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The substantial reductions in motor vehicle emissions that have occurred since the late 1960s have been accompanied by continuous increases in vehicle emission control costs, and cost increases or decreases due to changes in vehicle performance such as driveability, power, fuel economy, and vehicle maintenance. In this paper, a systematic approach has been developed to estimate emission control costs for motor vehicles. The approach accounts for all emission control parts installed on vehicles, and the costs of these emission parts are estimated through their prices. This paper does not estimate costs of the changes in vehicle performance and maintenance caused by emission control.

Using information on emission control parts and their prices for new light-duty vehicles sold in California in 1990, per-vehicle control costs and total control costs for all new light-duty vehicles have been estimated. The cost to vehicle manufacturers per vehicle for emission control ranges from $220 to $1,460, depending on vehicle size and manufacturer. The sales-weighted average cost to manufacturers is $445 per vehicle. The total cost of emission control technology for 1990 light-duty vehicles sold in California is estimated to be about $698 million.

The corresponding cost to consumers per vehicle for emission control ranges from $370 to $2,430, with a sales-weighted average of $748. The total cost for emission control of 1990 light-duty vehicles sold in California is about $1.2 billion to consumers. Per-vehicle costs for vehicles sold elsewhere in the U.S. in 1990 are similar since emission standards were similar that year.

Implications

The costs of vehicle emission control have been continuously increasing since the late 1960s when vehicle emissions began to be regulated. The stringent vehicle emission standards adopted both in the 1990 Clean Air Act Amendments and in California will increase control costs further. The estimated vehicle emission control costs in this study will help evaluate the cost-effectiveness of the current U.S. vehicle emission regulatory approach and aid in the search for an alternative approach to reduce control costs.

Today's motor vehicles emit much less air pollutants than vehicles of twenty and thirty years ago. For example, the U.S. EPA estimates that between pre-1968 model-year (the pre-emission control era) and 1992 model-year cars, per-mile emissions of hydrocarbon (HC) and carbon monoxide (CO) have been reduced by more than 90 percent, and nitrogen oxides (NO_x) by more than 75 percent.[1] These dramatic emission reductions are the result of the development and application of many new emission control technologies including improved and more careful control of fuel combustion. These changes were costly. But how costly? The answer is important for those countries about to imitate rules and technologies used in the U.S. and Japan, and for the U.S. as it begins to enter a new round of vehicle emission reductions.

The new round of emission reductions in the U.S., Europe, and elsewhere could be accomplished by applying more control technologies, introducing cleaner-burning alternative energy options, relying to a greater extent on market-based regulatory approaches, focusing on non-technology pollution control strategies (including new forms of post-purchase inspections), or some combination of these strategies. The cost implications of choosing one path over another are huge. Unfortunately, knowledge of emission control costs for current vehicles is woefully inadequate to conduct a comparative analysis of these strategies.

Past studies of emission control costs have been conducted mainly for analyzing economic impacts of proposed vehicle emission standards and have therefore tended to generate aggregate cost estimates, that is, most cost estimates have been for a generic light-duty vehicle group, ignoring cost differences across vehicle models and manufacturers. Those studies were often neither systematic nor comprehensive, and resulted in large cost disparities. Previous studies do not provide the inputs needed to design and evaluate cost-effective vehicle emission control strategies, including emission trading programs. Some past studies will be discussed in detail in the following section.

In this paper, a systematic approach is developed to estimate per-vehicle emission control costs by vehicle size and by manu-

Table I. Retail-equivalent prices of selected emission control systems. Source: Lindgren.[1]

Emission control system	Retail price[a] (1990 $)
Air injection system	54.80
EGR system	12.07
Pelleted oxidation catalyst	109.38
Monolithic oxidation catalyst	66.49
Oxygen sensor	4.78

[a] Lindgren's original estimated prices were in 1977 dollars. The prices are converted into 1990 dollars, using the consumer price index for new cars.

facturer. Control costs are estimated using a detailed survey of prices of emission control parts.

Alternative Cost-Estimating Approaches

Emission control costs may be categorized as follows: emission control hardware costs, changes in operating costs associated with the use of hardware, and monetary value of reduced vehicle performance such as driveability and power. Changes in operating costs are mainly due to reduced fuel economy as a result of using certain hardware. The changes in vehicle operating costs and the reductions in vehicle performance resulting from the use of emission control hardware in today's gasoline-powered vehicles are minor (for example, Bresnahan and Yao[2] estimated that mainly due to use of fuel injection systems, emission control helped increase performance of 1981 model-year cars), although the changes and reductions were larger in the past and may be large in the future with the use of alternative energy and the next round of catalytic controls. This paper addresses only emission control hardware costs.

The past estimates of vehicle emission control costs are categorized here into four approaches: an engineering approach, to account for the material and labor cost of manufacturing a component; a Delphi approach, relying on experts' estimation of vehicle component costs; a vehicle-pricing approach, to derive emission control costs from the differentials in vehicle prices; and a part-pricing approach, relying on manufacturer's suggested retail prices of major emission parts. The first three approaches were followed in previous studies by others. The part-pricing approach is developed and applied in this paper. The four approaches are described here, including results from earlier studies.

The Engineering Approach

Using detailed information on the function of a component, the process to manufacture it, material inputs, and physical dimensions, one estimates the amount of materials (such as steel, aluminum, etc.) and the amount of labor needed to manufacture each component. With per-unit prices of the needed materials and appropriate wage rates, the material and labor cost of manufacturing the component is estimated. Then the costs of vehicle assembly and engine modifications needed for incorporating the component into the vehicle system are estimated. Next, various overhead costs (space, administrative, research and development, etc.) and profit margins are estimated. The total cost of components is calculated by adding together manufacturing costs (material and labor costs), costs of vehicle assembly and engine modifications, overhead costs, and profit margins.

The engineering approach was developed by Lindgren for the U.S. EPA.[3] Table I presents Lindgren's estimated retail-equivalent prices for some emission control systems.

In principle, the engineering approach should accurately estimate the cost of a component. In practice, however, the approach suffers from overwhelming information requirements on design and manufacture of individual components.

The first major problem is that information on material use and labor cost of manufacturing a component are generally known only by manufacturers' engineers, and treated as proprietary. Assumptions regarding material use and labor cost must be made on the basis of a researcher's professional judgement.

Second, in order to estimate the cost differences of the same component among different vehicle models and manufacturers, the differences in the component's specifications (e.g., size and weight) among models and manufacturers need to be identified. Few people are able to identify such differences among hundreds of vehicle models. Therefore, it is difficult and time-consuming to estimate emission control costs for each of hundreds of individual vehicle models. The design and manufacture of vehicle components are usually improved over time. At best, costs can be estimated for only a small number of vehicle models. In addition,

Table II. Per-vehicle emission control costs for new vehicles, 1968 to 1984. Sources: White,[13] Kappler and Gutledge,[14] Bresnahan and Yao[2]. (Costs are in 1990 dollars).

	Emission Control Cost[a]		Nonpecuniary Cost of Emission Control[d]
Model-year	White	Kappler and Gutledge	Bresnahan and Yao
1968	38.7	75.1	0.0
1969	38.7	121.6	n/a
1970	64.5	198.9	n/a
1971	64.5	269.6	n/a
1972	477.3	331.5	n/a
1973	1225.5[b]	437.6	1115.9
1974	1225.5[b]	570.2	n/a
1975	825.6[c]	837.6	625.7
1976	825.6[c]	769.1	n/a
1977	903.0	742.6	619.2
1978	903.0	773.5	n/a
1979	903.0	762.5	n/a
1980	1290.0	932.6	n/a
1981-1982	1806.0	1381.3	-167.6[e]
1983	n/a	1421.0	n/a
1984	n/a	1394.5	n/a

[a] Includes hardware and fuel economy penalty costs to consumers. White's original costs were presented in 1981 dollars. Kappler and Gutledge's original costs were presented in 1972 dollars. The costs were converted into 1990 dollars using the consumer price index for new cars.

[b] The substantial increase in the cost for 1973-1974 model-year vehicles was due to a reduction in fuel economy which resulted from the first-time use of NO_x control technology.

[c] Cost decreases in the 1975-1976 model year were due to hardware cost reductions and the fuel-economy benefit of replacing some control hardware with oxidation catalysts.

[d] Nonpecuniary cost is the dollar value of reduced driveability and acceleration and increased difficulty in starting cold engines, all of which are associated with emission control. The original costs were presented in 1981 dollars. The costs were converted into 1990 dollars using the consumer price index for new cars.

[e] The negative number means that the compliance with emission standards in that year helped improve vehicle performance.

Table III. Emission parts groups.[a]

Emission Control System	Emission Part
1. Dedicated Tailpipe Emission Control:	
1) Oxygen Sensor	(1) oxygen sensor
2) Catalytic Converter	(1) catalytic converter
3) PCV	(1) PCV (positive crankcase ventilation) valve
4) EGR System	(1) EGR (exhaust gas recirculation) valve
	(2) EGR temperature sensor
	(3) EGR amplifier
	(4) EGR thermo switch
	(5) EGR thermo valve
	(6) EGR frequency valve
	(7) EGR check valve
	(8) EGR duty cycle valve
	(9) EGR pressure reservoir
	(10) EGR pressure sensor
	(11) pressure feedback electronic EGR valve
	(12) Electronic vacuum regulator
	(13) EGR valve position sensor
	(14) constant vacuum generator
	(15) EGR solenoid
5) Air Injection System	(1) air pump
	(2) non-return valve
	(3) air injection valve
	(4) air injection check valve
	(5) air injection shutoff valve
	(6) air injection switch-over valve
	(7) air injection solenoid valve
	(8) air injection vacuum delay retard valve
6) Air Metering System	(1) air flow meter
	(2) air mass meter
	(3) manifold air pressure sensor
	(4) altitude sensor
	(5) atmospheric pressure sensor
	(6) air temperature switch
	(7) air temperature valve
	(8) air bleed valve
	(9) air control valve
	(10) bypass valve
7) Miscellaneous	(1) exhaust gas sensor
	(2) dashpot check valve
	(3) frequency solenoid valve
	(4) vacuum switch
2. Evaporative Emission Control:	
(1) Canister System	(1) canister
	(2) purge valve
	(3) air booster valve
	(4) two-way valve
	(5) frequency valve
	(6) switch-over valve
	(7) tank ventilation valve
	(8) thermo sensor
	(9) tank relief rollover valve
3. Multipurpose Technology:	
(1) Idle Speed Control	(1) idle speed control valve
	(2) idle switch
	(3) idle air regulator
(2) Fuel Assisting System	(1) coast fuel cutoff valve
	(2) throttle air control bypass valve
	(3) cold enrichment breaker system
	(4) cold mixture heating system
	(5) auxiliary accessory enrichment system
4. Electronic Control Components:	
	(1) on-board microcomputer
	(2) air temperature sensor
	(3) coolant temperature sensor
	(4) thermo sensor
	(5) thermo valve
	(6) switch valve
	(7) profile ignition pickup sensor
	(8) throttle body temperature sensor
	(9) crankshaft sensor
	(10) camshaft sensor
	(11) distance sensor
	(12) vacuum switch
5. Fuel Injection System:	
	(1) throttle body
	(2) injector
	(3) throttle position sensor
	(4) fuel injection control unit
6. Non-emission Parts:	
	(1) auxiliary air valve
	(2) air preheat control valve
	(3) ignition control unit
	(4) coolant thermostat
	(5) fuel pressure regulator
	(6) cold start valve
	(7) thermo time switch
	(8) knock control sensor
	(9) reference sensor
	(10) speed sensor
	(11) fuel pump
	(12) distributor
	(13) cold start injector

[a] Some emission parts are substitutes for others. A particular vehicle is equipped with only some of the emission parts presented in the table. Different manufacturers may use different names for the same part; whenever possible, the most common name for a part is used.

to estimate vehicle emission control costs, the engineering approach requires constant updating of component design and manufacturing information.

Third, this method is not suited to estimate costs of some electronic components. The problem is that even though the amount of material and labor used for making these electronic components may be small, the cost of the components may be high because of the high cost of the processing equipment involved. It is difficult to account for the differences in processing equipment used in manufacturing components.

Despite these difficulties, Lindgren's method has been widely used by the U.S. EPA and other organizations to estimate the costs of vehicle emission control, safety improvements, and fuel economy improvements.[4-9]

Using Lindgren's estimates of emission control component costs, a 1983 EPA[5] study estimated a per-vehicle cost to consumers of controlling light-duty vehicle hydrocarbon (HC) emissions to be \$156 to \$175 (1990 U.S. \$). (Virtually all studies cited in this paper presented costs or prices in current dollars of different years. The current dollars were converted into 1990 constant dollars, using the consumer price index for new cars. Therefore, all costs or prices in this paper are presented in 1990 constant dollars.) In another application of the engineering cost estimation method funded by EPA, the estimated per-vehicle emission control cost to manufacturers (which included the dollar value of fuel economy benefits or penalties due to use of some components) varied from \$91 to \$355 for 1982 model-year cars, depending on manufacturer and vehicle size.[10]

The Delphi Approach

This approach relies on experts' estimates of vehicle emission control costs based on their knowledge of automotive engineering. Although an individual expert may explicitly or implicitly use an engineering approach to estimate vehicle component costs, the estimating methods used by individual experts in this approach may not be exclusively based on detailed information on component design and manufacture.

Though the Delphi approach is a quick way of obtaining vehicle component costs, it heavily depends on an individual expert's personal judgements, is highly subjective, and the results are not amenable to documentation. Lindgren's engineering approach suffers from subjective personal judgements as well, but to a lesser extent than the Delphi approach. Since the component costs estimated at different times and by different experts may have been subject to different underlying assumptions, adding the component costs together as total vehicle emission control costs creates large potential errors.

The results from two recent Delphi studies illustrate the flaws of this approach. In one study, the California Air Resources Board (CARB) estimated the future cost of electrically heated catalysts to be $120 to $200 per vehicle.[11] In contrast, using the undocumented Delphi method, the Automotive Consulting Group, Inc. (ACG) of Ann Arbor, Michigan estimated the retail cost of an electrically heated catalyst to be over $850,[12] five times that of CARB's estimate. Because the method and assumptions are subjective and are not documented, the results cannot be replicated or explained.

Historical Cost Estimates Using Engineering and Delphi Approaches. Over the course of the last twenty-five years, the costs of individual emission control components have been estimated either with the engineering approach or with the Delphi approach. Drawing upon various historical regulatory documents, White[13] and Kappler and Gutledge[14] estimated total emission control costs for vehicles manufactured from the late 1960s through the early 1980s (Table II). These cost estimates have been used in various regulatory proceedings. The two studies did not explain why certain components were included. There are large discrepancies between the two studies.

All studies to date have major drawbacks. First, the estimate cannot account for the cost reduction due to improvements in designing and manufacturing individual components over time. Costs of particular components are usually estimated at the time when the technology using the components is first proposed or adopted. By not considering improvements over time in design and manufacture of emission control components, vehicle emission control costs tend to be overestimated.

Second, component cost estimates in historical regulatory documents were conducted either with the engineering approach or with the Delphi approach, by different authors, and at different times. The assumptions used vary greatly from one study to another. Estimating the total cost by adding component costs from different studies creates large potential errors.

Third, previous estimates of component costs were usually motivated by the regulatory practice of imposing uniform emission standards on all vehicles, and were thus not sensitive to differences across vehicle classes and manufacturers; the studies were conducted for a generic vehicle class. It is impossible to estimate the per-vehicle control costs for individual vehicle models and manufacturers using component costs for generic vehicle classes.

Table IV. Manufacturers surveyed.

Manufacturer	No. of Engine Families[a]	1990 Vehicle Sales Projection[b]	No. of Dealers in Survey[c]
Audi	6	7,000	1
BMW	5	22,000	1
Chrysler	23	101,000	2
Ford	38	307,000	1
General Motors	44	452,000	12[d]
Honda	14	173,000	2
Mazda	18	86,000	6[d]
Mercedes-Benz	7	80,000	2
Mitsubishi	12	82,000	1
Toyota	24	207,000	3
Volkswagen	8	26,000	2
Volvo	5	27,000	2
Total	**204**	**1,568,000**	**35**

[a] From CARB.[21] These are the engine families certified in California in 1990.

[b] These are sales for 1990 model year in California projected by manufacturers. The sales projections include passenger cars and LDTs.

[c] The number includes dealers that participated in both the first- and the second-round survey. The same dealer participated in both surveys for four manufacturers. For some European vehicles, manufacturers were contacted for prices of some emission parts. In these cases, the manufacturers were counted as "dealers."

[d] The larger number of GM and Mazda dealers participating is misleading. Because of time constraints resulting from difficulties in recruiting dealers from these two companies, a phone survey was used in which prices for only about 10-15 parts were requested from each dealer.

The Vehicle-Pricing Approach

In principle, an attractive method that responds to the drawbacks cited is one that analyzes changes in vehicle prices before and after the imposition of new regulations. By selecting different vehicle pairs over a long period of time during which vehicle emission standards are tightened, vehicle emission control costs at different emission control levels can be estimated.

The drawbacks with this approach are the difficulty of finding vehicle pairs that are identical other than in emission control changes. By deriving emission control cost from vehicle prices, the approach assumes that vehicle prices reflect the cost of producing vehicles. However, many factors besides production costs determine vehicle prices. Such factors include the tendency of manufacturers to price vehicles on the basis of competitiveness as well as cost consideration, and the aggregation of per-vehicle emission control costs. The cost of individual emission control components cannot be estimated with this approach. No study has estimated emission control costs with this approach.

Bresnahan and Yao[2] developed a similar approach, using the prices of used cars to estimate consumers' willingness to pay to avoid nonpecuniary disamenities associated with automobile emission standards (including reduced driveability and acceleration and increased difficulty in starting cold engines). They constructed car demand functions to estimate the "cost" of reduced car quality due to emission standards. Their estimated nonpecuniary cost of emission standards is shown in Table II. The nonpecuniary cost of 1981 model-year cars was negative, indicating that compliance with emission standards helped improve vehicle performance that year. This was a result of the introduction of fuel injection systems and electronic control units on vehicles in the late 1970s and early 1980s.

The Part-Pricing Approach

The relatively few attempts to estimate emission control costs, despite the huge costs involved, indicates the difficulty of the task.

The new method presented here has drawbacks as do the others, but it is systematic, rigorous, amenable to continuing refinements, needs less assumptions than the engineering approach, is less subjective than the Delphi approach, and has greater potential for achieving accurate cost estimates. The part-pricing approach uses the manufacturer-suggested retail prices (MSRPs) of vehicle emission parts to estimate vehicle emission control costs.

This approach entails several steps. First, emission control parts installed on individual vehicle models are identified. This information is available on emission certification application forms submitted by vehicle manufacturers to CARB and EPA for each engine family (an engine family usually contains several vehicle models). The application form contains detailed information on emission parts, technical specifications, operation parameters for emission tests, and vehicle models contained in an engine family.

Next, the MSRPs of these parts are collected. Vehicle dealers provided MSRPs for the names and part numbers of vehicle emission parts for each engine family.

Third, MSRPs are discounted from retail prices back to manufacturer costs, using the profit and cost markups of dealers and manufacturers.

Fourth, manufacturer costs for replacement parts are converted to manufacturer costs for initial parts. This step is necessary because the MSRPs obtained from vehicle dealers are for replacement parts, and prices of replacement parts charged by a manufacturer for after-market supply are usually higher than the prices charged by the manufacturer for the same parts supplied to vehicle assemblers (reflecting production run orders, lower marketing costs, long-term contracts, etc.). Initial parts costs are needed for this analysis because emission control costs incurred in the manufacture of a vehicle are estimated here.

Fifth, the cost of engine modifications made solely to incorporate emission parts into a vehicle system and the assembly cost associated with incorporating emission parts into the vehicle system are estimated.

Finally, the costs of individual emission parts installed on a vehicle model are added together to obtain the total emission control cost per vehicle.

The formula for estimating control cost with the part-pricing approach is:

$$ECC = \sum_{i=1}^{n} [MSRP_i/(1+DMF)/(1+MMF)/(R/I) \times (1+AC_i)]$$

Where:

- ECC = emission control cost ($/vehicle)
- n = total number of emission control parts installed on an individual vehicle
- $MSRP_i$ = manufacturer-suggested retail price for part i
- DMF = dealer markup factor on emission parts (differs by manufacturer dealer)
- MMF = manufacturer markup factor on emission parts (assumed to be same for all manufacturers)
- R/I = ratio of replacement parts prices to initial parts prices
- AC_i = cost of assembling part i into the vehicle system (as a fraction of the part cost)

The advantage of the part-pricing approach is that is does not need engineering information on vehicle parts design and manufacture as the engineering approach does. Also, the part-pricing approach needs information on vehicle system design and emission control strategies to a much lesser extent than the engineering approach. Much less expert judgements, if any, are involved in the part-pricing approach than in the Delphi approach. The part-pricing approach estimates the costs for individual control components as well as the total emission control cost per vehicle, while the vehicle-pricing approach provides only total emission control cost per vehicle. With the part-pricing approach, the assumptions regarding emission control components and their costs are explicitly presented.

The principal disadvantage of this approach is that it uses implicit (and often subjective) assumptions made by individual manufacturers in accounting for various cost components that determine the price of parts. Differences in accounting assumptions among manufacturers result in differences in estimated costs.

While the method of using emission parts MSRPs is useful to estimate emission control costs of existing vehicles, it suffers the additional drawback of being inappropriate for estimating costs of newly-developed control technologies, simply because the parts (and their prices) are unavailable. To estimate the cost of a new emission control technology, the engineering approach or the Delphi approach could be used.

The part-pricing approach can account for the cost of emission control hardware only. The approach cannot take into consideration effects of installed hardware on vehicle operation costs (e.g., effects on fuel economy and on vehicle maintenance schedule). To consider these effects, additional efforts must be made.

Table V. Dealer markup factors: results of dealer survey.[a]

Manufacturer	Dealer Markup Factor (percent)
Audi	35-40
BMW	38
Chrysler	40
Ford	40
General Motors	40
Honda	40
Mazda	60
Mercedes-Benz	38
Mitsubishi	40[b]
Toyota	40-65
Volkswagen	35-40
Volvo	40

[a] The difference between retail price and dealer cost varies among emission parts. The presented results are average for emission parts. Usually parts with lower sales volume have a higher markup factor.

[b] A factor of 40 percent was assumed for Mitsubishi because Mitsubishi dealers did not provide a markup factor.

Table VI. Cost of assembly and engine and vehicle modifications for emission parts as percentage of total manufacturing costs (based on Lindgren).

Emission Parts	Total Assembly Cost (as percent of Total Manufacturing Cost)
Valve and orifice	25
Air injection system	10
EGR system	18
Oxygen sensor	15
Catalytic converter	5

Table VII. Sales-weighted vehicle emission control costs to manufacturers ($ per vehicle).

	Dedicated tail-pipe emission control group (a)	Multipurpose technology group (b)	Electronic control system group (c)	Fuel injection system group (d)	Total cost [(a)+1/3(b) +1/3(c)+1/4(d)]
Manufacturer:					
Audi	420	197	313	554	728
BMW	505	81	195	225	654
Chrysler	143	0	130	139	221
Ford	253	21	77	151	323
General Motors	183	0	80	276	278
Honda	384	20	182	167	493
Mazda	402	47	218	403	591
Mercedes-Benz	1,228	62	178	590	1,456
Mitsubishi	323	0	253	399	507
Toyota	338	33	248	281	501
Volkswagen	407	26	202	484	604
Volvo	500	50	172	548	711
Manufacturer Group:					
American	203	7	85	215	288
European	843	63	189	515	1,056
Japanese	360	26	223	282	513
Vehicle Class:					
4 cylinder	301	20	170	250	426
5&6 cylinder	358	21	132	279	479
8&12 cylinder	289	14	92	305	401
Industry Average:	324	20	144	269	445

The part-pricing approach implicitly assumes that the function of a vehicle part is relatively independent from that of another. In practice, vehicles are now designed as an integrated system, and vehicle parts are interacted with each other. Vehicle systems are designed and engines are calibrated to maximize emission, power, driveability, and fuel economy. In the emission control cost estimate the part-pricing approach cannot take into account the implicit costs of emission control-related vehicle system design, vehicle part packaging, and engine calibration.

An uncertainty in estimating costs with the part-pricing method concerns the implicit assumption that the vehicle parts market is relatively competitive. In a competitive market, the retail price of a part represents its cost to manufacturers (cost of research and development, engineering design, facility use, retooling, material use, labor expenditure, and overheads) plus normal profits for manufacturers and dealers. Since in the U.S., emission parts are manufactured by both independent parts suppliers and by vehicle manufacturers, the assumption of competitiveness seems warranted at least for U.S. manufacturers. A competitive parts market especially exists for non-proprietary parts, the parts that can be made without patents or special technology which not all manufacturers may have. Additional evidence of the competitiveness of the U.S. vehicle parts market can be found in a survey reporting that vehicle parts are three times more expensive in Japan than in the U.S.[15] The less expensive prices of vehicle parts in the U.S. suggests the existence of a relatively competitive U.S. parts market.

However, the market-competitiveness assumption may not be always accurate. For example, one of the three precious metals used in catalytic converters, rhodium, is not traded in an open market; some parts are indeed proprietary (for example, the palladium-only catalytic converter designed and used by Ford Motor Company); some parts may be specific to certain parts suppliers and some successful product differentiation may exist; and parts prices charged by manufacturer dealers are usually higher than the prices charged by independent parts dealers. These effects may make manufacturers realize some monopoly profits, therefore distorting the competitiveness of the parts market. Although these distortions are probably relatively minor, there is no definitive evidence available.

Application of the Part-Pricing Method

Following the steps outlined earlier, the application of the part-pricing method to vehicles sold in California in 1990 is presented in detail in the following.

Determining Emission Parts for Individual Engine Families

Emission parts installed on individual engine families can be specified using the emission part information contained on emission certification application forms supplied by manufacturers to CARB and EPA. This study uses the CARB database for 1990 light-duty vehicles, the latest year available when the study began.

Emission parts information is usually presented in two lists on the application form: a high-cost part warranty list and an emission part warranty list. (Prior to 1990, CARB required manufacturers to include an emission part warranty list on emission application forms. Though CARB abandoned this requirement after 1990, manufacturers voluntarily include this information. In contrast, EPA did not require the emission part warranty list for the rest of the nation prior to 1990, but required the emission warranty list after 1990.) The high-cost warranty list contains emission parts whose prices are above a given limit. The price limit is determined by EPA and CARB.

Although there are general guidelines provided by EPA and CARB for manufacturers to determine which parts should be included in the emission part warranty list, it is manufacturers who determine which parts are included in the emission part warranty list. In general, manufacturers include the vehicle parts that directly control or affect vehicle emissions. Though there is general agreement concerning the inclusion of many parts, there are some differences among manufacturers. For example, some include the fuel metering system and the ignition system, while others do not.

In order to create a consistent part list among manufacturers, decisions had to be made regarding which parts would be included in this study. Whenever possible, the decisions were discussed with manufacturers' representatives. To aid in the decision, emission parts were divided into six groups, depending on the primary purpose of individual parts (see Table III). The arbitrary division of emission parts into different groups helps calculation of per-vehicle emission control costs. The decision about which parts belong to which groups is subject to personal judgements of the relationships between vehicle parts and vehicle systems.

Emission parts in the dedicated tailpipe emission control category (Group 1) are installed on vehicles solely for controlling tailpipe emissions. The full costs of these parts were accounted for in estimating vehicle emission control costs. The parts in the evaporative emission control category (Group 2) are used for controlling evaporative emissions (currently, hot soak and diurnal evaporative emissions must be controlled). Because of a lack of information on evaporative emission parts for some manufacturers, evaporative emission parts were not included in estimating emission control costs.

The parts listed under the multipurpose technology category (Group 3) help reduce emissions, as well as improve fuel economy, vehicle startability, and vehicle driveability. One-third of the cost of these parts was allocated to emission control, based on dividing the part costs evenly among the three vehicle attributes of emissions, fuel economy, and performance.

Electronic control systems and related sensors (Group 4) are now used on virtually all motor vehicles to optimize emission control, fuel economy, and performance. In estimating emission control costs, one-third of these costs was allocated to emission control.

Fuel injection systems (Group 5) help reduce emissions mainly by precisely controlling the air/fuel ratio. They also help increase fuel economy and engine output power. Virtually all new vehicles are fuel-injected. Although fuel injection systems have been used by some European manufacturers since the 1960s to achieve higher engine power, their extensive use beginning in the early 1980s was primarily due to stringent vehicle emission standards. Without the urgency of meeting emission standards, many manufacturers claim that they would not have introduced fuel injection systems so quickly. Therefore, fuel injection systems were included in the estimate of emission control costs. [To precisely account for the cost of a fuel injection system in an emission control cost estimate, the cost difference between a carburetor system and a fuel injection system should be considered, because a vehicle must have a fuel injection management system. However, costs of hypothetical carburetor systems for the individual engine families involved in this study were not available. The cost of fuel injection systems, rather than the cost difference, is used here. The smaller fraction of fuel injection system cost (one-fourth) used here for calculating emission control costs intends to minimize the problem of using the cost of fuel injection systems.] Since the primary function of fuel injection systems is to manage vehicle fuel systems, one-fourth of their cost was arbitrarily allocated to emission control.

Non-emission parts (Group 6) were not included in the estimate of vehicle emission control costs, although they are provided by some manufacturers in the emission part warranty list. The cost of these parts was not included because they are used primarily for other purposes (for example, engine protection and vehicle performance maintenance), although their use also reduces emissions.

There is no single definitive method to determine which parts are emission control parts and which are not because vehicles have increasingly become integrated systems in which emissions, fuel economy, and other vehicle performance parameters are optimized through on-board electronic control units. The approach of allocating a certain percentage of the costs of parts to emission control is crude. Regulatory agencies and manufacturers might have different reasons to include or not include certain vehicle parts in estimating vehicle emission control costs.

Obtaining MSRPs: Surveys of Vehicle Dealers

Names and numbers of emission parts were collected from the emission parts warranty list on engine family application forms. Parts numbers are assigned to vehicle parts by vehicle manufacturers so parts can be identified by dealers and mechanics. A list of emission parts (with their corresponding parts numbers) was created for each of the manufacturers. A survey form containing the names and numbers of all emission parts for a manufacturer was created and sent to the manufacturer's dealers in Northern California to obtain MSRPs of emission parts. Thirteen manufacturers were originally selected for inclusion in the study. However, the parts numbers from the application forms for Nissan engine families did not match the parts numbers from Nissan dealers, so Nissan was dropped from the study. Table IV presents summary information on the remaining twelve manufacturers.

Two rounds of the mail survey were conducted. In the first round, dealers were asked to provide the MSRPs for the survey parts based on the part numbers provided. This generated usable information from a number of dealers. However, in some cases, the part numbers obtained from manufacturers' application forms did not match the numbers dealers had separately obtained from manufacturers; consequently, dealers were unable to locate prices for some parts. This inconsistency in numbers is probably due to changes in part numbers between the time of vehicle certification and actual vehicle production (there is about a one year lag between certification and actual production).

In order to obtain MSRPs for the remaining parts, a second survey form was designed and administered that provided information on the emission part names, the vehicle models using the parts, and specifications of the vehicle models to dealers. When the same parts were used on several vehicle models, the most popular model was used. This additional information was obtained from the engine family application forms and the executive orders by CARB for individual engine families.

Since dealers had to go through several steps to find part prices in the second-round survey, it was quite time consuming and many dealers were unwilling to complete the entire second-round survey. Consequently, the survey form for some manufacturers was divided into sections and one dealer was asked to complete each section. This resulted in more than one dealer participating in the second-round survey for many manufacturers. Since each manufacturer's dealers obtain the same MSRPs, the prices are consistent for different dealers of the same manufacturer. Table IV

Table VIII. Vehicle characteristics and emission rates.

	American	European	Japanese
Vehicle Characteristics[a]			
Weight (lb)	3,392	3,284	2,862
Engine displacement (in^3)	196	154	119
Horse-power	136	149	115
Seconds for 0-60 mph	12.1	11.2	12.2
Certified emissions at 50,000 miles (grams per mile)[b]			
HC	0.20	0.19	0.19
CO	2.55	1.38	1.82
NO_x	0.30	0.17	0.20

[a] From Heavenrich Murrell.[22] These are for 1990 model-year cars and nationwide sales-weighted averages.

[b] From CARB.[21] These are sales-weighted average emissions for the 1990 California new light-duty vehicles. Three vehicle types are included: passenger cars, light-duty trucks 1 (gross vehicle weight less than or equal to 3,999 lbs), and light-duty trucks 2 (gross vehicle weight greater than 3,999 lbs but less than 6,000 lbs). Passenger cars in that year were subject to grams-per-mile emission standards of 0.41 for HC, 7.0 for CO, and 0.4 for NO_x; light-duty trucks 1 to 0.41, 9.0, and 0.4; and light-duty trucks 2 to 0.5, 9.0, and 1.0.

presents the number of dealers who participated in the emission part price survey.

In responding to the emission part price survey, most dealers provided the MSRPs of emission parts, the prices dealers usually charge to individual customers. A few dealers provided wholesale prices, the prices dealers usually charge to mechanical shops. When wholesale prices were provided, the dealers were asked the price difference between retail and wholesale. Based on the 15 to 25 percent difference, retail prices were calculated. The emission part price survey was conducted between October 1990 and July 1991.

Dealer and Manufacturer Markup Factors

The emission parts prices obtained in the surveys are retail prices to individual consumers. Retail prices were discounted to manufacturing costs by first subtracting profit and cost markups for dealers and their manufacturers.

Two studies[3,16] conducted by Lindgren and Jack Faucett Associates (JFA) for EPA reported a manufacturer markup factor (difference between cost to parts or vehicle manufacturers and cost to dealers) of 19 to 20 percent, and so 20 percent was accepted for this study.

Lindgren[3] and JFA[16] differed on dealer markups, however. Lindgren's study used a markup factor of 40 percent for dealers, while JFA estimated only 5.7 percent. JFA estimated dealer markup by considering dealers' interest expense, profit markup, and sales commission, all of which are costs that dealers must recover from sales. The estimated dealer markup in the 1985 study is probably a conservative estimate. To resolve the discrepancy, dealers were asked for the price difference between retail prices and dealer costs for emission parts; the results are presented in Table V. These dealer markup factors are consistent with Lindgren and are used in subsequent calculation here.

Ratio of Replacement Parts Prices to Initial Parts Prices

The prices calculated in the previous step are for after-market replacement parts, which are more expensive than initial parts manufactured for use in new cars. Lindgren[3] estimated that parts supplier costs for vehicle assemblers were one-fifth to one-fourth of the retail prices for after-market replacement parts, meaning that retail prices of after-market replacement parts are about 4.5 times as much as supplier costs. He calculated retail prices of initial parts from parts supplier costs by assuming a corporation allocation factor of 20 percent, a manufacturer markup factor of 20 percent, and a dealer markup factor of 40 percent. (The corporation allocation factor represents the expense of a manufacturer's administrative, supervision, and space support for parts production. This expense is included here as part of parts production cost because real resource consumption is involved.) His assumptions imply that retail prices of initial parts are 1.96 times as much as supplier costs [(1+0.2+0.2) x (1+0.4)]. Comparing the relative prices of replacement parts with those of initial parts, the ratio of replacement parts prices to initial parts prices is about 2.3. That ratio was used in this study to convert replacement parts prices to initial parts prices.

Costs of Incorporating Emission Parts into a Vehicle System

To account for the full cost of an emission part, the cost of incorporating the emission part into a vehicle system in terms of assembly and engine and vehicle modifications (assembly costs) needs to be included. Lindgren's study estimated the assembly cost as well as the manufacturing cost of major emission parts. Using the cost information in that study, assembly cost as a percentage of total manufacturing cost was calculated for some emission parts (Table VI). Assembly costs of emission parts for today's vehicles are probably lower than those for vehicles produced in the late 1970s because emission parts are designed, manufactured, and assembled as part of the integrated vehicle system.

The data in Table VI were used to estimate the assembly cost of emission parts. Unfortunately, Lindgren's study included neither electronic control units and related sensors, nor information on fuel metering systems (i.e., fuel injection systems). Assembly cost for an electronic control unit is assumed here to be the same as that for an oxygen sensor because an electronic control unit includes many sensors whose manufacture is similar to that of an oxygen sensor. Therefore, assembly cost for electronic control units is assumed to be 15 percent of the manufacturing cost. Assembly cost for fuel injection systems is also assumed to be 15 percent, the median value of the costs in Table VI.

Calculating Emission Control Costs

Emission control costs for each engine family were separately estimated for each of four emission control system groups. Total emission control costs were calculated by accounting for all dedicated tailpipe emission control costs, one-third of the multipurpose technology costs, one-third of the electronic control unit costs, and one-fourth of fuel injection system costs. Costs of evaporative emission control systems were not included because of incomplete cost data for some manufacturers. Using vehicle sales projected by manufacturers, sales-weighted average costs by manufacturer, by engine size, and by manufacturer group were calculated.

Since a standard set of emission parts is used for an engine family, vehicle models within an engine family have virtually the same emission control systems and, therefore virtually the same emission control costs. Although some additional emission parts may be installed on some of the vehicle models within the engine family, these parts were not accounted for because their contribution to total emission control costs is minimal. All vehicle models within an engine family were assumed to have the same emission control cost.

Results

Table VII reports the sales-weighted average emission control costs to manufacturers. The emission control costs reported in the table are by manufacturer, manufacturer group, and vehicle class. The final row in the table reports the industry averages. Costs were calculated for each of four parts categories—dedicated tailpipe emission control, multipurpose technology, electronic control systems, and fuel injection system—and allocated to total emission control costs as indicated earlier: 100 percent of the dedicated tailpipe emission control costs, one-third of the multipurpose technology costs, one-third of the electronic control system costs, and one-fourth of the fuel injection system costs.

As indicated in Table VII, the manufacturers' cost for controlling emissions is about $445 per vehicle, about two-thirds of

Table IX. Comparison of vehicle emission cost estimates by different authors (hardware cost per vehicle to consumers, 1990 dollars).

Study	MY Vehicles	Cost[a]	Estimating Approach
JFA[16]	1982	337	Engineering
This study	1990	748	Part-pricing
White[13]	1981	775	Mixed[b]
Kappler and Gutledge[14]	1984	1,161	Mixed[b]

[a] Hardware cost only.
[b] Cost data were from different studies which might use different approaches.

which are accounted for by dedicated tailpipe emission control technology ($324). Costs vary greatly between manufacturers but not between vehicles with different engine sizes. Chrysler has the lowest average total control cost ($221 per vehicle), and Mercedes-Benz the highest ($1,456 per vehicle). The substantial cost differences among manufacturers reflect differences in engine-out emissions, level of control, economies of scale, technical expertise, use of different materials to produce parts, mix of vehicles, and risk-taking strategies.

Among the three manufacturer groups, American manufacturers have the lowest cost, European manufacturers have the highest, and Japanese manufacturers are in between.

The higher emission control costs for European manufacturers are due in large part to the large portion of luxury cars in their mix. Luxury cars with higher performance generate higher engine-out emissions, resulting in higher cost to meet emission standards. Also, the higher cost of luxury cars translates in various ways into higher emission control costs—through higher overhead costs, lower production volumes, and higher quality.

Meanwhile, Japanese manufacturers also have relatively high costs — almost twice that of American manufacturers ($513 versus $288) — even though, as shown in Table VIII, Japanese cars tend to be smaller than other vehicles and have less powerful engines. This apparent anomaly is explained mostly by the risk-averse strategy adopted by the Japanese; during interviews, they emphasized their abhorrence of bad publicity, for example, recalls of vehicles in violation of emission standards.[17] Thus they invest more in emission control in order to reduce emissions far below the allowable limit and thereby reduce the possibility of recalls[1]. Emission certification data presented in Table VIII supports this explanation. American cars have higher emission rates than Japanese cars. Since European cars also have lower emission rates, European manufacturers seem to take the same risk-averse strategy as Japanese manufacturers do.

Another reason for higher costs with European and Japanese manufacturers than with American manufacturers is probably the economy of scale to produce vehicles that meet U.S. emission standards. Three U.S. companies can certainly devote the majority of their production lines to producing vehicles to be sold in the U.S., while European and Japanese manufacturers have to diversify their production lines to producing vehicles to be sold at home and in the U.S. where vehicles have to meet very different emission standards. Therefore, as the three U.S. companies have the opportunity to reduce production cost with the economy of scale, European and Japanese companies may not have such an opportunity.

This study found little difference in control costs between small and large vehicles (measured by number of engine cylinders). In fact, as indicated in Table VII, costs were higher for 4-cylinder vehicles than for much larger 8-cylinder vehicles. This apparently counter-intuitive result occurs because most large vehicles are sold by three U.S. manufacturers, and the emission control costs of large vehicles produced by domestic companies are lower than the costs of small vehicles produced by foreign companies (as explained with respect to Japanese cars). The straight-average emission control costs (without using sales as the weighing factor) for the three vehicle classes show that the cost is $437 for small vehicles, $491 for intermediate vehicles, and $508 for large vehicles. Thus, as expected, the average emission control costs of large vehicles are higher than those of the medium and small vehicles produced by a given manufacturer.

Using vehicle sales data and the estimated per-vehicle emission control costs, the total emission control cost to manufacturers for 1990 model-year light-duty vehicles sold by the twelve manufacturers in California is estimated to be $508 million if only dedicated control costs are included, and $698 million if total emission control costs are included.

Table X. Average certified emissions of 1990 model-year light-duty vehicles sold in California (grams per mile at 50,000 miles).[a]

Manufacturer	HC	CO	NO_x
Audi	0.26	1.90	0.20
BMW	0.21	1.36	0.16
Chrysler	0.26	2.35	0.30
Ford	0.19	2.39	0.31
General Motors	0.20	2.70	0.29
Honda	0.17	2.00	0.20
Mazda	0.19	1.86	0.18
Mercedes-Benz	0.15	1.02	0.18
Mitsubishi	0.25	1.88	0.21
Toyota	0.18	1.64	0.21
Volkswagen	0.18	1.71	0.11
Volvo	0.26	2.06	0.20

[a] Emissions presented in this table are sales-weighted average emissions for 1990 California new light-duty vehicles, which consist of three vehicle types: passenger cars, light-duty trucks 1 (gross vehicle weight less than or equal to 3,999 lbs), and light-duty trucks 2 (gross vehicle weight greater than 3,999 lbs but less than 6,000 lbs). 1990 passenger cars were subject to grams-per-mile emission standards of 0.41, 7.0, and 0.4 for HC, CO, and NO_x; light-duty trucks 1 subject to 0.41, 9.0, and 0.4; and light-duty trucks 2 subject to 0.5, 9.0, and 1.0.

Note: There are two types of costs that manufacturers encounter when meeting emission requirements: initial vehicle control cost (up-front initial cost to manufacturers) and the cost of recalls. This study estimates the up-front cost. While Japanese cars have higher up-front cost than American cars, the former have lower potential recall cost than the latter. Both risk-taking and risk-averse strategies may minimize the sum of the up-front cost and the recall cost.

The corresponding control costs to consumers are $544 per vehicle for dedicated emission control, $748 for total per-vehicle costs, and $1.2 billion for all consumers in California in 1990.

Discussion

Cost Comparison Among Different Studies

Table IX presents emission hardware costs (excluding indirect effects on performance and fuel consumption) estimated in four studies. The costs are at the consumer level and in 1990 dollars. Note that the costs estimated by JFA,[18] White,[13] and Kappler and Gutledge[14] are for U.S. cars produced between 1981 and 1984, and that the costs estimated by this study are for California light-duty vehicles produced in 1990. U.S. cars produced between 1981 and 1984 were subject to grams-per-mile emission standards of 0.41 for HC, 3.4 for CO, and 1.0 for NO_x. California cars produced in 1990 were subject to standards of 0.41, 7.0, 0.4. Vehicle emission standards and emission control technology did not vary greatly between the U.S. and California, nor over time between the early 1980s and 1990.

As can be seen, the per-vehicle cost estimated by JFA with the engineering approach is the lowest, and that estimated by Kappler and Gutledge is the highest. The costs estimated by this study and by White are comparable. This comparison suggests that the engineering approach underestimates costs.

Tailpipe Versus Evaporative Emission Control Costs

Vehicle emission control costs estimated in this study do not include costs of vehicle evaporative emission control systems. Currently, diurnal and hot soak evaporative emissions are regulated by EPA and CARB. Running loss evaporative emissions will begin to be regulated in 1995 in California, and will probably be regulated in the rest of the nation. To control vehicle evaporative emissions, carbon canister systems are installed on gasoline vehicles. A canister system includes a canister, vapor lines from the fuel tank to the canister and from the canister to the engine system, and vapor purge control valves. The manufacturer's cost of such a canister system could range from $15 to $40 per vehicle.

Up-Front Cost Versus Recall Cost

When meeting vehicle emission requirements, vehicle manufacturers encounter two types of costs: initial vehicle control cost (up-front initial cost) and the cost of recall. This study estimates the up-front cost only. The cost of recall is what a manufacturer has to spend for fixing vehicles that fail to meet emission standards during their useful lifetime (currently defined as 5 years or 50,000 miles, whichever is reached first). To ensure that vehicles meet emission standards during their useful lifetime, manufacturers tend to design vehicles to produce emissions below emission standards, creating a margin of safety. As indicated by Khazzoom,[19] manufacturers may reduce the sum of the up-front cost and the recall cost by lowering both.

As the up-front cost increases, emissions decrease, resulting in a large margin of safety (therefore a small recall cost). Table X presents sales-weighted average vehicle emissions by manufacturer. Comparing cost results in Table VII with emission results in Table X, one can find that the three U.S. manufacturers with lower up-front costs have higher average emissions, implying that they face high potential recall costs. Further analysis would be needed to calculate the total of up-front costs and recall costs.

Conclusion

The U.S. Clean Air Act Amendments of 1990 require a new round of more stringent rules and regulations to bring the metropolitan areas of the country into compliance with ambient air quality standards. Motor vehicles are the largest source of urban air pollution and are a prime target for further emission controls. But how much should emissions from mobile sources be reduced and how? Should those reductions be targeted at the vehicles themselves or at the users of the vehicles?

The answer to those questions requires an assessment of the costs associated with reducing emissions from vehicles. This study indicates that the cost is substantial: $748 per vehicle for 1990 model-year vehicles sold in California, plus some amount for evaporative emission control. The exact cost cannot be precisely and accurately known, even to vehicle manufacturers, because of unresolvable questions over cost allocation.

As a result of new emission standards and rules in California and the rest of the nation, emission control costs will soon be increasing, perhaps sharply, for petroleum-powered internal combustion engines. The results of this study provide a better basis for estimating costs associated with more stringent control of vehicular emissions, comparing the cost-effectiveness of various pollution control strategies, and designing and evaluating the benefits of mobile source emission trading programs (see Wang[20]).

At some point, the cost of reducing emissions from internal combustion engines, and the cost of uniform emission standards, becomes politically and economically untenable. California has responded by devising a program that allows trading of emission reduction credits among vehicle manufacturers, scheduled to phased in beginning in 1994, and adopting rules that initiate a transition to electrically-powered vehicles. The cost analysis conducted in this paper, and follow-up cost studies, are at the very heart of policy analyses needed to guide those important initiatives.

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