>6,911</td>
<td>14,483</td>
<td>$1989</td>
</tr>
<tr>
<td>Damage cost</td>
<td>Sierra--overall</td>
<td>5,071</td>
<td>0</td>
<td>$1994(?)</td>
</tr>
<tr>
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<td>0</td>
<td>$1994(?)</td>
</tr>
<tr>
<td>Control cost</td>
<td>CAPUC</td>
<td>20,374</td>
<td>28,524</td>
<td>$1992</td>
</tr>
<tr>
<td>Control cost</td>
<td>SCAQMD</td>
<td>8,500</td>
<td>30,000</td>
<td>$1991</td>
</tr>
<tr>
<td>Control cost</td>
<td>CEC</td>
<td>18,900</td>
<td>26,400</td>
<td>$1989</td>
</tr>
<tr>
<td>Other Air Basins:</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ventura-damage cost</td>
<td>CEC</td>
<td>286</td>
<td>1,647</td>
<td>$1989</td>
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<tr>
<td>Ventura-damage cost</td>
<td>Sierra--marginal</td>
<td>812</td>
<td>0</td>
<td>$1994(?)</td>
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<tr>
<td>Sacramento-damage cost</td>
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<td>4,129</td>
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<td>$1989</td>
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<tr>
<td>Sacramento-damage cost</td>
<td>Sierra--marginal</td>
<td>417</td>
<td>0</td>
<td>$1994(?)</td>
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<tr>
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<td>90</td>
<td>7,345</td>
<td>$1989</td>
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<td>Bay Area-damage cost</td>
<td>Sierra--marginal</td>
<td>337</td>
<td>0</td>
<td>$1994(?)</td>
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<tr>
<td>San Diego-damage cost</td>
<td>CEC</td>
<td>98</td>
<td>5,559</td>
<td>$1989</td>
</tr>
<tr>
<td>San Diego-damage cost</td>
<td>Sierra--marginal</td>
<td>958</td>
<td>0</td>
<td>$1994(?)</td>
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</table>
Table 2.B-1 cont’d.

<table>
<thead>
<tr>
<th>Air Basin Estimation Approach</th>
<th>Source of Estimate*</th>
<th>ROG cost estimate ($/ton)</th>
<th>NOx cost estimate ($/ton)</th>
<th>Current dollar basis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventura-control cost</td>
<td>CEC</td>
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<td>16,500</td>
<td>$1989</td>
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<td>Sacramento-control cost</td>
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<tr>
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<td>10,200</td>
<td>10,400</td>
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<tr>
<td>San Diego-control cost</td>
<td>CEC</td>
<td>17,500</td>
<td>18,300</td>
<td>$1989</td>
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</tbody>
</table>

*Sources of estimates are:
  - Small and Kazimi (1995)--baseline estimates from Table 5
  - CEC (California Energy Commission) --CEC (1993, Table 4-1)
  - CAPUC (California Public Utilities Commission)--reported in Fulmer and Bernow (1995, Table 8-5)
  - Sierra Research (1995b)--marginal and overall benefit-effectiveness ratios from Tables 3-2 and 3-4; estimates based on zero ppm as threshold for ozone damage
  - SCAQMD (South Coast Air Quality Management District, 1992)--as reported in Hahn (1995, p. 229)

Range of Assumed Emission Changes

The damage-cost estimates are not all based on variations in emissions in even the same general range. The latter distinction is discussed with the aid of Figure 2.B-1. In the figure, the daily level of emissions (tons of ROG+NOx, say) is measured on the horizontal axis. On the vertical axis we measure the total dollar value of damage per day due to the pollution created by those emissions. The bold curve is the "social costs of pollution" function; for each emission rate, we can read off this curve the daily pollution costs that would result from emissions generated at that rate. The curve is drawn using the standard assumption that each additional ton of emissions generated per day in an area adds more to pollution cost than did the previous ton.
Figure 2.B-1 The Marginal Benefits of Emission Reduction Differ According to the Current Level and the Size of the Reduction

Notes:
- Bold curve gives total pollution costs (dollars per day) as a function of the emission level (tons per day)
- $C$ is current level of emissions
- $\$C$ is the daily cost of pollution associated with current level of emissions
- A is level of emissions that would achieve attainment
- $\$A$ is the daily cost of pollution associated with attainment levels of air quality
- Social benefits of an emission reduction (dollars per ton) are given by slope of the cost function in the range of the reduction contemplated
Two levels of emissions are delineated on the horizontal axis: C is the current emissions rate and A is the rate that would be necessary to achieve attainment with (federal, say) air quality standards. The corresponding levels of daily pollution damage are denoted by $C$ and $A$. If we were to reduce emission rates from $C$ to $A$, (we would achieve attainment, and) according to the figure pollution costs would fall by $C$-$A$ per day. For this reduction in emissions, the dollar value per ton of emissions reduction would be $(C-A)/(C \text{ tons} - A \text{ tons})$ dollars of benefit (i.e., reduction in pollution cost) per ton. This rate can be read off the diagram as the slope of the line connecting the points on the curve corresponding to C and A. In contrast, suppose we were to reduce emissions by only a small amount starting at C. In that case dollar benefits per ton of emission reduction would be much higher (because of the assumption that pollution costs per ton get higher and higher as emission levels get higher). The benefits per ton for such a reduction would be measured by the slope of the line tangent to the social cost of pollution function above point C. Finally, for small reductions in emissions starting near A, dollar benefits per ton are relatively low, and can be measured from the figure as the slope of the line tangent to the curve above point A.

Thus, another source of difference between damage estimates in the table is the range of emission reduction assumed in forming the estimate. It is often not easy to tell what change in emissions is implicit in a damage estimation exercise. In fact, it often seems that information is combined from various (e.g., epidemiological) studies that reflect quite different levels of exposure to pollutants. Small and Kazimi (1995, pp. 15-16) pay particular attention to this issue, and finesse it by assuming linearity of the relevant functions. As reported in Table 2.B-1, Sierra (1995b) presents separate sets of estimates that involve different levels of emission reductions. In particular, their "marginal" and "overall" benefit-effectiveness ratios

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332 We have not reviewed the (very large) relevant literature in sufficient detail even to begin to sort this out.

333 See, for example, the discussion in Small and Kazimi (1995, p. 21) of using estimates of Krupnick and Portney (1991) and Hall et al. (1992), which involve very large changes in pollution levels.
BERs) are relevant to small and large changes in emissions from the status quo, respectively, as might result alternatively from a single regulation or an entire state implementation plan. (Sierra, 1995b, pp. 39-41.) As can be seen from Table 2.B-1, the marginal BER estimated for the South Coast by Sierra is almost three times as large as the estimated overall BER (i.e., $14,148/ton vs. $5,071/ton). In terms of the figure, the marginal BER might be interpreted as the slope of the tangent above C and the overall BER more like the slope of the line corresponding to emissions reduction from C to A.

South Coast Compared with Other Areas

Damage cost estimates per ton for the South Coast are much higher than those for other non-attainment areas in California. Since the South Coast has the worst air quality, these estimates provide some support for the view that the social cost of pollution function gets steeper (i.e., pollution causes increasing marginal damage) as the emissions rate gets higher.334 Moreover, they suggest that some emission-reduction strategies that are economically worthwhile in the South Coast might not be economically worthwhile in other urban areas of California.

Similarity of Estimates

The variation in estimates in damage cost per ton for the South Coast is perhaps surprisingly small given the issues discussed above (i.e., differences in components of damage included and in the range of emission reduction implicit in the estimates). The largest damage-cost estimate is the Sierra marginal BER estimate, which should also be interpreted recalling that it is developed assuming that all costs are attributable to ROG (and implicitly that there is no damage due to NOx). Most important for our purposes is the fact that the ideas we develop in the text using estimates of the social costs of air pollution in California are broadly consistent with all of these estimates.

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334 They also reflect, however, the larger population exposed to pollution in the South Coast.
6.A SIERRA ESTIMATES OF INCREMENTAL COSTS OF TLEV'S, LEV'S, AND ULEV'S

Sierra presents estimates of the total incremental costs of TLEV's, LEV's, and ULEV's over the cost of a Tier 0 vehicle and the incremental costs of a CA93 (same as Tier 1) vehicle over a Tier 0 vehicle (Sierra, 1994a, pp. 101). We subtract the incremental cost of a CA93 vehicle over a Tier 0 vehicle from the incremental costs of the low-emission vehicles over a Tier 0 vehicle to determine the incremental costs of the low-emission vehicles over a CA93 vehicle.

Sierra estimates incremental costs at production volumes equal to (1) California vehicle sales and (2) national vehicle sales. As shown in Table 6.A-1, incremental costs are between 10 and 35 percent lower at national volumes. Our analysis takes as given that twelve states in the northeast and the District of Columbia have adopted the California Low-Emission Vehicle Program (although only two have adopted the ZEV component of the program).335 Judging by new-vehicle registrations by state in 1994, the combined sales of the twelve northeast states, the District of Columbia, and California, are 3.5 times the sales of California (Automotive News, May 24, 1995, p. 40). We thus use the Sierra estimates to estimate incremental costs at 3.5 California volume. We do this by linearly interpolating between the incremental cost at production volume equal to California sales (9.6 percent of national sales), and production volume equal to national sales. The resulting calculations are presented in Table 6.A-1.

Sierra does not directly report the breakdown of total incremental cost into fixed cost, variable cost, and dealer margin. Rather, it reports separate percentage breakdowns for TLEV's, LEV's, and ULEV's, but unfortunately, Sierra does not tie the percentage breakdowns to production volume. Applying these percentages to the incremental total costs is the only method available for decomposing total costs into fixed costs, variable costs, and dealer margin. The outcomes for 3.5

335The states are Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, and Virginia.
times California volume is reported in Table 6.1-2. These breakdowns should be used cautiously because the percentages should vary for different volume assumptions.

Table 6.A-1

| Sierra Estimates of Total Incremental Costs of TLEVs, LEVs, and ULEVs Compared with 1993 California Vehicles (dollars per vehicle) |
|---|---|---|---|
| | TLEV | LEV | 4-cyl | 6-cyl |
| Sierra manufacturer (discounted to 1993) | | | | |
| California volume | 589 | 1,416 | 1,809 | 2,526 |
| National volume | 393 | 1,018 | 1,395 | 1,956 |
| 3.5x CA volume | 538 | 1,312 | 1,701 | 2,377 |
| Sierra best-case (discounted to 1993) | | | | |
| California volume | 319 | 875 | 613 | 1,331 |
| National volume | 200 | 631 | 466 | 1,203 |
| 3.5x CA volume | 288 | 812 | 575 | 1,298 |

aSierra (1994a), p. 101
bInterpolated from estimates for California volume and national volume.
7.A COMPETITIVE, SHORT-RUN ANALYSIS OF MARKET EFFECTS OF THE NEW ICEV HARDWARE REGULATIONS

7.A.1 WHY FOCUS ON THE SHORT RUN?

We use a "short-run" competitive analysis to consider the effects of the new regulations on prices and quantities. What this means is that we consider effects during a time period shorter than it would take automobile manufacturers to adjust their production capacities, product offerings and dealer networks. We think of the short run as a period of at least several years.

In the short run, some costs are fixed or "sunk"--e.g., the costs of research, product development, plant, and equipment--and, hence, do not affect prices. A "long-run" analysis would be relevant to a time period long enough for every aspect of the business--production capacities, product offerings, dealer networks, and presence in the California market--to be adjusted.

Use of a long-run competitive model would predict that all cost increases due to the regulations would be passed on in prices (because companies would not be willing to invest further in serving the California market unless they expect to be able to cover their costs). We do not emphasize the long-run competitive interpretation for two reasons:

- The long run in the automobile industry would seem to involve many years, if not decades (and, as economists often remind each other: "in the long run we are all dead");
- The applicability of the long-run predictions of a competitive model to the California LDV market is equivocal because, for example, of the importance of (non-price) competition based on product styling, quality, innovation.

In sum, we think it very useful to apply a competitive model for a short-run analysis, but are much less sanguine about the applicability of a competitive model for a long-run analysis.
Figure 7.A-1
Short-Run Supply and Demand for New LDVs Without the New ICEV Hardware Regulations

Note:
* Pertains to market for all LDVs (i.e., illustrates the "market interpretation")
* Q = quantity (in millions) of LDVs sold in California in a year
* P = (average) price ($/vehicle) of LDVs sold during the year
* D = demand curve without the new regulations
* S_f = relatively flat short-run supply function without the new regulations
* S_u = (distinctly) upward-sloping short-run supply function without the new regulations
* The two supply functions are alternative assumptions
* Point O is the competitive equilibrium point without the new regulations
* $20,000 = assumed average price of new LDVs in California without the new regulations
* 1.5 (million) = assumed quantity of new LDVs sold per year in California without the new regulations
7.A.2 SHORT-RUN PRICE AND QUANTITY DETERMINATION WITHOUT THE NEW REGULATIONS

Figure 7.A-1 depicts the short-run supply and demand conditions assumed to prevail in the entire California LDV market without the regulatory elements that require ICEV hardware improvements. These demand and supply conditions determine the total annual sales of LDVs in California and the (average) price of these vehicles in the absence of the new regulations.

We first discuss the supply and demand curves, then we consider how they are put together to determine the selling price that will prevail in the market and numbers of vehicles bought and sold (at that price). The discussion also provides segment-level interpretations. We then use this framework to characterize the market with the new regulations, thus allowing us to analyze how the new regulations affect market prices and quantities.

**Demand.** The demand curve (D) summarizes the market behavior of all potential buyers. This curve tells us for each potential price (measured on the vertical axis) the total number of vehicles (in the entire market or in a segment) that California buyers (individuals, households, fleets) will want to purchase if that price prevails in the market. As depicted in Figure 7.A-1, the demand curve slopes downward to reflect the standard assumption that the lower the price is—holding constant other factors that determine demand—the more vehicles buyers would be willing to purchase.

**How much buyers respond to price.** The steepness of the demand curve reflects the degree to which buyers in the California market are sensitive to price. In particular, the flatter this curve is, the more the quantity demanded falls in response to a particular price increase. Economists often find it useful to measure responsiveness of quantities to price in terms of elasticities. A demand elasticity, for example, measures the percentage decrease in quantity demanded that would result from a 1 percent increase in price.

To consider the effects of the new regulations quantitatively, we will have to put numbers on various parameters, including the elasticity of demand for new LDVs in the California market. Within the industry,
the elasticity of demand at the national market level is generally taken to be very close to -1 (e.g., if the prices of all manufacturers were to increase by 5 percent, all other factors held constant, industry analysts would expect the number of vehicles sold nationwide to fall by 5 percent).

We take -1 as a lower bound (in absolute value) for the elasticity of demand relevant for our purposes based on the following reasoning. Many of the new regulations being analyzed apply only in California, so they will tend to increase production costs for California vehicles more than they will for vehicles produced for sale in other states. Thus we would expect the new regulations to have less effect on prices in other states than in California. This means that as we consider the responsiveness of California demanders to price increases in California, we should be thinking in terms of prices in other states not rising along with prices in California (or at least not as much). Since it is possible for Californians to buy new vehicles outside the state, we would expect that buyers would be more responsive to price increases in

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336 Maximizing profits would lead manufacturers to incorporate hardware modifications made in response to California regulations into vehicles for sale outside of California, as well, when it is less costly to do this than to produce different vehicles for sale inside and outside of California. As long as vehicles sold in California under the new regulations would have some hardware that is not incorporated in vehicles for sale outside California, then production costs of vehicles sold in California will increase more than for vehicles sold outside of the state.

337 There are some major disincentives to doing this, however. In California, to register a vehicle with less than 7500 miles on it that was purchased outside the state, the vehicle must meet California certification standards and the buyer must pay California sales tax. In addition, buying a vehicle outside the state involves time and inconvenience (the more so the farther the buyer lives from the state border). Many California residents may find it worthwhile to deal with these impediments and buy a vehicle outside of California—for example, buy a new vehicle and register it outside the state, bring it to California, drive it for 7500 miles and then register it in California, which requires passing I&M (but avoids the sales tax and the certification requirement). Clearly, there is more incentive to do this the larger the price premium is that one must pay to buy a vehicle in California. It is unclear how much of this behavior we might reasonably expect.
California than they would be if prices were rising in all states along with the prices in California.

We also consider an elasticity of -2. Elasticities of more than -2 would suggest that the possibility of buying new vehicles outside California would double the responsiveness of quantity demanded to price. An adjustment larger than this seems implausible.\(^{338}\)

**Supply.** In a competitive model, the behavior of sellers (i.e., manufacturers and their dealers conceptualized as integrated entities) is represented by a market- (or segment-) level supply curve. This curve tells us for each potential price the total number of vehicles (in the market or a segment) that will be offered for sale by all manufacturers together if that price prevails in the market. The supply curve is the result of each company's choosing for each potential market price the production level that will maximize its own profits.

The position and slope of the supply curve is determined by the number of manufacturers and the costs to them of producing and selling additional LDVs in the California market—what economists call the marginal costs of LDVs. The basic idea is that when producers believe that their production or output levels will not affect the prevailing market price, they would be willing to produce and sell another LDV if and only if the selling price of that vehicle is at least as high as the extra cost of producing and selling the vehicle.

**How much sellers respond to price.** The slope of the supply curve plays an especially important role in the analysis because a fairly wide range of slopes is plausible. Figure 7.A-1 depicts two alternative supply curves: a distinctly upward sloping curve labeled \(S_U\) and a nearly flat one labeled \(S_f\). Both supply curves incorporate the idea that more vehicles will be offered for sale if the selling price is higher. The two curves differ concerning how much the quantity offered for sale would increase in response to any particular increase in price: the flatter (more elastic) the supply curve, the more responsive is the industry-level quantity supplied to any particular increase in price.

\(^{338}\)Because of the impediments to buying vehicles out of state and the fact that none of the major cities in California is nearby the border of another state.
In fact, the supply curve would be perfectly flat if the industry quantity supplied can be increased without increasing the marginal cost of producing and selling a vehicle in California. If production can be expanded for sales to the California market (generally in plants used to supply vehicles for many locations including California) without approaching planned or capacity production rates, then supply to California should be very elastic. In contrast, if expansion of production for the California market requires increases in marginal cost (for example, because assembly plants would need to operate overtime and pay premium wages), then the supply curve in the California market will be distinctly upward sloping. In short, if expanding production increases the cost of producing an additional vehicle, the market will have to offer manufacturers higher prices to induce them to increase the numbers of vehicles they will offer for sale.

**How competitive markets determine short-run price and quantity.**

Putting the supply and demand curves together (i.e., considering how buyer and seller behaviors interact in the market) allows us to determine the market price of each vehicle and the number of vehicles bought and sold. In a graphical representation of a competitive model like that in Figure 7.A-1, the market (or equilibrium) price and quantity can be found at the point where the supply and demand curve intersect—point O in Figure 7.A-1. (For convenience, Figure 7.A-1 is drawn so that this point is the same for either of the supply curves.) In the figure the equilibrium price and quantity are shown as $20,000 and 1.5 million vehicles, the values we use to represent the average price of LDVs and annual sales levels in California without the new regulations.

**7.A.3 Qualitative Effects of the New Regulations on Market Prices and Quantities**

The ICEV hardware regulations affect the market price and quantity by affecting the costs of producing ICEVs. These cost increases imply (in terms of the model) that the supply curve with the regulations in place will shift upward by the amount that marginal production costs
increase. Figure 7.A-2 analyzes the effects of such increases in marginal cost on market price and quantities.\footnote{Again, because we focus on the short run, only variable costs of production are relevant to predicting price increases.}

**How cost increases affect supply.** Figure 7.A-2 adds to the three curves in Figure 7.A-1 two supply curves that represent (cost and) supply conditions with the new regulations in place. The two new supply curves (labeled $S_{uw}$ and $S_{fw}$) are respectively the upward sloping and flat supply curves from Figure 7.A-1 each displaced upward by $K$ dollars per vehicle.\footnote{I.e., the vertical distance between $S_1$ and $S_{uw}$ and between $S_2$ and $S_{fw}$ is exactly $K$ for every value on the horizontal scale.} The quantity $K$ is a generic notation for the increase—which is assumed constant over vehicles—in the marginal cost of producing and selling a California ICEV associated with changes required to comply with the new regulations. Under the market interpretation of the model, $K$ is the average, across all California LDVs, of the extra per-vehicle production cost incurred in the short run because of hardware modifications attributable to complying with the new regulations.\footnote{In the figure, $K$ appears to be large relative to the price of a vehicle; there is no quantitative significance to this, it is done merely to make it easy to see the qualitative implications of the analysis.}

**Prices and quantities with the new regulations.** In Figure 7.A-2, points $U$ and $F$ are the model’s predicted equilibria with the new regulations in place, assuming alternatively that supply is relatively flat (point $F$) or supply is distinctly upward sloping (point $U$). The equilibrium prices and quantities with the new regulations in place under the alternative assumptions about the steepness of the supply curve are labeled $(P^*_uw, Q^*_uw)$ and $(P^*_fw, Q^*_fw)$. Comparing the equilibria with and without the regulations lets us predict how the new regulations will affect prices and quantities of new ICEV sales in California and how the sizes of the effects depend on the steepness of the supply curve, which reflects the value of the elasticity of supply.
Figure 7.A-2

Effects of the New ICEV Hardware Regulations on the Price and Sales of New LDVs in California

Notes:
- Situations with the new regulations are denoted by "w/"
- Q = quantity (in millions) of LDVs sold in California in a year
- P = (average) price ($/vehicle) of LDVs sold during the year
- D = demand curve both with and without the new regulations
- S_f = relatively flat short-run supply function without the new regulations
- S_u = (distinctly) upward-sloping short-run supply function without the new regulations
- K = increase in marginal cost due to the new regulations (assumed constant over units of production)
- S_{fw/} = relatively flat supply function with the new regulations
- S_{uw/} = (distinctly) upward-sloping supply function with the new regulations
- Point O is competitive equilibrium point without the new regulations
- Point F is competitive equilibrium point with the new regulations and relatively flat supply
- P_{fw/} and Q_{fw/} are predicted price and quantity with new regulations and relatively flat supply
- Point U is competitive equilibrium point with the new regulations and (distinctly) upward sloping supply
- P_{uw/} and Q_{uw/} are predicted price and quantity with new regulations and (distinctly) upward sloping supply
Qualitative effects on price and quantity. Some implications of the figure apply regardless of the size of K or the steepness of the supply or demand curve:

- The increase in marginal production cost will increase the price of new ICEVs in California
- The increase in marginal production cost will decrease the quantities of new ICEVs sold in California
- Profits of manufacturers and dealers will fall.

The first two predictions would result from the basic structure of the model as long as the demand curve is downward sloping and the supply curve is not exactly vertical.342

Profits—for both manufacturers and their California dealers—will tend to decrease for two reasons: increases in costs may not be completely passed on in prices and sales will fall because of the price increase.

How much of the increased cost of production should we expect the price increase to represent? How much should we expect sales of new LDVs to decrease in California? Given any assumed responsiveness of demand to price and the size of the cost increase, the sizes of these price and quantity effects depend on the steepness of the supply curve. Comparing points F and O provides predictions assuming that the supply curve is relatively flat (i.e., increases in production rates involve minor increases in marginal production costs), and comparing points U and O provides predictions assuming that the supply curve is relatively steep (i.e., increases in production rates to increase supply to California involve substantial increases in marginal production costs).

When the supply curve is relatively flat (point F), the increase in price is predicted to be larger than when the supply curve is relatively

342 For example, the only ways—according to the model—that an increase in cost would not lead to an increase in price are: (i) if the demand curve were horizontal (i.e., demand were perfectly elastic), which would mean (totally implausibly) that an increase in price from the prevailing level would deter all potential California new LDV buyers from buying; or (ii) the supply curve were vertical (i.e., supply were perfectly inelastic), which would mean (also totally implausibly) that manufacturers would not be willing to expand production in response to a higher price in the market.
steep (point U); i.e., \( P^{fw} > P^{uw} \). In the extreme, if the supply curve were completely flat (i.e., production can be expanded without any increase in marginal cost, which is not entirely implausible), the increase in cost of K dollars per LDV will result in an equal increase in price. (In common parlance, the entire cost increase will be passed on in price.)

Holding supply conditions constant, what would make effects of the new regulations on new LDV prices and quantities relatively large or small? For any given steepness of the supply curve:

- Holding demand conditions constant, the price increase and the quantity decrease will be larger the larger \( K \) is (i.e., the larger in the effect of the regulations on marginal production costs);
- Holding the cost increase constant, the price increase will be smaller and the quantity decrease larger, the more responsive demand is to price (i.e., the flatter is the demand curve).

The former prediction is a straightforward extension of the idea that it is the cost increase that is leading to the price and quantity effects of the new regulations. The later prediction reflects the common sense that a smaller portion of a cost increase will be "passed on" to buyers the more responsive they are to price increases (and the consequently larger effect on quantities).  

\[^{343}\text{All of the price effects discussed here can be verified using the formula: } dP = (\kappa(1-\eta))K, \text{ where } dP \text{ represents the increase in price, } K \text{ is the increase in marginal cost, } \kappa \text{ is the elasticity of supply, and } \eta \text{ is the elasticity of demand (which is defined to be negative). For example: i) if supply is perfectly elastic (i.e., } \kappa \text{ is infinite), the increase in price equals the increase in cost as long as } \eta \text{ is finite (i.e., demand is not infinitely elastic); ii) there will be a price increase unless supply is perfectly inelastic (} \kappa=0 \text{) or demand is infinitely elastic (} \eta \text{ is infinite); iii) otherwise the price increase will be between zero and the cost increase; iv) the price increase will be smaller, other things equal, the more elastic is demand; and v) the price increase will be larger, other things equal, the larger is the cost increase. (The formula can be derived, for example, along the lines of Garber and Klepper, 1980.)\]
7.B THE COURNOT MODEL AND SOME BASIC RESULTS

The model. Suppose that there are only two firms competing in an LDV market segment—firms 1 and 2. Assume that they produce identical products and let the quantities each firm produces be denoted by $q_1$ and $q_2$, respectively. The price prevailing in the market—denoted by $P$—depends on the total quantity offered for sale in the market: $Q = q_1 + q_2$. The demand curve is of the very simple linear form: $P(Q) = 1 - Q$. (note that if $P > 1$ the quantity demanded is zero.) Assume further that the firms each have constant marginal costs of production (both less than one) denoted by $c_1$ and $c_2$, respectively. Under the Cournot assumption about strategic behavior, each firm maximizes its profits assuming that the other firm holds its output fixed at some conjectured level. An equilibrium (price and pair of quantities) has the property that the quantity conjectures of the two firms are consistent with profit-maximizing behavior by both firms.

Some basic results. In this very simple setup, the outputs of the two firms are given by

$$q^*_1 = \frac{1}{3} (1 - 2c_1 + c_2) \text{ and } q^*_2 = \frac{1}{3} (1 - 2c_2 + c_1).$$

Inspection of these equations shows that each firm will produce more output the lower is its cost and the higher is its rival's cost. The equilibrium market price (determined using the demand curve and the equilibrium market quantities $q^*_1$ and $q^*_2$) is given by:

$$P = \frac{1}{3}(1 + c_1 + c_2).$$

Thus, the market price is a compromise between the cost levels of the two firms.

Effects of increasing costs. Interpret the results above as giving price and firm quantities without a set of regulations. Now consider

---

The development here borrows liberally from Tirole (1988, pp. 218-220).
regulations that increase the marginal production costs of the two firms. Assume that the firms incur compliance costs (increases in marginal costs due to the new regulations) of $K_1$ and $K_2$, respectively. Then, using the equations for $q^*_1$ and $q^*_2$ given above, it is easy to see that if neither firm's cost increase is at least twice as large as the other's, then the output of both firms fall. Using the price equation above, it follows that the increase in price is given by

$$DP = \frac{1}{3}(K_1 + K_2).$$

Finally, it can be shown that the profits of each firm decline because of the cost increases unless one firm's cost increase is two or more times as large as the cost increase of the other (in which case the profits of the low-cost complier increase).
7.C A MODEL OF PRODUCT DIFFERENTIATION AND SOME BASIC RESULTS\textsuperscript{345}

The model. Suppose that there are only two firms competing in a market segment--firms 1 and 2. They offer products that are different from the point of view of buyers, whose tastes differ. Each firm charges the same price to all of its customers--firm 1 charges $p_1$ and firm 2 charges $p_2$--and attracts customers in competition with the other seller according to how each potential buyer evaluates the relative qualities of the two products (according to his or her personal tastes) and the prices set by the two sellers.

We need a way of representing the idea that the products offered by the firms are valued differently by different buyers. This is done by assuming that for each potential buyer there is a product variant that is ideal according to his or her tastes, and the quality of a product is judged by each buyer in terms of the distance between the actual quality and that buyer's ideal quality. To make these notions tangible, it is helpful to think explicitly in terms of geographic location of buyers and sellers. The model can be interpreted much more generally, but more abstractly.

Specifically, assume that buyers live at locations spread evenly over a street that is one mile long, and that the two sellers have stores located at two different places on the street. In order to buy from a seller, a buyer must visit a firm's store and doing so costs a buyer more the farther the buyer must travel from his or her residence to the store's location. (So, in the geographic-location interpretation of the model, what makes buyers differ in their valuations of the two products is that they live different distances from the places where they would have to go to buy the products.) Assume that if a buyer must travel distance $X$ to buy from a seller, that the buyer experiences a cost of $tX^2$.

\textsuperscript{345}The development here borrows liberally from Tirole (1988, pp. 279-281), but generalizes the results reported there to allow firms to have different levels of cost.
Assume that firm 1 is located a distance of $a < 1$ miles from the western end of the street and firm 2 is located $b < 1$ miles from the eastern end of the street. (E.g., if firm 1 is $1/4$ mile from the eastern end of the street, $a = .25$.) Assume also that firm 1 is located to the east of firm 2. Assume that the marginal cost of the product to firm 1 is $c_1$ and the marginal cost of the product to firm 2 is $c_2$.

To keep things simple, assume that each buyer will buy one unit of the good (one vehicle) from one of the two sellers. Each buyer will buy from the seller who offers the best package of location and price.

Here sellers compete by setting prices. The assumption about strategic behavior is that each firm chooses its price to maximize its profits assuming that the other firm holds its price fixed at some conjectured level. An equilibrium (pair of prices and quantities) has the property that the price conjectures of the two firms are consistent with profit-maximizing behavior by both firms.

**Some basic results.** In this model, the equilibrium prices of the two firms are given by

$$p_1^* = (4/3)(a + .5 b) t_k + tk^2 + (2/3)c_1 + (1/3)c_2 \quad \text{and}$$
$$p_2^* = (4/3)(b + .5 a) t_k + tk^2 + (2/3)c_2 + (1/3)c_1$$

where $k = 1-a-b$. The first two terms of these equations capture how pricing is affected by the locations of the two stores ($a$ and $b$) and the travel costs of the customers ($t_k$) -- which determine the relative attractiveness of their products given the distributions of customer locations or tastes. Our focus is on how costs ($c_1$ and $c_2$) affect pricing, and these effects are captured in the last two terms of each expression.

It can also be shown that the equilibrium quantities sold by the two firms are given by:

$$q_1^* = a + k/2 + (p_2-p_1)/2tk, \quad \text{and}$$
$$q_2^* = b + k/2 + (p_1-p_2)/2tk.$$

\[346\] This means that $a < 1 - b$. 
**Effects of increasing costs.** Interpret the pricing equations above as applying in the absence of the new regulations (i.e., $c_1$ and $c_2$ are the firm's marginal costs without the regulations). Now consider regulations that increase the marginal production costs of the two firms by $K_1$ and $K_2$, respectively. Then, using the equations for $p^*_1$ and $p^*_2$ given above, it can be seen that:

- if both firms have the same cost of compliance (i.e., $K_1 = K_2$), then the two firms raise their prices by the same amount

- if compliance costs are not identical, the firm with the higher compliance cost will raise price more than its rival

To see what happens to sales of each firm, use the equations for equilibrium quantities to conclude that:

- If both firms have the same cost of compliance, their quantities do not change;

- Otherwise, the firm with the larger cost of compliance will lose sales relative to its rival.

Thus this model suggests the conclusions summarized in the text.\textsuperscript{348}

\textsuperscript{347}The results also imply that the price increases are exactly equal to the cost increases, but this prediction is not emphasized because it is sensitive to the (convenient, but not at all substantively attractive) assumption that all buyers buy one unit of the product no matter what the prices are. In a model where buyers can react to higher prices by not buying at all (as in the previous two models), we would not expect cost increases to be fully transmitted into price increases.

\textsuperscript{348}Because of the assumption that total market demand does not depend on prices, the model cannot address the effects of the regulations on sales of LDVs (but the conclusion that prices will increase is suggestive of decreases in sales) or on sellers' profits. The analysis in no way contradicts these conclusions.
9.A EFFECTS OF A LARGE, ONGOING AVR PROGRAM ON VEHICLE MARKETS

Most discussions or proposals for AVR programs assume that to be eligible for scrappage under the program, a vehicle must be at least a certain age (e.g., 12 or more years old); we refer to vehicles that are old enough to qualify for the program as "age-eligible" vehicles. AVR programs as implemented or proposed generally have other eligibility criteria such as having been registered in the region for the previous two years, being in running order, having recently failed an I&M inspection, having received an I&M waiver, or having relatively high actual or suspected emissions rates based on remote sensing.

An ongoing AVR program, like the one described in the state implementation plan, involves purchase and scrappage of vehicles for several successive years, and the operation of the program in a particular year affects the market environment in which the program operates in later years. In particular, taking older vehicles off the road in the present decreases--other things equal--the number of older vehicles on the road in the future and thereby affects the pool of older vehicles on which the AVR program operates in the future.

The age-eligible vehicle market. To begin to analyze the market effects of an AVR program, we consider first the relevant older-vehicle market in the South Coast in a particular year, which we refer to generically as "year T." The commodity whose market is studied in detail is age-eligible vehicles—that is, the market under consideration is the South Coast market for vehicles that meet the AVR program age criterion for scrappage in year T, regardless of whether they meet other eligibility criteria. We assume that, except for different emissions rates, these vehicles are identical in the eyes of buyers and sellers and hence all sell for the same price.

The measure of quantity in this analysis is not a number of vehicles bought and sold. It is, rather, the absolute number or stock of vehicles in the market during the period. This quantity concept is used because a primary interest is emissions from age-
eligible vehicles, which depend on the number of age-eligible vehicles on the road and the number of age-eligible vehicles scrapped, regardless of whether these vehicles are bought and sold during the period.

Vehicles are considered to be in the market for age-eligible vehicles in year T if and only if:

- They are in use in the South Coast at the beginning of year T and remain in use in the South Coast during the year, or
- They are purchased from an owner in the South Coast and scrapped in the South Coast (either as part of the program or commercially), or
- They are purchased from an owner outside the South Coast and used during the year in the South Coast, or
- They are purchased from an owner outside the South Coast and scrapped in the South Coast during the year (presumably by commercial scrap yards because most AVR programs would not purchase a vehicle that was not in the region at the beginning of the year)

In sum, vehicles in the market under consideration in year T are age-eligible in that year and may have started the year either inside or outside the South Coast, but all end the year in the South Coast. Such vehicles can end the year in two situations: "in service" or "scrapped."

The quantity of vehicles in the market—i.e., the number in the South Coast (in service or scrapped) at the end of the year—is denoted as $Q_e$ (the $e$ denotes "(age)-eligible"), and the price of these vehicles is denoted $P_e$. The definitions of suppliers and demanders in this market are more subtle than in a new-vehicle market. In a new vehicle market, suppliers are potential or actual sellers and demanders are potential or actual buyers. This is not the case in a used-vehicle market (as treated here); the essential difference is that to understand a used-vehicle market we must deal with the fact that consumers start the period with stocks of the commodity (used vehicles). We address this complication as follows.

By definition, suppliers in this market either:
• Sell age-eligible vehicles to buyers in the South Coast, or
• Start the year with an age-eligible vehicle in the South Coast and keep it in the South Coast.

Suppliers in the second category are not sellers; they can be thought of as supplying vehicles to themselves during the year.

By definition, demanders in this market either:
• Buy a vehicle (that began the year inside or outside the South Coast), and either keep it in service in the South Coast or scrap it in the South Coast;
• Start the year with an age-eligible vehicle in the South Coast and keep it in the South Coast.

Demanders in the second category are one and the same as suppliers in the second category of suppliers; viewed as demanders, they can be thought of as demanding vehicles from themselves during the year.

**Price and quantity effects of the AVR program.** The market for age-eligible vehicles is depicted in Figure 9.A-1 with quantity measured horizontally and price measured vertically. The figure depicts the market both with and without the AVR program.

Demand conditions without the program are summarized by the line labeled $D_{Tw/o}$. As in the case of the competitive analysis of new ICEV markets in Section 7.2, the slope of the supply curve (elasticity of supply) plays a crucial role in the analysis. In the figure, we consider (as we did in Appendix 7.A) two alternative assumptions about supply conditions: $S_{Tf}$ and $S_{Th}$ are respectively a relatively flat and a distinctly upward-sloping supply function for age-eligible vehicles. Using either supply function, point 0 is the equilibrium point in the market in the absence of the AVR program. (This assumption is made to simplify the diagram.)
Figure 9.A-1

Year T Prices and Quantities in South Coast of Vehicles That Are Age-Eligible for AVR Program With and Without Program

Notes:
• Situations with and without AVR program in South Coast denoted by "w/" and "w/o" respectively
• \( Q_e \) = quantity of age-eligible vehicles in South Coast in year T (number in service plus number scrapped)
• \( P_e \) = South Coast price ($/vehicle) of each age-eligible vehicle in year T
• \( D_{Tw/o} \) = demand for age-eligible vehicles in year T without AVR program
• AVR program assumed to buy and scrap \( N \) vehicles in year T
• \( D_{Tw/w} \) = demand for age-eligible vehicles in year T with AVR program (quantity demanded is \( N \) vehicles more at every price than without the program)
• Supply of age-eligible vehicles is from vehicles in South Coast at beginning of year T and vehicles brought in during year
• \( S_{Tf} \) = relatively flat supply function with and without AVR program
• \( S_{Tu} \) = (distinctly) upward-sloping supply function with and without AVR program
• Point O is equilibrium point without AVR program
• \( P^*_{ew/o} \) and \( Q^*_{ew/o} \) are price and quantity of age-eligible vehicles without AVR program
• Point P is equilibrium point with AVR program and relatively flat supply
• \( P^*_{efw} \) and \( Q^*_{efw} \) are predicted price and quantity of age-eligible vehicles with AVR program and relatively flat supply
• Point U is equilibrium point with AVR program and (distinctly) upward sloping supply
• \( P^*_{euw} \) and \( Q^*_{euw} \) are predicted price and quantity of age-eligible vehicles with AVR program and upward sloping supply
How does an AVR program affect this market? The AVR program introduces a new set of demanders in the market who buy vehicles with the intention of scrapping or retiring them. Assume that the program is designed to buy and scrap N age-eligible vehicles in year T. Assume further that the program succeeds in doing this.\(^{349}\) (For example, in the program described in the state implementation plan, N is 75,000 vehicles starting in 1999, and we are assuming that under the program 75,000 vehicles will be purchased and scrapped in the year under consideration.) In the figure the demand for age-eligible vehicles with the program in place—denoted \(D_{W}^p\)—then involves quantities demanded at every price that are N vehicles higher than without the program. (I.e., the demand curve with the program lies N units to the right of the demand curve without the program.)

How does the program (i.e., this assumed shift in demand) affect prices and quantities in this market? To see this we compare the equilibrium without the program (point O) to the equilibrium with the program. The equilibrium point with the program is U assuming that the supply curve is distinctly upward sloping and is F assuming that the supply function is relatively flat. In either case we conclude that the program:\(^{350}\)

- Increases the price of age-eligible vehicles;
- Increases the quantity of age-eligible vehicles in the region by less than N units.

The first conclusion has implications for projecting program costs: estimation of the necessary bounty level to attract the target number of vehicles should consider the price prevailing in the presence of the program, not the price in the absence of attempts to

\(^{349}\)We do not analyze how many of the vehicles scrapped in the AVR program would have been scrapped even in the absence of the program. This is a very important issue in designing and evaluating AVR programs, but it is not crucial to the issues explored with our model: the potential for price increases and drawing older vehicles into the South Coast.

\(^{350}\)Only if the supply curve is vertical (perfectly inelastic) or horizontal (perfectly elastic) does the model predict a pure price or pure quantity effect (respectively). We discuss the latter situation below.
purchase a large number of vehicles. The second conclusion must be interpreted with special care. Recall that quantities in the market include vehicles in service and vehicles that are scrapped, and that these vehicles started the year in either the South Coast or outside the region. The number starting in the South Coast is fixed at the beginning of the year. The predicted increase in quantity, then, is the number of vehicles drawn into the region because of the AVR program and includes the N vehicles scrapped in the program. Since the increase in quantity is less than N (as can be seen by inspection of the figure, recalling that the horizontal distance between the two demand functions is exactly N vehicles), we conclude that the program draws less than N vehicles into the region and reduces the number of age-eligible vehicles in service (which is the market quantity with the program minus N).

Note further that:

- The increase in price is larger the steeper is the supply function;
- The increase in quantity is smaller the steeper is the supply function.

Because the increase in quantity due to the program includes a fixed number (N) of scrapped vehicles, the decrease in the number of age-eligible vehicles in service in the South Coast in year T will be larger the steeper is the supply function.

Consideration of an extreme (i.e., limiting) case is instructive. Suppose that the supply function were completely flat (horizontal), as is almost the case with $S_{Tv}$. In this case:

- There would be no increase in price;
- The increase in quantity would be exactly N vehicles;
- The program would have no effect whatever on the number of age-eligible vehicles in service in the South Coast in the year, even though the program is assumed to succeed in purchasing and scrapping N age-eligible vehicles. (This does not mean, however, that the program cannot have any effect on emissions, because (e.g.) the emissions levels of the vehicles scrapped
need not be the same as those of the vehicles drawn into the
region.)

This limiting case suggests that if the supply function were
almost horizontal (very elastic), then the program would have almost
no effect on the number of age-eligible vehicles in service in the
South Coast in the year even though the program is assumed to succeed
in purchasing and scrapping N age-eligible vehicles. This is because
when supply is very elastic, no price increase is needed to draw
vehicles into the region. Thus, as suggested above, the slope of the
supply curve is indeed a crucial issue, and we should explore the
conditions under which the supply function is relatively flat or
relatively steep.

Are price or quantity effects likely to be more pronounced? The
slope of the supply curve tells us how responsive the quantity of
age-eligible vehicles supplied—to remain in service or be scrapped
in the South Coast—is to the price in the South Coast. Age-eligible
vehicles supplied in the South Coast must start the year either in
the South Coast or outside the South Coast. The number that begin
the year in the South Coast is a constant (when we are considering
the effects of the operation of the program for a single year, as we
are at the present). Thus the responsiveness of quantity (defined as
we have defined it) supplied to price in a particular year is
determined by the extent to which owners of age-eligible vehicles
that begin the year outside the South Coast require higher prices to
sell more of their vehicles in the South Coast.\footnote{351}

We would expect that if there were to be a significant inflow of
vehicles into the South Coast, it would be accomplished largely by
used-vehicle wholesalers responding to the realization that a profit
can be made by buying older vehicles outside the South Coast,
transporting them to the South Coast, and selling them there. For this activity to be profitable, the price of a vehicle must be higher in the South Coast than outside the area, and the price differential must be enough to cover the costs of buying vehicles outside the South Coast, transporting them to the South Coast, and selling them.

What does this all imply about whether the supply function is likely to be steep or flat? In any year of the program, supply would be very flat (elastic) if and only if there are 75,000 age-eligible vehicles available from outside the South Coast to be shipped into the South Coast in response to a quite minor increase in price. Is this plausible?

In the absence of the program, prices inside and outside the South Coast would be expected to be in balance (or equilibrium) with each other in the sense that there is no profit to be made by shipping vehicles in or out. In the first year of the program, it might be plausible for 75,000 vehicles to be available for shipping into the South Coast in response to a small price increase in the South Coast because there might be 75,000 such vehicles in counties bordering or otherwise quite nearby the South Coast--i.e., vehicles that could be brought into the South Coast at very low cost.

However, as years pass it seems likely that: a) shipping of vehicles into the South Coast from nearby areas in previous years will increase prices in those areas, thus requiring a larger price increase in the South Coast to attract more of them; and b) attracting vehicles into the South Coast from more distant locations will require higher prices in the South Coast because the transport cost will be higher the farther vehicles must be shipped. Our

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352 The possibilities of owners bringing vehicles into the South Coast to sell them themselves or South Coast residents going outside the region to buy vehicles are also real. The basic economic considerations emphasized in the text apply equally to individuals bringing vehicles into the region. The text focuses on wholesalers for concreteness and simplicity in exposition.

353 An additional factor supporting this conclusion pertains to vehicles that might be shipped into the South Coast from outside California: used vehicles brought into California must pay a $300 fee and pass an I&M test to be registered in the state.
conclusion, then, is that the supply function might be extremely elastic only during the early years of a large, ongoing AVR program in the South Coast—if at all—and in the later years of the program supply might be considerably less elastic than in the early years. Thus, even if the program does not have appreciable effects on prices of older vehicles in early years it may nonetheless have substantial price effects in later years. The good news is that the more price rises, the less in-migration tends to nullify the decrease in the stock of old vehicles caused by the AVR program.

There is another reason to predict that effects on the prices of older vehicles will grow over time. To the extent that the AVR program in any year scraps more vehicles than are attracted into the South Coast, the program reduces the stock of age-eligible vehicles with which the South Coast begins the next year. In terms of the supply and demand analysis, what this means is that the fact that the program has operated in the past decreases the supply (shifts the supply curve to the left) from where it would have been in the absence of the program, and decreases in supply tend to produce increases in price.

**Effects on prices of newer vehicles.** The AVR program may also be expected to increase the prices of vehicles that are too new to be age-eligible for the AVR program. We would expect a large, on-going AVR program to increase prices of newer used vehicles to some (unknown, perhaps small) extent, and have little if any effect on new vehicle prices.

If the AVR program increases prices for age-eligible vehicles—and we have suggested reasons to expect this to happen—this will tend to increase the demand for newer used vehicles (which are substitutes for age-eligible vehicles). We would expect the supply of newer used vehicles to be more elastic than for age-eligible ones because the costs of bringing used vehicles of any age into the South Coast should be similar but any such cost represents a smaller percentage of the price of a newer vehicle. Thus we might expect some, perhaps minor, effects of the AVR on the prices of newer used vehicles. If price increases for newer used vehicles are relatively
minor, this suggests relatively small increases in demand for new vehicles because newer used vehicles are closer substitutes for new vehicles than are older used vehicles. With relatively small increases in demand for new vehicles and--as discussed in Section 7.2--relatively elastic supply of new vehicles, we would not expect prices of new vehicles to increase much, if at all.
10.A SIMULATION OF EV INCREMENTAL LIFETIME OPERATING COSTS

In this appendix we first describe how we calculate incremental vehicle operating costs for a given set of parameter values. We then describe how we estimate the distribution of incremental operating costs given assumptions about the probability distributions about the values of the underlying parameters. For comparison with the distribution reported in Section 10.2 when the parameters are uniformly distributed, we conclude by reporting the distribution when the parameters follow normal and triangular distributions.

10.A.1 CALCULATION OF INCREMENTAL EV LIFETIME OPERATING COST

We calculate incremental electric vehicle lifetime operating costs using the following equations:

\[
(1) \quad \text{EV incremental operating cost} = \sum_{t=1}^{12} B^{t-1} (e_{t} - g_{t})
\]

\[(2) \quad e_{t} = m_{t}(e_{\text{elec}}/e_{\text{eff}} + g_{\text{r}}e_{\text{r}}/e_{\text{r}}) + \text{battery}_{t}
\]

\[(3) \quad g_{t} = m_{t}(g_{\text{as}}/g_{\text{eff}} + g_{\text{r}})
\]

where

elec = cost of electricity in $/kwh,
eveff = EV efficiency (wall to wheels) in mi/kwh,
evrmfac = EV repair and maintenance costs as a fraction of ICEV repair and maintenance costs,
gas = gasoline cost in $/gallon,
gveff = ICEV efficiency in miles per gallon
gvrm = ICEV repair and maintenance costs ($0.029 per mile)
m_{t} = miles traveled in year t
B = discount factor (1/(1+.04))
battery_{t} = battery purchase cost in year t.

The value for ICEV repair and maintenance costs ($0.029 per mile) is taken from CARB (1994b), "Present Value Analysis" appendix. We select a
4 percent discount rate because it is the midpoint of the 3 to 5 percent range for discount rates found in the studies reviewed.

The vehicles are assumed to last 12 years and accumulate a total mileage of 129,000 as shown in Table 10.A-1 (the mileage time profile used in CARB (1994b), "Present Value Analysis" appendix).

We assume that two battery packs of equal cost are required during the vehicle lifetime: one when the car is purchased and the second at the beginning of year 6 when roughly half of the lifetimes vehicle miles have been accumulated. Battery costs in year 1 and year 6 are:

\[
\begin{align*}
\text{battery}_1 &= (129,000 \text{ miles/ev eff}) \times \text{chgeff} \times \text{lifecost}/2 \\
\text{battery}_6 &= (129,000 \text{ miles/ev eff}) \times \text{chgeff} \times \text{lifecost}/2
\end{align*}
\]

where

\[
\text{chgeff} = \text{efficiency of battery charging system (0.8)},
\]

\[
\text{lifecost} = \text{battery cost per kwh delivered ($/kwh delivered)}
\]

The total number of kwh required from the battery is determined by dividing lifetime vehicle miles (129,000) by the electric vehicle efficiency (wall to wheels) and then adjusting for charging losses (20 percent). This adjustment is required because the number of kwh needed from the battery is determined by battery-to-wheel efficiency, not wall-to-wheel efficiency. Multiplying the kwh required by each of the two batteries by the battery cost per kwh delivered produces the cost of each battery.
Table 10.A-1
Mileage Accrued by EVs and ICEVs
by Year

<table>
<thead>
<tr>
<th>Year</th>
<th>Mileage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14,000</td>
</tr>
<tr>
<td>2</td>
<td>13,000</td>
</tr>
<tr>
<td>3</td>
<td>13,000</td>
</tr>
<tr>
<td>4</td>
<td>12,000</td>
</tr>
<tr>
<td>5</td>
<td>12,000</td>
</tr>
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<tr>
<td>10</td>
<td>9,000</td>
</tr>
<tr>
<td>11</td>
<td>8,000</td>
</tr>
<tr>
<td>12</td>
<td>8,000</td>
</tr>
<tr>
<td>Total</td>
<td>129,000</td>
</tr>
</tbody>
</table>

Note that by specifying cost in terms of $/kwh we make no explicit assumptions about vehicle range. Vehicle range does affect the number and timing of battery-pack purchases during an EV's lifetime. It thus affects the sum of discounted battery costs (although it does not affect the total nominal battery costs given an assumption about battery cost in $/kwh delivered).

To give some idea of how different patterns of battery replacement during an EV's lifetime would affect discounted lifetime operating costs, we compared discounted battery costs for different assumed battery replacement patterns holding other factors constant. Assuming two battery packs are purchased causes discounted battery pack costs to be approximately 10 percent lower than they would be if only one pack were required using a 4 percent discount rate. Increasing the number of battery packs above two does not cause discounted costs to fall a great deal more: the discounted costs fall about another 5 percent when the number of packs required increases to 5. It is very unlikely that more than 5 packs would be required during 129,000 mile vehicle lifetime. Batteries account for 50 to 65 percent of EV operating costs, which attenuates the effect of battery pack replacement pattern on overall EV lifetime operating costs.
10.A.2 PROBABILITY DISTRIBUTION FOR INCREMENTAL EV OPERATING COSTS

In Section 10.2, we developed ranges for the values of five key parameters that enter into the calculation of incremental EV lifetime operating costs:

- EV efficiency,
- battery cost per kWh delivered,
- EV repair and maintenance cost relative to ICEVs,
- gasoline cost, and
- electricity cost.

We assume that these five parameters are statistically independent and alternatively follow three distributions over these intervals: uniform, triangular, and normal. In the uniform distribution each parameter has equal probability of being in any subinterval of the parameter range of fixed width. In the triangular case, the probability density for each parameter increases linearly from zero at the lower endpoint of its range until the midpoint of the range and the decreases linearly to zero at the upper endpoint. For the normal distribution, we center the distribution at the midpoint of the interval and assume that there is 5 percent probability that the parameter is below the lower endpoint and 5 percent probability that it is above the upper endpoint (we can calculate the variance of the distribution given these assumptions).

We use a modified numerical integration technique with a trapezoidal rule to approximate the distribution of incremental EV operating costs given the distributions of the five underlying parameters. To do this we divide each parameter interval into \( N \) subintervals of equal probability. Using available time and computing resources, we set \( N=6 \).\(^{354}\) We then evaluate incremental operating costs for every combination (there are \( N^5 \)) of the subintervals. Because the parameters are independently distributed, each of the combinations has equal probability. The technique is called trapezoidal because the function is evaluated at the 50th percentile of each parameter subinterval.

\(^{354}\)Raising \( N \) to 10 affected the 5th and 95th percentiles of incremental operating costs by less than 2 percent when the parameters were uniformly distributed.
10.A.3 INCREMENTAL EV OPERATING COST WHEN PARAMETERS FOLLOW NORMAL AND TRIANGULAR DISTRIBUTIONS

Table 10.A-2 reports the distribution of incremental operating costs between 1998 and 2002 excluding gasoline taxes when the parameters follow normal or triangular distributions. These can be compared to the distribution in Table 10.2-7 when the uniform parameter distributions are used. We report results for the distribution only out to the 5th and 95th percentiles, because accuracy of the method decreases beyond these ranges.355

<table>
<thead>
<tr>
<th>Percentile</th>
<th>Passenger Car</th>
<th>Pickup or Minivan</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normal</td>
<td>Triangular</td>
</tr>
<tr>
<td>5</td>
<td>2,997</td>
<td>4,251</td>
</tr>
<tr>
<td>10</td>
<td>3,806</td>
<td>4,828</td>
</tr>
<tr>
<td>15</td>
<td>4,419</td>
<td>5,263</td>
</tr>
<tr>
<td>20</td>
<td>4,933</td>
<td>5,627</td>
</tr>
<tr>
<td>25</td>
<td>5,386</td>
<td>5,950</td>
</tr>
<tr>
<td>30</td>
<td>5,804</td>
<td>6,247</td>
</tr>
<tr>
<td>50</td>
<td>7,342</td>
<td>7,341</td>
</tr>
<tr>
<td>70</td>
<td>9,003</td>
<td>8,491</td>
</tr>
<tr>
<td>75</td>
<td>9,504</td>
<td>8,827</td>
</tr>
<tr>
<td>80</td>
<td>10,071</td>
<td>9,206</td>
</tr>
<tr>
<td>85</td>
<td>10,748</td>
<td>9,650</td>
</tr>
<tr>
<td>90</td>
<td>11,622</td>
<td>10,208</td>
</tr>
<tr>
<td>95</td>
<td>12,959</td>
<td>11,040</td>
</tr>
</tbody>
</table>

355 For uniform and triangular distributions, one can approximate percentile values farther out in the tails by linearly interpolating between the function values at the 5th (95th) percentile and the value of the function when all parameters are set at the lower end (upper end) of their ranges.
10.B. CALCULATION OF ELECTRIC VEHICLE NARROW COST EFFECTIVENESS

The narrow cost effectiveness ratio for electric vehicles sold between 1998 and year tau (NCER$_\tau$) is the ratio of the lifetime discounted costs and the discounted emission reductions of the vehicle sold:

\[
NCER_\tau = \frac{\sum_{\tau=1998}^{\tau} \beta^{\tau-1995}C_\tau}{\sum_{\tau=1998}^{\tau} \beta^{\tau-1995}E_\tau}, \quad \tau = 2010, 2020, \infty
\]

where

- $\beta$ = discount factor (1/(1+discount rate)),
- $C_\tau$ = lifetime incremental costs of EVs sold in year $\tau$ discounted to year $\tau$ (dollars),
- $E_\tau$ = lifetime ROG + NOx emission reductions of vehicles sold in year $\tau$ discounted to year $\tau$ (tons).

NCER is thus in units of $/(ton \, ROG+NOx)$. We first describe the calculations that determine discounted incremental costs then turn to the calculations for discounted emission reductions.

10.B.1 INCREMENTAL ELECTRIC VEHICLE COSTS

The incremental costs of an electric vehicle sold in year $\tau$ over a comparable ICEV sold in the same year are:

\[
(2) \quad C_\tau = (incvar_\tau + incop_\tau)*evsales_\tau + fixed_\tau
\]

\[
(3) \quad evsales_\tau = mandate_\tau*sales
\]

where

- $incvar_\tau$ = incremental variable production cost of EV over variable production cost of comparable ICEV in year $\tau$ ($/ per vehicle),
\( \text{incop}_t = \text{incremental lifetime operating cost of an EV sold in year } t \text{ over a comparable ICEV discounted to year } t \text{ ($ per vehicle}). \)

\( \text{fixed}_t = \text{fixed costs of EV program in year } t \text{ (dollars)} \)

\( \text{evsales}_t = \text{EV sales in year } t \text{ (vehicles)}, \)

\( \text{mandate}_t = \text{EV mandate percentage in year } t \text{ (percent of total light-duty vehicle sales)}, \)

\( \text{sales} = \text{total annual light-duty vehicle sales (vehicles per year)}. \)

Total annual light-duty vehicle sales are held constant at 2.48 million units throughout the analysis. This corresponds to 1994 LDV sales in California, Massachusetts, and New York. Incremental operating costs are incurred over the life of the vehicle, and then discounted back to the time of sale (year \( t \)) for inclusion in Equation (2). We discuss incremental variable production costs, fixed costs, and incremental operating costs in turn.

**Incremental Variable Production Costs**

During the first five years of the mandate, incremental EV variable production costs per vehicle are set to a fixed level. This value is specified in each simulation. After 2002, incremental EV variable production costs are determined by:

\[
\begin{align*}
\text{(4)} & \quad \ln(\text{evar}_t) = (\ln(\text{rate})/\ln(2)) \cdot \ln(N_t) + C_0 \\
\text{(5)} & \quad \text{incrvar}_t = \text{evar}_t - \text{gvar} \quad \text{if } \text{evar}_t \geq \text{gvar} \\
& \quad = 0 \quad \text{if } \text{evar}_t < \text{gvar}
\end{align*}
\]

where

\( \text{evar}_t = \text{total EV variable costs predicted by experience curve}, \)

\( \text{rate} = \text{experience curve learning rate (between 0 and 1)}, \)

\( N_t = \text{cumulative EV production from 1998 to year } t, \)

\( C_0 = \text{experience curve intercept for variable production costs}, \)

\( \text{gvar} = \text{variable production cost of ICEVs ($10,000 per vehicle)} \)
Equation (4) implies that total EV variable production costs (as opposed to incremental) decline by (1-rate)*100 percent each time cumulative EV output doubles. $C_0$ is determined by solving Equation (4) given a total EV variable cost and cumulative output. This sets the level of output and cost at which long-term learning begins. As shown in Equation (5), we assume that total EV variable production costs fall as predicted by the experience curve until they equal ICEV variable production costs.

**Fixed Production Costs**

Fixed EV production costs are calculated as:

\[
\text{fixed}_t = \begin{cases} 
\frac{\text{fcost}}{7} & t=1998, 1999, \ldots, 2004, \\
\frac{\text{fcost}}{(2*5)} & t=2003, 2004, \ldots, 2007, \\
\frac{\text{fcost}}{(4*5)} & t=2008, 2009, \ldots, 2012, \\
\vdots & \\
\vdots & 
\end{cases}
\]

where

\[
\text{fcost} = \text{estimate of fixed costs required during first 7-year product cycle.}
\]

Fixed costs are assumed to fall 50 percent in each consecutive 5-year product cycle and are assumed to be spread out evenly during each product cycle.

**Incremental EV Operating Costs**

Incremental EV operating costs per vehicle are set to a fixed level during the first five years of the mandate in each simulation. These levels are based on simulations described in Appendix 10.A. After 2002, incremental EV variable production costs are projected by:

---

\[\text{Note that fixed}_t\text{ has two components in 2003 and 2004. This reflects--following Booz\text{-}Allen--the idea that a second product cycle begins in 2003 before the fixed costs of the first product cycle are fully amortized.}\]
\begin{align}
(7) \quad \ln(\text{evop}_t) &= (\ln(\text{rate})/\ln(2)) \times \ln(N_t) + C_1 \\
(8) \quad \text{incop}_t &= \text{evop}_t - \text{gvop} \quad \text{if } \text{evar}_t \geq \text{gvop} + \text{ultincop} \\
&= \text{ultincop} \quad \text{if } \text{evar}_t < \text{gvop} + \text{ultincop}
\end{align}

where
\begin{align}
\text{evop}_t &= \text{total lifetime operating cost for an EV sold in year } t, \text{ discounted to year } t, \\
\text{gvop} &= \text{total lifetime operating costs of an ICEV sold in year } t, \text{ discounted to year } t (\$6,500 \text{ per vehicle}), \\
\text{ultincop} &= \text{eventual incremental EV discounted lifetime operating costs}, \\
\text{rate} &= \text{experience curve learning rate (between 0 and 1)}, \\
N_t &= \text{cumulative EV production from 1998 to year } t, \\
C_1 &= \text{experience curve intercept for operating costs}
\end{align}

The calculations for vehicles sold between 1998 and 2010 and vehicles sold between 1998 and 2020 (\(\tau = 2010\) and 2020) is straightforward. To calculate long-term NCER, we calculate costs through the year 2100 and then make an adjustment for costs in later years. We approximate costs in the later years by calculating the infinite discounted sum assuming that total incremental costs (variable production, fixed, and operating) remain at their 2100 level. This provides an upper bound for remaining costs. One half of this sum is then added to the discounted costs through 2100 to approximate the infinite sum of discounted costs. For the scenarios considered, this adjustment (and whether or not we divide by a factor of two) made very little difference.

\textbf{10.B.2 ELECTRIC VEHICLE EMISSION REDUCTIONS}

We first explain how emission reductions for EVs sold through 2010 and 2020 are determined and then how emission reductions are calculated for long-term NCER.
Emission Reductions for EVs Sold Between 1998 and 2010 or 1998 and 2020

Emission reductions for vehicles sold in year \( t \) are

\[
(9) \quad E_t = \text{evsales}_t \cdot \sum_{s=1}^{10} B^{s-1} (\text{emreduct}/10)
\]

where

\[
\text{emreduct} = \text{lifetime emissions reductions of EV (tons of ROG + NOx)}.
\]

We assume for simplicity that an electric vehicle stays on the road for 10 years and that the emission reductions generated during each year of the vehicle's life are constant. Constant annual reductions are needed in the calculations of long-term NCERs described below. It seems likely that the overall discounted emission reductions would not change a great deal if emission reductions varied to some extent over the life of the vehicle, or if the vehicle life was somewhat longer (say 12 rather than 10 years).

Emission Reductions for Long-Term Narrow Cost Effectiveness Ratios

The calculations of emission reductions for the long-term NCERs are based on determining the emission reductions for a constant number of EVs that are sold starting in a given year and continue to sell at that level every year thereafter. We first demonstrate how the emission reductions for such a set of vehicles can be calculated and then show how we generalize to an increasing number of EVs that are sold over time.

Assume that \( Z \) electric vehicles are sold in 1998 and every year thereafter. Also assume that an electric vehicle stays on the road for 10 years and, for simplicity, that the emission reductions generated in each year of the vehicle's life are equal to \( X \) (equal to emreduct/10). Then the emission reductions discounted to 1995 are

\[
(10) \quad Z B^3 \left[ \sum_{s=0}^{\infty} B^s X + \sum_{s=1}^{\infty} B^s X + \ldots + \sum_{s=9}^{\infty} B^s X \right].
\]
Equation (10) can be derived by writing out the 10 terms for the discounted benefits of cars sold in 1998, the ten terms for the discounted benefits sold in 1999, and so on. The result is the 10 infinite sums in Equation (10). This equation simplifies to:

\[ Z^3 [10/(1-B) - 9 - 8B - 7B^2 - 6B^3 - 5B^4 - 4B^5 - 3B^6 - 2B^7 - B^8]. \]

Now generalizing to the case where the number of EVs sold can increase over time, the denominator in the long-term narrow cost-effectiveness ratio is

\[ \sum_{t=1998}^{\infty} B^{t-1998}E_t = \sum_{t=1998}^{\infty} B^{t-1998}(\text{evsales}_t - \text{evsales}_{t-1})^* \]

\[ \text{mult} = [10/(1-B) - 9 - 8B - 7B^2 - 6B^3 - 5B^4 - 4B^5 - 3B^6 - 2B^7 - B^8] \]

where

\[ \text{evsales}_t \geq \text{evsales}_{t-1}, \]

\[ \text{evsales}_{1997} = 0. \]

Equations (10) through (13) require that the emission reductions of a single EV in any year of its life are constant.
11.A. TWO GENERAL APPROACHES TO PREDICTING EV DEMAND AND THEIR LIMITATIONS FOR OUR PURPOSES

Various researchers have studied the demand for EVs. Several studies have taken one of two general approaches: a) quantifying potential demand for EVs by counting households with travel patterns and other characteristics that appear to make them plausible candidates for EVs; and b) econometric analyses of survey responses to questions concerning willingness to buy an EV.\textsuperscript{357} We describe these approaches, review leading studies pursuing them, and explain why we think that they provide little information about our central question: the demand for the kinds of EVs that Big 7 companies will market during 1988 to 2002.

Travel behavior, household characteristics and potential demand.

Several studies have examined the potential market for EVs by estimating a number or fraction of households for which the technical limitations of EVs seem not to be a major problem. There are several papers in this tradition, going back at least as far as the 1970s.\textsuperscript{358}

For example, following other researchers who focused on range limitations of EVs, Greene (1985) develops and applies a method for estimating the distributions of daily usage of individual vehicles from longitudinal data on refueling dates and odometer readings at the times of refueling. This enables Greene (1985, p. 355) to make inferences such as "...with 95 percent probability, 25 percent of the vehicles will travel less than 98.1 miles in a day, at least 98 percent of the days."

Nesbitt, Kurani and Delucchi (1992) emphasize the importance of home recharging in addition to range limitations for the near-term household demand for EVs. They use data from 1985 to estimate the "largest possible initial market for battery-powered electric vehicles," viewing households as potential buyers if and only if they: own a primary residence with a carport or garage, would also have a vehicle

\textsuperscript{357}See Turrentine and Kurani (1995, pp. 17-21) for a review of studies discussed here and other studies.

\textsuperscript{358}Greene (1985) reviews several such studies referring to them as "market niche" or "economic tradeoff" studies. GAO (1994, pp. 30-31) refers to such studies as "technical constraints" studies.
capable of long-range trips and have a vehicle used for purposes other than commuting more than 80 miles round-trip (Nesbitt, Kurani and Delucchi, 1992, p. 11). They conclude that in 1985, 28 percent of households (28 million in all) met these criteria. They caution the reader: "However, our analysis says nothing about whether those who could use an EV, as per our criteria, would actually buy one" (Nesbitt, Kurani and Delucchi, 1992, p. 18).

**Econometric analyses of stated preferences for EVs.** Observation and analysis of actual market choices cannot provide much information about the demand for EVs. This applies generally because EVs are very different from conventional vehicles, and consumers have not been offered EVs in the market place to any substantial degree. Moreover, households and fleet managers have not been presented with any opportunity to purchase the kinds of EVs that the Big 7 are likely to offer under the mandate. Thus, researchers have attempted to assess the demand for EVs by presenting people with descriptions of different (hypothetical) vehicles and their prices and asking them to make choices. In some studies such information is analyzed using (rather advanced) econometric methods designed to analyze such discrete choices. We discuss three studies of households and one of fleet managers.

In Beggs, Cardell, and Hausman (1981), hypothetical choices of 193 respondents from nine different cities--selected because they were expected to be unusually receptive to the possibility of an EV purchase--were obtained and analyzed. More specifically, each respondent was presented with descriptions of sixteen vehicles characterized by various combinations of nine attributes (e.g., price, fuel cost, range between refueling, time required to refuel, top speed, number of seats, length of

---

359Henderson and Rusin (1994, pp. 37-38) discuss the extent to which results of "hedonic studies" of consumers' willingness to pay for abstract vehicle attributes (e.g., acceleration, operating costs, reliability, safety) based on observed market behavior are likely to be useful in assessing demand for EVs. They conclude--and we concur--that the prospects are poor. For example, they write: "Because the current vehicle population does not have the limited range associated with EVs, there is no way to confidently use hedonic studies to value this attribute." (Henderson and Rusin, 1994, p. 37.) See also Gordon and Richardson (1995, pp. 5-6).
warranty) designed to reflect characteristics of gasoline and electric vehicles. Respondents were then asked to rank the choices with which they were presented from highest to lowest. Their estimates led Beggs, Cardell, and Hausman (1981, p. 19) to conclude that "Individuals do not seem receptive to electric vehicles that have limited range and long refueling periods."

In a study that is similar in some ways, Calfee (1985) analyzes 47 responses to a take-home survey form (administered in 1980). Each respondent was asked to make 30 separate vehicle choices from 30 sets of three hypothetical vehicles where each vehicle is described by five numbers representing the vehicle’s purchase price, operating cost per mile, seating capacity, and (for EVs) range and top speed. Emphasizing that the most-viable market for EVs may be located in "odd market niches representing somewhat unusual tastes" (Calfee, 1985, p. 287), Calfee estimates separate preferences for each respondent and uses these to predict market shares for EVs (characterized in various ways) in competition with gas-powered vehicles. Attempting to estimate how many people would buy EVs under what conditions is an important aspect of Calfee’s study, but there are technical reasons to be concerned about the reliability of his estimates. Calfee (1985, p. 298) concludes:

\[\text{In contrast, econometric demand studies often estimate demand functions characterizing an average or typical consumer; such demand functions are often of considerable interest. Average tastes are of limited interest in our context because the key question is the price at which a minority of buyers large enough to satisfy the mandate would buy an EV.}\]

\[\text{Beggs, Cardell, and Hausman (1981) estimate their model alternatively assuming homogenous and heterogeneous tastes among their respondents and find considerable evidence of heterogeneity. But in analyzing the results for the model allowing for heterogeneity they focus nonetheless on the average tradeoffs among respondents who are estimated to have different tastes. (Beggs, Cardell, and Hausman, 1981, Table 4.) The authors apparently chose not to present and analyze separate estimates of individuals’ tastes—e.g., to examine what fraction of respondents are somewhat receptive to EVs—because there is too little information to estimate reliably the tastes of each individual separately. In particular, there are only five degrees of freedom for estimating each individual’s tastes (Beggs, Cardell, and Hausman, 1981, p. 14) and thus the ‘required asymptotic approximations are suspect.’ (Beggs, Cardell, and Hausman, 1981, fn. 10, p. 15.) Calfee’s study design suffers from a similar difficulty—25 degrees of}\]
"Electric vehicles of modest performance, such as could be produced very soon, are likely to have no significant market."

More recently, Bunch et al. (1993) studied responses to a 1991 mail questionnaire from 692 residents of the South Coast. Each respondent was presented with five choice sets of three vehicles each—with vehicles described in terms of fuel type, fuel availability, range, fuel cost per mile, level of pollution, performance—and asked to choose the most preferred vehicle in each of the five sets. Preferences are assumed to be homogeneous, thus the results are interpreted as characterizing the preferences of an average or typical respondent. The estimates suggest that, other things equal, the average respondent would require very large price discounts to compensate for limited vehicle range (e.g., $16,000 and $10,000 to compensate for a ranges of 75 and 125 miles, respectively) and limited availability of fuel ($8,000 and $2,000 to compensate for recharging capability at 10 percent and 50 percent as many locations as gasoline, respectively), but also a substantial willingness to pay for lower emissions (e.g., an extra $10,000 per vehicle to reduce emissions from that of gasoline vehicles to 10 percent of that level).

Hill (1987) analyzed data from 474 respondents in a phone survey during mid-1983 of managers of commercial vehicle fleets. Each respondent was presented with a scenario consisting of a pair of ranges (per charge) and life-cycle costs (purchase price plus lifetime operating costs) relative to conventional vehicles and was asked whether such a vehicle would be useful to the operations of the respondent’s fleet and, if so, how many the respondent would buy. The three ranges considered were 30, 60 and 90 miles, and the three life-cycle costs were 10 percent less, 15 percent more and equal to the life-cycle costs of a conventional vehicle. Econometric analysis of the data led Hill (1987,

freedom even under the doubtful assumption of independence across observations for each individual respondent—but Calfee proceeds to estimate and analyze results estimated separately for individuals.

Only half of the respondents were presented with choice sets including EVs. (The study examined demand for clean-fuel vehicles including non-electric vehicles.)

Recruitment letters were sent to "a random sample of households in the California South Coast Air Basin." (Bunch et al., 1993, p. 240.)
p. 284) to conclude: "Our analysis provides strong evidence that firms would be willing to cope with the limited range of electric vehicles if these vehicles were able to provide a less costly means of doing business."

**Synthesis.** None of these studies, taken at face value, provides a basis for optimism about the demand for EVs. The conclusions of the household demand studies speak for themselves. As far as fleet demand is concerned, Hill's fundamental conclusion is discouraging in light of our review of the evidence in Section 10.2, which indicates that during the time period under consideration, lifetime operating costs of EVs--including all batteries--are likely to be $1,000 to $11,000 more than for comparable ICEVs. For life-cycle costs of EVs to be below those of ICEVs, then, purchase prices of EVs would have to be $1,000 to $11,000 below those of comparable ICEVs.

**Usefulness for our purposes.** The basic conclusion of Hill (1987)--that fleet managers would trade off range and cost--seems unassailable. However, we have fundamental concerns about the relevance of the studies of household demand for the questions at hand. For example, Beggs, Cardell, and Hausman (1981) and Calfee (1985) analyze survey responses collected more than fifteen years ago; Beggs, Cardell, and Hausman (1981) and Bunch et al. (1993) characterize the preferences of average or typical respondents; and, perhaps most important, the respondents in all three studies have much less information about EVs than consumers would have if EVs were actually marketed under the mandate. Thus we conclude that the household studies provide quite limited information about the real-world demand for the kinds of EVs that the Big 7 are likely to market to households during 1998 to 2002, but that taken at face value the results of these studies are likely to understate substantially that demand.365

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364See also, Henderson and Rusin (1994, pp. 41-42), who review results from "vehicle demand and hedonic studies," and calculate "a minimum estimated net penalty for passenger EVs of $6,700 to $7,700 per vehicle."

365GAO (1994, p. 32) in commenting on the pessimistic conclusions of two polls of consumer preferences for EVs reads: "Consumer preference studies about such an unfamiliar technology as EVs probably measure little more than consumers' underlying uncertainties about the
reliability and stability of EV technology itself and the relative importance of certain attributes of current ICEV technology that have previously received little consideration..." We are inclined to agree. See Gordon and Richardson (1995, pp. 6-7) for a contrary view.
11.B LONG-TERM CONSIDERATIONS IN BIG 7 EV MARKETING DECISIONS DURING 1998 TO 2002

The analysis of Big 7 company behavior in the text considers only the short-term costs and rewards of selling EVs. Some potential long-term rewards warrant consideration. Is it likely that these potential long-term rewards during 1998 to 2002 are large enough to outweigh the potential short-term losses and that Big 7 companies would market substantial numbers of EVs during 1998 to 2002 even without the mandate?

As is likely the case with many new products, and entirely consistent with basic economic principles, companies might be willing to market EVs at a loss (i.e., at prices that don't cover production and marketing costs) for a period of years, but only if and when doing so seems attractive to them in terms of long-term profitability. Long-term benefits to a company of marketing EVs could include the value to the company of:

- the knowledge gained about EV technology, effective EV marketing strategy, and EV owner behavior;
- getting ahead of the competition as an early successful innovator in electric-drive transportation;
- enhancing the company reputation for technical capability.

The information we have, however, is consistent with the idea that few, if any, of the Big 7 believe that--even once such longer-term advantages to the company are considered--the time to market EVs has come.

Companies are likely to value the knowledge they would gain by marketing EVs during 1998 to 2002. However, it may be that only one of the Big 7 has developed a product that could be expected to provide the company with major reputation benefits if marketed during the first five years of the mandate period. Specifically, the General Motors Impact appears to have the potential to please its owners, generate a lot of attention among car enthusiasts and car owners generally, and contribute to GM's reputation for technological capability.\textsuperscript{366} With that single

\textsuperscript{366}See the discussion in the text.
potential exception, it seems likely that companies believe that the vehicles they could market in the near term would have negative long-term effects on their companies because they would detract from their reputations for technological capability and are not up to the standards of drivability and convenience that companies believe characterize their ICEVs and are essential to consumer perception of their products generally.
11.C. AN ANALYSIS OF THE MARKET FOR EV CREDITS DURING 1998 TO 2002

As discussed in the text, according to the rules of the ZEV mandate during 1998 to 2002, every time that a non-Big 7 company sells an EV in California, it can sell an EV credit to a Big 7 company, which in turn can use the credit to offset one unit of its mandated quantity. Our analysis in the text emphasizes the production costs of vehicles marketed by Big 7 companies and the market for those EVs. In this appendix we consider how sensitive our conclusions might be to allowing explicitly for the possibility that the Big 7 companies will purchase credits from other EV producers. We do so using a model of the market for EV credits--i.e., the market in which these credits are bought and sold--during 1998 to 2002 and developing some simple, intuitively plausible implications.

While it would be useful to extend the present analysis in various ways, the model seems very helpful in sorting out some fundamental forces underlying the operation of the credit market. The analysis described here provides:

- Basic insights into the determinants of the prices and quantities of credits and the most likely sources of these credits;
- A foundation on which to develop more refined models and analyses of the EV credit market;
- A basis for explaining systematically our claims that if credits contribute substantially to the Big 7 companies' meeting of their mandated quantities, the major source of credits is likely to be ICEV companies that are subject to the mandate starting in 2003.

The Demand for EV Credits

Because only the Big 7 companies have any intrinsic use for EV credits, we assume that only Big 7 companies would buy (or demand) EV
credits.\textsuperscript{367} We further assume that in determining their demand (or willingness to pay) for credits, the Big 7 companies pursue the goal of minimizing their costs in meeting their mandated quantities (a goal which is conducive to short-term profit maximization). An implication—and the key to understanding the demand for EV credits—is that a Big 7 company would always be willing to buy an EV credit if the price of a credit is less than the cost to the company of any alternative means of satisfying one unit of its mandated quantity. The alternative means are:

a) producing and selling one of its own EVs, which involves a cost equal to the marginal loss to the company, if any, of doing so (i.e., the marginal revenue of its own EVs minus their marginal production cost);

b) paying the fine (non-compliance penalty) of $5,000, which involves a cost to the company of that $5,000 payment plus any additional cost that the company ascribes to paying a penalty.\textsuperscript{368}

For simplicity we assume that all of the Big 7 companies impute a cost of $f$ (which may equal zero) for every unit of their mandated quantities covered by paying the fine. Then each company perceives a cost of $(5,000 + f)$ for each $5,000 fine it pays.

Figure 11.C-1 depicts the demand side of the credit market. The quantity of credits is denoted by $C$ and the price of credits by $P_C$. This demand curve—labeled $D_C$—represents the combined demand for credits by all of the Big 7 companies. The height of the demand curve at any particular quantity of credits represents the willingness to pay of some Big 7 company for one additional credit.

\textsuperscript{367}Thus we ignore the possibility that other companies (e.g., EV credit brokers) would buy credits to resell them.

\textsuperscript{368}As discussed in the text, any additional cost would result from factors such as adverse publicity or reputation loss from paying the fine or additional risk of stockholders’ suits.
Market Demand Curve for EV Credits--1998 to 2002

Notes:
• $C = \text{quantity of EV credits}$
• $P_C = \text{price of credits (}/credit)$
• $D_C = \text{demand curve for EV credits from all Big 7 companies together}$
• $\$f = \text{cost Big 7 companies attribute to paying the fine in addition to the } \$5000 \text{ payment}$
• $E_m = \text{total number of EVs the Big 7 are mandated to sell}$
The horizontal segment at the level $(5,000+f)$ reflects the implication of cost minimization that no company will pay more for a credit than the cost attributed to the alternative of paying the fine. The downward sloping segment of the demand curve represents the marginal loss levels of those companies (which may be all of them) that can produce and sell EVs at marginal losses less than $(5,000 + f)$. The vertical segment represents the fact that the Big 7 companies would never buy more credits than $E_m$, the total mandated quantity of all Big 7 companies together, because additional credits are of no value if the Big 7 companies are meeting the mandate.

The figure incorporates the assumptions that Big 7 companies are willing to pay the fine, and sales of EVs are not profitable at the margin for at least some Big 7 EVs companies for some quantities below their mandated quantities. Some alternative possibilities deserve mention, but have such straightforward implications that they need not be analyzed in detail. First, suppose companies are not willing to pay the fine but selling EVs does involve marginal losses for Big 7 companies. In this case, there is no horizontal segment to the demand curve and each point on the demand curve represents a marginal loss associated with a Big 7 EV displaced by buying a credit. Second, if Big 7 companies can produce and sell EVs without incurring losses at the margin, then they would not be willing to pay anything for credits. If there is no demand for credits, there will be no credit market (i.e., no credits will be sold and no EV producer could get a positive price for a credit).

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When a Big 7 company can produce and sell an EV while incurring a loss of less than $(5,000+f)$, doing so is its best alternative to buying a credit and the cost of this alternative is the marginal loss from producing and selling another one of its EVs. In that situation the value of buying an additional credit is avoiding the marginal loss.
The Supply of EV Credits

We assume that the only companies that would sell credits are non-Big 7 companies.\textsuperscript{370} These might include companies that convert ICEVs to EVs, producers of niche vehicles, and ICEV companies other than the Big 7. We assume that there are enough such companies selling EVs for there to be competition on the selling side of the credit market and enough companies potentially purchasing credits for there to be competition on the buying side of the market.\textsuperscript{371}

The prices at which the non-Big 7 companies would be willing to sell (or supply) credits to the Big 7 depend on the costs to the non-Big 7 companies of producing credits. To produce an additional credit, a non-Big 7 company must produce and sell an additional EV. The (net) cost to the company of doing this is the marginal cost of producing the EV minus the price at which the EV is sold. Thus to analyze the supply of EV credits, we must examine the market for the EVs that produce the credits—i.e., the EVs produced and sold by companies not subject to the mandate. After doing so, we analyze the market for credits.

The Market for EVs of Non-Big 7 Companies

Figure 11.C-2 depicts the market for EVs produced by non-Big 7 companies. The quantity of EVs sold by all of these companies together is denoted by $Z$ and the price at which these vehicles are sold is denoted by $P_Z$. We initially assume that the EVs sold by each non-Big 7 company are identical. We relax this assumption in applying the basic lessons derived from the simple model.

\textsuperscript{370}This rules out the possibility, for example, that some Big 7 companies would sell more than their mandated quantities of EVs and sell credits to other Big 7 companies.

\textsuperscript{371}Allowing for lack of strong competition among EV producers would be a worthwhile extension of the analysis. The most obvious implication (based on standard economic models of market power by sellers) is that companies that generate credits would be expected to take advantage of their power in the credit market, thus increasing the price and decreasing the quantity of credits relative to the competitive case. (This—see below—suggests that fewer non-Big 7 EVs would be produced than the analysis here predicts.)
Figure 11.C-2
Market for EVs Offered by Non-Big 7 Companies

Notes:
- \( Z \) = quantity of EVs produced by non-Big 7 companies
- \( P_Z \) = price of EVs produced by non-Big 7 companies
- \( D_Z \) = demand for EVs produced by non-Big 7 companies given offerings by Big 7
- \( MC_Z \) = marginal cost of producing EVs
- \( Z^*, P_Z^* \) = equilibrium quantity and price of non-Big 7 EVs if Big 7 are not allowed to use credits
- \( Z^+ \) = arbitrary quantity of \( Z \) greater than \( Z^* \)
- \( P_{Z^+} \) = price at which \( Z^+ \) non-Big 7 EVs could be sold
- \( MC_{Z^+} \) = marginal production cost at \( Z^+ \)
- \( MC_{C^+} = MC_{Z^+} - P_{Z^+} \) = marginal cost of producing credits if non-Big 7 produce and sell \( Z^+ \) EVs
The demand curve—labeled $D_2$—represents the willingness of households and fleet managers to pay for the vehicles offered by the non-Big 7 companies. In thinking about the position of this demand curve, we must not only consider the physical attributes of these vehicles but also the fact that these vehicles will be competing with the vehicles being offered by the Big 7 at prices allowing them to satisfy their mandated quantities (in combination with any credits purchased and fines paid).\textsuperscript{372}

The curve labeled $MC_2$ in the figure is the marginal production cost curves for EVs aggregated over all of the EV companies. Recall that we concluded that the marginal cost of an EV credit is the marginal production cost of an EV minus the price at which the EV is sold. Whether the marginal cost of a credit differs from the marginal cost of producing an EV, then, depends on whether credits command a positive price. This depends on the conditions in the market for non-Big 7 EVs and the quantity of these EVs sold.

First consider quantity levels below $Z^*$, which is the equilibrium quantity of non-Big 7 EVs sold in the absence of any right to sell credits (i.e., if the Big 7 were not allowed to use credits to cover part of their mandated quantities). For these quantities of EVs, the price of $Z$ is greater than marginal production cost, and thus the marginal "cost" of producing a credit in this range is negative—EV companies would be willing to produce these units of EVs even if they cannot sell credits for a positive price. For quantity levels in this range, companies are willing to produce and sell EVs even without the extra incentive provided by the ability to sell credits, and because this is true credits will not command a positive price. (In a supply

\textsuperscript{372}Our analysis of the operating costs of EVs relative to ICEVs has led to the conclusion that Big 7 companies might have to price their EVs well below the price of comparable ICEVs. (The possibility that EV technology, especially battery technology, will not progress as rapidly as is hoped reinforces this prediction.) Since we do not expect EV companies to offer vehicles that are superior in performance to the EVs offered by the Big 7, EV companies may not be able to sell any significant numbers of their EVs (thousands per year, say) unless their prices are substantially below those of ICEVs comparable to the EVs offered by Big 7 companies.
and demand model, equilibrium prices equal marginal costs; if the cost of producing credits is zero, the price of credits will be zero.)

Next consider quantity levels greater than $Z^*$. In this range, the price at which an additional EV can be sold is less than the marginal cost of producing it. For example, consider $Z^+$, an arbitrary quantity greater than $Z^*$. If the non-Big 7 companies were to produce $Z^+$ units of Z, the price at which they could be sold would be $P_Z^+$, the marginal production cost would be $MC_Z^+$, and companies would suffer a loss of $MC_Z^+ - P_Z^+$ at the margin; this difference is the marginal cost of producing a credit at $Z^+$ units of EV production and sale. Non-Big 7 companies would be willing to produce that unit of Z, then, only if the price of credits is at least as high as $MC_Z^+ - P_Z^+$.

This example illustrates the following lessons:

- credits would be supplied up to a quantity of $Z^*$ even at a zero price of credits;
- quantities of Z above $Z^*$ will be produced only if the price of credits is positive;\footnote{If credits do command a positive price, the ability to sell credits can be thought of as a production subsidy mechanism.}
- for quantities above $Z^*$, the price necessary to get a marginal credit supplied is the distance between the $MC_Z$ and $D_Z$ curves.

With these results about the supply of credits, we can analyze the credit market and complete the discussion.

The Market for EV Credits

We start with two simple, but powerful, premises:

- For the price of credits to be positive, output of EVs by non-Big 7 companies must be above $Z^*$, the level that would be produced even if credits couldn't be sold.
- If the price of credits is positive in equilibrium, the number of credits sold must be equal to the number of EVs sold by the non-Big 7 companies.

The discussion just above establishes the former premise. Let $Z^{**}$ denote the quantity of EVs produced by non-Big 7 companies in the presence of a credit market and $C^*$ be the equilibrium number of credits sold.
sold. In technical terms, then, the latter premise is: if $P^*_C > 0$, then $Z^{**} = C^*$.\(^{374}\) This allows us\(^{375}\) to analyze both C and Z in Figure 11.C-3, which depicts the credit market. The demand curve is the same as Figure 11.C-1.

Figure 11.C-3 considers three alternative supply curves for credits, corresponding to three alternative sets of hypothetical conditions in the market for EVs offered by non-Big 7 companies (i.e., alternative views of what the MCz and Dz curves in Figure 11.C-2 look like.)

The highest of the supply curves, $S_1$, represents a situation in which the cost of producing credits is very high (relative to what any Big 7 company would pay for a credit). In fact, as drawn, $S_1$, reflects a situation where the price of credits must be at least $(MC_{z10} - P_{z10}) > $5000 + f to get even a single credit supplied. Based on the discussion of Figure 11.C-2, the term $(MC_{z10} - P_{z10})$ represents the marginal cost of the least-cost EV producer minus the price at which it could sell even its first EV.\(^{376}\) Under these conditions, the cost of producing even a single credit (i.e., EVs offered by non-Big 7 companies are so unprofitable) is so high that no credits can be produced at a cost as low as any Big 7 company will pay for even a single credit. In this case no credits will be sold, and, in fact, other EV companies will sell no EVs.\(^{377}\)

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\(^{374}\)This follows because: a) the other non-Big 7 companies cannot sell more credits than they produce and they can produce credits only by selling EVs (i.e., C is less than or equal to Z), and b) if there were a positive price for credits and not all of the (Z in number) available credits are being sold (i.e., Z > C), then EV companies with unsold credits would offer to lower the price of credits to sell their excess credits because they have no value any other way (this contradicts Z > C). Thus we have concluded that in equilibrium if $P_C > 0$ then we must have $C^* = Z^{**}$.

\(^{375}\)Assuming that $P_C > 0$. This will be the case unless: production of EVs would be high enough even without credits to meet the mandate quantities of all of the Big 7; Big 7 companies are not willing to pay for credits; or both. (In either case the price of credits is zero).

\(^{376}\)Visually, this means that the MCz curve is higher than the Dz curve even at Z=0.

\(^{377}\)As argued above, if an EV company sells an EV, this generates a credit, and the EV company would be willing to sell the credit for any positive price rather than not sell it at all. Thus, if no credits are
The lowest of the supply curves, $S_3$, represents a situation in which the cost of producing (at least some) credits is relatively low. As pictured, EV companies can produce $Z_3^*$ EVs profitably even without selling credits. To induce them to produce more EVs than this, credits must command a positive price, so (as drawn) the curve $S_3$ rise from that point. It takes higher and higher prices of credits (i.e., the supply curve is upward sloping) because to sell more and more EVs requires a lower price (i.e., $D_2$ is downward sloping as in Figure 11.C-2) and (perhaps less important) the marginal costs of producing EVs rises. The equilibrium price of credits is $P_3^*$ and $C_3^*$ credits are sold. Big 7 companies buy credits, produce some EVs themselves (since $C_3^* < E_m$), but don’t pay any fines. EV companies produce and sell a total of $Z^{**} = C_3^*$ EVs.

The supply curve $S_2$ represents a case where the costs of producing credits are in an intermediate range. Here EV companies would produce relatively few (i.e., $Z_2^*$) EVs even without an ability to sell credits, but will not produce more EVs (and thereby produce more credits) unless the price of credits is positive. Big 7 companies buy $C_2^*$ credits at the price of $P_2^* = $(5000 + f). In this case, the Big 7 companies produce some EVs themselves, buy some credits and pay some fines. EV companies produce and sell a total of $Z^{**} = C_2^*$ EVs.

being sold we can infer that EV companies are not producing any credits (i.e., they aren’t selling any EVs). (This is an example of the power of the result that if $P^*_C > 0$, then $Z^{**} = C^*$.)
Figure 11.C-3

Market for EV Credits--1998 to 2002

Notes:
- \(C\) = quantity of EV credits
- \(P_c\) = price of credits ($/credit)
- \(D_c\) = demand for EV credits from all Big 7 companies together
- \(S_1, S_2, S_3\) = alternative supply curves for EV credits (reflecting different hypothetical conditions in the market for EVs from non-Big 7 companies)
- \(MC_{Z10} - P_{Z10}\) = marginal loss on first unit of sales of Z under first set of hypothetical conditions in the market for EVs from non-Big 7 companies
- \(Z_2^*, Z_3^*\) = equilibrium quantities of EVs that EV companies would sell if Big 7 companies were not allowed to use credits
- \(Z_2^*, P_2^*, P_3^*\) = equilibrium prices of credits corresponding to supply curves \(S_2\) and \(S_3\)
- \(C_2^*, C_3^*\) = equilibrium quantities of credits corresponding to supply curves \(S_2\) and \(S_3\)
General Implications

We draw several lessons from this discussion.

If the Big 7 companies can meet the mandate on their own without selling any EVs at a marginal loss, then they would not be willing to pay anything for credits (i.e., there is no demand for credits) and the price of credits will be zero. EV companies will produce and sell EVs under these conditions only if they can do so profitably without any subsidy from the credit market and despite the competition from Big 7 EVs.

If Big 7 companies cannot meet their mandated quantities while avoiding marginal losses:

- The less profitably the Big 7 companies can produce and sell EVs, other things equal, the more credits they will tend to buy and the higher will be the price of credits.\(^{378}\)
- The more profitably non-Big 7 companies can sell EVs (given the offerings of the Big 7), other things equal, the lower will the price of credits tend to be and the more EVs will be sold by non-Big 7 companies.\(^ {379}\)
- If EV sales by non-Big 7 companies are more unprofitable at the margin than are EV sales by Big 7 companies, then the price at which non-Big 7 companies are willing to supply credits is higher than the price at which Big 7 companies are willing to buy them. In this case non-Big 7 companies will not find it profitable to produce EVs even if they can sell the credits because they cannot sell the credits for enough to compensate for their marginal losses on EVs.

\(^{378}\)This conclusion follows from the fact that the demand for credits increases with decreases in the profitability of Big 7 EVs.

\(^{379}\)This follows from the fact that the supply of credits increases with increases in the profitability of non-Big 7 EVs. In the extreme, if EV companies can profitably (at the margin) sell enough EVs to meet the mandated quantities for the Big 7, credits will not be scarce, the Big 7 will meet the mandate entirely by buying credits (for next to nothing) and all of the mandate will be met by EV companies.
Will Many Credits Be Sold, and, If So, By What Companies?

Finally, the analysis here provides a systematic basis for explaining why we are doubtful that during the period 1998 to 2002 credits (i.e., production of EVs by non-Big 7 companies) will account for a substantial proportion of EVs produced because of the ZEV mandate, with the possible exception of credits generated by ICEV companies that become subject to the mandate in 2003.

The basic lessons from the analysis are:

- Non-Big 7 companies will find it profitable to sell EVs only if their marginal losses are smaller than those of the Big 7 and smaller than the cost Big 7 companies ascribe to paying fines.
- The marginal cost of producing credits will increase with more EV sales because prices will have to be lowered to sell more EVs.

Because of the ZEV mandate, the Big 7 companies will be tough competitors in the EV market. All indications are that they are gearing up to produce and sell at least large fractions of their mandated quantities.\(^{380}\) We have concluded that they can be expected to produce and market EVs that are as similar as possible to their ICEVs of comparable size and body style, and to sell anything close to their mandated quantities, the Big 7 are likely to price their EVs below, and perhaps far below, the prices of comparable ICEVs. Under these conditions, demand for non-Big 7 EVs is likely to be quite low, and much lower than it would be if the Big 7 did not have the mandate pushing them to sell thousands of EVs.

For other companies to sell more than a small fraction of the total mandated quantities—say, more than 2,500 per year during 1998 to 2,000 and 6,000 during 2001 and 2002, which are not insubstantial numbers of vehicles in such an immature market—in competition with the Big 7 would seem to require quite low prices. Different types of EV producers are in different situations:

\(^{380}\)Relatively little reliance on the EV credit market may be a self-fulfilling prophecy on the part of the Big 7. By gearing up to produce most—if not virtually all--of their mandated quantities themselves, they make it harder for other EV producers to compete and reduce the availability of EV credits.
• EV converters are competing directly with ICEVs and EVs produced by the Big 7. To sell more than a handful of vehicles per year would seem to require prices well below those of Big 7 EVs, which themselves may be far below the prices of comparable ICEVs. Unless the production costs of converters are well below those of the Big 7, their marginal losses may not be much below those of the Big 7. To sell lots of vehicles, their prices might need to be very low and, if so, their marginal losses will approach the marginal costs of producing vehicles.

• Producers of niche vehicles that don't compete directly with ICEVs are likely to find some—and perhaps many—buyers who want an EV for uses other than those of an ICEV. But for them to be selling thousands vehicles per year at substantial prices (more than $10,000 per vehicle, say) during the introductory years in face of such stiff competition from other EVs does not seem plausible.

The most plausible scenario under which converters or producers of niche vehicles would sell thousands of EVs per year before 2003 would be if the Big 7 companies have very high willingness to pay for credits and most of the revenues of EV companies are from credits.

We think it more likely that the predominant source of credits will be the ICEV companies that are first subject to the mandate in 2003. They must meet the 10 percent mandate level starting in 2003. These companies—faced with selling substantial numbers of EVs in 2003—may perceive substantial benefits (e.g., related to marketing, manufacturing experience, public relations) to selling some EVs in California before 2002.\footnote{This discussion assumes that the companies that become subject to the mandate in 2003 will plan to produce EVs. We are doubtful that these companies would plan to rely on paying fines after 2003 for the same reasons we are doubtful that the Big 7 will rely heavily on fines during 1998 to 2003. It also seems doubtful that they will plan to rely heavily on buying credits, for example, from the Big 7. This is because ICEV companies do seem to believe that the worldwide market for electric-drive vehicles will be quite large eventually, and they are unlikely to plan to fall far behind in the long-term competition to be successful in those markets.}
compensation for their marginal losses from selling EVs. This, in turn, suggests that the non-Big 7 ICEV companies may be more willing to sell EVs--and produce EV credits--than the short-term analysis here implies.\textsuperscript{382}

\textsuperscript{382}EV converters and producers of niche vehicles may also perceive substantial long-term benefits of selling EVs during 1998 to 2002, but they don't have the considerable incentive of having to gear up for very substantial mandated sales levels in 2003.
11.D ESTIMATING CONSUMERS' SURPLUS IN THE EV MARKET DUE TO THE ZEV MANDATE 1998 TO 2002

The two demand curves used to calculate consumers' surplus in the EV market (in Table 11.5-2) are depicted in Figure 11.D-1.\textsuperscript{383} These are interpreted as market demand curves for the average Big 7 EV (on which the entire analysis is based).\textsuperscript{384} Willingness to pay is expressed in terms of $P^*$, the price paid by buyers net of the 10 percent federal tax credit.

To calculate values for consumers' surplus in the EV market, we must specify the entire demand curve for EVs above the price expected to prevail in the market. As discussed in Section 11.3.2, there is very little empirical evidence available to guide us. We rely heavily on the range of views about the maximum prices that (all but very small fractions of) EV buyers would be willing to pay when comparing EVs to comparable ICEVs and the prevalence of buyers willing to pay substantial premiums. As above, we assume that buyers consider full life-cycle costs (i.e., purchase prices plus the present value of all future operating costs) when they compare EVs and ICEVs.

The demand functions are specified by choosing a value for the maximum premium a substantial fraction of EV buyers are willing to pay for an EV in terms of its full life-cycle costs relative to a comparable ICEV. It seems widely agreed that some substantial fraction of EV buyers are willing to pay a premium. The information we have leads us to conclude that a $5,000 premium would be considered optimistic by most

\textsuperscript{383}Neither demand curve in Figure 11.D-1 looks like the one in Figure 11.3-1, which is more realistic. We use the simpler curves in Figure 11.D-1 to estimate upper and lower bounds for consumers' surplus (taking other assumptions as given) because--unlike the demand curve in Figure 11.3-1--the forms of these functions allow one to construct a demand curve by specifying values for a few parameters about which available information provides some guidance.

\textsuperscript{384}In Appendix 11.H, we provide a more refined interpretation of these demand curves relying on our analysis of how the ZEV mandate may change the prices of ICEVs. (If the mandate does change ICEV prices, this shifts the demand for EVs--because they are substitutes for ICEVs--and the more refined interpretation takes this into account.)
people and a premium of $1,000 would be widely considered pessimistic.\textsuperscript{385} We use these values to construct bounds for consumers' surplus in the EV market. In both cases we assume that enough buyers are willing to pay the maximum premium to satisfy 25 percent of the mandate quantity.\textsuperscript{386}

The bold demand curve--labeled \(D_{E1}\)--is constructed using relatively optimistic assumptions about the maximum premium and the alternative demand curve--labeled \(D_{E2}\)--is constructed using relatively pessimistic assumptions about it. Both demand curves are assumed to go through the point \((E_m, P^-_m)\). (Table 11.5-2 presents two values for consumers' surplus for each assumed pair \((E_m, P^-_m)\).) The two curves differ in their heights at quantities less than \(E_m\), to represent different levels of willingness to pay of EV buyers for the EVs they purchase.\textsuperscript{387}

**Upper bounds on consumers' surplus.** The bold demand curve incorporates the assumptions that:

a) the maximum premium over the full life-cycle costs of a comparable ICEV that any EV buyer would be willing to pay--net of the federal tax credit of 10 percent of purchase price--is $5,000,

b) enough consumers are willing to pay this $5,000 premium to satisfy 25 percent of the mandated quantity, and

c) from that point \((.25E_m, P^-_m + $5000)\), demand falls off smoothly (linearly) to point \((E_m, P^-_m)\).

\textsuperscript{385}Recall that the analysis is being done in terms of the average Big 7 ICEV. For example, these bounding values are likely to strike readers as too small if they think in terms of a vehicle like the General Motors Impact, an expensive sports car, and too large if they think in terms of a small electric pickup truck or small electric sedan with a comparable ICEV selling for less than $15,000.

\textsuperscript{386}Consider in this regard: "Our previous research, though informal, seems to confirm the opinion that not many consumers will pay extra for electric vehicles." (Turrentine and Kurani, 1995, p. 9.) "Our analysis provides strong evidence that firms would be willing to cope with the limited range of electric vehicles if these vehicles were able to provide a less costly means of doing business." (Hill, 1987, p. 284.)

\textsuperscript{387}As seen presently, the heights of the demand functions for quantities greater than \(E_m\) are irrelevant to the calculations of consumers' surplus.
Figure 11.D-1

Alternative Demand Assumptions for Big 7 Companies' EVs During 1998 to 2002 Used to Estimate Consumers’ Surplus in EV Market

Notes:
- $D_{E1}$ and $D_{E2}$ are alternative EV market demand curves for EVs offered by Big 7 companies
- $D_{E1}$ is more optimistic about willingness of buyers to pay for Big 7 EVs
- $P^*$ = price paid by EV buyers; i.e., price charged by companies minus federal tax credit (the purchase subsidy)
- $P^{-} - P^{-}_{m}$ = price to buyers at which companies can sell mandated number of EVs (either $9,000 or $19,000 in simulations, see Tables 11.5-1 and 11.5-2)
- $E$ = number of EVs demanded at market level
- $E_{m}$ = mandated quantity for all Big 7 companies together
- $A + B$ = lower bound on consumers' surplus in EV market (equals ($1,000) (5/8) E_{m}$)
- $A + B + C$ = upper bound on consumers' surplus in EV market (equals ($5,000) (5/8) E_{m}$)
This demand curve implies for example, that if the price to buyers is $19,000, the higher of the assumed values in Table 11.5-2, half of the buyers of EVs would be willing to pay $22,333 or more despite the availability of comparable ICEVs for $20,000 and an operating cost disadvantage of EVs relative to ICEVs of $1,000.\textsuperscript{388} If the price to buyers is $9,000 (the lower of our assumed values for $P^-_m$), half of the buyers of EVs would be willing to pay $12,333 or more despite the availability of comparable ICEVs for $20,000 and an operating cost disadvantage relative to ICEVs of $11,000.

**Lower bounds for consumers' surplus.** The demand curve labeled $D_{g2}$ incorporates the assumptions that:

a) the maximum premium over the full life-cycle cost of a comparable ICEV that any EV buyer would be willing to pay---net of the federal tax credit of 10 percent of purchase price---is $1,000,

b) enough consumers are willing to pay this $1,000 premium to satisfy 25 percent of the mandated quantity, and

c) from that point ($0.25E_m, P^-_m + $1000), demand falls off smoothly (linearly) to point ($E_m, P^-_m$).

This second demand curve implies, for example, that if the price to buyers is $19,000, half of the buyers of EVs would have been willing to pay at least $19,667, $333 less than the price of a comparable ICEV despite an operating cost disadvantage of EVs relative to ICEVs of $1,000. If the price to buyers is $9,000, half of the buyers of EVs would have been willing to pay at least $9,667, despite the availability of comparable ICEVs for $20,000 and an operating cost disadvantage of EVs relative to ICEVs of $11,000.

**Calculating consumers' surplus.** Consumers surplus for each case considered in Table 11.5-2 is calculated as the area between the relevant demand curve and the horizontal line representing the (net of subsidy) price actually paid by EV buyers ($P^-_m$). For $D_{g2}$ this is the total---in Figure 11.D-1---area of the rectangle labeled A plus the triangle labeled B. For $D_{g1}$ consumers' surplus can be calculated by

\textsuperscript{388}Recall that the net price of $19,000 is derived assuming a price of $20,000 for a comparable ICEV and the lower-bound value of the operating cost disadvantage of an EV of $1,000,
adding to A+B the area between the two demand curves, which is labeled C in Figure 11.D-1. Given the shapes of these areas, consumers' surplus can be calculated as 5/8 of the product of the maximum premium and the mandated quantity.
11.E. PUTTING DOLLAR VALUES ON THE MARGINAL LOSSES TO A BIG 7 COMPANY FROM SELLING AN EV

How much might we expect a Big 7 company to lose from selling each additional EV during 1998 to 2002? Here we explain why this can be approximated by the difference between the average variable cost of producing EVs and the selling price of the EV.

Since losses are costs minus revenues, the additional losses due to selling an additional EV—which we call the "marginal loss on an EV"—is the additional cost of producing an EV (the "marginal cost" of an EV) minus the additional revenue from selling an additional EV (the "marginal revenue" of an EV).

Marginal costs relative to variable costs per EV. As discussed in Section 10.2, we expect average variable costs to be falling in the ranges of EV production relevant during 1998 to 2002 because larger levels of production will involve taking advantage of economies of scale experienced internally or by parts suppliers. It is a logical necessity that if average variable cost is falling then marginal cost must be less than average variable cost. As reflected in Figures 10.2-1 and 11.4-2, we expect marginal costs to be less than average variable costs, but not dramatically so.

Marginal revenue relative to the price of an EV. What happens to revenues when an additional EV is sold? The company collects the price of this EV, but this is not the only factor changing EV revenues as a whole. This is because the company faces a downward sloping demand curve for its EV: in order to sell one more EV, the company must price all EVs a little lower than it could if it were to sell one fewer. To calculate marginal revenue, then, we must deduct from the selling price the amount of revenue the company gives up by lowering the price on all

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389 In the case of parts made by the vehicle manufacturer and vehicle assembly, economies of scale would directly lower average variable costs as production increases. In the case of parts purchased by the vehicle manufacturer, economies of scale in parts production would presumably allow the vehicle manufacturer to negotiate lower prices for parts if more parts are purchased.
of its EVs to sell the additional EV. For example, suppose that a company is selling 2000 EVs at $15,000 and that to sell an additional EV, it must lower the price of (all) EVs by one dollar per EV. Then marginal revenue is $12,999.\textsuperscript{390} Thus, marginal revenue must be less than price (whenever a company has to lower price to sell more units), and how much less depends on how sensitive quantities demanded are to price. We have argued that once price is low enough to sell the mandated quantities, then demand should be quite responsive to price. Thus, we expect that marginal revenue for EVs would not be dramatically less than price at the level of EV sales relevant to determining the implicit costs of selling more ICEVs.

Putting the two pieces together, if marginal cost is below but near average variable cost and marginal revenue is below but near price, then the marginal loss—marginal cost minus marginal revenue—should be close to average variable cost minus price.

\textsuperscript{390}I.e., the $14,999 selling price of the additional EV minus the $2000 forgone on the 2000 EVs that could have been sold at a price one dollar higher.
11.F CHOICES OF DEMAND ELASTICITIES FOR HYPOTHESES 1 AND 2 ABOUT PRICING BEHAVIOR OF NON-BIG 7 COMPANIES

Here we explain the choices of assumed demand elasticities facing the Big 7 companies under the two hypotheses about the pricing behavior of the non-Big 7 companies. The basic idea is that for any given price increase by the Big 7 companies, they will lose a smaller proportion of their sales if the non-Big 7 match the price increases than if they do not match.

Under Hypothesis 1, the non-Big 7 companies are assumed to match price increases by the Big 7, and hence both sets of companies are expected to experience comparable proportionate decreases in sales. This proportion will depend on how much prices increase and the elasticity of demand for new ICEVs in California in total. We use a value of -2 to represent this elasticity. As discussed in Section 7.2, this choice is based on the consideration that prices in neighboring states will not be increasing because of regulation-induced costs of selling vehicles in California and that some buyers are likely to respond to price increases in California by buying a new vehicle outside the state.

Under Hypothesis 2, the non-Big 7 companies are assumed not to increase their prices while the Big 7 companies do. In this case the responsiveness of demand for Big 7 vehicles to the Big 7 price increases will be larger than in the case where the non-Big 7 also raise their prices. This is because the increase in Big 7 prices relative to those of other companies will induce some buyers to shift their purchases from the Big 7 companies to the non-Big 7 companies. Under Hypothesis 2, then, the relevant elasticity of demand for Big 7 vehicles is larger than under Hypothesis 1. There is no precise basis for specifying a numerical value; we use a value of -4, twice the elasticity assumed under Hypothesis 1. This value means, for example, that if the Big 7 companies were to increase their prices by 2 percent then they would lose 8 percent of their sales. This choice reflects our view that demand should be considerably more responsive if the non-Big 7 hold
their prices constant, but that many buyers would not shift their purchases to the non-Big 7 even if the Big 7 were to raise prices.
11.G DETAILLED RESULTS FOR EFFECTS ON ICEV MARKETS ASSUMING NO DISPLACEMENT AND FULL DISPLACEMENT

The two tables in this appendix differ from Table 11.6-1 only in the degree to which EV sales are assumed to displace ICEV sales. (Table 11.6-1 assumes 50 percent displacement; i.e., that for every two EV sales one ICEV sale is displaced.) The tables in this appendix redo the calculations in Table 11.6-1, assuming alternatively that EV sales do not displace ICEV sales at all ("no displacement"--Table 11.G-1) and that EV sales displace ICEV sales one for one ("full displacement"--Table 11.G-2). Results from Tables 11.6-1, 11.G-1, and 11.G-2 are collected and compared in Table 11.6-2.
Table 11.G-1
Projected Gains and Losses in California ICEV Market from ZEV Mandate
Assuming No Displacement of ICEV Sales by EV Sales (Ignores Benefits of Emission Reductions)

<table>
<thead>
<tr>
<th>Case assumptions:</th>
<th>Hypothesis 1 (prices matched):</th>
<th>Hypothesis 2 (prices not matched):</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost to company of unit increase in mandate quantity</td>
<td>500 5000 14700 500 5000 14700</td>
<td>500 5000 14700 500 5000 14700</td>
</tr>
<tr>
<td>Mandate percentage</td>
<td>0.02 0.02 0.02 0.05 0.05 0.05</td>
<td>0.02 0.02 0.02 0.02 0.02 0.02 0.05</td>
</tr>
<tr>
<td>Implicit marginal cost of Big 7 ICEVs sold in CA ($/ICEV)</td>
<td>10 102 300 26 263 774</td>
<td>10 102 300 26 263 774</td>
</tr>
<tr>
<td>Average ICEV price without ZEV mandate ($ thousands)</td>
<td>20 20 20 20 20 20</td>
<td>20 20 20 20 20 20 20</td>
</tr>
<tr>
<td>Big 7 ICEV Sales without ZEV mandate (M vehicles/yr)</td>
<td>1.240 1.240 1.240 1.240 1.240 1.240</td>
<td>1.240 1.240 1.240 1.240 1.240 1.240</td>
</tr>
<tr>
<td>Other ICEV Sales without ZEV mandate (M vehicles/yr)</td>
<td>0.260 0.260 0.260 0.260 0.260 0.260</td>
<td>0.260 0.260 0.260 0.260 0.260 0.260</td>
</tr>
<tr>
<td>Elasticity of demand for Big 7 ICEVs</td>
<td>-2.0 -2.0 -2.0 -2.0 -2.0 -2.0</td>
<td>-2.0 -4.0 -4.0 -4.0 -4.0 -4.0</td>
</tr>
<tr>
<td>Elasticity of supply of ICEVs</td>
<td>5 5 5 5 5 5</td>
<td>5 5 5 5 5 5</td>
</tr>
<tr>
<td>Degree of ICEV demand displacement</td>
<td>0.00 0.00 0.00 0.00 0.00 0.00</td>
<td>0.00 0.00 0.00 0.00 0.00 0.00</td>
</tr>
</tbody>
</table>

Prices and quantities of Big 7 ICEVs:

| Big 7 price increase (dollars per ICEV) | 7 73 214 19 188 553 6 57 167 15 146 430 |
| Proportionate Big 7 price increase       | 0.000 0.004 0.011 0.001 0.009 0.028 0.000 0.003 0.008 0.001 0.007 0.021 |
| Big 7 sales change (thousands of vehicles) | -0.9 -9.0 -26.6 -2.3 -23.3 -68.5 -1.4 -14.1 -41.3 -3.6 -36.3 -106.6 |
| Proportionate Big 7 sales decrease        | 0.001 0.007 0.021 0.002 0.019 0.055 0.001 0.011 0.033 0.003 0.029 0.086 |
| Big 7 sales with mandate (million vehicles/year) | 1.2391 1.2310 1.2134 1.2377 1.2167 1.1715 1.2386 1.2259 1.1987 1.2364 1.2037 1.1334 |

Prices and quantities of other ICEV companies:

| Other ICEV companies price increase (dollars per ICEV) | 7 73 214 19 188 553 0 0 0 0 0 0 |
| Other ICEV companies sales change (thousands of vehicles) | -0.2 -1.9 -5.6 -0.5 -4.9 -14.4 0.7 7.0 20.7 1.8 18.1 53.3 |

Dollar gains and losses in ICEV market ($M/yr):

| Cost to California new ICEV buyers | 11 109 318 28 279 806 7 70 203 18 179 510 |
| Change in Big 7 revenues on ICEVs | -9 -91 -271 -23 -237 -723 -21 -212 -627 -54 -549 -1645 |
| Change in Big 7 variable cost ($10K/ICEV) | -9 -90 -266 -23 -233 -685 -14 -141 -413 -36 -363 -1066 |
| Change in Big 7 manufacturer and dealer profit in ICEVs | 0 -1 -6 0 -4 -38 -7 -71 -214 -18 -187 -579 |
| Change in other ICEV companies revenues | -2 -19 -57 -5 -50 -152 14 141 413 36 363 1066 |
| Change in other ICEV companies variable cost ($10K/ICEV) | -2 -19 -56 -5 -49 -144 7 70 207 18 181 533 |
| Change in other ICEV companies and dealer profit | 0 0 -1 0 -1 -8 7 70 207 18 181 533 |
| ICEV Cost to CA (Consumer loss-15% of profit change) | 11 109 319 28 280 813 7 70 204 18 179 517 |
### Table 11.G-2
Projected Gains and Losses in California ICEV Market from ZEV Mandate
Assuming Full Displacement of ICEV Sales by EV Sales (Ignores Benefits of Emission Reductions)

<table>
<thead>
<tr>
<th>Case assumptions:</th>
<th>Hypothesis 1 (prices matched):</th>
<th>Hypothesis 2 (prices not matched):</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cost to company of unit increase in mandate quantity</td>
<td>500  5000  14700  500</td>
<td>500  5000  14700  500</td>
</tr>
<tr>
<td>Mandate percentage</td>
<td>0.02  0.02  0.02  0.05</td>
<td>0.05  0.05  0.02  0.02</td>
</tr>
<tr>
<td>Implicit marginal cost of Big 7 ICEVs sold in CA ($/ICEV)</td>
<td>10   102   300   26</td>
<td>263  774  10   102</td>
</tr>
<tr>
<td>Average ICEV price without ZEV mandate ($ thousands)</td>
<td>20   20    20    20</td>
<td>20   20    20    20</td>
</tr>
<tr>
<td>Big 7 ICEV Sales without ZEV mandate (M vehicles/yr)</td>
<td>1.240 1.240 1.240 1.240</td>
<td>1.240 1.240 1.240 1.240</td>
</tr>
<tr>
<td>Other ICEV Sales without ZEV mandate (M vehicles/yr)</td>
<td>0.260 0.260 0.260 0.260</td>
<td>0.260 0.260 0.260 0.260</td>
</tr>
<tr>
<td>Elasticity of demand for Big 7 ICEVs</td>
<td>-2.0  -2.0  -2.0  -2.0</td>
<td>-2.0  -2.0  -4.0  -4.0</td>
</tr>
<tr>
<td>Elasticity of supply of ICEVs</td>
<td>5     5     5     5</td>
<td>5     5     5     5</td>
</tr>
<tr>
<td>Degree of ICEV demand displacement</td>
<td>1.00   1.00   1.00   1.00</td>
<td>1.00   1.00   1.00   1.00</td>
</tr>
</tbody>
</table>

### Prices and quantities of Big 7 ICEVs:

| Big 7 price increase (dollars per ICEV) | 7  73  214  19 | 188  553  6  57  167  15  146  430 |
| Proportionate Big 7 price increase      | 0.000 0.004 0.011 0.001 | 0.009 0.028 0.000 0.003 0.008 0.001 0.007 0.021 |
| Big 7 sales change (thousands of vehicles) | -21.4 -29.4 -46.6 -53.5   | -73.6 -116.9 -21.9 -34.3 -61.2 -54.7 -86.0 -153.4 |
| Proportionate Big 7 sales decrease      | 0.017 0.024 0.038 0.043 | 0.059 0.094 0.018 0.028 0.049 0.044 0.069 0.124 |
| Big 7 sales with mandate (million vehicles/year) | 1.2186 1.2106 1.1934 1.1865 | 1.1664 1.1231 1.2181 1.2057 1.1788 1.1853 1.1540 1.0866 |

### Prices and quantities of other ICEV companies:

| Other ICEV companies price increase (dollars per ICEV) | 7  73  214  19 | 188  553 0  0  0  0  0 |
| Other ICEV companies sales change (thousands of vehicles) | -4.5 -6.2 -9.8 -11.2 | -15.4 -24.5 -3.6 2.6 16.0 -9.0 6.6 40.3 |

### Dollar gains and losses in ICEV market ($M/yr):

| Cost to California new ICEV buyers | 11  108 315 28 | 274  790 7  69  202 18  175 500 |
| Change in Big 7 revenues on ICEVs | -419 -500 -677 -1047 | -1253 -1718 -431 -618 -1027 -1077 -1552 -2602 |
| Change in Big 7 variable cost ($10K/ICEV) | -214 -294 -466 -535 | -736 -1169 -219 -343 -612 -547 -860 -1534 |
| Change in Big 7 manufacturer and dealer profit in ICEVs | -205 -206 -211 -513 | -517 -549 -212 -275 -415 -530 -691 -1067 |
| Change in other ICEV companies revenues | -88 -105 -142 -220 | -263 -360 -72 52 321 -180 133 807 |
| Change in other ICEV companies variable cost ($10K/ICEV) | -45 -62 -98 -112 | -154 -245 -36 26 160 -90 66 403 |
| Change in other ICEV companies and dealer profit | -43 -43 -44 -107 | -108 -115 -36 26 160 -90 66 403 |
| ICEV Cost to CA (Consumer loss-15% of profit change) | 48 145 354 121 | 367 889 44 107 240 111 269 600 |
11.H Calculating Changes in Consumers' Surplus in the ICEV Market Due to the ZEV Mandate, 1998 to 2002

In this appendix we explain how we calculate the consumers’ surplus lost in the ICEV market (what we have called costs to consumers) if the ZEV mandate results in an increase in the price of ICEVs. (If not, there is no cost to consumers in the ICEV market due to the mandate.) The discussion also allows precise statement of how we decompose the sales effects of the ZEV mandate on the ICEV market into (demand) displacement effects and price effects, and explains a refinement of the interpretation of the demand curves used to calculate consumers’ surplus gains in the EV market.

Conceptual Foundations

The policy being analyzed is the ZEV mandate during 1998 to 2002. It is analyzed in terms of annual effects—i.e., differences in equilibrium market conditions without and with the mandate—during each of those years. For simplicity, it is assumed that in the absence of the mandate, no EVs would be produced and sold in California.

We start with a simple description of how the effects of the policy are conceptualized. We then provide a (more detailed) graphical interpretation. The effects of the EV mandate on the ICEV and EV markets may be thought of as having the following components:

- The mandate leads the Big 7 (and perhaps other companies because of the ability to sell EV credits) to produce EVs (roughly 25,000 in each of the first three years and 60,000 in each of the next two years).

- Because EVs become available, the demand for ICEVs falls somewhat; this is what we have called the displacement effect. For example, the sale of 60,000 EVs might reduce demand for ICEVs by 30,000 vehicles, in which case we say there is a 50 percent displacement effect.

- The ZEV mandate increases the marginal cost of selling ICEVs in California and, as suggested by basic economic reasoning, these
cost increases lead to increases in the prices of ICEVs in California.\textsuperscript{391}

- The price increases for ICEVs tend to increase the demand for EVs.

All of these factors are represented in the two panels of Figure 11.H-1. The left panel (panel a) represents the ICEV market (with quantity denoted by $Q$ and price by $P_Q$). The right panel (panel b) represents the EV market (with quantity denoted by $Z$ and price by $P_Z$). Each panel contains two demand curves for vehicles. ($D_Q$ denotes demand for ICEVs and $D_Z$ denotes demand for EVs.) Another notational convention is that situations (demand levels, prices, quantities) without and with the mandate are denoted by "w/o" and "w/" respectively. The symbols used in each diagram are detailed in the notes below that diagram. The discussion here provides an overview.

The lower demand curve for ICEVs pertains to the situation with the mandate. The decrease (downward shift) in demand due to the mandate represents what we have termed the displacement effect. It is defined precisely as the horizontal distance between points A (the equilibrium without the mandate) and D. This distance is the decrease in demand due to the mandate, measured at the equilibrium price without the mandate. In the diagram, this distance is denoted by $d$. For example, if the ZEV mandate leads to the production of 62,000 EVs per year and the displacement fraction is 50 percent, $d$ is 31,000 ICEVs. The movement up the lower demand curve (from point D to point B) is what we refer to as the price effect of the ZEV mandate.

\textsuperscript{391}As discussed in Section 11.6, we do not dismiss the possibility that the ZEV mandate will not increase the costs of selling ICEVs in California. We have also discussed in the text the controversial issue of the extent to which ICEV cost increase would be factored into pricing decisions for California ICEVs. If there is no cost increase, there will be no effect on prices of ICEVs and there will be no consumer losses in the ICEV market due to the mandate. This appendix focuses on how the consumers' surplus analysis is performed for cases in which price effects are projected.
ICEV Market with and without ZEV mandate

Notes:
• $Q$ = quantity of ICEVs
• $P_q$ = price of ICEVs
• $D_{qw/o} (P_q; P_z > P_{z0})$ = demand curve for ICEVs without the mandate
  (positioned by price of EVs without mandate: $P_z > P_{z0}$)
• $D_{qw} (P_q; P_z = P^*_z)$ = demand curve for ICEVs with the mandate
  (positioned by price of EVs with mandate: $P_z = P^*_z$)
• $Q^*_{w/o}, Q^*_w$ = equilibrium quantities of ICEVs without and with the ZEV mandate
• $d$ = decrease in demand for ICEVs due to ZEV mandate (i.e., displacement effect, which holds $P_q$ at level without the mandate)
• $P^*_{qw/o}, P^*_qw$ = equilibrium prices of ICEVs without and with the ZEV mandate

EV Market with and without ZEV mandate

Notes:
• $Z$ = quantity of EVs
• $P_Z$ = price of EVs
• $D_{zw/o} (P_Z; P_q = P^*_qw/o)$ = demand curve for EVs without the mandate
  (positioned by price of ICEVs without mandate: $P_q = P^*_qw/o$)
• $D_{zw} (P_Z; P_q = P^*_qw)$ = demand curve for EVs with the mandate
  (positioned by price of ICEVs with mandate: $P_q = P^*_qw$)
• $Z^*_{w/o}$ = equilibrium quantity of EVs with the ZEV mandate ($Z^* = 0$
  assumed without the mandate)
• $P^*_zw$ = equilibrium price of EVs with the ZEV mandate ($P^*_z > P_{z0}$
  assumed without the mandate)
To this point we have discussed the displacement effect in terms of the rate at which EVs sales displace (or reduce the demand for) ICEVs sales. In this appendix we follow standard economic reasoning—which allows us to apply standard tools of cost-benefit analysis—and interpret the decrease in demand for ICEVs as being due to a decrease in the price of EVs (a substitute for ICEVs). More specifically, and as detailed in panel b and its notes, we assume that without the mandate EV sales are zero because the price of EVs is higher than the price at which anyone would demand EVs (Pz0 in the diagram, the vertical intercept of the demand curve for EVs without the mandate). An effect of the mandate is to induce companies to offer EVs for sale at a lower price, denoted P*zw/. Formally, this is what causes the demand for ICEVs to decrease.

Panel b of the figure indicates that the increase in the price of ICEVs tends to increase the demand for EVs. This is represented as an upward shift in the EV demand curve. (We refer back to this below.)

How Do We Measure Consumers' Surplus Lost in the ICEV Market?

As we have explained, the costs to buyers in the ICEV market are due to the increase in the price of ICEVs. These costs are the decreases in consumers' surplus in the ICEV market. In Figure 11.H-1(a), this is the sum of two areas:

- The rectangle with corners P*qw/, B, C, and P*qw/o, which represents the extra payments for ICEVs by consumers who buy ICEVs despite the price increase due the mandate.
- The triangle defined by the points A, B and C, which represents losses to consumers due to the decrease in the equilibrium quantity of ICEVs.

Thus, the lost consumers' surplus here is not—as is often taken to be the case—an area under a single demand curve. This is because the price change being analyzed (that of ICEVs) is itself the result of a
price change in another market (the EV market), which causes the demand for ICEVs to shift.\footnote{The reasoning involved—which is intricate—is detailed in a different context in Sugden and Williams (1978, pp. 137-144). (Only especially dedicated readers will want to read on in this footnote. We are about to show in the text that the distinction is of little practical significance in the present application.) Adapting the arguments of Sugden and Williams to our application, the key to seeing why the area of the triangle DBA is part of the proper calculation (even though the movement from point A to point D is due to the shift in demand, not the ICEV price increase) is thinking of the price decrease of EVs and the price increase of ICEVs as taking place one infinitesimal unit at a time. As the price of EVs falls and the price of ICEVs rises, some buyers will shift from ICEV purchases to EV purchases. The tipping point for each buyer who does shift reveals the amount that buyer is just willing to pay for ICEVs, which is the key to measuring each consumer's surplus. Each of these valuations is revealed by a different pair of prices and hence the proper measures are taken from (slightly) different demand curves. (In many applications, where demand curves aren't shifting while prices change, there is only one demand curve to deal with.)}

In our application, however, the area of the triangle DBA (which we do include in our measure of consumers' surplus lost in the ICEV market) is a small fraction of the total measure. The base of triangle DBA is of length $d$—the quantity displaced. Even for full displacement and the 5 percent mandate level, this is only $1/19$ of the base of the area of the rectangle included in the measure of lost consumers' surplus. Noting that the heights of the rectangle and triangle are the same, we conclude that the area of the rectangle is at least 38 times as large as the area of the triangle.

**Refining the Interpretation of Consumers' Surplus in the EV Market**

In Appendix 11.D, we introduced two demand curves used to estimate upper and lower bounds on the gains to consumers in the EV market due to the mandate. For the same reasons that we cannot strictly conceptualize the lost consumers' surplus in the ICEV market as involving a single demand curve, we cannot strictly conceptualize the consumers' surplus gained in the EV market as involving a single demand curve when ICEV prices change because of the mandate: prices are changing in a related market and this shifts the demand for EVs. The proper interpretation of consumers' surplus in the EV market (when ICEV prices increase) is the
area of a triangle formed by the points E, F and G in panel b. While this refinement is of conceptual relevance, we do not think it is of practical significance in the current circumstances. For example, we think the refinement is of very small quantitative significance relative to the imprecision with which we are able to specify points like E and F (which leads us to calculate bounds, ranges of effects, etc.).
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An annotated bibliography, CP-253 (12/95), provides a list of RAND publications in the civil justice area through 1995. To request the bibliography or to obtain more information about the Institute for Civil Justice, please write the Institute at this address: The Institute for Civil Justice, RAND, 1700 Main Street, P.O. Box 2138, Santa Monica, California 90407-2138, or call (310) 393-0411, x6916.