

would be associated with the actual reduction in vehicle activity as well as the change in vehicle operating conditions on the roadway. As traffic congestion is reduced and operating conditions move closer to free flow, traffic flows are smoothed and emission rates per mile of travel are expected to decrease.

Until a few years ago, analysts had sufficient confidence in existing emission models of the Environmental Protection Agency (EPA) and the California Air Resources Board (CARB) to generate quantitative answers to congestion pricing impact questions. Indeed, given postulated changes in vehicle activity from congestion pricing scenarios, any number of consulting firms could use the existing emission modeling regime to prepare an analysis of congestion pricing emission impacts. However, the most recent literature in both the vehicle activity and emission rate modeling research indicates that many of the problems associated with using the existing modeling regime for impact analyses of this type are insuperable. These factors will be considered in the analyses and interpretation of empirical findings.

Accurate quantitative estimates of congestion pricing impacts on air quality are not possible at this time because a number of fundamental problems exist: (a) the changes in vehicle miles of travel (VMT) and trip making are difficult to predict accurately; (b) the effects that pricing will have on vehicle fleet composition and the vehicle operating environment are unclear; (c) the primary operating environment characteristic of concern in the existing modeling regime, average vehicle speed, is difficult to estimate reliably; and finally (d) the cause-effect relationships at work between the vehicle operating environment and emission rates are poorly modeled and highly uncertain, making emission impact assessments using average speed changes very unreliable.

The goal of this paper is to examine the air quality impacts likely to result from congestion pricing. A number of key questions must be answered: What effect will congestion pricing have on trip making and VMT? How will traffic volumes change on priced and unpriced routes? How will the change in traffic volume affect the operating environment of vehicles (examined as a change in average vehicle speed under the current modeling regime) and the resulting emission rates per unit of vehicle activity? What changes in vehicle emissions are expected to result from overall changes in vehicle activity and emission rates? In this paper, the focus is on the effects of postulated changes in average vehicle operating speeds on emission rates. The accompanying paper by Harvey in this volume on changes in travel behavior is used as input to the analysis.

Congestion Pricing and Motor Vehicle Emissions

An Initial Review

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Traffic congestion is now widespread on freeways and arterials in most urban areas. The Federal Highway Administration estimates that more than 65 percent of urban freeways are congested during peak periods, creating more than 2 billion vehicle-hr of delay and user costs in excess of \$15.9 billion per year (GAO 1991). Congestion levels are also rising, meaning that the delay, energy, and air quality impacts of congestion continue to worsen. Because there has recently been increased regulatory focus on implementing economic incentives in the environmental arena (EPA 1992a; Guenster 1992; Ketcham 1991; Regulatory Flexibility Group 1991; South Coast Air Quality Management District 1991; Hahn and Stavins 1990), it is natural that congestion pricing would be explored as a means to achieve transportation behavioral changes in the urban areas with the worst air quality.

Congestion pricing has the potential to fundamentally change trip-making behavior, yielding changes in the number of trips, types of trips, trip length, mode choice, and so forth. In theory, congestion pricing will increase the efficiency and capacity of the existing highway system by reducing the use of vehicles during peak periods. Emission reductions

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Reductions in vehicle activity and trip making and VMT, assuming no changes in vehicle operating conditions, can be readily translated into percentage emission reductions, although many would argue that even these estimates could be questioned (Guenster 1993a). That area is not the focus of this paper. Instead, the existing emission modeling regime for average speed changes is examined, and a range of emission rate changes based on the projected changes in average vehicle operating speeds is provided. Using projected changes in average vehicle speeds provided by Harvey in the accompanying paper, percentage changes in emission rates associated with the implementation of four congestion pricing scenarios are examined.

The large ranges surrounding the projected percentage change in emission rates are based on the confidence intervals associated with the use of speed correction factors (SCFs) (Guenster 1993b). The actual range in emission rate impact is even greater than presented here, because there are additional sources of uncertainty for which statistical inferences of confidence have yet to be developed, such as the relationship between operating environment and changes in cold- and hot-start emission rates (Guenster 1993a).

SOURCES OF EMISSION MODELING UNCERTAINTY

Modeling results are highly uncertain because the models were only designed to roughly estimate a "bulk" emission inventory and were not designed to evaluate policy issues in the manner that they are often used. Discussions of specific emission modeling problems, such as off-cycle and modal emissions, characterization of the vehicle fleet, cold- and hot-start emissions, evaporative emissions, potential interaction between emission model correction factors, and specific quantification and spatial allocation of vehicle activity, can be found in many sources (Guenster 1993a; Harvey 1993; Bruckman and Dickson 1993; Pollack et al. 1992; Austin et al. 1992; Ashbaugh et al. 1992; TRB 1992; Bruckman and Dickson 1992; Purvis 1992; Benson 1992; Guenster and Geraghty 1991; Gertler and Pierson 1991; SAI 1991; Guenster et al. 1991; Ismart 1991; Lawson et al. 1990; FHWA 1990). It can be concluded that the current modeling methodologies, both for vehicle activity and emission rate estimates, are fraught with uncertainty.

Uncertainty is pervasive in all three emission modeling components: vehicle activity, activity-specific emission rates, and emission rate correction factors. Uncertainty is compounded in the methodologies used to develop the emission inventory. That is, vehicle activity uncertainty is combined with emission rate uncertainty that has already been combined with correction factor uncertainty. However, simple statistical formulas representing suspected ranges of uncertainty cannot be applied to the estimates to determine the net uncertainty. There are simply too many unanswered questions regarding the fundamental emission relationships and the basic applicability and usefulness of much of the data collected.

Without detailed reanalysis of the data used to develop the algorithms in existing emission rate models, practitioners cannot accurately identify the individual model components that yield the greatest uncertainty in emission estimates. Confidence interval analysis (based on reanalysis of the original data) can reveal how representative each of the model algorithms really is. Confidence interval analysis has been undertaken with the data originally used to develop the speed correction factors in existing emission rate models (Guenster 1993b), and these confidence intervals are used to examine how congestion pricing is likely to affect average vehicle operating speeds and the resulting vehicle emission rates.

CHANGES IN EMISSION-PRODUCING VEHICLE ACTIVITIES

The potential impacts of congestion pricing will be revealed through changes in vehicle activity, modeled as resulting from changes in land use configuration, trip generation, mode choice, trip distribution, and route selection, ideally in an iterative process (Harvey 1993). The implementation of congestion pricing may have the following effects on VMT, trip making, and trip characteristics, most of which are not accurately (or at all) addressed by travel demand models:

- Fewer trips due to increased costs;
- Elimination of some nonessential trips and shifting of others to off-peak periods;
- Shorter trips due to increased costs;
- Some increase in VMT if diversion to unpriced routes occurs;
- Longer trips if diversions around paid routes exist;

- Encouragement of peak spreading (shifting of trips to unpriced shoulders of the peak);
- An increase in trip chaining activity;
- Shifting of trips to carpools, transit, and paratransit due to increased travel costs;
- Changes in transit access mode;
- Changes in spatial resolution of vehicle route;
- Increases in average vehicle operating speeds on priced routes; and
- Smoother traffic flow, due to reduced acceleration/deceleration activity.

The number of trips undertaken is important from an emission modeling standpoint because the emission levels of all pollutants are elevated during the first few minutes of operation (Jacobs et al. 1990; CARB 1989; Heywood 1988; Joy 1992; Stone et al. 1990; Pozniak 1980) and hot- and cold-start emissions become important contributors to the on-road emissions inventory. In 1987 cold- and hot-start operations were estimated to contribute about 27 percent of hydrocarbon emissions, 35 percent of carbon monoxide emissions, and 19 percent of oxides of nitrogen emissions from the automobile fleet in the Los Angeles basin (CARB 1990). Because congestion pricing may change the number of vehicle trips made, emission reductions may result from reduced cold- and hot-engine starts. If congestion pricing results in an increase in trip chaining, some cold-start trips may be changed to hot-start trips, reducing emissions.

Figure 1 shows the cumulative hydrocarbon emissions for a typical modern catalyst-equipped vehicle making a 10-mi (16-km) trip at an average speed of 26 mph (42 km/hr) after a cold start. Approximately 55 percent of the hydrocarbon emissions are associated with the cold start, another 10 percent of the emissions with the engine hot soak (evaporation after shutting the engine off), and only 35 percent with the hot stabilized combustion on a per mile basis. Although the overall emission rates are much lower, modern, fuel-injected, catalyst-controlled vehicles emit a larger percentage of their emissions during cold start and hot soak than does the average in-use fleet. This indicates that trip-end emissions will become increasingly important as vehicle fleet turnover continues (but may be partially mitigated by new vehicle certification requirements, because manufacturers are expected to achieve much of their reduction in California through the control of cold-start emissions).

Harvey's study in the South Coast Air Basin indicates that congestion pricing will have only a modest effect on VMT and trip making. Region-

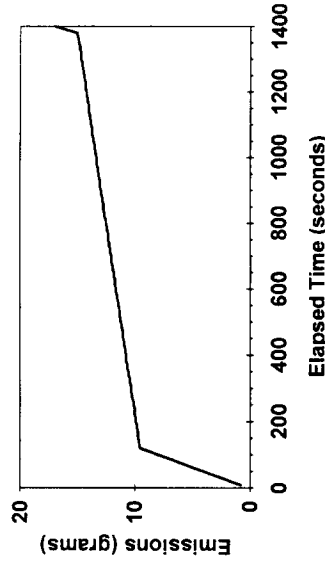


FIGURE 1 Cumulative emissions versus time, VOC emissions, 1987 average vehicle fleet (with catalyst), 10-mi trip at 26-mph average speed (16-km trip at 42-km/hr average speed).

wide congestion pricing of \$0.15/mi (\$0.09/km) (a market-clearing price designed to yield Level of Service D or E) may yield a VMT reduction of about 5.0 percent and trip reduction of 3.8 percent (Cameron 1991). In reality, this implies roughly a 4 percent decrease in engine start and hot soak emissions and a 5 percent decrease in VMT-related emissions—roughly a 4 percent decrease in automobile emissions overall, provided that vehicle operating conditions remain unchanged.

Yet, it is not likely that emission rates will remain stable as congestion pricing strategies are implemented. Changes in the composition of the vehicle fleet are likely to occur, and congestion reduction yields changes in the vehicle operating environment that in turn affect the emission rates. It is the expected change in vehicle operating conditions and subsequent emission rates that many analysts believe will yield the greatest emission benefit. But how sure is this?

POTENTIAL CONGESTION PRICING IMPACTS ON EMISSION RATES

Motor vehicle emission rates are functions of vehicle parameters, fuel parameters, vehicle operating conditions, and the vehicle operating environment. The accompanying text box lists some of the important variables that can be considered in developing emission rate estimates (Guenster 1993b). Congestion pricing can affect vehicle fleet parameters (such as model year, emission control technology, accrued vehicle mileage, etc.),

VEHICLE PARAMETERS, FUEL PARAMETERS, VEHICLE OPERATING CONDITIONS, AND ENVIRONMENTAL CONDITIONS KNOWN TO AFFECT MOTOR VEHICLE EMISSION RATES (Guenzler 1993b)

Vehicle Parameters

Vehicle class* (weight, engine size, HP, etc.)
Model year
Accrued vehicle mileage
Fuel delivery (e.g., carbureted or fuel injected)
Emission control system
On-board computer control system
Control system tampering
Inspection and maintenance history

Fuel Parameters

Fuel type
Oxygen content
Fuel volatility
Sulfur content (SO_x precursor)
Benzene content
Olefin and aromatic content
Lead and metals content
Trace sulfur effects on catalyst efficiency*

Vehicle Operating Conditions

Cold- or hot-start mode (unless treated separately)
Average vehicle speed
Modal activities that cause enrichment*
Load (e.g., A/C, heavy loads, or towing)
Influence of driver behavior*
Vehicle Operating Environment
Altitude
Humidity
Ambient temperature
Diurnal temperature sweep
Road grade*

*These components are not explicitly included in the EPA and CARB emission rate models.

fuel parameters (i.e., if modes that use clean fuels are encouraged), and vehicle operating conditions (such as average speed and acceleration).

Vehicle and fuel parameters that affect emission rates are functions of the composition of the vehicle fleet. If the composition of the fleet changes, fleet average emission rates also change. Recent studies indicate that older vehicles tend to fall into sociospatial patterns of ownership (Rajan 1993). That is, older vehicles are more likely to be owned by lower-income individuals or as supplemental vehicles in middle- and upper-income households (perhaps a vehicle for teenager use), and the patterns of ownership appear to exhibit a clustering effect. On the average, the emission rates for older vehicles are higher, although older vehicles are generally driven fewer miles per year. The vehicle activities undertaken by various socioeconomic groups also appear to differ (Micozzi and Bowen 1993). If VMT and trip-making reductions are significant in the lower-income quintiles and insignificant in the upper-income quintiles, or if the ownership and operation of higher-emitting vehicles are higher in the lower-income quintiles, the composition of the vehicle fleet with respect to emission production will change. Because a small fraction of the vehicle fleet is believed to be responsible for a large percentage of fleet emissions (Lawson et al. 1990; Pollack et al. 1992), further studies into the spatial and socioeconomic allocation of superemitting and malmaintained vehicles and vehicle activity seem warranted. These issues are tied to potential equity impacts that also must be addressed before the implementation of congestion pricing strategies.

Harvey's work (see the accompanying paper) indicates that pricing will have a varied impact on different income groups, noting that congestion pricing of \$.15/mi is likely to produce significant reduction in trip making and VMT within the first two income quintiles compared with the last two. Thus, fleet composition appears likely to change along the affected routes. The composition of the vehicle fleet is also important in estimating emission changes resulting from changes in operating conditions, because these factors are not independent. Emission behavior with respect to average vehicle speed differs between older and newer vehicle technology groups, complicating the emission impact analyses.

SPEED-RELATED MODELING REGIME

The existing baseline exhaust emission rates used in emission models were derived through the testing of thousands of new and in-use motor vehicles under the federal test procedure (FTP), a certification testing cycle for new

vehicles. The FTP consists of a defined set of modal patterns (start, stop, acceleration, deceleration, idling, and constant-speed cruise operations) and is composed of three subcycles, known as the Bag 1, Bag 2, and Bag 3 cycles (emissions are collected in separate sample bags for each subcycle). Bag 1 contains emissions from a cold engine start and running exhaust, Bag 2 contains only running exhaust emissions and is collected after the engine is hot and combustion is stabilized, and Bag 3 contains emissions from a hot-engine start and running exhaust. The bag samples are analyzed to determine the average emission rates for the vehicles operating under the test parameters. In California, the baseline exhaust emission rate for each vehicle class is the average emission result under Bag 2 of the FTP [the hot-stabilized subcycle with an average operating speed of 16 mph (26 km/hr)].

Because the certification cycle is used to test new vehicles for compliance with federal emissions requirements and in-use vehicles for evaluation of inspection and maintenance program effectiveness, numerous data are available for vehicles operating under the FTP Bag 2 cycle. However, emission rates noted under the Bag 2 testing conditions can differ significantly from the emission rates for the same vehicle when tested under other hot-stabilized testing cycles. Because thousands of vehicles have been tested under the FTP to develop the baseline exhaust emission rates, the desire on the part of regulatory agencies to define a relationship between baseline emission rates and emission rates at other average speeds seems logical. In this way, ongoing testing of vehicles can be conducted on the single certification cycle rather than on numerous cycles (saving substantial agency resources).

To model emission rates at speeds other than 16 mph, EPA and CARB developed SCFs, or statistically derived emission ratios (Guenster 1993b; Guenster et al. 1993; EPA 1992b; CARB 1992a; CARB 1992b; Caltrans 1992; EEA 1991; EPA 1988). These ratios can be thought of as the average emission rate for a vehicle group at the average speed in question divided by the average emission rate for the same vehicle group under Bag 2 of the FTP. To approximate vehicle emissions at speeds other than 16 mph, the baseline exhaust emission rate is multiplied by the statistically derived emission ratio. The SCFs were developed through the testing of more than 500 light-duty vehicles on laboratory dynamometers under a variety of chassis dynamometer cycles, including the certification cycle (Guenster 1993b).

The current emission inventory methodologies model SCFs and gram/mile vehicle emission rates as nonlinear functions of average operating

speed. Figures 2 through 4 present the relationships between speed and emissions for modern (1986 and later model year) fuel-injected automobiles. These figures present the multiplier that determines the emission rate for any operating speed compared with the average emissions for the vehicle class at 16 mph (Bag 2 of the FTP). Thus, in Figure 2, the carbon monoxide emission rate (grams/mile) at 5 mph (8 km/hr) is modeled to be roughly double that of the baseline exhaust emission rate for an average speed of 16 mph.

Research at the University of California at Davis indicates that speed-related emission factors currently used in emission modeling techniques are highly uncertain (Guenster 1993b). These emission correction factors, by the nature of their statistical derivation, yield uncertain results with high standard errors. The dashed lines in Figures 2 through 4 indicate the 95 percent confidence intervals that surround the SCF curves, based on statistical analysis of the original data used to develop the speed curves. Thus, in Figure 2, the carbon monoxide emission rate (grams/mile) at 5 mph is between 0.1 and 3.9 times that of the baseline exhaust emission rate for an average speed of 16 mph at a confidence level of 95 percent. This

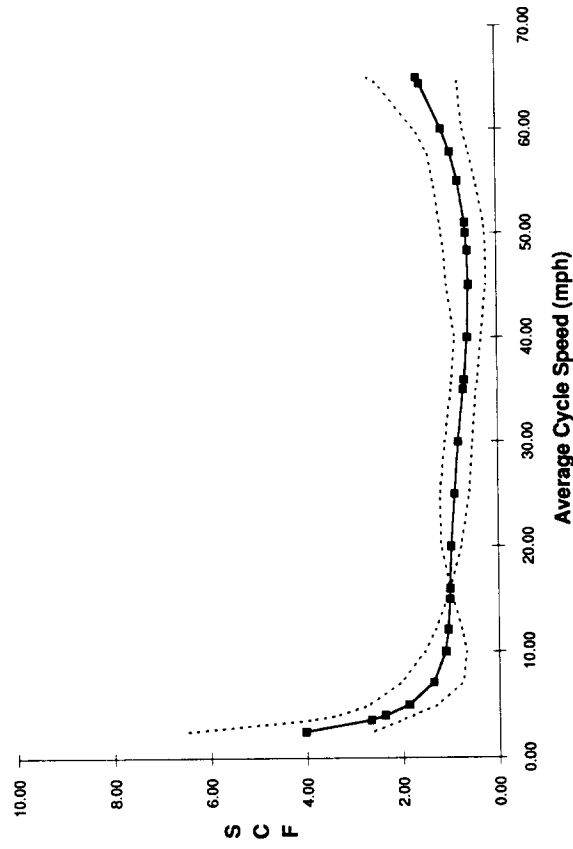


FIGURE 2 SCF (grams per mile) and 95 percent confidence interval, weighted disaggregate method, bootstrap approach, carbon monoxide, 1986 or later model year, fuel-injected vehicles. (Note: 1 mph = 1.6 km/hr and 1 gm/mi = 0.621 gm/km.)

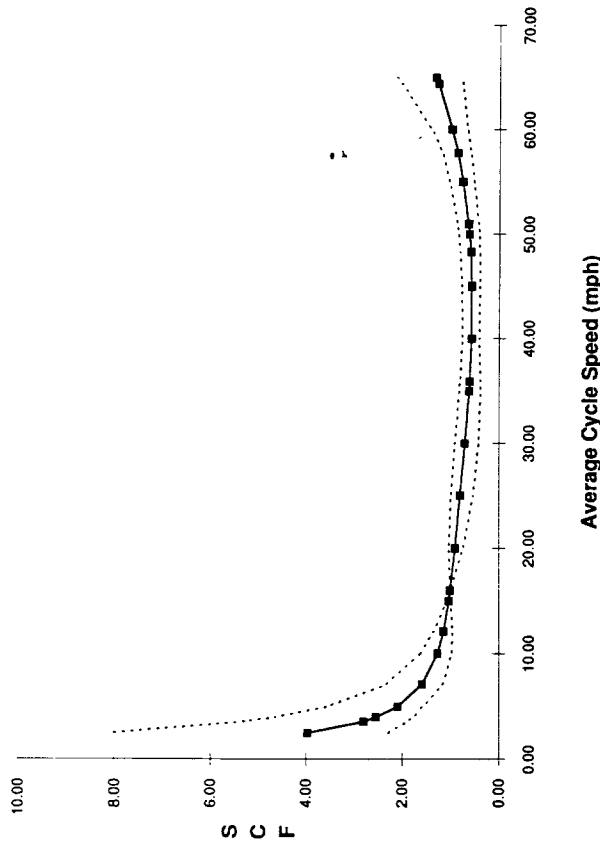


FIGURE 3 SCF (grams per mile) and 95 percent confidence interval, weighted disaggregate method, bootstrap approach, hydrocarbons, 1986 or later model year, fuel-injected vehicles. (Note: 1 mph = 1.6 km/hr and 1 gm/mi = 0.621 gm/km.)

is a huge range of uncertainty, yet there are additional sources of uncertainty unaccounted for in this analysis (e.g., intercorrelation of variables, representativeness of the test fleet, etc.) that make even these recently published uncertainty estimates conservative (Guenster et al. 1993).

AVERAGE SPEED ANALYSIS OF CONGESTION PRICING SCENARIOS

The four congestion pricing scenarios examined by Harvey include pricing on some freeways where no alternative routes are available (i.e., bridges), pricing on some freeways where alternative unpriced freeways are available for diversion, pricing on all freeways where alternative unpriced arterials are available for diversion, and pricing on all roads.

Table 1 summarizes the potential changes in average vehicle operating speed on the various affected facilities that are expected to result from the four congestion pricing scenarios postulated. For example, Harvey's analyses (see accompanying paper) indicate that targeted freeway pricing with

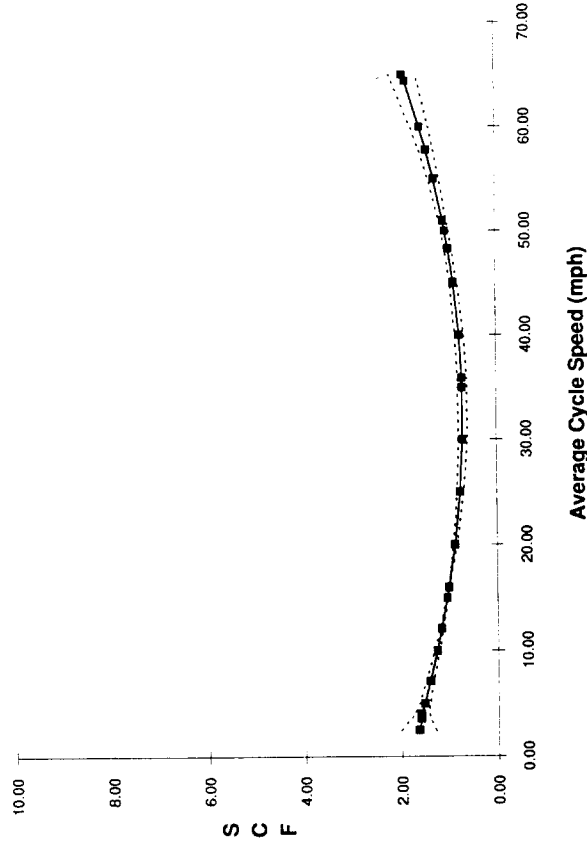


FIGURE 4 SCF (grams per mile) and 95 percent confidence interval, weighted disaggregate method, bootstrap approach, oxides of nitrogen, 1986 or later model year, fuel-injected vehicles. (Note: 1 mph = 1.6 km/hr and 1 gm/mi = 0.621 gm/km.)

no alternative unpriced routes (Scenario 1) may increase average freeway speeds from 30 to 50 mph (48 to 80 km/hr) during the peak periods and reduce average speeds on the priced freeways during the shoulder of the peak from 55 to 50 mph (89 to 80 km/hr) (because of peak spreading, caused by a price-induced delay in trip start times).

If the average speed of travel on a freeway were increased from 30 to 50 mph, emission models would predict a decrease in gram/mile emission rates for carbon monoxide and hydrocarbons and an increase in the emission rates for oxides of nitrogen along these routes. The estimated percentage changes in emission rates resulting from increased average operating speed were calculated for two significantly different groups of vehicles in the fleet: pre-1986 model year carbureted vehicles and 1986 and later model year fuel-injected vehicles.

Emissions models would predict that increasing average vehicle operating speeds from 30 to 50 mph would decrease carbon monoxide emission rates by 24 percent and hydrocarbon emission rates by 12 percent and increase oxides of nitrogen emissions by 50 percent for 1986 and later model year fuel-injected vehicles.

TABLE 1 Changes in Average Vehicle Speed Resulting from Four Postulated Pricing Scenarios

Pricing Scenario	Changes in Average Vehicle Speed by Facility
Targeted freeway pricing (no alternative unpriced routes)	Priced freeways (peak): 30 → 50 mph Priced freeways (peak shoulder): 55 → 50 mph Other facilities: no change
Partial freeway pricing (alternative unpriced freeways) (alternative unpriced arterials)	Priced freeways (peak): 30 → 45 mph Unpriced freeways (peak): 40 → 35 mph Freeways (peak shoulder): uncertain Other facilities: uncertain
Comprehensive freeway pricing (alternative unpriced arterials)	Priced freeways (peak): 30 → 45 mph Unpriced arterials (peak): 30 → 20 mph Peak shoulder: modest declines
Comprehensive pricing (no alternative unpriced routes)	Uncertain changes, higher speeds everywhere

NOTE: 1 mph = 1.6 km/hr.

Given the predicted changes in emission rates, one could easily surmise that the increases in average vehicle operating speeds are likely to yield significant reductions in carbon monoxide and hydrocarbon emission rates, concurrently increasing the emission rates of oxides of nitrogen. However, the point estimates do not tell the whole story. When the calculated emission rate changes include estimates of uncertainty, it becomes clear that the emission change estimates are questionable. For example, the 95 percent confidence interval for the estimated 24 percent reduction in carbon monoxide emissions associated with increasing average vehicle speeds from 30 to 50 mph for 1986 and later model year fuel-injected vehicles ranges from a 72 percent decrease to a 75 percent increase in emission rates. The range of uncertainty is huge.

Tables 2 through 4 contain estimates of carbon monoxide, hydrocarbon, and oxides of nitrogen emission rate changes for modern fuel-injected vehicles associated with the average vehicle speed changes postulated by Harvey (see Table 1). A bootstrap approach was used to calculate the upper and lower bound estimates in Tables 2 through 4 (Guenster 1993b). Because of multicollinearity of terms in the regression

TABLE 2 Predicted Changes in Carbon Monoxide Gram/Mile Emission Rates for 1986 and Later Model Year Fuel-Injected Vehicles Resulting from Postulated Changes in Average Vehicle Operating Speeds Estimated with Bootstrap Approach

Change in Avg Speed (mph)	Percent Change in Carbon Monoxide Gram/Mile Emission Rate		
	Low	Predicted	High
	30 → 50	-72	-24
30 → 65	+5	+105	+234
55 → 50	-51	-22	-2
30 → 45	-72	-25	+50
40 → 35	-14	+17	+58
30 → 20	0	+22	+58

NOTE: 95 percent upper and lower confidence limits used. 1 mph = 1.6 km/hr.

TABLE 3 Predicted Changes in Hydrocarbon Gram/Mile Emission Rates for 1986 and Later Model Year Fuel-Injected Vehicles Resulting from Postulated Changes in Average Vehicle Operating Speeds Estimated with Bootstrap Approach

Change in Avg Speed (mph)	Percent Change in Hydrocarbon Gram/Mile Emission Rate		
	Low	Predicted	High
	30 → 50	-48	-8
30 → 65	-1	+90	+220
55 → 50	-33	-17	-2
30 → 45	-47	-17	+41
40 → 35	-13	+9	+26
30 → 20	+11	+30	+76

NOTE: 95 percent upper and lower confidence limits used. 1 mph = 1.6 km/hr.

TABLE 4 Predicted Changes in Oxides of Nitrogen Gram/Mile Emission Rates for 1986 and Later Model Year Fuel-Injected Vehicles Resulting from Postulated Changes in Average Vehicle Operating Speeds Estimated with Bootstrap Approach

Change in Avg Speed (mph)	Percent Change in Oxides of Nitrogen Gram/Mile Emission Rate	
	Low	High
30 → 50	+32	+71
30 → 65	+110	+251
55 → 50	-22	-14
30 → 45	+16	+36
40 → 35	-11	-5
30 → 20	+15	+39

NOTE: 95 percent upper and lower confidence limits used. 1 mph = 1.6 km/hr.

model, the results are highly sample dependent, raising questions about whether test samples were representative of the fleet.

On the basis of more detailed analysis of percentage emission rate change for combinations of initial and final average speed (in 5-mph increments), the following conclusions can be drawn (Guenster 1993b):

1. Changes in average vehicle speed yield greater percentage changes in carbon monoxide and hydrocarbon emission rates for older carbureted vehicles than for newer fuel-injected vehicles (except at speeds exceeding 50 mph, where the emission change estimates for older carbureted vehicles are highly uncertain).
2. Changes in average vehicle speed appear to provide greater percentage changes in oxides of nitrogen emission rates for newer fuel-injected vehicles than for older carbureted vehicles.
3. Percentage changes in emission rates are more stable (i.e., the confidence band is narrower) for older carbureted vehicles than for newer fuel-injected vehicles, making the percentage change estimates more certain for older carbureted vehicles than for newer fuel-injected vehicles (except at speeds exceeding 50 mph, where the emission change estimates for older carbureted vehicles are highly uncertain).

4. Predicted increases in emission rates are fairly certain for all pollutants when moving toward extremely low speeds (i.e., 5 mph), and predicted decreases are fairly certain for all pollutants when moving from extremely low speeds.

5. Increasing average vehicle speeds from low [0 to 30 mph (0 to 48 km/hr)] to moderate [30 to 45 mph (48 to 72 km/hr)] should provide carbon monoxide emission benefits for older vehicles and hydrocarbon emission benefits for all vehicles. However, the carbon monoxide benefits for modern fuel-injected vehicles associated with these speed changes are highly uncertain.

6. Increasing average vehicle speeds from very low [below 15 mph (24 km/hr)] to low to moderate [perhaps between 15 and 40 mph (24 and 64 km/hr)] should provide an emission benefit for oxides of nitrogen.

7. Model-predicted emission changes for carbon monoxide and hydrocarbons are extremely variable for increases from moderate to very high average travel speeds. The confidence bands are wide and encompass both positive and negative predictions. However, on the basis of the presumed cause-effect relationship between engine load and vehicle enrichment, moving toward very high free-flow travel speeds from moderate speeds is likely to significantly increase emission rates and prove detrimental to air quality. It is probably reasonable to expect increases in both hydrocarbon and carbon monoxide emission rates at high speeds even though the confidence bands are wide.

8. Changes in carbon monoxide and hydrocarbon emission rates associated with small relative average speed changes at high speeds (e.g., increasing average speed from 50 to 55 mph) are too uncertain to assess accurately. Given the highly variable response of vehicles to the changes in average test cycle speed, the limited number of vehicles tested, and the nature of the high speed cycles themselves (high initial acceleration rates), the high degree of uncertainty is to be expected for carbon monoxide and hydrocarbon emissions (Guenster et al. 1993).

9. Decreasing average vehicle speeds from above 60 to below 55 mph [but remaining above 35 mph (56 km/hr)] is likely to provide large emission benefits for oxides of nitrogen and moderate emission benefits for hydrocarbons, and may also provide carbon monoxide benefits (as indicated by the bootstrap analysis).

10. The average speed modeling regime for oxides of nitrogen is probably not unreasonable. The range of confidence for changes in oxides of nitrogen emissions is narrow even for high-speed operations, indicating that the oxides of nitrogen increases are likely to be significant and fairly

certain at high speeds. Because emissions of oxides of nitrogen are more important in ozone formation than was previously realized by air quality management planning agencies (NRC 1991), evaluation of oxides of nitrogen emissions changes is paramount in congestion pricing impact assessments for many areas.

EFFECTS OF MODAL ACTIVITY

Average speed does not cause emissions. Two trips with the same average speed can be made by a vehicle, but the emissions from each trip may differ significantly because emissions are a function of combustion parameters and emission control systems. The modal characteristics of the trip (acceleration, deceleration, and cruise and idle patterns) appear to be much more likely to cause changes in combustion parameters and control system efficiency than does the average speed.

Second-by-second laboratory tests indicate that changes in operating mode (acceleration and deceleration) are capable of producing significant emissions but are not currently modeled (Darlington et al. 1992; CARB 1991; Benson 1989; Calspan 1973a, 1973b; Kunselman et al. 1974; P. J. Groblicki, presentation at CARB meeting, Nov. 5, 1990). Recent laboratory testing indicates that high acceleration rates are significant contributors to instantaneous emission rates and that one sharp acceleration may cause as much carbon monoxide pollution as the entire remaining trip (CARB 1991; Carlock 1992). Pollutant "emission puffs" occur, typically when the vehicle goes into enrichment and not enough air is available to facilitate complete combustion, and these events may be associated with high rates of acceleration or deceleration. Surprisingly, even vehicle operations at a relatively stable high-speed flow appear to show some variability in emission rates that may be associated with accelerations and decelerations, even though the rates of acceleration and deceleration at these speeds are low (Guenzler 1993a). Modal effects are not directly addressed in "average speed" emissions analysis.

Congestion pricing is likely to smooth vehicle flows and reduce the number of significant acceleration and deceleration events that cause elevated emission rates. But the impact of flow smoothing is not well represented in an average speed modeling regime that is based on a limited number and variety of test cycles used in developing the relationships (Guenzler 1993b). Better tools are needed to assess both the actual changes

in modal operations and the changes in emission rates associated with the changes in modal operations.

It can be postulated, however, that when congestion pricing smooths vehicle flows on freeways, emission reductions will result—the change in emission rate should be toward the optimistic end of the confidence interval. Similarly, if congestion pricing causes increased congestion on arterials, emission increases will result—the change in emission rate should be toward the pessimistic end of the confidence interval.

CONCLUSIONS

The emissions impacts of congestion pricing on trip making and VMT are relatively straightforward if the operating environment of the vehicle remains unchanged. A percentage reduction in trip ends (starts and engine shutdowns) can be translated into percentage changes in trip-end emissions. Similarly, reductions in VMT can be translated into reductions in running emissions. However, recent research (Cameron 1991; accompanying paper by Harvey) indicates that pricing-induced changes in trip making and VMT are expected to be small (less than 5 percent). Rather, analysts have been advocating congestion pricing primarily for the benefits in reducing traffic congestion, expecting that the changes in the vehicle operating environment (i.e., average speed) will produce significant emission reductions.

The analyses described here indicate, however, that changes in average vehicle operating speed yield highly uncertain emission impact estimates. Even so, a number of conclusions can be drawn from the analyses. If congestion pricing policies are implemented, it is fairly certain that they should be designed to (a) increase average vehicle speeds from below 15 to above 15 mph (but below 40 mph) for emission benefits in all pollutants, (b) increase average vehicle speeds from below 30 to above 30 mph (but below 40 mph) in areas where reductions in carbon monoxide and hydrocarbon emissions are desired, (c) avoid allowing previously congested routes to exceed 40 mph average speed as a result of the pricing policy, and (d) avoid creating congestion on arterial unpriced routes. Thus, from an air quality perspective, congestion pricing is recommended only in areas where average speeds are currently below 35 mph (demand exceeds capacity). Market-clearing prices should be set so that average speeds do not increase beyond 40 mph. Pricing strategies should also ensure that significant reductions in average vehicle speeds do not result on arterials.

Because the travel demand and emission rate models do not well represent the actual cause-effect relationships at work (especially for modal activities), it is impossible to determine the overall emission impacts of congestion pricing policies. However, many of the changes noted in vehicle activity and the factors that affect emission rates are positive from the perspective of cleaning the air. The likely impacts of congestion pricing on vehicle activity and the variables that affect vehicle emission rates are summarized in Table 5.

Because changes in average vehicle speed yield significantly different percentage changes in emission rates for older carbureted vehicles and newer fuel-injected vehicles (as well as relative certainty associated with these percentage changes), the fleet composition under congestion pricing scenarios is important. If the bottom two income quintiles own a greater percentage of carbureted vehicles and are also affected more by congestion pricing (i.e., trips and VMT are reduced to a greater extent) than those in the upper-income quintiles, fewer of the older vehicles will be present in the postpricing fleet. Thus, the composition of the vehicle fleet resulting from congestion pricing (i.e., the vehicle and fuel parameters affecting fleet emission rates) may play a significant role in net emissions estimates and should be examined in detail. This factor will probably create equity considerations that will need to be addressed.

Congestion reductions (or increases on arterials) that arise from congestion pricing will yield changes in vehicles' modal operating environment. When average speed increases and flows are smoothed, the change in emission rate should be toward the optimistic end of confidence intervals. When average speeds decrease and flows become less smooth, projected emission rate changes should be toward the pessimistic end of the confidence intervals.

FURTHER STUDIES

Over the short term, EPA is evaluating the FTP and will likely make changes to the test method (Guenster 1993a). However, because the FTP improvement effort only directly addresses adequacy of baseline exhaust emission rate estimates, it is unlikely that estimation of the emission inventory and analysis of scenarios such as congestion pricing will be significantly improved. Further research into modal modeling being undertaken by the Georgia Institute of Technology, the University of California at Los Angeles, and the University of California at Davis should

TABLE 5 Potential Impacts of Congestion Pricing on Emission-Producing Vehicle Activities and on Variables Expected To Affect Vehicle Emission Rates

	Impact
Emission-producing activities	
Vehicle miles traveled	↓
Engine starts and hot soaks	↓
Diurnal evaporation	NC
Vehicle refueling ^a	↓
Modal behavior (and idling) ^b	↑
Vehicle and fuel parameters	
Vehicle age ^c	↓
Accrued vehicle mileage	↓
Tampering and inspection and maintenance ^c	↓
Vehicle operating conditions	↓
Average vehicle speed ^d	↑
Vehicle load	↓

NOTE: NC = not likely to significantly change activity or emission rates. ↓ = likely to decrease activity or emission rates. ↑ = likely to partially increase and partially decrease activity or emission rates.

^a Changes in emissions associated with vehicle refueling will also be a function of changes in trip making as well as changes in fuel efficiency associated with retained trips (DeLuchi et al. 1992).

^b Pricing will reduce congestion and pollutant emission rates from modal activities on routes where flows are smoothed. However, reductions cannot be reliably quantified at this time. Not also that emissions may increase along those routes that become more congested as a result of traffic diversion.

^c Congestion pricing may result in a change in vehicle fleet composition. The demand elasticity for operators of older vehicles will likely yield a smaller percentage of older vehicles in the peak-period fleet. In general, older vehicles have higher emission rates and are more likely to be tampered with (although this assertion is currently being debated). Because the emissions behavior of older and newer vehicles is significantly different, the potential emissions impact of fleet composition is important. Note that potential impact on fleet composition may also have serious equity implications.

^d The emission rate decreases are for CO and HC, and increases will result for NO_x. Note also that emission rates for all pollutants may be substantially increased if high-speed operations result.

help shed light on the significance of the modal emissions component in the evaluation of congestion pricing scenarios. Disaggregate data are now becoming available for instrumented vehicles, and modeling work in this area continues. But the development of significantly improved emission inventory modeling methodologies will require the collection and analysis of huge amounts of new data on new testing cycles and new testing equipment, probably with second-by-second emission resolution (Guenster 1993a).

It took more than 1 year to assess the uncertainty associated with the use of speed correction algorithms in the models, so modelers are a long way from deriving uncertainty estimates for other modeling components. Nevertheless, the reanalysis of SCFs demonstrates how other modeling components could be examined if sufficient resources were allocated and how uncertainty analysis for each modeling component could be incorporated into the analytical framework. In addition, this paper did not include sensitivity analysis of the models, that is, how sensitive the models are to errors in estimation of the independent variable, average speed (Bruckman and Dickson 1992).

This paper only examined estimates of uncertainty in percentage change in emission rates, and a detailed empirical study of net emissions change should follow. The new analysis should use predicted changes in number of trips, predicted changes in VMT along each route, predicted changes in average speeds along each route, and SCF uncertainty estimates (Guenster 1993b) to predict the total emission impacts of the proposed congestion pricing policies and the confidence intervals around the predictions.

Decisions in the air quality and transportation arenas are made in the face of tremendous uncertainty. Most decisions, unfortunately, are made by policy makers who do not know the magnitude of uncertainties involved. This problem arises partly because not enough research on emission rate and activity uncertainty has been conducted and partly because institutional policy-oriented learning is a slow process hindered by the structure and nature of the policy arena. It is hoped that this paper will help apprise policy makers of the uncertainty involved in assessing the emissions impacts of policies designed to change average vehicle speeds and will communicate the need to gather, disseminate, and analyze new and better emissions data.

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ABBREVIATIONS

CARB	California Air Resources Board
Caltrans	California Department of Transportation
EEA	Energy and Environmental Analysis

EPA	Environmental Protection Agency
FHWA	Federal Highway Administration
GAO	General Accounting Office
NRC	National Research Council
SAI	Systems Applications International
TRB	Transportation Research Board

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