TRANSPORTATION RESEARCH RECORD 648

Environmental and Conservation Concerns in Transportation: Energy, Noise, and Air Quality

TRANSPORTATION RESEARCH BOARD

COMMISSION ON SOCIOTECHNICAL SYSTEMS
NATIONAL RESEARCH COUNCIL

NATIONAL ACADEMY OF SCIENCES
WASHINGTON, D.C. 1977

Transportation Research Record 648
Price $4.80
Edited for TRB by Mary McLaughlin

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Library of Congress Cataloging in Publication Data
National Research Council. Transportation Research Board.
Environmental and conservation concerns in transportation.

(Transportation research record; 648)
1. Transportation–Energy conservation–Congresses. 2. Traffic noise–Congresses. 3. Air–Pollution–Congresses. 4. Automobiles–Motors–Exhaust gas–Congresses. I. Title. II. Series.
TE7.H5 no. 648 [TJ163.5.T7] 380.5'08s [388]
ISBN 0-309-02677-6 78-13538

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Impact of Mandatory Fuel Economy Standards on Future Automobile Sales and Fuel Use

Damian J. Kulash,* Congressional Budget Office
Carmen Difiglio, U.S. Department of Energy

This paper provides a basis for projecting and evaluating the impact of mandatory fuel-economy standards and gasoline taxes on automobile sales and fuel consumption. The analytical procedures are based on explicit estimates of the cost to improve the technical efficiency of new automobiles and a behavioral model of consumer choice of automobile by market class. Alternative policies are evaluated in terms of their impacts on fuel consumption, sales-weighted fuel economy, automobile sales, scrappage of vehicles, fleet composition, and vehicle kilometers of travel. Increases in gasoline prices were found to have considerable potential for reducing automotive fuel consumption but only at the expense of creating equally sizable reductions in vehicle kilometers of travel and in the number of automobiles sold. Fuel-economy standards, such as those contained in the Energy Policy and Conservation Act of 1975, also appear to have a significant beneficial effect on fuel consumption but relatively little impact on automobile sales and travel. Early indications suggest, however, that the standards incorporated in the existing legislation may be unattainable and that revisions in both the standards and the penalty structure might produce better results.

Now that energy conservation has become a national priority, much of the concern about fuel conservation naturally focuses on automobiles. Automobiles consume almost a third of the nation's petroleum products; it is widely assumed that much of this consumption is inessential and could be eliminated by more fuel-efficient vehicles, travel patterns, and life-styles. One automobile is now in use for each 2.3 Americans (including children), and the average automobile travels about 18 500 km/year (11 500 miles/year) and consumes 3300 L (870 gal) of gasoline along the way. Among the many opportunities for conservation implicit in these statistics are reductions in the widespread ownership and use of automobiles and improvements in the fuel efficiency of individual vehicles.

Although this report concentrates on opportunities for improved fuel efficiency, it recognizes that, because of the complex ties that exist among the U.S. automobile industry, the consumer, and the federal government, other areas cannot be ignored. Some of these ties are direct, such as government standards on automotive safety, emissions, or fuel economy. Others are indirect, such as the connection between automobile sales and energy costs. Attempting to analyze an industry as large and complex as the U.S. motor vehicle industry necessarily involves simplification, and in turn this simplification restricts the range of problems for which analytic structure is appropriate.

This paper describes projections based on a forecasting model for the automotive sector, which was developed for the purpose of examining various government policies that affect new-automobile fuel economy—specifically, excise taxes and rebates, fuel economy standards, and policies that influence the price of gasoline. The aim is to simulate how future automobile sales, the stock of automobiles in use, vehicle kilometers of travel, new-automobile prices and fuel economies, and automotive fuel consumption will be affected by various policies that might be enacted by the federal government. The paper focuses on a specific family of policies, namely, fuel economy standards for new automobiles. It examines how variations in the standards themselves and in the associated penalties for noncompliance can influence policy effectiveness. The aim of the investigation is to develop some preliminary information on the likely effects of the Energy Policy and Conservation Act (EPCA) and to explore whether changes in that legislation might enhance its effectiveness or lessen any of its undesirable side effects.

ENERGY POLICY AND CONSERVATION ACT

The Energy Policy and Conservation Act of 1975 (Pub. L. 94-163) will impose mandatory fuel-economy standards on automobile manufacturers starting in 1978 and continuing through 1985. These standards are given below (1 km/L = 2.35 miles/gal):

Year	Standard (km/L)
1978	7.65
1979	8.08
1980	8.50
1981 to 1984	To be determined by the Secretary of Transportation
1985	11.69

Between 1981 and 1984, the Secretary of Transportation must set fuel economy standards that will (a) provide for the maximum feasible fuel economy levels in each year from 1981 through 1985 and (b) result in steady progress toward meeting the 1985 goal of 11.69 km/L (27.5 miles/gal). The 1985 goal may be changed by the Secretary of Transportation, but any change that reduces the 1985 standard below 11.05 km/L (26 miles/gal) or raises it above 11.69 km/L must be submitted to Congress for approval.

The fuel economy standard is applied to the average fuel economy of all automobiles manufactured by each firm. Manufacturers whose sales-weighted fleet fuel economy is below the standard are liable to a civil penalty of $11.76 for each 0.1 km/L ($50/mile/gal) that their fleet average is below the fuel economy standard for each automobile manufactured. Because these penalties may not be treated as expenses in computing corporate income taxes, their after-tax effect is approximately twice the statutory level; e.g., an extra kilometer per liter of fuel economy offsets expenses of about $235/automobile for a manufacturer whose output falls beneath the fuel economy standard.

CONSUMER DEMAND FOR AUTOMOBILES

The methodology used in making these forecasts combines two distinct parts: automobile demand prediction and automobile industry simulation. The automobile demand model is based on the following set of econometric relations:

$$N_t = (286\,721.3)\,[O_t^* - (\text{autos}_t - D_t)]^{0.2178}\,(X_t^*)^{-1.7039} \quad (1)$$

$$O_t^* = \left(\sum_I H_I P_{It}\right) \text{HHLD}_t \quad (2)$$

$$H_I = 0.017\,86\,I^{0.4743} \quad (3)$$

$$S_t = 1/(1 + \exp\{-[-4.1749 - 1.8660(X_t^S) + 3.5093(X_t^M) + 5.6428(S_{t-1})]\}) \quad (4a)$$

$$M_t = 1/(1 + \exp\{-[-4.1749 - 2.0765(X_t^M) + 3.5450(X_t^S) + 0.2589(X_t^L) + 5.6428(M_{t-1})]\}) \quad (4b)$$

$$L_t = 1/(1 + \exp\{-[-4.1749 - 0.4299(X_t^L) + 1.8117(X_t^M) + 5.6428(L_{t-1})]\}) \quad (4c)$$

$$\text{SPG}_t = 0.4068 - 0.0784(P_n)_t - 0.0155(U_t) \quad (5)$$

$$\text{KMT}_t/\text{HHLD}_t = -85\,244.5 + 24\,275 \log(\text{DI}_t\text{HHLD}_t) - 3546.6 \log(\text{CPKM})_t + 10\,196.6\,(\text{autos}_t/\text{HHLD}_t) \quad (6)$$

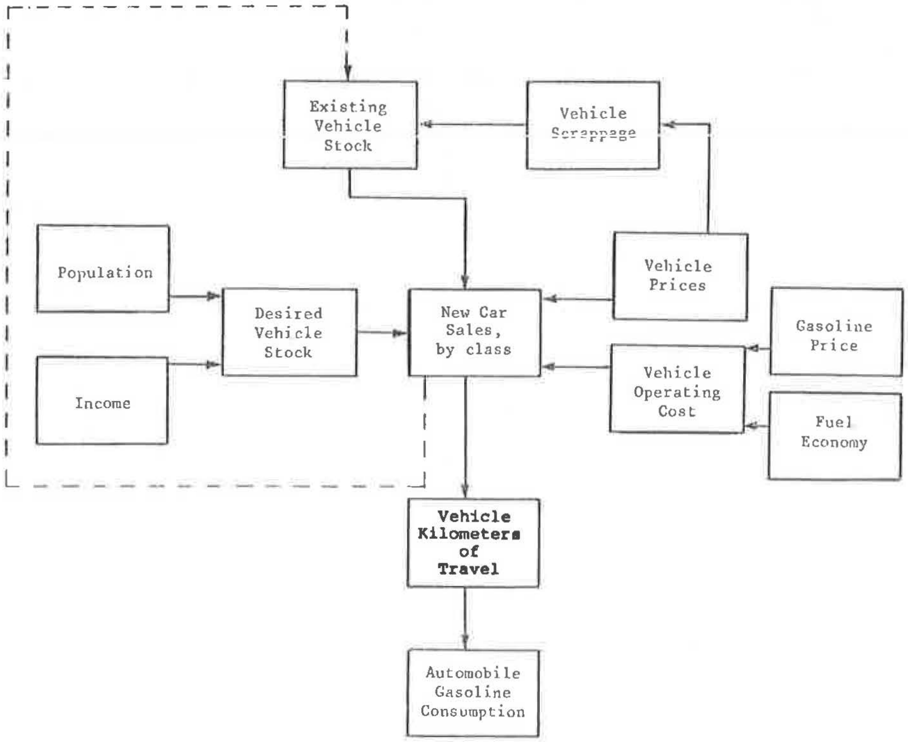
where

N_t = total new automobile sales in year t;
O_t^* = target ownership of automobiles in year t;
$(\text{autos})_t$ = stock of automobiles on hand as of January 1 of year t;
D_t = number of automobiles scrapped during year t;
X_t^* = index of the real generalized price of new automobiles (1967 = 1.00);
P_{It} = fraction of total households in year t with income (I);
HHLD_t = total number of households existing in year t;
H_I = characteristic automobile ownership for households with income (I);
I = average household income;
S_t, M_t, L_t = market shares of small, medium, and large automobiles respectively in year t;
X_t^S, X_t^M, X_t^L = index of the real generalized price of small, medium, and large automobiles respectively relative to that of all new automobiles in year t (1967 = 1.00);
SPG_t = rate of scrappage in year t of vehicles 8 or more years old (an index relative to the average rate for vehicles in each age group);
$(P_n)_t$ = index of the real price of new automobiles in year t (1967 = 1.00);
U_t = unemployment rate in year t;
DI_t = total real disposable income in year t;
KMT_t = total vehicle kilometers traveled in year t; and
CPKM_t = index of the fleet real gasoline cost per mile in year t (1967 = 1.00).

These relations are applied recursively for each year of the forecast period, as shown in Figure 1.

Central to the model is the forecasting procedure for sales of new automobiles (Equations 1 through 4). Projections of new-automobile sales are based on a modified stock-adjustment concept in which the "desired" stock of automobiles (Equations 2 and 3) is determined from population and income forecasts and the "actual" stock of vehicles is based on previous stock less scrappage. The degree to which actual stock attains the desired level is based on the cost of purchasing and operating new vehicles (Equation 1). Sales by vehicle size class are determined by a market-shares estimator that is based on the prices of purchasing and operating vehicles in each class (Equation 4). The total number of vehicles scrapped, which is applied in forecasting new-automobile sales, is based on the detailed age composition of the automobile fleet. The scrappage rate of the older vehicles in the fleet is computed based on the replacement costs (i.e., costs of new automobiles) that prevail at the time of replacement (Equation 5). Vehicle kilometers of travel are computed based on the stock of vehicles, the affluence of the population, and the costs of operating a vehicle (Equation 6). The fuel consumed

Figure 1. Automobile sales forecasting model.



in driving the projected number of kilometers is calculated by distributing total vehicle-fleet travel to individual vehicle types (age and size class) and then computing fuel consumption by using fuel economies characteristic of each of these vehicle types.

The rationale for this process is to integrate vehicle ownership, sales, use, and fuel consumption harmoniously with expected future demographic, economic, and policy factors, as detailed elsewhere (1, 2). The aim of this paper is to apply this structure to determine how various federal energy policies would affect automotive energy consumption and personal mobility.

AUTOMOBILE INDUSTRY RESPONSE TO POLICY STEPS

Before the results of the automobile demand forecasting process are examined, a brief discussion of the responses the automobile manufacturing industry is expected to make to the types of federal policy that will be examined will be helpful. The industry-simulation aspect of the methodology is based on an assessment of feasible technological improvements and their costs as well as a set of assumptions about how the automobile industry as a whole would choose various technological combinations in response to alternative policy conditions. The automobile industry is assumed to act to minimize the generalized price of vehicles within each vehicle size class. The generalized price of an automobile is defined as

$$Y_{c,t} = C_{c,t} + bG_t/F_{c,t} \tag{7}$$

where

$Y_{c,t}$ = generalized price of a new vehicle of class c in year t;
$C_{c,t}$ = price of a new vehicle of class c in year t;
b = 52 853, a constant that reflects the lifetime, discounted, perceived kilometers of travel of the automobile;
G_t = price of gasoline in year t; and
$F_{c,t}$ = fuel economy of a new vehicle of class c in year t (km/L).

That is, the automobile manufacturers act to minimize the sum of the purchase price and the perceived lifetime operating cost of the vehicle. Operating cost, as used here, includes only gasoline costs; maintenance, insurance, and other operating costs are assumed to be unaffected by the policy alternatives being analyzed. The constant (b) is based on actual annual travel patterns recorded in the Nationwide Personal Transportation Survey of the Federal Highway Administration (3); an annual discount rate of 10 percent and a perception factor of 80 percent, which reflects consumers' imperfect awareness of future operating costs, are assumed.

If fuel economy standards and noncompliance penalities are in force, then the automobile manufacturers are assumed to respond by producing vehicles that minimize the generalized net price of penalties and that are priced to pass penalty payments along to consumers. That is, the automobile makers are assumed to continue to improve fuel economy up to the point where the marginal cost of improving it (i.e., the added new-automobile price) is equal to the marginal penalty payments that would be avoided by making the improvements. This can happen in either of two ways, depending on whether or not the standards are ultimately met, as discussed below.

Standards Met

Manufacturers might in some instances meet fuel economy standards only because of fuel cost savings, and as a result the imposition of a standards program would produce no further changes. Alternatively, setting penalties lower than the statutory level might be sufficient to prompt manufacturers to comply by making only some limited improvements. In both of these situations, the marginal penalty payment associated with an increase in vehicle fuel economy is zero because no further penalty savings are to be gained by the manufacturer once the prescribed standard has been met.

Compliance with fuel economy standards might theoretically be accomplished by automobile manufacturers in various ways: One vehicle class could be upgraded substantially, in terms of fuel economy, while others remain virtually unchanged, or all vehicle classes might be upgraded approximately to the same extent. It is assumed here that improvements are made to each vehicle class so that the marginal cost of fuel economy improvements less the marginal value of the associated fuel savings is equal for all vehicle classes. This assumption results in improvements being made in an even-handed fashion across all vehicle classes, subject to the costs of those improvements. Whether or not an individual vehicle class is itself above standard has no particular bearing on whether or not fuel economy improvements will be made to vehicles of that class.

Standards Not Met

Each manufacturer would be willing to spend only an amount per additional kilometer per liter of fuel economy up to the amount of the after-tax penalty per kilometer per liter; at some point, therefore, it is more economical to pay penalties than to make further technological improvements. As a result, the marginal penalty reductions eventually fall to either of two values: zero, if standards are met, or the after-tax value of the penalty if standards are not met. In the second case, all vehicle classes would be upgraded to the point where an equilibrium is struck between penalty payments and other factors such as price and fuel savings (4, 5).

ASSUMPTIONS

The projections in this paper examine automobile-related behavior through the next 25 years. Obviously, the growth rates and the consumption patterns that characterize the automobile industry today cannot be expected to continue that long. The table below compares some general trends from the past 25 years with the assumptions used and the results projected here.

	Rate of Growth (%)			
Period	Population of Households	Disposable Income per Capita	Real Price of Automobiles	Real Price of Gasoline
1950 to 1975 (actual)	2.05	2.10	1.52	0.25
1975 to 2000 (assumed)	1.65	2.00	1.00 (baseline) 1.59 (EPCA)	0

The major assumptions used in this analysis relate to future growth rates in (a) the population of households, (b) disposable income per household, (c) the price of gasoline, and (d) the price of new automobiles. The table presented above gives projected growth rates for these items compared with the actual growth rates experienced during the past quarter century and includes census data for households, Bureau of Economic Analysis data for disposable income, and data from the consumer price index for gasoline and automobile prices. As the table indicates, future growth in the number of households is expected to taper off slightly, the growth in disposable income per capita is expected to slow down, the historic decline in real automobile prices is projected to reverse itself, and the price of gasoline is expected to remain fixed in terms of constant dollars. These assumptions and other market-saturating influences will tend to dampen somewhat the rapid growth in automobile sales, ownership, use, and fuel consumption evident during the period from 1950 to 1975.

These projections are also based in part on assumptions about future federal policy on safety and the environment. It is assumed that the statutory emissions standards of the Clean Air Act of 1970 will be enforced starting in 1978. The table below gives the assumptions made in this study about pollutant emissions, based on the exhaust emission test procedure applied by the U.S. Environmental Protection Agency (1.6 g/km = 0.06 oz/mile):

Year	HC (g/km)	CO (g/km)	NO_x (g/km)
1975	0.932	9.323	1.927
1976	0.932	9.323	1.927
1977	0.932	9.323	1.243
1978 and after	0.255	2.113	0.249

It is also assumed that continued vehicle improvements in the areas of crash avoidance, crashworthiness, and damageability will be mandated between now and 1990. The following table gives projected vehicle improvements in these categories (1 km = 0.62 mile):

Year	Crash Avoidance	Crashworthiness	Damageability
1980	Improved hydraulic brake systems, hoses, fluids	Upgraded bumpers in low corner impacts, improved system integrity	Redesigned steel bumpers
1985	Antilock brakes	Passive belt system, upgraded side and roof structure, 32-km/h side impact, and 48-km/h rollover	Soft-face bumpers with steel back beams
1990	No further changes	Upgraded front, side, roof, and rear structure; 54-km/h front impact; 48-km/h side and rear impacts; and 48-km/h rollover	No further changes

POLICY OPTIONS

The six policies examined in this analysis are given in Table 1. These policy alternatives assume that the safety and environmental policies previously summarized are in effect. (All prices are in constant 1974 dollars.)

All but the first policy option involve government policies directed toward improving fuel economy and reducing fuel use. The Secretary of Transportation may set the 1985 fuel economy standard at or between the stringent (11.69 km/L) and moderate (11.05 km/L) levels and must specify the corresponding 1981 and 1984 standards to provide a smooth transition between the 1980 and the 1985 standards.

Two additional policy options were also tested that assume that fuel taxes of $0.10/L ($0.40/gal) are applied in 1976 and maintained thereafter. In one of these, the gasoline tax was tested for the baseline case to determine the impact of the tax alone; in the other the gasoline tax was examined in conjunction with the moderate EPCA standards.

POLICY IMPACTS

Fuel Economy of New Automobiles

Table 2 gives the forecast sales-weighted fuel economies of each of the alternatives for the years 1978 to 1985. The highest 1985 fuel economy results from combining EPCA with doubled civil penalties (policy 6). At 10.49 km/L (24.7 miles/gal) in 1985, this option represents a 15 percent improvement in sales-weighted fuel economy over that of the baseline case (policy 1). As currently mandated, EPCA with either moderate or stringent standards will result in a 1985 sales-weighted fuel economy of about 9.87 km/L (23.2 miles/gal). The domestic sales-weighted fuel economy of 9.61 km/L (22.6 miles/gal) implies that the domestic automobile industry will be liable for $1.7 billion of civil penalties in 1985 under the moderate standard and $2.6 billion under the stringent standard. Because the sales-weighted fuel economy of foreign automobiles is forecast to be 11.56 km/L (27.2 miles/gal), foreign manufacturers as a group do not face civil penalties. Although individual foreign manufacturers may be liable, the number of automobiles involved would be so small as to make any foreign liability insignificant in comparison with projected domestic liability.

Gasoline taxes may reduce fuel consumption, but their impact on sales-weighted fuel economy appears to be marginal, particularly when a $0.10/L ($0.40/gal) gasoline tax is applied in addition to EPCA standards. Increased gasoline costs affect the operating cost of large automobiles more than those of small and mid-sized automobiles, but an inelastic demand inhibits any sizable reduction in sales of large automobiles. The increased operating cost for small and mid-sized automobiles tends to reduce their sales more substantially because the demand for smaller automobiles is more elastic. The additional technological stimulus afforded by a gasoline tax also appears to be marginal; the potential for technological improvements in fuel economy in each vehicle size class has been largely exploited under the EPCA. The net effect of both market shifts and technological improvements, created by combining the EPCA with gasoline-tax policies, is an increase of only 0.04 km/L (0.1 mile/gal) in 1985 sales-weighted fuel economy (Table 2). The gasoline tax applied to the baseline case would have a larger (although still marginal) impact of 0.13 km/L (0.3 mile/gal) in 1985. The greater potential of gasoline taxes to improve fuel economy outside the EPCA framework is explained by the fact that the most cost-effective technological fuel economy improvements are attributed to the fuel tax increase instead of to EPCA.

Automobile Sales

Mandatory fuel economy standards have conflicting effects on automobile prices and sales: They tend to raise average automobile costs by precipitating technological fuel economy improvements and by requiring payment of civil penalties that are ultimately reflected in the purchase price of inefficient automobiles. They can reduce lifetime vehicle costs by lowering expected vehicle operating costs.

The net impact of mandatory EPCA standards on automobile sales is negligible until 1981 but becomes substantial by 1983 (Table 3). If the moderate standard is assumed to be in force, automobile sales, relative to the baseline, are down by 0.1 million in 1981, by 0.5 million in 1983, and by 0.9 million in 1985. The drop in 1985 automobile sales attributable to EPCA enforcement thus respresents a 7.1 percent reduction from baseline sales, the greatest projected percentage sales loss for any year between 1976 and 2000. If the stringent standard mandated by EPCA is maintained, the loss of sales in 1985 increases to 1.4 million automobiles (or 11.1 percent). This further reduction in sales is caused by the increase in the civil liability, which is assumed to be passed on to buyers of new automobiles. The stringent standard adds a substantial civil penalty but does not have much impact on the marginal incentive for manufacturers to improve the fuel economy of new automobiles. Higher sales-weighted fuel economies (Table 2) are achieved by combining doubled civil penalties and moderate standards, i.e., by doubling the marginal incentive to improve fuel economy. The higher sales-weighted fuel economies produce lower aggregate civil penalties than do the statutory civil penalties or the stringent standard combined with penalties. In fact, automobile sales are not much lower under the double-penalty option than they are under the single-penalty option. The projected maximum difference in sales between these two options is 0.3 million automobiles in 1985 (2.6 percent) and is generally less than 0.1 million in subsequent years.

Table 1. Major fuel-economy policies studied.

Policy	Type	Assumptions
1	Baseline	No government policy for improved fuel economy and reduced fuel use; fuel price of $0.16/L from 1976 through 2000
2	Gasoline tax	No government policy for improved fuel economy and reduced fuel use; fuel price of $0.26/L from 1975 through 2000 (possibly by means of $0.10/L increase in the federal excise tax on gasoline)
3	EPCA (moderate)	Mandatory EPCA fuel-economy standards; 1985 standard of 11.05 km/L; constant fuel price of $0.16/L
4	EPCA (stringent)	Mandatory EPCA fuel-economy standards; 1985 standard of 11.69 km/L; fuel price held to $0.16/L from 1975 through 2000
5	EPCA (moderate) and gasoline tax	Mandatory EPCA fuel-economy standards; 1985 standard of 11.05 km/L; fuel price held to $0.26/L from 1975 through 2000
6	EPCA (moderate) and double penalties	Mandatory EPCA fuel-economy standards; 1985 standard of 11.05 km/L; fuel price held to $0.16/L; doubled civil penalties for noncompliance ($235/automobile per kilometer per liter by which a manufacturer's sales-weighted fuel economy is below the mandated standard)

Note: 1 L = 0.26 gal; 1 km/L = 2.35 miles/gal.

Table 2. Projected fuel economy for six policies.

	Fuel Economy (km/L)					
Year	1	2	3	4	5	6
1978	7.752	7.752	7.698	7.968	7.934	8.088
1979	8.143	8.185	8.423	8.423	8.372	8.577
1980	8.686	8.776	8.895	8.895	8.955	9.087
1981	8.734	8.827	9.202	9.253	9.304	9.393
1982	8.789	8.912	9.444	9.457	9.533	9.788
1983	8.874	8.976	9.567	9.563	9.674	10.043
1984	8.938	9.104	9.661	9.699	9.788	10.299
1985	9.066	9.206	9.852	9.886	9.895	10.494

Note: 1 km/L = 2.35 miles/gal.

Table 3. Projected automobile sales for six policies.

	Automobile Sales (000 000s)					
Year	1	2	3	4	5	6
1980	12.0	10.3	12.0	11.9	10.3	12.0
1985	12.6	11.0	11.7	11.2	10.3	11.4
1990	12.9	10.9	12.2	11.8	10.3	12.2
1995	14.1	11.7	13.2	12.7	11.0	13.2
2000	15.0	12.3	14.0	13.5	11.6	14.0

Table 4. Projected vehicle kilometers of travel for six policies.

	Vehicle Kilometers of Travel (trillion/year)					
Year	1	2	3	4	5	6
1980	1.95	1.77	1.96	1.96	1.77	1.98
1985	2.24	2.01	2.24	2.22	2.01	2.27
1990	2.51	2.27	2.46	2.42	2.24	2.48
2000	3.11	2.78	3.04	2.99	2.74	3.06

Note: 1 km = 0.62 mile.

The most severe impacts on automobile sales are created when the $0.10/L ($0.40/gal) gasoline tax is applied, either with or without the EPCA standards. The gasoline tax alone immediately reduces sales by 30.6 percent or 3.7 million automobiles. This loss diminishes to 12.7 percent (1.6 million automobiles) in 1985 and remains about the same thereafter. When the gasoline tax is applied with the EPCA standards, sales are reduced by an additional 0.5 to 0.8 million automobiles in 1985 and after.

Vehicle Kilometers of Travel

Data given in Table 4 show that all of the policies examined here that include mandatory fuel-economy standards have only a marginal impact on vehicle kilometers of travel. The maximum percentage reduction in vehicle kilometers of travel from the baseline—3.6 percent—would be achieved in 2000 under policy 4 (EPCA with stringent standards). Under the double-penalty case, vehicle kilometers of travel in 2000 are reduced by only 1.6 percent. The high sales-weighted fuel economy associated with this policy option results in the lowest driving cost per kilometer and thus relatively high vehicle kilometers of travel.

Substantial reductions in vehicle kilometers of travel are projected to occur under policies that substantially increase the gasoline tax. A 10.3 percent reduction in travel in 2000 is projected with a $0.10/L ($0.40/gal) gasoline tax (policy 2), and a reduction of 11.9 percent in 2000 is expected if EPCA is also adopted (policy 5). Despite the lower cost of driving associated with higher fleet fuel economy, the impact on the total automobile fleet of the gasoline tax combined with EPCA results in less travel than is projected if only gasoline taxes are imposed. This is significant, however, only after 1990 when the cumulative sales impact on fleet size is more significant.

Fuel Consumption

Mandatory fuel economy standards could contribute substantially to reduced fuel use, but it will be several years before significant fuel savings are realized by enacting these policies. Table 5 gives projected fuel consumption for each of the six policies examined here. (All results in this paper assume that the fuel economy of new vehicles reported by the U.S. Environmental Pro-

Table 5. Projected gasoline consumption for six policies.

	Gasoline Consumption (000 000 m^3/year)					
Year	1	2	3	4	5	6
1980	284	261	283	283	260	283
1985	271	241	259	257	233	254
1990	283	252	260	257	235	248
1995	312	276	283	279	255	267
2000	348	307	315	310	283	297

Note: 1 m^3 = 264 gal.

tection Agency is actually achieved by operating vehicles. More recent studies have shown that actual fuel economy tends to fall beneath federal estimates. In separate analyses, we have found that adjusting for this factor has significant implications on future projections of fuel consumption but that it creates only relatively small changes in the fuel savings attributable to alternative policies.)

EPCA achieves a 4 to 5 percent reduction in fuel use from the baseline by 1985 and an 8 to 9 percent reduction by 1990. The lower limit in each year assumes the moderate standard and the upper limit assumes the stringent standard. If the moderate standard is applied with double civil penalties, fuel savings increase to 6 percent in 1985 and 12 percent in 1990. In 2000, the double-penalty structure results in savings of 15 percent compared with savings of 9 to 11 percent for EPCA. After 1989 the double-penalty policy results in greater fuel savings than does the gasoline tax, but the EPCA standards result in less fuel savings than does the gasoline tax throughout the projection period. The only policy alternative tested that results in greater fuel savings than the double-penalty option is that of moderate standards combined with a gasoline tax (policy 5): This alternative results in 17 percent fuel savings in 1990 and 19 percent fuel savings in 2000.

PROJECTED GROWTH OF AUTOMOBILE OWNERSHIP AND USE

Although the results presented above show distinct differences in consumer behavior relative to the automobile, these differences appear relatively minor when the projections are compared with the experience of the preceding 25 years. The table below gives the annual percentage growth rates for various categories of automobile ownership and use. Actual data include census figures for households, Federal Highway Administration statistics for vehicle kilometers of travel, and data from Automotive News for automobiles in use (1 km = 0.62 mile):

	Rate of Growth (%)		
Category	Actual (1950 to 1975)	Base-Case Projection (1975 to 2000)	EPCA Projection (1975 to 2000)
Automobiles in use	4.26	1.60	1.28
Automobiles per household	2.33	-0.05	-0.37
Annual vehicle kilometers of travel	4.30	2.50	2.37
Per automobile	0.04	0.89	1.08
Per household	2.36	0.84	0.71

The growth rates of automobiles in use and of vehicle kilometers of travel are projected to fall by about 60 and 40 percent, respectively.

The slowing of the growth of automobile stock is attributable to two factors—the decline in the growth rate of the population and a slight decrease in automobile ownership per household attributable to higher vehicle prices. Vehicle kilometers of travel per household are projected to grow at about a third of the rate experienced during the past 25 years. Annual vehicle kilometers of travel per automobile, roughly constant in the preceding quarter of a century, are expected to increase slightly.

CONCLUSIONS

The forecasts presented here reflect some tapering off of the rapid growth in automobile ownership and use experienced in the past quarter century. Nevertheless, they imply 80 percent more automobile travel than occurs today—a figure that will have drastic energy consequences unless action is taken to prevent the amount of fuel consumption by automobiles that is implied by these figures. The relative attractiveness of fuel economy policies, however, cannot be determined by their impact on a single indicator such as fuel consumption. The combined effect on automobile sales, sales-weighted fuel economy, travel, and fuel consumption must be taken into consideration.

Lower fuel consumption is a desirable result, and it can be achieved by any of the following: (a) improving sales-weighted fuel economy, (b) reducing automobile sales (and ownership), or (c) reducing travel per automobile. To the extent that a policy reduces fuel consumption by improving sales-weighted fuel economy and does so with minimal impacts on automobile sales and travel, it achieves an important conservation goal without adversely affecting goals related to economic health or personal mobility. Judged by this standard, moderate fuel-economy standards with double civil penalties appear to achieve the most desirable impact. Fuel consumption is reduced by 12.4 percent in 1990 and automobile sales and vehicle kilometers of travel are down by only 5.4 percent and 1.3 percent respectively, relative to the baseline. In contrast, the gasoline tax examined here reduces 1990 fuel consumption by slightly less (11 percent), but automobile sales and vehicle kilometers of travel are down by much more—15.5 percent and 9.8 percent respectively. The moderate fuel economy standards achieve 1990 reductions of 8.2 percent in fuel use, 5.4 percent in automobile sales, and 1.9 percent in vehicle kilometers of travel. The stringent standards result in reductions in automobile sales and travel of 8.5 and 2.6 percent respectively. These impacts are not as favorable as those achieved by using the double-penalty approach, but they compare very favorably with gasoline taxes, offer considerable conservation benefits compared with the baseline policy, and result in relatively minor economic and travel disbenefits.

None of the options tested here that incorporate mandatory standards produced industrywide fuel economies in excess of the standards for 1985 and after. However, this is partly a result of the assumptions about pollutant emissions. Relaxing these emissions standards would help the cause of achievable fuel economies.

Although substantial uncertainties are implicit in the analytical procedures used here, their impact on relative conclusions about policy effectiveness is apt to be less than their impact on absolute forecasts of fuel use, automobile sales, and vehicle kilometers of travel for each policy alternative. Assumptions about future population growth, economic conditions, safety and environmental regulations, and automotive technology are subject to error, but such errors tend to affect all projections in similar ways. Very substantial errors would be required to alter the rankings of the various policies.

Based on these rankings and the judgment that less fuel use and more mobility are desirable, the mandatory fuel economy standards of the Energy Policy and Conservation Act offer an effective approach to resource conservation but one that appears open to improvement by an increase in the severity of the penalties and a decrease in the stringency of the standards. These modifications would tend to reduce the civil penalties that automobile companies and consumers must pay while increasing the marginal incentive to produce and consume fuel-efficient automobiles.

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Publication of this paper sponsored by Committee on Energy Conservation and Transportation Demand.

**Mr. Kulash was with Jack Faucett Associates, Inc., when this research was performed.*

Energy-Saving Potential of Transit

Phillip S. Shapiro,* Metropolitan Washington Council of Governments,
Washington, D.C.
Richard H. Pratt, R. H. Pratt Associates, Inc., Kensington,
Maryland

In a study initiated by the Federal Energy Administration in response to growing national concern over the rapidly expanding rate of energy use and possible fuel shortages, an analysis was done of the energy efficiencies of various urban passenger transportation modes, including automobile and bus, rail rapid and commuter rail transit, and dial-a-ride. The study was primarily concerned with the potential impacts and energy efficiencies of short-term policies designed to induce automobile drivers to shift to transit. Policies to induce such mode shifts were grouped as scenarios for evaluation. Possible transportation energy savings for urbanized areas as well as reductions in vehicle kilometers of travel were first estimated for individual representative cities and then expanded to provide a national estimate for each of four tested scenarios.

Two major study tasks were undertaken in the Federal Energy Administration's evaluation of policies to enhance public transportation (1):

1. Determine the energy consumption and efficiency of transportation modes in urbanized areas and
2. Evaluate scenarios designed to achieve shifts from the automobile mode to public transportation, estimate the possible energy savings, and recommend scenarios to be implemented.

Major emphasis was placed on obtaining more definitive national estimates of urban transportation energy efficiency than had previously been available and on determining quantitatively which strategies for shifting travel from the automobile to transit could achieve significant energy savings. The amount of energy that could be conserved through individual actions and groups of actions was specifically estimated.

It should be pointed out, however, that this study was designed to provide only a macroscale estimate of the possible energy savings in individual cities and in the nation. Moreover, all data were derived from currently available material; compilation of new data was not possible. For these reasons, the energy savings determined in this study should be considered estimates and should not be taken as detailed forecasts.

NATIONAL ENERGY-USE CHARACTERISTICS FOR URBANIZED AREAS

Any analysis of energy conservation potential must be based on a description of existing energy use and efficiency. Person-travel energy consumption and efficiencies in urbanized areas are a function of the amount of person travel involved, average passenger loadings, and the applicable vehicular fuel consumption rates. National estimates of these and related characteristics, which were developed particularly for use in this study, were derived from data originally collected by the U.S. Department of Transportation (2, p. 52), the American Public Transit Association (3), and others.

Average urban energy consumption rates for individual vehicle types were estimated as follows (1 MJ/km = 1525 Btu/mile):

Vehicle Type	Energy Consumption Rate (MJ/km)
Automobile	7.2
Bus	
Gasoline-minibus	17
Diesel	22.8
Propane	30
Rail car	
Rapid	40.6
Commuter	74.1

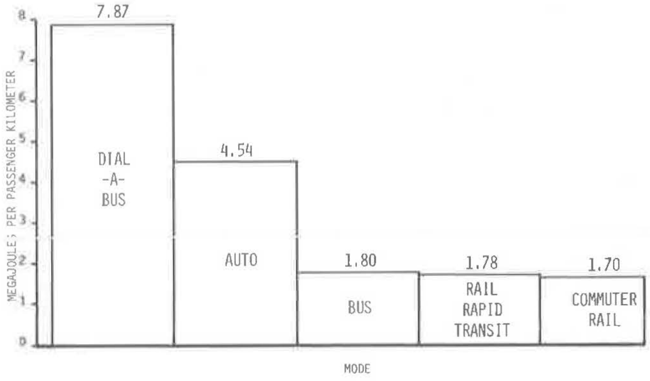
Data describing national travel characteristics and energy consumption by mode for urbanized areas allowed calculation of energy per passenger kilometer traveled and total energy required by conventional modes. The total energy required was calculated on the basis of energy consumption per vehicle kilometer by mode and total vehicle kilometers. As expected, the automobile was found to dominate passenger travel in urbanized areas; it accounted for 98.1 percent of the 151 million m^3 (952 million bbl) of gasoline used in 1971 and 92.4 percent of the 1232 billion passenger·km (766 billion passenger-miles) traveled. The graph shown in Figure 1 provides a summary of passenger transportation efficiencies in urbanized areas.

All conventional transit modes require about the same amount of energy per passenger kilometer: 1.7 to 1.8 MJ/passenger·km (2590 to 2740 Btu/passenger-mile). In contrast, automobile travel requires more than 2½ times the energy per passenger kilometer required by conventional transit or about 4.5 MJ/passenger·km (6930 Btu/passenger-mile). Less conventional modes of transit such as dial-a-ride systems require about 7.9 MJ/passenger·km (12 000 Btu/passenger-mile), almost twice as much as the automobile and 5 times as much as conventional transit modes.

Estimates of energy efficiency for person travel were also independently prepared for four individual urbanized areas: Albuquerque, San Diego, Baltimore, and Chicago. Automobile energy efficiency was computed based on vehicle kilometers traveled and the average automobile occupancy for each urbanized area. In all four areas this efficiency was calculated to be approximately 4.9 MJ/passenger·km (7500 Btu/passenger-mile).

Estimated energy efficiencies for transit in the four representative cities are given in Table 1. Energy efficiencies for bus systems ranged from 1.3 to 3.1 MJ/passenger·km (1950 to 4800 Btu/passenger-mile), compared with a national average of 1.8 MJ/passenger·km (2750 Btu/passenger-mile). The commuter rail (electric) operation in Chicago requires 1.3 MJ/passenger·km (2000 Btu/passenger-mile), considerably less than the national average of 1.8 MJ/passenger·km (2700 Btu/passenger-mile). This difference is not a function of fuel consumption per car kilometer (which was not specifically investigated except to distinguish between diesel and electric operation) but is instead attributable to the comparatively high average passenger loadings in Chicago. Chicago's rail rapid transit (diesel) system has an energy efficiency of 1.5 MJ/passenger·km (2300 Btu/passenger-mile), which is closer to the national average of 1.7 MJ/passenger·km (2600 Btu/passenger-mile).

Figure 1. Relative energy efficiency of urbanized-area transportation modes.



NOTE: 1 MEGAJOULE/PASSENGER KILOMETER = 1,525 BTU/PASSENGER MILE

In short, the automobile proved to be more energy intensive than transit in urbanized areas, both on a national basis and in the individual cities studied. Transit is not, however, 17 times more efficient than the automobile, as some sources suggest; its energy efficiency is between 1½ and 5 times that of the automobile. The efficiency of transit is also highly dependent on the type of service offered and the city involved.

PROCEDURES FOR ESTIMATING ENERGY SAVINGS

The central objective of the study was to quantify the nationwide mode shifts and energy savings that would be caused by implementation of alternative transit-oriented strategies. To provide the required estimates, an analysis procedure was chosen that addressed itself to site-specific conditions. For this purpose the four cities—Albuquerque, San Diego, Baltimore, and Chicago—were selected as being representative in certain ways of national urbanized areas. Data derived for these four cities were used to estimate national energy savings and impacts.

The four cities were chosen in the following way:

1. The more than 240 urbanized areas in the United States were categorized into four groups according to the reported percentage of transit use for travel to and from work and the presence or absence of an extensive rail transit system.
2. A representative city was chosen from each of these groups.

Different transportation policies and actions necessarily lead to different shifts in mode use. A mode-use sensitivity model was developed to evaluate potential mode shifts in the representative cities. In the model,

Table 1. 1974 energy efficiencies of public transportation in representative cities.

City	Mode	Annual Passengers (000s)	Average Trip Length (km)	Annual Passenger Kilometers (000s)	Annual Vehicle Kilometers (000s)	Passenger Kilometers per Vehicle Kilometer	Annual Terajoules	Megajoules per Passenger Kilometer
Albuquerque	Bus	3 537	5.8[a]	20 487	4 220	4.9	64.6	3.1
San Diego	Bus	32 032	6.7	213 889	18 315	11.7	350.5	1.6
Baltimore	Bus	113 396	7.0[b]	790 025	41 346	19.11	1068	1.3
Chicago	Bus	511 667	5.8[c]	2 963 780	141 890	20.9	3787.1	1.3
	Elevated and subway	171 415	10.9[c]	1 861 695	78 490	23.7	2835.4	1.5
	Electric commuter	15 478	30.1	465 707	7 384	63	594	1.3
	Diesel commuter	25 348	33.8	857 332	18 236	47	1231.7[d]	1.5

Note: 1 km = 0.62 mile; 1 J = 9.48 x 10^{-4} Btu.

[a] No data were given by Albuquerque that would allow the calculation of average bus trip length; an estimate of 5.8 km was used based on data from the U.S. Department of Transportation National Transportation Study for urbanized areas with populations between 100 000 and 250 000.

[b] From average transit running time at 16.1 km/h (10 mph) as simulated by the BMATS program.

[c] Derived from Chicago Area Transportation Study origin-destination survey data.

[d] Includes electric standby energy at terminals, which comprises an additional 15 percent above diesel energy used.

a set of mathematical relations was used to describe the sensitivity of transit ridership to changes in the transportation system, expressed as averages for urban sectors or entire urbanized areas. These relations were based on the transit ridership sensitivities displayed by travel mode-choice models of logit formulation calibrated for Denver; Minneapolis-St. Paul; Washington, D.C.; and San Diego (4).

The transit ridership sensitivities inherent in the mode-choice models for the various regions were similar and yet showed sufficient variation to preclude use of a single formula. Instead, a set of equations describing high, medium, and low transit-use response were developed and used to prepare high, medium, and low estimates. The model was validated by using data from three urban areas in which major policy changes had already been implemented.

The mode-use sensitivity model was applied to each of the four representative cities to estimate the effectiveness of different actions (strategies) and groups of actions (scenarios) in saving energy. The actions investigated for energy savings can be broken down into those actions that affect

1. Transit excess time,
2. Transit running time,
3. The cost to the rider of using transit, and
4. The cost of operating an automobile.

Each of the above categories is equivalent to one of the explanatory variables addressed in the model.

The so-called transit excess time experienced by transit riders is the sum of the time spent walking to and from the transit service plus the time spent waiting for a bus or a train. An increase in transit-service frequency or an increase in the density of routes (coverage) or both will reduce excess time.

Each strategy and scenario first had to be translated into changes in the explanatory variables for analysis with the mode-use sensitivity model. The expected change in transit use was then calculated. This provided an estimate of the number of new transit trips that would result from application of a strategy or a scenario.

Not all new trips attracted by transit improvements would be made by persons who had previously been automobile drivers. Some would previously have been automobile passengers or pedestrians or would have made no trip at all. An estimate was made of the proportion of new transit trips that represented prior automobile trips, and fuel savings were attributed only in the case of prior automobile drivers.

A survey undertaken after fare and service changes were made to the Atlanta Transit System (5) was the primary source of information on the mode used by new riders before the transit service enhancement. The proportions derived from this survey were validated by comparing them with those derived from other available surveys. Separate automobile-driver proportions were developed for work and nonwork trips as well as for three basic types of changes to the transportation system.

The Atlanta data revealed that 50 percent of new transit riders who are using transit for work trips and 25 percent of those using it for nonwork trips were previously automobile drivers. These percentages were applied by the study to the new transit riders attracted by bus transit improvements. Because rail service improvements typically affect longer distance travel, there is little likelihood of attracting bicycle users, pedestrians, or those using other transportation modes best suited for shorter distances. The percentages for rail system improvements were therefore adjusted to reflect a correspondingly higher proportional attraction of transit trips from the automobile driver mode. The values used for rail improvements were 59 percent for work trips and 33 percent for nonwork trips. The percentages of prior automobile drivers shifted to transit by means of highway disincentive strategies were estimated to be 71 percent for work trips and 55 percent for nonwork trips. The high percentage of prior automobile drivers in this case reflects the lack of induced travel when disincentives are applied.

Trips diverted from the automobile to transit were multiplied by an appropriate trip length to determine the vehicle kilometers of automobile travel eliminated. Energy savings were calculated on the basis of vehicle kilometers saved. Fuel consumption varies among different automobile trips within a city; thus, to select the appropriate energy intensities, speed, stops per kilometer, and trip length were estimated and then applied to derive the energy savings.

The additional vehicle kilometers of transit service that would be required to accommodate all new riders were then determined on the basis of the 2-h p.m. peak capacity of each system, current capacity utilization, and the additional riders attracted during that period. Transit vehicles were added to accommodate new riders only if the appropriate maximum load ratio of passengers to seats was exceeded. The additional daily bus kilometers that would be required were calculated by assuming a constant ratio between peak service requirements and daily transit vehicle kilometers.

In the case of bus transit, when additional vehicle kilometers are added, the service frequency increases and the passenger wait time decreases. Therefore, when additional buses were required to accommodate the new passengers gained as a result of the various actions in a scenario, an additional decrease in wait time was taken into account and the concomitant number of new passengers attracted by the additional service improvement was estimated. The amount of energy required for the additional transit vehicle kilometers was calculated on the basis of the existing fuel economy of each transit system. The net energy savings for each strategy and scenario were determined by subtracting the additional energy required by the transit system from that saved by the reduction in vehicle kilometers of automobile travel.

Some of the more important limitations that should be considered when the results of the analysis are reviewed are

1. Data voids, which often required estimating the necessary values based on available information and judgment;
2. Model limitations, such as the inability to predict changes in attitude and other intangibles; and
3. The means employed by new riders to gain access to transit service, which was not analyzed but could add to the new total energy use if an automobile were used.

ANALYSIS OF INDIVIDUAL STRATEGIES

The actual evaluation of the energy savings made possible through actions to induce mode shifts began with an analysis of individual transportation strategies. This analysis weighed the effects of each individual strategy, identified the strategies that exhibited significant energy-saving potential, and then grouped these strategies in suitable alternative scenarios. Estimates of the potential energy savings of individual strategies were made only for San Diego and Chicago and were based on a less detailed analysis than the subsequent scenario evaluations.

The effect of individually applied strategies may differ substantially from their combined effect in scenario groupings. For example, when excess (walk and wait) time is reduced, transit riders are attracted to the system, but there is little or no net impact on energy use because of the large corresponding increase in the number of transit vehicle kilometers required. When this action is combined with other actions, however, the additional transit vehicle kilometers may prove to serve the purpose of carrying passengers attracted to transit by other actions in the scenario. In such a case, a decrease in excess time contributes to the benefit of the total scenario.

In San Diego, the current excess capacity of the bus system was such that additional bus kilometers were not needed to handle peak loads unless the increase in peak-period riders caused by a mode-shift strategy exceeded 3100 persons. Few individual strategies were found to be so effective as to require additional bus kilometers except when an increase in service was inherent in the strategy. This is not to say that additional bus kilometers would not be required when two or more strategies are combined; many of the scenario evaluations showed a need for substantial additional service.

The key findings of the San Diego analysis of individual strategies were as follows:

1. It would be more effective to institute improvements to both radial and circumferential bus routes concurrently than to either configuration alone.
2. It would be more productive in terms of energy savings to decrease all bus running times by applying traffic engineering improvements and bus priority and other measures than to implement a comprehensive express bus system to serve longer trips. This finding is a function of the low density of the San Diego central business district (CBD), the fact that express bus service would not improve service to local riders, and the extra bus kilometers and energy that would be required to provide the total service.
3. Alternative fare structures established within the constraint of a single average fare show no significant potential for increased ridership nor for decreased energy use related to changes in the ridership mix. However, overall decreases in bus fares would be effective in inducing mode shifts.
4. Strategies whose effectiveness depends on penalizing automobile travel achieve about twice as much energy saving per transit passenger gained as do strategies designed to induce new ridership by enhancing transit because the only new transit riders obtained through disincentives are previous automobile drivers or automobile passengers.
5. The effect of percentage increases in existing parking fees would be less in San Diego than corresponding percentage increases in gasoline cost, probably because of the current low parking cost in the CBD and the lack of parking charges outside the CBD. However, a universal parking surcharge (or equivalent automobile toll) in the CBD and the central city would have strong potential for inducing mode shifts.

In the following table, representative, quantitative estimates of mode shifts and energy savings are given for the strategies that proved to be among the more productive in San Diego (1 m^3 of gasoline = 6.3 bbl).

Strategy	Increase in Transit Use (%)	Gasoline Equivalent of Net Energy Saved (m^3/d)
Decrease excess time		
By 5 percent	12.4	1.1
By 15 percent	42.6	3.5
Decrease bus running time		
By 5 percent	6.2	2.2
By 10 percent	12.9	4.8
Decrease transit fare		
By $0.05	5.2	1.7
By $0.10	10.6	3.5
Increase gasoline cost		
By 25 percent	5.6	3.7
By 100 percent	24.8	15.3
Central city-CBD parking surcharge		
$0.72	15.0	7.9
$1.44	38.8	21.6

The net energy savings should be compared with a total automobile energy use in the San Diego area of approximately 5247 m^3/d (33 000 bbl/d) of gasoline.

The energy savings attributed to the automobile disincentive strategies account only for the impact of traveler diversion from automobile to transit. Automobile disincentives will also cause curtailment of less essential trips and increased participation in car pools. No attempt was made in this study to quantify these additional energy-saving impacts.

The analysis of individual strategies in San Diego was of significant value in weeding out the less productive strategies. An investigation was also made of the effectiveness of individual strategies in Chicago, an urbanized area in which travel characteristics are quite different.

The one major difference between the evaluation results for individual strategies for San Diego and Chicago was that, when bus and rail service was increased to reduce excess time throughout the Chicago metropolitan area, there was a loss of transportation energy. This finding, which was not totally unexpected because of the already extensive transit service in the city of Chicago, demonstrates that there exists a point of diminishing returns if transit service is intensified under present conditions (if no other strategies are imposed).

In the analysis of bus-service increases in Chicago, estimated energy losses occurred mostly in the central city. A separate test of decreasing bus excess time was made only in the suburbs, and it was found that slight energy savings could be expected from this action.

The results for the Chicago central city do not necessarily eliminate the feasibility of changes in the level of bus service as a potential energy-saving action. It was pointed out earlier that, when combined with other strategies, service increases may meet a need for additional capacity. Nevertheless, in view of the Chicago results, the scenarios subsequently tested were adjusted to include differential application (to the city versus the suburbs) of any additional bus service required to meet capacity needs.

All of the remaining individual strategies examined for Chicago showed transit ridership increases and energy savings similar to those in the San Diego tests, although the absolute changes were greater and, for the most part, the percentage changes were less. In view of the greater reliance on transit in metropolitan Chicago, these results were expected.

ANALYSIS OF SCENARIOS

The knowledge gained in the preliminary analysis of individual strategies was essential to the development of

Table 2. Policy scenarios and medium-estimate results for representative cities.

City and Scenario	Decrease in Transit Fare (¢)	Decrease in Transit Running Time (%)	Increase in Gasoline Cost (%)	Increase in Parking Cost ($)		Decrease in Transit Excess Time (%)	Decrease in Transit Wait Time (%)	Increase in Transit Use (%)	Daily Additional Passenger Trips (linked)	Daily Reduction in Automobile Travel (km)	Reduction in Kilometers of Automobile Travel (%)	Daily Gasoline Saved (m^3)	Total Automobile Energy Saved (%)
				CBD	Central City								
Albuquerque													
1	10	5	25	—	—	5	—	34	3 200	9 815	0.14	1.6	0.11
2	20	10	25	—	—	15	—	99	9 200	26 709	0.39	3.8	0.27
3	20	10	100	0.70	1.00	15	—	162	15 000	50 523	0.73	8.7	0.60
4	—	—	100	0.70	1.00	—	—	25	2 300	11 424	0.16	2.4	0.16
San Diego													
1	10	5	25	—	—	5	20	68	47 700	120 675	0.48	14.3	0.27
2	20	10	25	—	—	15	40	184	127 400	302 331	1.19	25.4	0.50
3	20	10	100	0.70	1.00	15	67.5	426	295 900	753 173	2.96	65.2	1.24
4	—	—	100	0.70	1.00	—	50	144	100 300	239 258	0.94	20.7	0.40
Baltimore													
1	10	5	25	—	—	5	30	66	165 300	493 157	2.37	41.3	1.35
2	20	10	25	1.00	—	15	35	128	319 400	946 575	4.55	106.5	2.58
3	20	10	100	2.00	1.00	15	55	256	639 600	2 067 565	9.95	259.1	6.25
4	—	—	100	2.00	1.00	—	50	121	302 500	1 043 276	5.02	139.9	3.34
Chicago													
1	10	5	25	—	—	5	5[a], 50[b]	26	437 200	1 948 338	3.05	120.8	0.92
2	20	10	25	1.00	—	15	—[a], 55[b]	58	963 600	4 335 451	6.79	265.5	2.02
3	20	10	100	2.00	1.00	15	25[a], 65[b]	106	1 763 100	8 319 656	13.03	699.4	5.31
4	—	—	100	2.00	1.00	—	35[a], 60[b]	64	1 077 600	6 089 100	9 53	602.5	4.53

Note: 1 km = 0.62 mile; 1 m^3 = 6.3 bbl.

[a] City. [b] Suburb.

the four scenarios examined in the course of this study. These scenarios were structured to include the entire range of possible actions—from those requiring minimal government intervention to those that would require significant federal and local government input as well as the imposition of substantial cost penalities on the average automobile driver. These scenarios included the following actions:

1. Decrease transit fare,
2. Decrease transit running time,
3. Increase gasoline cost,
4. Increase selected parking costs,
5. Decrease transit excess time, and
6. Decrease transit wait time.

Scenario 1 requires the least intervention and incorporates trends that to some extent are already evident. Scenario 2 requires that there be substantial modification and enhancement of transit service but can still be considered a strategy of "carrots" in that few disincentives are imposed on automobile travel. Scenario 3 requires the same carrots in terms of transit service enhancements as scenario 2 but adds bigger "sticks" in the form of substantial disincentives to automobile travel. Scenario 4 differs from the other three in that it includes no carrots other than the decrease in transit wait time that would be required to provide any necessary additional capacity; it relies entirely on disincentives to automobile travel identical to those included in scenario 3 to achieve mode shifts.

These four scenarios were applied in each of the representative urbanized areas. In general, each scenario is similar for all areas. However, the scenarios were not exactly the same for each area in the degree of their application. An explicit description of the scenarios evaluated in each representative area, as well as information on the corresponding reductions in automobile travel and energy savings, is given in Table 2.

Albuquerque

As shown by the estimates given in Table 2, the potential energy-saving effects of the four scenarios in the Albuquerque urbanized area were disappointingly slight. Even scenario 3, which would cause a projected increase of 162 percent in transit ridership, would achieve only a 0.6 percent decrease in energy use and a 0.7 percent reduction in automobile travel. The three less intensive scenarios would cause only a 0.1 to 0.3 percent decrease in energy use, a 0.1 to 0.4 percent decrease in automobile travel, and a 25 to 99 percent increase in transit ridership.

In this type of city, current transit ridership is so small that even an astronomical increase in transit ridership will have little effect on total automobile travel. It is difficult to provide good, convenient transit service to cities such as Albuquerque, which have low population densities. Because there is little congestion on Albuquerque's extensive road network, transit travel in that city cannot be highly competitive. Downtown areas are normally a major source of transit trips, but the Albuquerque CBD is neither strong nor extensively developed.

There is enough excess capacity in the present Albuquerque transit operation to accommodate all of the riders who would be attracted to the system by any of the four scenarios. Only those increases in service explicitly called for in scenario actions would be required. As the test results for scenario 4 show (Table 2), large increases in gasoline cost and parking surcharges are relatively ineffective in encouraging transit ridership. The structure of the city of Albuquerque and of its present transportation system does not allow transit service to provide a viable alternative to the automobile.

San Diego

San Diego represents U.S. cities that have moderate transit use. Of the four representative cities examined, San Diego exhibits the highest percentage increase in transit use attributable to the various mode-shift strategies. Implementation in San Diego of the substantial actions in scenario 3 would result in an estimated increase in transit ridership of over 400 percent, energy savings of 1.2 percent, and a reduction in automobile travel of nearly 3 percent. The more moderate actions in scenarios 1 and 2 would achieve between 68 and 184 percent ridership increases and between 0.3 and 0.5 percent reductions in energy use respectively.

Cities in this category tend to have enough of a transit-service base for transit improvements to show a high potential for attracting riders. At the same time, however, they retain a total ridership low enough for transit improvements to have only a slight impact on energy conservation in urbanized areas. Like cities in the group represented by Albuquerque (although not to as extreme a degree), cities represented by San Diego have a relatively low population density, and the CBD is typically not a dominant focus of travel.

Major elements of the San Diego transit system currently operate well below capacity. A number of new riders could be added to the system before additional buses would be required. These new passengers, who would fully use the excess capacity available in the transit system, would produce larger energy savings than would any additional new riders who would make it necessary to operate additional vehicles.

Automobile disincentives, when tested alone in scenario 4, showed as much potential for saving transportation energy through inducing mode shifts as did the full package of transit enhancements included in scenario 2 without the automobile disincentives. Neither transit enhancements nor automobile disincentives showed much potential for reducing transportation fuel use in the San Diego area. In both scenarios 2 and 4, energy savings were estimated at less than 0.05 percent, which illustrates the limitations of transit as an alternative to the automobile in San Diego and similar cities.

Baltimore

Baltimore was used to represent cities that have relatively high patronage of an all-bus transit system. As in the analyses of other representative cities, scenario 3 exhibited the greatest energy-saving impacts, showing a potential ridership increase of approximately 250 percent, or some 640 000 riders/d. The shift to transit would result in a 6.2 percent reduction in automobile energy requirements and just short of a 10 percent reduction in automobile travel. Scenario 1, which has the least potential impact, would yield a 66 percent increase in transit use, or some 165 300 additional riders, and an energy reduction of 1.4 percent and a reduction of 2.4 percent in vehicle kilometers traveled.

Baltimore has many characteristics that cities like San Diego and Albuquerque lack, which serve to make it supportive of extensive transit travel. These include a strong and well-developed CBD, significant highway congestion, and other qualities common to older and more densely populated urbanized areas. In cities of this type, transit has a much better chance of competing with the automobile for discretionary ridership. Because of this, those actions that were shown to be relatively ineffective in Albuquerque or San Diego would have a much greater impact in the Baltimore metropolitan area. The current Baltimore transit system is also sufficiently effective that automobile disincentives alone (scenario 4) could work to save more energy than could be saved by the scenarios oriented primarily toward transit-service enhancements (scenarios 1 and 2).

Chicago

Chicago was used to represent the major urbanized areas in the United States that have relatively extensive rail rapid and commuter rail systems. In the Chicago area, scenario 3 would double transit ridership, or add some 1.8 million daily transit users. This shift in mode use is accompanied by savings of 5.3 percent for current transportation energy use and 13 percent for automobile travel. Of the scenarios that concentrate on transit service enhancements without major automobile disincentives, scenario 1 would save 0.9 and 3 percent and scenario 2 would save 2 and 6.8 percent in energy and vehicle kilometers of travel respectively.

Characteristics supportive of heavy transit use are quite pronounced in the city group represented by Chicago. The extensive existing transit use in these cities makes it difficult to achieve the large percentage increases in transit ridership demonstrated in the other representative cities. On the other hand, a mere 10 percent increase in ridership in Chicago would account for more transit trips than would a doubling of transit use in San Diego. Thus, the impact on automobile use would be more noticeable.

In the Chicago estimates of scenario impacts, the automobile disincentives of scenario 4 would produce nearly as much in estimated energy savings as would a combination of the strategies with the major transit enhancements of scenario 3. Thus, it appears that automobile disincentives work more efficiently toward decreasing energy use than do transit enhancements in cities that have preexisting, extensively developed transit systems. These cities can be contrasted with cities that have less extensive transit operations, in which both carrots and sticks are needed to promote mode shifts. On the other hand, when the medium scenario estimates were constructed to exclude the more onerous automobile-disincentive strategies, none of the representative cities exhibited energy savings in excess of 2.6 percent of transportation fuel consumption for the urbanized area. In the smaller cities, expected savings without major sticks were well under 1 percent.

National Energy Savings

The analysis of potential energy savings for the representative cities, although noteworthy in itself, also provides the quantitative groundwork for an analysis of potential energy savings at the national level. Data derived for the representative cities were expanded and weighted to represent possible national annual energy savings for each scenario. The expected annual energy savings represent the national energy savings for passenger transportation in urbanized areas only.

Energy savings for the representative cities were calculated for an average weekday, and these figures were converted to annual estimates through multiplication by a series of annualization factors: 345 for overall kilometers of travel by automobile and energy used, 290 for additional transit ridership as well as kilometers of travel by automobile and energy saved, and 300 for additional annual kilometers of transit travel and the energy that would be required.

The procedure chosen in this study to estimate national energy savings is relatively simple. The population and total vehicle kilometers of travel for urbanized areas were determined for each city group by using data from the 1970 census and the 1974 National Transportation Study. The cubic meters of gasoline required for travel in urbanized areas by each group were determined at a rate of 0.0002 m^3/vehicle·km (0.0013 bbl/vehicle mile), which is equivalent to the previously derived average for urban areas of 7.2 MJ/vehicle·km (10 950 Btu/vehicle mile). The percentage reductions in annual vehicle kilometers and gasoline as determined for each scenario and representative city were applied to the vehicle kilometers traveled and gasoline used for the appropriate city group to obtain the nationwide energy savings. As before, high, medium, and low estimates were calculated.

Medium estimates of reductions in vehicle kilometers of travel and energy use for the four scenarios by city group are given in Tables 3 and 4. City groups 3 and 4, those in which the greatest transit use occurs, clearly

Table 3. Medium national estimates of impacts of four scenarios: vehicle kilometers saved per year.

	Vehicle Kilometers for Four Scenarios							
	1		2		3		4	
City Group	Number (000 000s)	Percent	Number (000 000s)	Percent	Number (000 000s)	Percent	Number (000 000s)	Percent
1	182	0.12	492	0.32	933	0.61	211	0.14
2	594	0.40	1 490	1.00	3 710	2.49	1 179	0.79
3	5 027	1.99	9 649	3.83	21 076	8.37	10 635	4.22
4	4 299	2.56	9 566	5.70	18 355	10.95	13 434	8.01
Total or average	10 102	1.40	21 197	2.94	44 074	6.12	25 459	3.53

Note: 1 km = 0.6 mile.

Table 4. Medium national estimates of impacts of four scenarios: energy saved per year.

	Energy for Four Scenarios							
	1		2		3		4	
City Group	Gasoline (m^3)	Percent	Gasoline (m^3)	Percent	Gasoline (m^3)	Percent	Gasoline (m^3)	Percent
1	29	0.09	69	0.22	160	0.51	44	0.14
2	69	0.22	119	0.39	305	0.99	97	0.31
3	563	1.08	1046	2.01	2564	4.94	1388	2.67
4	250	0.72	542	1.57	1465	4.24	484	3.70
Total or average	911	0.61	1777	1.20	4494	3.03	2013	1.89

Note: 1 m^3 = 6.3 bbl.

Table 5. Total national estimates of impacts of four scenarios: vehicle kilometers saved per year.

	Vehicle Kilometers for Four Scenarios							
	1		2		3		4	
Estimate	Number (000 000s)	Percent	Number (000 000s)	Percent	Number (000 000s)	Percent	Number (000 000s)	Percent
High	14 244	1.98	28 170	3.91	59 501	8.24	31 644	4.39
Medium	10 101	1.40	21 197	2.94	44 075	6.12	24 655	3.53
Low	6 792	0.94	14 355	2.01	33 081	4.59	20 135	2.80

Note: 1 km = 0.6 mile.

Table 6. Total national estimates of impacts of four scenarios: energy saved per year.

	Energy for Four Scenarios							
	1		2		3		4	
Estimate	Gasoline (m^3)	Percent	Gasoline (m^3)	Percent	Gasoline (m^3)	Percent	Gasoline (m^3)	Percent
High	1242	0.84	2397	1.61	5980	4.03	3488	2.35
Medium	911	0.61	1777	1.20	4494	3.03	2808	1.89
Low	628	0.43	1198	0.81	3470	2.34	2286	1.54

Note: 1 m^3 = 6.3 bbl.

show the highest potential for reducing vehicle kilometers of travel and saving energy. Although these two groups account for only 63 percent of the urban area population and 58 percent of automobile travel and gasoline use, they would contribute 89 to 94 percent of the expected reduction in automobile travel and 89 to 95 percent of the gasoline savings expected in all urbanized areas.

Tables 5 and 6, which merge all city groups together for total national estimates, give high, medium, and low estimates of reductions in vehicle kilometers of travel and energy savings for each of the four scenarios. Scenario 3, which produces a 3.0 percent reduction in energy use for passenger transportation in urbanized areas, is seen to be more than half again as effective as scenario 4. Scenario 3 is almost twice as effective as scenario 2 in reducing vehicle kilometers of travel and energy use, and scenario 2 is in turn about twice as effective as scenario 1. Scenario 1 combined with elements of scenario 3 would be the most likely candidate for initial implementation.

CONCLUSIONS

The estimates presented here show that a reduction in the amount of energy used for personal transportation can be realized through actions designed to shift persons from the automobile to mass transit but that it is extremely difficult to conserve large quantities of energy in this way. The potential short-term fuel savings attainable from shifts to transit range from less than 1 percent up to a maximum of 3 or possibly 4 percent of national, urban area fuel consumption for person travel. The maximum reductions would involve twofold to threefold and greater transit ridership increases in individual cities, with corresponding transit subsidy increases.

Transit fare reductions, decreased running time, increased service coverage and frequency, and automobile disincentives all serve to increase transit ridership and, in most instances, to conserve energy. However, the energy savings that result from individually applied policy actions are less than those that result from appropriate joint applications of policy.

It should be noted that automobile-disincentive strategies will not only generate the energy savings estimated in this study for mode shifts to transit at the least added cost to the transit agency but will also cause additional energy conservation attributable to increased car and van pooling, shortened trip lengths, and trip elimination.

Increased coverage and frequency of transit service are particularly effective in inducing mode shifts; this, however, is the one otherwise useful strategy that, when applied alone under the wrong circumstances, can increase net energy consumption. To conserve energy, increased coverage and frequency are best provided in connection with fare reductions, decreased running time, or automobile disincentives.

Of course, improvements to transit systems offer benefits in addition to the relatively small energy savings obtained. The potential for reducing vehicle kilometers of automobile travel in today's urban areas is twice as great as the total energy-saving potential; it ranges from 1 or 2 percent up to a maximum of 6 or possibly 8 percent for the highest impact group of mode-shift strategies examined.

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Publication of this paper sponsored by Committee on Energy Conservation and Transportation Demand.

**Mr. Shapiro was with R. H. Pratt Associates, Inc., when this research was performed.*

Rail Rapid Transit and Energy: The Adverse Effects

Charles A. Lave, Department of Economics and Institute of Transportation Studies, University of California, Irvine

Because it is generally believed that transportation energy can be saved by diverting people from automobiles to rail transit, the United States is now building or planning a number of multi-billion-dollar rail systems. These new-generation rail systems were examined and found to be a net user of energy. The two main points prompting this conclusion are that (a) the energy invested in building a rail system is enormous and thus difficult to repay and (b) the possible savings in operating energy are small, or even negative, because most rail passengers are diverted from buses and buses are more energy efficient than modern rail systems. The analysis was done for San Francisco's Bay Area Rapid Transit (BART) system, but evidence is cited to show that the results are typical for other modern rail systems as well. To the extent that BART is atypical, it appears to be atypically efficient. The analysis takes into account the reduced demand for automobiles and buses because their passengers are diverted to rail and then calculates the energy saved because these conventional vehicles are not built or driven and the roads on which they would travel are not constructed. It is concluded that even radical improvements in automobile diversion, rail patronage, and load factors would not significantly alter the results.

This paper examines the overall energy impact of modern rail transit systems and concludes that they are energy users. Although the analysis is done for a single example, the San Francisco Bay Area Rapid Transit (BART) system, it is shown that the conclusions are probably general. These conclusions are the result of two main points: (a) that the energy required to build a rail system is enormous and thus hard to repay and (b) that the possible savings in operating energy are small, or even negative, because most rail passengers are diverted from buses rather than from automobiles and buses are much more energy efficient than modern rail systems.

First, calculating the energy required to build BART and the amount of energy saved by building fewer kilometers of freeway as a result of the diversion of automobile and bus users to rail transit yields the net energy investment. This net figure would be essentially the same even if a doubling of the diversion figures were assumed. Next, energy figures are developed for automobile, bus, and rail operation that take into account the energy required to build the vehicle as well as to operate it. Finally, the length of time it would take to repay the net energy invested in constructing the system is calculated by using various assumptions about BART patronage. Under most of these assumptions the BART system can never repay the energy investment.

Had this analysis been done several years ago, it would have assessed the BART system in terms of the dollars of social cost rather than the units of energy expended. However, since the oil crisis focused attention on energy, many people have begun to discount financial analyses of alternative transportation systems by claiming that dollars do not matter—only energy matters.

Many economists may find the analysis that follows strange because it uses energy as the measure of all things. But, because a dispute over ways of measuring social cost would only compound the transportation issues, the joule—an energy measure—is used as a basis for assessing the effectiveness of BART.

The literature on energy use in transportation has

Table 1. Former travel mode of current rail passengers for three systems.

System	Formerly Used Bus (%)	Formerly Used Automobile (%)	Formerly Used Other Modes (%)	Formerly Did Not Make Trip (%)	Calculated Fraction of Former Automobile Users (%)	Calculated Fraction of Former Automobile Drivers (%)
BART	44.6	38.7	1.6	15.2	46.5	33.7
Lindenwold Line (Philadelphia)	49	38	0	13	43.7	28
South Shore MBTA extension (Boston)	52	29	3	16	35.8	N.A.

been preoccupied with the question of operating energy. In the case of modern rail transit systems, however, careful attention must be given to the energy investment required to build the system in the first place. This energy requirement is so large compared with the number of people the system transports that it is one of the most important factors in determining the overall energy efficiency of rail transit.

The construction of a rail transit system has both negative and positive effects on energy use in transportation. The negative effect is the enormous amount of energy needed to build the system. The positive effect is that, as the system diverts people from automobiles and buses, there is less need for highways.

ENERGY USED TO BUILD A RAIL TRANSIT SYSTEM

In constant 1974 dollars, BART cost \$2.28 billion (3, p. 163), of which \$161 million was for transit vehicles. Healy and Dick (6, p. 25) analyzed the energy expenditure on BART when it was about half completed (classifying expenditures by input-output table categories and then using the known energy weights for each category) and concluded that the average conversion ratio was 81.9 MJ/dollar (22.7 kW·h/dollar). Hirst (7, p. 23), using a different method and other data, estimated essentially the same conversion ratio. The total energy invested in BART can be calculated as follows (1 MJ = 0.28 kW·h):

$$(\$2.28\text{ billion} - \$0.161\text{ billion}) \times 81.9\text{ MJ/dollar} = 174\text{ PJ} \qquad (1)$$

The cost of BART, in constant 1974 dollars, amounts to \$20.0 million/km (\$32.1 million/mile) of system. The average projected cost, in constant 1974 dollars, of three other systems now under construction—Boston's Massachusetts Bay Transportation Authority (MBTA), Atlanta's Metropolitan Atlanta Rapid Transit Authority (MARTA), and Metro in Washington, D.C.—is \$21.4 million/km (\$34.4 million/mile) of system (3, p. 163). Because the BART figure represents an actual measurement and the other figure is based on projections (and such projections have been underestimated in the past), it can safely be concluded that BART is not an unusually capital-intensive system and thus that the amount of energy invested in building it is not atypical of modern rail transit systems.

ENERGY SAVED BY OPERATING A RAIL TRANSIT SYSTEM

Because a rail transit system attracts passengers from automobiles and buses that now use highways, the need for highway lane kilometers is reduced and the energy saved by not building these lane kilometers should be credited to the rail system. Table 1 gives the former modes of travel used by BART passengers and passengers of two other modern rail transit systems (3, pp. 108, 110, 136, 137; 8, p. 17). The large fraction of commuters now using the system who had made no trip before creates a problem for the analysis. Some of these people represent a trip-generation effect of the rail system: Because long-distance commuting is now easier and more luxurious, people are encouraged to move farther from the city to find better housing. These additional kilometers of travel should be treated as net energy loss; they are the waste encouraged by the rail system. (The average observed BART trip length is 40 percent longer than was forecast, and there is evidence that this trip-generation, energy-wasting effect is substantial.) However, some of the people who had not formerly made the trip simply represent the normal effects of changing jobs and housing in this mobile society. Because it is not known how people who formerly made no trip should be divided between the normal-mobility and the trip-generation hypotheses, the assumption most favorable to rail transit is made: These people are treated as representing normal mobility and are simply divided proportionately between bus and automobile. The small number of people who formerly used other modes are apportioned in the same way.

The calculated fraction of current rail passengers who formerly used the automobile ranges from a high of 46.5 percent for BART to a low of 35.8 percent for MBTA. (Because BART has been unusually successful in this dimension, the results of the calculations are biased in favor of the energy effectiveness of rail systems.) Not all of the people who formerly commuted by automobile were drivers, however; some were passengers. That is, the rail system is diverting some of its passengers from car pools, which represents a net energy loss. As passengers, these people used no extra energy and created no extra demand for automobiles or highways, and now, on the rail system at rush hour, they create a demand for more transit cars and more operating energy. The calculated fraction of former automobile drivers adjusts the calculated fraction of former automobile users to reflect this; for example, only 33.7 percent of the people who currently ride BART were formerly automobile drivers.

BART ridership in 1975 was 127 000/d, and it was not growing (3, p. 71). If this is rounded off to 130 000 trips/d, it can then be calculated that BART removed 43 800 automobile trips or 21 900 automobiles/d (or 33.7 percent of 130 000) from the highways. Not all of these 43 800 trips represent reduced demand for highways, however. It is only at rush hour that highways operate at capacity; at any other time, the presence or absence of an additional automobile does not affect congestion. Because highways are constructed to meet peak-hour loads, they have excess capacity in off-peak periods and it is only the reduction in peak-hour traffic that reduces the need to invest energy in highways. Fifty-nine percent of BART daily traffic occurs each day during the four peak hours (3, p. 86). If the average BART trip is 20.9 km (12.9 miles) and highway capacity is 2000 automobiles/lane·h (4, p. 304), putting these figures together results in the following (1 km = 0.62 mile):

$$\begin{aligned}&(0.59 \times 43\,800\text{ peak·h automobile trips/d} \times 20.9\text{ km/trip})\\&\quad \div (4\text{ h/peak} \times 2000\text{ automobiles/lane·h}) = 67.5\text{ lane·km of highway}\end{aligned} \qquad (2)$$

where 0.59 is the peak factor. That is, BART diverts enough people from automobiles to reduce highway capacity needs by 67.5 lane·km (42 lane miles).

BART also attracts passengers from buses, and buses too are highway users. The bus capacity of a highway is 1200 buses/lane·h (4, p. 304). The average number of passengers per bus on the San Bernardino express bus service is 44 (10, p. A-26), but, because San Francisco service may not be this efficient, the estimate used here is 25. Thus,

$$(0.59 \times 0.535 \times 130\,000 \text{ trips/d} \times 20.9 \text{ km/trip}) \div (25 \text{ people/bus} \times 1200 \text{ buses/lane·h} \times 4 \text{ h/peak}) = 7.15 \text{ lane·km} \quad (3)$$

where 0.535 is the BART bus fraction. Thus, by reducing the number of automobiles and buses on the highway during peak hours, BART saves a total of 74.7 lane·km (46.5 lane miles) of highway.

Keeler (9, p. 28) estimates the average cost of building a lane kilometer of freeway in California as \$0.789 million for an urban central-city site and \$0.258 million for an urban-suburban site. BART is about evenly divided between these two kinds of sites. Calculating an average of these two figures, converted into constant 1974 dollars, results in \$0.579 million/lane·km (\$0.932 million/lane mile) for construction costs. Using an energy conversion ratio of 118 MJ/dollar (32.8 kW·h/dollar) (1, p. 670) gives

$$74.7 \text{ lane·km} \times \$0.579 \text{ million} \times 118 \text{ MJ/dollar} = 5.1 \text{ PJ} \quad (4)$$

That is, BART diverts enough buses and automobiles from the highways to reduce the necessary highway energy investment by 5.1 PJ (1.4 billion kW·h). Subtracting this from the total construction energy of 174 PJ (48.1 billion kW·h) gives a net energy investment in BART of 169 PJ (46.7 billion kW·h).

This figure for net energy investment is quite robust with respect to changes in the underlying assumptions. If BART daily patronage were to double and thus divert more automobiles and buses from the highways and reduce the number of lane kilometers of highway needed, the net energy investment would decrease by only 3.5 percent. Similarly, if BART were somehow to become so attractive that 100 percent of its passengers came from automobiles, the decrease in lane kilometers of highway needed would only be enough to reduce the net energy investment by 5.9 percent. That is, the net energy investment in building the system is so large that no conceivable change in patronage is going to affect it significantly.

VEHICLE OPERATING ENERGY

To simplify some of the calculations, a nonstandard definition of operating energy is used: The energy required to build the vehicle is added to the energy required to operate it, and thus the invested energy is treated as a variable cost. This is justified by the fact that the decision to purchase or replace a vehicle is a relatively flexible one and the decision to use a vehicle once it is purchased is even more flexible. The vehicle is treated here as though it had a given, innate number of kilometers of service, and the vehicle user is treated as making a decision about the time rate of use of these kilometers of service. Thus, a stock of invested construction energy becomes a flow of vehicle services, and

$$\text{Vehicle operating energy per kilometer} = \text{vehicle consumption energy per kilometer} + (\text{vehicle construction energy} \div \text{vehicle lifetime kilometers}) \quad (5)$$

Because energy consumption estimates in the literature vary widely and generally give little information as to their derivation, the assumptions, the figures, and the derivation used here are made as explicit as possible in Table 2. The main focus of the table is operating power per passenger kilometer, and it is worth commenting on the sensitivity of these figures to the intermediate assumptions. Automobile kilometers per liter and service lifetime are both taken, as national averages, from census data and are presumably reliable (they are certainly of plausible size); average occupancy is also taken from census data and is supported by recent observation of automobile occupancy on the San Francisco-Oakland Bay Bridge (12) and in the Caldecott Tunnel (13). Power consumption and average occupancy data for BART are actual measurements. They are similar to data for the Lindenwold Line, for which marginal power consumption is 66 MJ (18.3 kW·h) and average occupancy is 22 passengers/vehicle (2, p. 1). Service lifetime for BART is a guess, from a single source, but either doubling or halving it would change the final figures by only 1 percent. Bus fuel efficiency and occupancy are national averages; the lifetime figures are taken from a single source, but doubling or halving them would change the final figures by only 3 percent. Some idea of the sensitivity of automobile energy to vehicle size can be gained by comparing the two different automobile categories in Table 2. Because automobile manufacturers are under congressional mandate to produce automobiles that average 11.7 km/L (27.5 miles/gal) (sales-weighted average) by 1985 (8, p. 15), data for the 907-kg (2000-lb) automobile will probably be more accurate than data for the av-

Table 2. Vehicle operating energy.

Vehicle	Energy Used to Construct Passenger-Carrying Vehicle[a] (MJ)	Service Life of Vehicle[b] (km)	Marginal Operating Power per Vehicle Kilometer[c] (MJ)	Total Operating Power per Vehicle Kilometer (MJ)	Average Number of Passengers per Vehicle[d]	Operating Power per Passenger Kilometer[e] (MJ)
Average automobile[f]	139 000	180 000	6.26	7.09	1.3	5.44
Future automobile[g]	75 600	180 000	3.19	3.64	1.3	2.79
BART	4 430 000	4 800 000	65.5	66.6	21.4	3.11
Bus (diesel)[h]	1 080 000	1 600 000	21.2	21.8	11.5	1.90

Notes: 1 MJ = 0.28 kW·h; 1 km = 0.62 mile; 1 kg = 2.2 lb; 1 L = 0.26 gal; 1 km/L = 2.35 miles/gal.
For energy data, 37.3 MJ/L (10.36 kW·h/L) of gas and 41.2 MJ/L (11.44 kW·h/L) of diesel are used, which includes energy lost in the refining process (5, p. 14). Electrical energy is computed as power-plant-source energy.

[a] (4, p. 300; 5, p. 14).
[b] (4, pp. 303-304; 10, p. 8).
[c] (4, p. 302; 11).
[d] (10, 12, 13).
[e] Vehicle-construction energy plus marginal energy.
[f] 1633 kg (3600 lb) and 5.95 km/L (14 miles/gal).
[g] 907 kg (2000 lb) and 11.7 km/L (27.5 miles/gal).
[h] 1.94 km/L (4.5 miles/gal).

Table 3. Sensitivity analysis of results: time required to repay BART energy investment.

	Years to Repay	
Situation	5.95-km/L Automobile Efficiency	11.7-km/L Automobile Efficiency
Current BART (130 000 trips/d, 30 percent load factor, 46.5 percent of passengers from automobiles)	535	Never; more energy wasted each year
Current but with 75 percent of passengers from automobiles	163	Never; more energy wasted each year
Current but with 50 percent load factor	139	502
Current but with 260 000 trips/d	266	Never; more energy wasted each year
Ideal (260 000 trips/d, 50 percent load factor, 75 percent of passengers from automobiles)	44	168

Note: 1 km/L = 2.35 miles/gal.

erage automobile in projecting the lifetime energy characteristics of a system like BART.

IMPACT OF OVERALL SYSTEM

By using the estimates for net energy invested in BART and the energy required to operate the system, an overall evaluation of the system's energy characteristics can be formulated. First, current energy use per year is calculated as follows:

$$130\,000 \text{ trips/d} \times 20.9 \text{ km/trip} \times 260 \text{ d/year} = 706 \text{ million passenger}\cdot\text{km/year} \quad (6)$$

$$706 \text{ million passenger}\cdot\text{km/year} \times 3.1 \text{ MJ} = 2.2 \text{ PJ/year} \quad (7)$$

for operation with the BART system. What it would have cost to produce the same number of yearly passenger kilometers if 46.5 percent of these people had used automobiles and 53.5 percent had used the bus (the pro-BART figures given in Table 1) can also be calculated, as follows:

$$0.465 (706 \text{ million}) \times 5.4 \text{ MJ} + 0.535 (706 \text{ million}) \times 1.9 \text{ MJ} = 2.5 \text{ PJ/year} \quad (8)$$

to operate without the BART system. That is, because of BART, 0.32 PJ/year (87 million kW·h/year) of operating energy are saved. If the energy investment in building the system, 169 PJ (46.7 billion kW·h), is divided by the energy saving per year, it will take 535 years of operation before the initial energy investment is repaid.

Thus, an overall evaluation of the effects of BART that takes into account the energy saved by building fewer lane kilometers of highway and the energy saved by building fewer automobiles and buses indicates that the energy invested in BART is so enormous and the yearly operating energy savings are so small that it will take 535 years even to repay the initial investment, much less to save any energy. Even this figure is based on the assumption that the efficiency of automobiles will continue at 5.95 km/L (14 miles/gal) for the next 535 years.

If it is assumed that the congressionally mandated 11.7-km/L (27.5-miles/gal) average is fulfilled (which is reasonable because such vehicles do exist), then BART actually wastes operating energy. A simple, weighted average of the energy efficiencies for automobile and bus shows that

$$46.5 \text{ percent } (2.8 \text{ MJ}) + 53.5 \text{ percent } (1.9 \text{ MJ}) = 2.3 \text{ MJ/passenger}\cdot\text{km} \quad (9)$$

That is, the automobile-bus combination of modes requires 2.3 MJ/passenger·km (1 kW·h/passenger-mile), but BART requires 3.1 MJ/passenger·km (1.4 kW·h/passenger-mile). This means that shutting BART down altogether would save 0.6 PJ (160 million kW·h) of operating energy per year.

SENSITIVITY ANALYSIS

The results calculated above are clearly surprising in view of the conventional wisdom about rail transit. Are they believable? Perhaps the best way to examine their credibility is to compute their dependence on the assumptions made in the analysis. Table 3 gives the results of such a sensitivity test, which radically changes each of the five key assumptions and then recomputes the number of years it would take to repay the invested energy.

If the automobile-diversion percentage could somehow be increased to 75 percent, the payback period would still be 163 years given the current (unlikely) automobile efficiency and would become infinite given the probable future automobile efficiency. But BART already has the highest automobile-diversion percentage among the modern transit systems, and an increase to 75 percent seems essentially impossible.

The current load factor for BART is about average for the United States. No system has ever achieved a 50 percent load factor or is likely to do so, given the need to run trains both with and against traffic and during both peak and off-peak hours. But even were this possible, the payback periods would still be 139 and 502 years.

A doubling of current patronage is not likely to occur, given that patronage has been essentially constant since the opening of the trans-Bay tubes. In any case, this hypothetical change only lowers the payback period to 266 years.

Finally, in a situation referred to as the transit ideal, all of these essentially impossible changes have come to pass. Even so, and even with the 5.95-km/L (14-miles/gal) automobile, the payback period would still be 44 years. As an internal rate of return this would be equivalent to an investment that paid 1.5 percent per annum. But even this figure is far too optimistic, for any combination of circumstances that could double patronage, divert 75 percent of automobile trips, and persuade passengers to put up with the peak-load crowding implied by a 50 percent average load factor would have to produce a universal demand for an efficient, 11.7-km/L (27.5-miles/gal) automobile. Thus, even in the ideal situation, there would be a 168-year payback period.

SUMMARY AND CONCLUSIONS

Rail transit, examined from the perspective of energy use, was clearly found to be an inefficient mode of transportation. Although the analysis was done in terms of a single example—BART—cited evidence shows that the results are typical of modern rail transit systems; in fact, to the extent that BART is atypical of rail transit, it is probably atypically efficient.

These conclusions are the result of a relatively broad analysis of the BART system that takes into account the reduction in the number of automobiles and buses caused by passenger diversion to BART and the effects of energy saved by not building or driving those conventional vehicles and not constructing the roads on which they travel. Furthermore, the conclusions are robust in that even radical improvements in rail patronage, load factors, and automobile diversion do not significantly alter the results.

ACKNOWLEDGMENTS

The research in this paper was begun while I was employed by Charles River Associates in Cambridge, Massachusetts. I owe an enormous debt to the intellectual stimulation from my colleagues there and particularly to the encouragement and support of Harrison Campbell. Alistair Sherret of Peat, Marwick, Mitchell and Company has patiently gone through several drafts of this article and provided valuable improvements. The views here, and any remaining errors, are of course my own responsibility.

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Discussion

E. L. Tennyson, Pennsylvania Department of Transportation

Lave has assembled his data from a collection of references to which he applied ratios of energy consumption to dollar values of construction and kilometer rates for operation. He then calculated alternatives in the same way, using the ratio of automobiles and buses that made up the former modes of Bay Area Rapid Transit (BART) passengers. He then tested the results against variations in use to show that the conclusions were not sensitive to wide fluctuations and found that, based on the assumed data, (a) BART would save so little energy that it would take 535 years to recover the energy invested in it and (b) even if automobile efficiency could be increased as mandated by Congress, BART would be a waste of energy.

This is not a valid conclusion. Unlikely values were assigned for highway construction costs, transit load factors, and other elements of the study. More realistic values will produce far different and much more likely conclusions.

ENERGY INVESTMENT IN TRANSIT CONSTRUCTION

Two aspects of energy investment in transit construction must be considered. One is the cost of energy to construct BART, and the other is the cost of constructing alternative transportation capacity. Lave uses an estimated BART construction-energy cost of 81.9 MJ/dollar (77 600 Btu/dollar). This figure appears high. In 1974, the year calculated, the cost of 81.9 MJ of energy was \$0.215 on the dollar of total cost (1 MJ = 948 Btu):

$$81.9\ \text{MJ/dollar} \div 41\ \text{MJ/L} = 2\ \text{L/dollar of cost} \times \$0.107/\text{L} = \$0.215/\text{dollar} \tag{10}$$

Labor input can be approximated at 70 percent of construction cost. Material and land, excluding energy, make up approximately 20 percent of construction cost (14):

$$2000\ \text{employees} \times 5\ \text{years} \times \$10.70/\text{h} \div \$307\,000\,000 = 70\ \text{percent} + 20\ \text{percent for material} + 10\ \text{percent for energy} \tag{11}$$

$$10\ \text{percent} \div 21.5\ \text{percent} \times 81.9\ \text{MJ} = 38\ \text{MJ} \tag{12}$$

Allowing for some variation in the estimate, it appears obvious that the energy used to construct rail rapid transit could not be much more than 36 to 40 MJ/dollar (34 120 to 37 912 Btu/dollar) of construction cost. BART construction-energy cost is more likely to be 84 PJ than the 174 PJ used by Lave:

$$(\$2.28 \times 10^9 - \$0.161 \times 10^9) \times 40\ \text{MJ/dollar} = 84\ \text{PJ} \tag{13}$$

CONSTRUCTION ENERGY SAVED BY RAIL TRANSIT

To calculate the energy saved by rail transit, the energy cost of alternative highway capacity for the likely split between automobiles and buses must be calculated. Lave calculated this split in Table 1 based on data for BART, the Lindenwold Line, and the Massachusetts Bay Transportation Authority. Table 1 is in error. Table 4 duplicates the format of Table 1 but corrects Lave's figures. For example, Table 1 reports zero percentage of passengers on the Lindenwold Line who formerly used other modes. This is not the actual or reported fact. Only 36 percent of Lindenwold passengers formerly used the bus. Eleven percent used commuter trains stopping at Haddonfield or the shuttle subway to Camden and a feeder bus beyond. This changes the automobile-bus split to 52 to 48 percent and exceeds the rate of trip at-

Table 4. Former travel mode of current rail passengers.

System	Formerly Used Bus (%)	Formerly Used Automobile (%)	Formerly Used Other Modes (%)	Formerly Did Not Make Trip (%)	Calculated Fraction of Former Automobile Users (%)	Calculated Fraction of Former Automobile Drivers (%)
BART	43	39	3	15	48	36.5
Lindenwold Line (Philadelphia)	36	40	11	13	52	35
South Shore MBTA extension (Boston)	52	29	3	16	36	24
Riverside Line (Boston)	4	46	35	15	68	49

traction found in preliminary BART experience. Lave assumes BART has the highest trip attraction, but this too is in error. Lave uses only the trans-Bay automobile-diversion data (46.5 percent), whereas most BART riders are local to either side of the Bay (58.5 percent) where much higher diversion from automobiles occurs (42.6 percent versus 35 percent) (15, p. 13; 16, p. 195). Overall BART automobile diversions should be used.

A July 1967 route map of the Massachusetts Bay Transportation Authority (MBTA) shows that the 52 percent of passengers on the South Shore extension who formerly used buses were basically feeder-bus riders to Ashmont or Fields Corner rapid transit stations; thus, they were for the most part already rail riders. A few buses ran all the way through. On the west edge of Boston, when the Riverside trolley line was inaugurated through Newton, 18 000 passengers/d were attracted. About 1200 were formerly railroad commuter riders, and 2400 were Middlesex and Boston bus riders (17, p. 124). The balance of 80 percent came from automobiles and new trips, primarily from automobiles. Conversely, when the Chicago, Aurora and Elgin Railroad, a third-rail commuter line, was abandoned, it was carrying 12 500 passengers/d. The Leyden Motor Coach Line replaced it (18, pp. II-14 and II-38). Because only 1250 passengers used the buses, the service was soon abandoned. The ability of the bus to hold rail passengers was only 10 percent. In the BART case, however, where there is a toll bridge across a significant water barrier plus a long tradition of rail commuting, the bus alternative does unusually well. San Francisco has one of the highest transit ridership rates in the nation.

The nation's commuter rail lines have declined only 25 percent since the era of the 6-d workweek, and the older rail rapid transit lines have declined 40 percent in passengers carried. In contrast, city bus lines have lost 71 percent of their riders in spite of expansion, and suburban bus lines have lost 74 percent (19, p. 30; 20, p. 30). The basic point is that, at best, buses could not be expected to carry more than 52 percent of BART riders because the trans-Bay bus service is already one of the best in the nation (21, p. 6).

The transit peak is much sharper than are the calculated average 2-h morning and evening highway peak periods. BART carries 25 000 riders in a single peak hour (22, p. 9) of whom 48 percent have been found to be diverted from automobiles. My personal observation has resulted in the following calculation: (10 trains × 2 directions × 8 cars × 140 passengers) + (5 trains × 2 directions × 4 cars × 70 passengers). If 48 percent of these are diverted from automobiles, this would require the movement of 9000 automobiles/h at an observed occupancy rate for divertible peak-hour commuters of 1.3 passengers/automobile. At 2000 vehicles/lane•h on the freeway, the movement would require $4\frac{1}{2}$ more lanes, but additional local street capacity would also be needed to deliver the added traffic to parking areas. Assuming only 15 percent of the added movement on local streets, this would require $13\frac{1}{2}$ more lanes over 3.14 km (1.95 miles) (23, p. 316), as follows (1 km = 0.62 mile):

$$667\ \text{vehicles/lane}\cdot\text{h} = 9000\ \text{vehicles/h} = 13\tfrac{1}{2}\ \text{lanes} \times (0.15 \times 21\ \text{km}) \tag{14}$$

The freeways would require 17.8 km (11.05 miles) [20.93 - 3.14 = 17.8 (13 - 1.95 = 11.05)] × $4\frac{1}{2}$ lanes or 80 lane•km (61.7 lane miles) of freeway.

Freeways in heavily developed urban centers cannot be built for $0.579 million/lane•km ($1 million/lane mile) as Lave assumes, particularly where bridges, subways, or elevated structures are required. If rights-of-way were available, BART could have used them instead of doing its own costly construction. Using the cost per lane kilometer of urban Interstate transfer highways typical of the rail transit alternative results in a construction cost of approximately $6.2 million/km ($10 million/mile). Local streets could probably be widened for $0.579 million/km so that the total dollar and energy cost would be 80 lane•km × $6.2 million = $496 million; $13\frac{1}{2}$ lanes × 3.14 km × $0.579 million = $24.6 million; and highway and street capacity worth $520.6 million × 118 MJ/dollar (111 840 Btu/dollar) = 61.4 PJ (58.2×10^{12} Btu).

To this must be added the cost of additional downtown parking. If one uses Lave's 23 725 automobile round trips, 59 percent of which are rush-hour commuter trips and the rest of which turn over twice daily, 18 861 parking spaces would be required at a dollar cost of $94.3 million and an energy investment of 3.8 PJ (3.6×10^{12} Btu), at the energy-per-dollar rate for complex structures [40 MJ/dollar (37 912 Btu/dollar)].

Buses for the BART riders who do not drive automobiles will also require highway space, but buses cannot serve passengers at the assumed rate of 1200/lane•h. This is a theoretical figure for constant motion with no stops. To pick up or discharge passengers, only 120 buses/lane•h can be moved at even minimal speed. Terminal expansion would be needed for even this number of buses. To avoid terminal cost, I assume that curb stops for 120 buses/h will require 1.67 lanes in each direction, except at the 10-km (6.2-mile) Bay crossing where there are no stops and where one lane each way would be adequate. In all, 56 more lane kilometers (35.4 lane miles) will be needed for buses at $0.579 million/lane•km ($1 million/lane mile), for a total of $32.4 million. Because of the Bay Bridge, there would be no low suburban costs. In fact, some freeway-level costs are likely.

If energy costs 118 MJ/dollar, the construction of highway capacity for buses to equal present BART operation would require 3.8 PJ (3.6×10^{12} Btu). However, BART is using only 60 percent of its cars and 75 percent of its routes because of initial electronic difficulties. When these problems are solved and all lines commence operation, BART may carry 33 percent more people for the same construction energy. This will require a 33 percent further increase in the relative energy cost of the highway alternative. Total highway construction energy would then approximate 69 PJ.

VEHICLE OPERATING ENERGY

Actual rail transit experience has revealed operating energy requirements of 15.6 MJ/car·km (14 785 Btu/car-mile) and 6.7 MJ (6350 Btu) for station lighting and other auxiliary uses. (For the highway alternative, no energy consumption was calculated for parking lots for automobile commuters, traffic controls, highway lighting, or bus-terminal operation.) BART expects its expensive choppers to recover and return 20 percent of its energy, but this can be ignored as experimental. The proven figures show that BART operating energy will be about 22.3 MJ/car·km (21 136 Btu/car-mile), not the 65.5 MJ/km (62 081 Btu/car-mile given in Table 2. This will reduce the comparable operating power per passenger kilometer to 2.2 MJ (3271 Btu/passenger-mile). Even this figure could be much improved if BART inaugurated service on the Richmond-San Francisco line to dilute the low efficiency of the Fremont-Richmond line, which shares its passengers between Oakland and Fremont with the heavier San Francisco line. Operating power for BART would thus be

$$\begin{aligned}&707 \text{ million passenger·km/year}\\ &\times 1.05 \text{ MJ/passenger·km} = 740 \text{ million MJ}\end{aligned} \tag{15}$$

Operating power without BART would be

$$\begin{aligned}&0.48\,(707 \text{ million}) \times 5.4 \text{ MJ/passenger·km}\\ &+ 0.52\,(707 \text{ million}) \times 1.9 \text{ MJ/passenger·km} = 3.3 \text{ PJ/year}\end{aligned} \tag{16}$$

Setting BART power-system losses against added lighting requirements for highway lanes, bus stations, and bus garages, BART would save 2.6 PJ/year (2.5 × 10^{12} Btu/year) in operating energy. If 15.76 PJ (14.9 × 10^{12} Btu) are added for BART construction, the energy invested in BART will be recovered in 6 years, well within the life expectancy of BART facilities:

$$15.76 \text{ PJ} \div 2.6 \text{ PJ} = 6 \text{ years} \tag{17}$$

Because BART is not yet operating all of its routes and because its car fleet is not yet operating at conventional efficiency (22, p. 6), no effort will be made to compare BART with proposed future automobile efficiency, particularly because BART's energy-recovery system is not assumed to be working either.

SUMMARY

Not only can the energy invested in BART be recovered during its lifetime, but also the type of energy BART uses is far superior to present bus and automobile energy, which must come from foreign petroleum and must be burned in congested, heavily populated areas. BART energy can come from water, coal, nuclear power, or oil and can be burned at a controlled site where it will not impinge on the local population. In the future, BART energy should also be much less costly per joule than foreign petroleum.

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W. H. T. Holden, Daniel, Mann, Johnson, and Mendenhall, Los Angeles

There is a growing concern today about energy efficiency in all aspects of our existence. Because some degree of mobility is essential to everybody, the energy consumed has become a matter of concern. At the same time, another nonrenewable resource should also be considered, one that is ignored by some authors of papers in this field: time. The necessity of considering a trade-off between the loss of time and increases in the consumption of energy to reduce time loss is especially apparent in the case of long-distance travel, in which air travel, in spite of its well-known high consumption of energy, has largely replaced the use of land transport.

The two modes considered today for providing urban mobility by means of public transit systems are bus and rail rapid transit. The bus system entails minimal capital costs but involves high operating costs because the productivity of platform labor is severely limited by the single-unit vehicle per operator. Rail systems involve higher capital costs but show lower total costs at sufficiently high volumes.

Many of the conclusions expressed in Lave's paper on rail transit and energy are erroneous. My analysis, which differs in its methods, is based on the following data (1 MJ = 948 Btu):

Fuel	Specific Gravity	Megajoules per Kilogram
Automobile gasoline	0.739	48.85
Diesel fuel	0.904	42.51

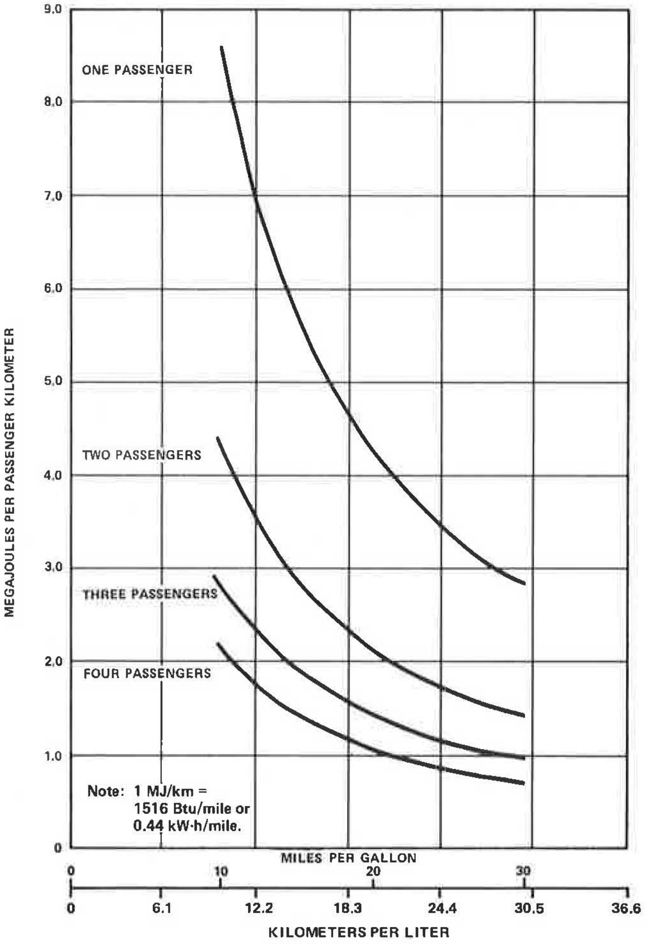
If 3.8 L (1 gal) of gasoline converts to 136.9 MJ (129 829 Btu) of energy, then for the automobile the following can be calculated (1 km/L = 2.35 miles/gal and 1 MJ/km = 1526 Btu/mile):

Kilometers per Liter	Megajoules per Passenger Kilometer			
	1 Passenger	2 Passengers	3 Passengers	4 Passengers
4.25	8.51	4.26	2.84	2.13
6.38	5.70	2.85	1.90	1.43
8.51	4.26	2.13	1.42	1.07
10.64	3.41	1.70	1.13	0.85
12.76	2.84	1.42	0.97	0.71

These figures are shown graphically in Figure 1.

The following April 1976 data were furnished by the New York City Transit Authority (NYCTA) (25) for the

Figure 1. Automobile energy consumption.



case of the standard diesel-engine transit bus (1 km = 0.62 mile, 1 L = 0.26 gal, and 1 L/km = 0.43 gal/mile):

Division	Bus Kilometers	Bus Hours	Fuel Consumed (L)	Liters per Kilometer
Brooklyn	4 892 559	414 968	3 344 739	0.68
Staten Island	1 625 638	82 339	812 159	0.50
Queens	1 977 609	136 018	1 194 175	0.60
Manhattan	489 661	52 783	326 819	0.68

Data of the Southern California Regional Transportation District show a figure of 0.50 L/km (0.213 gal/mile). Although there is some variation with operating speed (bus kilometers per bus hour), a conservative value of 0.5 L/km (0.21 gal/mile) will be used, equivalent to 2.22 bus·km/MJ (0.0014 bus-mile/Btu). Data for the average load, or passenger kilometers per bus kilometer, are available only for the Manhattan Division of NYCTA, for which a brochure issued by the Tri-State Regional Planning Commission gives an average trip length of 4.84 km (3 miles) (24). The number of passengers carried in that period of April 1976 was 2 599 000; an estimate of 12 579 000 passenger·km (7 797 000 passenger-miles) gives an average load of 25.68; thus, energy per passenger kilometer is 1.12 MJ (1065 Btu).

For rapid transit operation, nonpropulsion energy must be separated from that actually used by the traction motors. Unfortunately, this is not usually done in reports of operating results.

The energy for propulsion is a function of maximum speed and of station spacing. The kinetic energy stored in the moving train is a quadratic function of maximum speed and is divided by station interval to express it in terms of distance. Some part of this energy can be recovered by regenerative braking, by energy storage in on-board flywheels, or by the use of line profiles dipped between stations. A second component of propulsion energy is the amount needed to overcome train resistance. This is a cubic function of maximum speed. Like kinetic energy, it is proportional to train mass for the linear and constant terms of the train-resistance force; the quadratic function is proportional to area of cross section. No attempt is made here to evaluate these quantities, but they are pointed out to indicate that values for different types of functions may differ widely.

NYCTA has separated propulsion energy from other uses according to fiscal year (26) (1 TJ = 277 000 kW·h, 1 MJ = 0.28 kW·h, and 1 km = 0.62 mile):

Item	Fiscal Year 1975	 1974
Total terajoules purchased	7390	7408
Terajoules lost in transmission and conversion to direct current	509	516
Terajoules of alternating current for lighting, signals, shops, and other uses	801	805
Terajoules of direct current used for operation of cars	6061	6068
Megajoules per car kilometer	12.3	11.7
Car kilometers	487 515 282	511 583 777

It should be noted that in 1975 the larger R-44 cars came into service. Car kilometers were thus reduced, but—because of the greater weight and speed of these cars—energy per car kilometer increased. The average operating speed of the New York City Rapid Transit System is rather low—29.5 km/h (18.3 mph)—corresponding to the short intervals between stations.

Haikalis of the Tri-State Regional Planning Commission has estimated average trip length on the New York system as 11.3 km (7 miles) so that the average load figure is 24.91. Megajoules per car kilometer are 12.31 (19 449 Btu/mile); energy per passenger kilometer is 0.493 MJ (754 Btu/passenger-mile). This, based on an overall efficiency of 34 percent, equals 2.3 MJ (2218 Btu) from fuel at a generating station. This appears to assume that all energy is provided by fossil-fuel generating stations. But some energy currently comes from nuclear-fission stations, and this fraction is expected to increase. Hydropower stations also carry some fraction of the total load. It is certain that in the more distant future other energy sources will be used, such as geothermal, solar, and fusion energy and other means not yet developed.

A more questionable item in the energy picture is the energy required for construction. In the paper by Lave, reference is made to the work of Healy (6) and Hirst (7) in which the dollar value of energy appears to be 1 MJ = $0.012 (1 kW·h = $0.044). There seems to be little relation between this and the actual cost of power. The dollars-to-energy conversion is erroneous. Furthermore, the life of many fixed works of a rapid transit system is indefinite. The London subway tunnels are more than 100 years old. The life of the iron elevated structures of 80 years ago is much less—about 50 years—but the life of a masonry or concrete structure may be very long. Some Roman aqueducts that are over 2000 years old could still carry a railroad track. In any case, inferring that the energy required to build can be determined by converting dollars to energy units is not a valid method of estimating construction energy. It must be recognized, however, that the funds invested in fixed works represent a fixed cost of the system. This can be evaluated on an annual percentage rate. Currently, 8 percent appears suitable. Equipment should be evaluated differently because it has a shorter life. There are also fixed costs of operation, which are independent of volume. But, in energy considerations, these costs seem irrelevant. The unit of output of the transportation system for passengers is taken to be the passenger kilometer.

Several analyses have been published recently in which the BART system is used as an example of modern rapid transit. In view of the many problems and the low availability of equipment experienced on this system, BART cannot be considered typical. Operation is still somewhat less than sufficiently reliable, and this appears to be a factor in the lower than expected patronage. Until its operational problems are overcome, the BART system is not a valid base for any general conclusions. For this reason, and because of the greater availability of detailed operations data, this discussion is based largely on New York data. At the same time, it must be noted that in many respects the New York operation does not take account of many advances in technology.

Finally, it should be noted that regenerative braking or energy storage can effect a 40 percent reduction in energy consumption with no sacrifice in performance. This lowers the energy at the generating station to 1.42 MJ/passenger•km (0.63 kW•h/passenger-mile). The automobile mode of travel can attain equally low values only at numbers of passengers per automobile that are difficult to achieve, and in New York the rather low schedule speed of rapid transit is still faster in Manhattan than automobile travel.

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George F. List, University of Pennsylvania

Lave's paper expresses some rather categorical conclusions about the energy requirements of rapid transit compared with those of freeways. Before accepting these conclusions one must examine for reasonableness and validity the assumptions, the parameter relations, the methodology, and the general approach used. If any one or several of these are found to be suspect, the possible effect on the results must be determined.

METHODOLOGY

Lave compares two quite different alternatives—rapid transit versus bus and automobile on freeway—without considering such items as

1. Level of service (speed, comfort, and dependability;
2. Differences in land requirements;
3. Environmental impacts (noise, air pollution, and community disruption);
4. Potential for growth (reserve capacity);
5. Differences in the location of the facility that cause differences in accessibility and differences in the required investment of energy;
6. Differences in terminal facilities (stations, bus stops, and parking garages); and
7. Differences in the prerequisites for using the system (for most automobile users, access to an automobile and a license to drive).

Although there are major differences between the two alternatives in all of these areas, these differences have been largely or totally ignored.

Lave's study also seems to be based on combinations of averages for many parameters. In many cases the distribution functions on which these averages are based are not independent of one another; the combined averages can thus be misleading. It is also true in transportation that these averages are not only mode specific but also time and location specific. They must therefore be used very carefully in analyses.

Lave's methodology compares the full energy investment of the BART alternative with the marginal energy investment for freeways to handle BART's present ridership (the study ignores the possibility that the marginal energy investment per freeway lane could be higher than the average for the entire system).

In Table 5, Lave's approach is used, but the full energy investment in BART is compared with the full energy investment required to provide a freeway of the same capacity. If Lave's energy-investment ratios are correct, it seems impressive that equivalent transportation can be provided by BART in about 14 percent of the space, about 2 percent of the downtown terminal area, and at only about 58 percent greater energy investment. In addition, 21 000 persons/h is only approximately 67 percent of BART's potential maximum capacity.

BASIC ASSUMPTIONS AND PARAMETER RELATIONS

Lave's study uses three basic assumptions:

1. The energy investment in facilities, which is a continuous linear function of the number of lane kilometers, has no constant term, and depends only on the mode and the general location;
2. The lane kilometers saved through diversion of trips to BART, which can be computed by a relation that can be restated as follows:

$$LM = \alpha P_m L_{avg}/NT_pC_m \tag{18}$$

where

LM = lane kilometers saved,
α = percentage of trips in peak hours,
P_m = total trips per day diverted from mode m,
L_{avg} = average trip length,
N = number of persons per vehicle,
T_p = total number of peak hours (four), and
C_m = highway capacity (vehicles per lane hour); and

3. Empirical estimates of energy consumption per vehicle kilometer.

Lave gives unique numbers for energy investment per lane kilometer for both rapid transit and freeways and throughout his paper allows no variation in these numbers. This procedure is correct only if the following conditions exist:

1. The numbers are extremely accurate and constant (very little variance),

Table 5. Comparison of energy investment for BART and freeway alternative.

Item	BART	Freeway
One-way capacity, persons/h	21 000[a]	22 400[b]
Total tracks or lanes, two ways	2[a]	14[b]
Minimum width,[c] m	7.3	51.2
Average speed, km/h	72[d]	48[e]
Maximum running speed, km/h	112[d]	48[e]
Typical location of facility	Through population centers	Between developed areas
Downtown terminal space required, hm^2	1.65[f]	78[g]
Energy required,[h] TJ	173 000	110 000

Note: 1 m = 3.3 ft; 1 km/h = 0.62 mph; 1 hm^2 = 2.5 acres; 1 TJ = 948 million Btu.

[a] 70 persons/automobile, 10-car trains, 2-min headways, one track each way.

[b] 2000 vehicles/lane·h over entire freeway length for long, sustained periods of time; 1.6 persons/automobile.

[c] 3.6 m/track or lane, no shoulders, medians, interchanges, or stations.

[d] Presently achieved values.

[e] Level of service E (27, p. 264).

[f] 6-m platform depth each side, 213-m length, four stations.

[g] 2.8 m^2/automobile, 1.6 passengers/automobile.

[h] Based on Lave's data.

2. The numbers resulting from the studies (6, 7) require few assumptions or else are insensitive to the assumptions made,
3. The energy investment is constant for every lane kilometer added (i.e., the high initial increment) and economies and diseconomies of scale do not exist (in the real world they can be highly significant),
4. Construction conditions are uniform throughout the region, and
5. The cost of building a bridge across the San Francisco Bay (six lanes in the peak direction at 1.6 persons/automobile and 2000 vehicles/h) is already included in the average of \$0.579 million/lane·km (\$0.932 million/lane mile) (Lave uses a number that is based on a 50 percent weighting each of urban and rural freeway construction in California).

In regard to lane kilometers saved through diversion of trips to BART, the equations Lave uses for determining the number of lane kilometers needed to satisfy a given highway demand (Equations 2 and 3) would never be used by a highway engineer for planning purposes because they are extremely restrictive. That is, they implicitly assume the following:

1. The time distribution of trips during the peak hours is uniform. The correct procedure for this analysis should use the methods explained in the Highway Capacity Manual (27).
2. The additional lane kilometers needed are reversible (taking total trips and dividing by 4 h necessarily implies the use in both peaks of any lane built). Reversible lanes, although economical, are difficult to design and operate and have therefore been used at only a few locations in the United States.
3. Lanes can be added in noninteger amounts. This is particularly unrealistic when the spatial distribution of flows is nonuniform.
4. The addition of more lane kilometers to the system includes the provision of expanded interchange capacity at all affected interchanges.
5. The highway capacity is fixed at 2000 vehicles/lane·h.
6. The bus flow rate will be 1200 buses/lane·h. This far exceeds any currently observable value. The Highway Capacity Manual (27) gives 690, and the highest achieved value at the present time is that for the Lincoln Tunnel approach—490 buses/lane·h (28).
7. The average bus occupancy is only 25 persons/bus during the peak.
8. Ample station capacity has been provided along the route for the buses (184 berths are required for the station that handles the 490 buses/h in New York).

Equations 2 and 3 will obviously yield extremely low estimates (probably the lower bound) of the number of lane kilometers required to just cover the present BART load. It would be easy to challenge Lave's conclusions by assuming different numerical values. His approach is unsound inasmuch as it requires implicit acceptance not only of his general approach and methodology but also of his parameter relations.

Lave's analysis of vehicle energy consumption appears to be generally correct in that he includes the energy required to construct the vehicle and takes account of the efficiency of the electric power plant. His use, however, of energy per passenger kilometer as a common unit can be very misleading because it masks many things including seating design, vehicle weight, and changes in load factor. Such a number, although interesting and necessary, is not a constant but rather a variable that is highly sensitive to many factors.

CONCLUSION

Because many aspects in the approach, methodology, assumptions, and parameter relations used by Lave are questionable, his conclusions may be misleading. His posture that the comparison of energy investment among alternatives should be done on an absolute basis without consideration of the nature and quality of the product (transportation system performance and its impacts) would lead to incorrect conclusions if applied to any investment decisions, as it did in Lave's comparison of rapid transit and freeways.

Estimating the errors in the numerical analyses presented by Lave can only be done by adopting a correct methodology. Studies by others (28, 29) as well as numerous estimates performed in planning actual transportation systems indicate that Lave's findings are not realistic.

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Thaddeus W. Usowicz and Miriam M. Hawley, San Francisco Bay Area Rapid Transit District

Lave's conclusions challenge not only the conventional wisdom that assumes that rail transit is an energy-efficient mode of transportation but also the conclusions reached by other knowledgeable analysts. Bezdek and Hannon (1) have concluded that energy savings would result from a diversion of funds from highways to rail transit, and Fels (4) has shown that rail rapid systems are lower in their consumption of energy than are automobiles. The analysis presented here produces a similar conclusion: BART is an energy-saving form of transportation.

Lave's analysis is faulty in several important aspects.

1. BART and highway capital costs are inflated to 1974 price levels although the factor used to convert dollars to joules is based on the energy intensity of the dollar in 1963.
2. An inappropriate conversion factor is used to equate BART construction costs with energy requirements.
3. A completely erroneous estimate of the costs of a highway alternative to BART is used.
4. Total BART requirements for operating energy are compared with an incomplete estimate of the operating costs of highway-based modes.
5. The comparison of highway and BART operating costs is further biased against BART by the use of an incorrect pre-BART modal-split factor for BART patronage.

Lave also asserts that the energy use of newly generated travel on the BART system should be charged only to BART rather than to the highway system. Obviously, the encouragement and service provided for such new trips are matters of transportation planning policy, and their costs should be properly allocated.

ENERGY COSTS OF CONSTRUCTING BART

Three estimates of the energy cost of BART construction are shown here and discussed below:

1. Lave's estimate: 174 PJ (48.1 billion kW•h or 16.4×10^{13} Btu),
2. The estimate used to illustrate the first case in this analysis: 74.1 PJ (7.03×10^{13} Btu), and
3. The estimate used to illustrate the second case in this analysis, which is considered to be the more appropriate measure: 41 PJ (3.89×10^{13} Btu).

The first estimate is based on BART construction costs inflated to 1974 dollars and on a factor for converting dollars to energy requirements derived by Healy (6, p. 32). Because Healy's conversion factor measures the energy intensity of 1963 dollars, its application to costs inflated to 1974 dollars provides, to a large degree, a measure of price inflation that bears little relation to the actual energy costs of building BART.

The second estimate also uses Healy's conversion factor but represents BART construction costs in constant 1963 dollars. Healy himself has recognized and cautioned that his conversion factor is somewhat erroneous and misleading even when applied to constant 1963 dollars of expenditure. The factor was derived on the basis of current dollar costs for each economic sector of expenditure for building the BART system. The overwhelming majority of BART costs were incurred after 1963, the reference year for measuring the energy intensity of the dollar, and thus the actual energy requirement shown is inflated.

The third estimate is based on a conversion factor of dollars to joules developed by Bezdek and Hannon (1, p. 670) and on BART construction costs of $902 million (1963 dollars). This estimate is realistic for the purposes of this comparison and is compatible with the conversion factor used to estimate the energy cost of highway construction, which was also developed by Bezdek and Hannon.

ENERGY COST OF CONSTRUCTING AN ALTERNATIVE HIGHWAY SYSTEM

Lave's analysis is negligent in its failure to consider that (a) highways must be built to support peak travel in two different directions during the day rather than in the single direction on which his costs are based, (b) any truly alternative highway system would parallel BART in extent and reach, (c) any highway built to support automobile and bus traffic would be built according to specifications for carrying trucks and would therefore incur the full costs derived by Keeler and others (9, p. 28), (d) high energy-cost premiums must be paid for constructing highway access through the East Bay hills and across the San Francisco Bay, and (e) parking facilities must be constructed in the San Francisco and Oakland central business districts (CBDs) to handle the additional influx of automobiles.

One analysis of the costs of a highway system parallel and equivalent to BART has allocated $1.28 billion in 1974 dollars of highway construction costs to the patronage now carried on BART (31). Converting these construction costs to 1963 dollars by using the Engineering News Record building construction cost index and using a figure of 118.4 MJ/dollar (112 200 Btu/dollar), we calculate a construction energy cost of 80.6 PJ (76.4×10^{12} Btu), which is greater than either of the acceptable estimated energy costs for constructing BART. Parking-structure costs would add another 3.4 PJ (3.2×10^{12} Btu).

We have also computed highway costs for two cases by using Lave's approach of measuring incremental highway requirements. The first case is the typical November 1976 BART demand pattern with a daily patronage level of 131 151 trips, which includes 20 997 trips in the single evening peak hour. (Average weekday patronage for 1976 was approximately 131 300/d for the current three-route service levels, and the annual growth rate of daytime patronage is statistically significant at 4.2 percent/year.) The second case is based on a realistic projection of BART patronage in 1981 of 185 000 trips/d with 36 000 trips in the peak hour. Service in 1981 will be provided on four routes and headways will be decreased from 12 to 8 min; additional peak-period service will be provided on the busy Concord-to-San Francisco route.

The incremental requirements for constructing urban highways in the Oakland and San Francisco CBDs and suburban highways in the remaining BART service area, according to BART origin-destination trip patterns, are given in Table 6. Construction costs were derived from total highway construction costs given by Keeler and others (9). Trans-Bay crossing requirements, derived from estimates of costs for the proposed Southern Crossing of the Bay (31, p. 3), are $27.04 million (1963 dollars) for a single lane to span the Bay. Berkeley Hills tunnel costs, derived from actual BART construction costs for drilling and boring 5.3 km (3.3 miles) of double tube, are $24.01 million (1963 dollars). Parking-structure costs are based on costs for downtown San Francisco's Firth and Mission Street garage (32, p. 125) and on an estimate of the 3-h peak-period requirement for automobile spaces.

Alternative automobile and bus patronage is allocated by using 1976 pre-BART modal-split factors for BART patronage, which have been developed from a May 1976 survey of BART patrons that showed that approximately 46.5 percent of pre-BART peak-period trips to the San Francisco CBD have been diverted from buses. Peak-hour modal-split figures generated from this source were used on a segment-to-segment basis to determine highway requirements. A highway lane capacity of 2000 automobiles/lane•h or 1250 buses/lane•h is used. Modal-split data for the entire day, for all patrons, show that 56.5 percent of the BART patrons who previously used either automobiles or buses had used automobiles. This factor was used to determine alternative highway operating costs (Table 7) even though a larger

Table 6. Incremental construction costs for highway alternative to BART.

Condition	Requirements for Both Directions	Total Construction Costs ($000 000s)[a]	Total Energy Costs (PJ)
Current BART demand (131 300 trips/d)			
Urban highways	20.5 lane·km	11.18[b]	1.32
Urban-suburban fringe highways	122.6 lane·km	21.88[b]	2.59
Berkeley Hills tunnel	2.3 lanes	27.56	2.26[c]
Trans-Bay crossing	3.5 lanes	95.45	11.30
CBD parking structures	12 672 spaces	28.70	1.98[d]
Total		184.77	19.45
Projected 1981 four-route service demand (185 000 trips/d)			
Urban highways	34.9 lane·km	19[b]	2.25
Urban-suburban fringe highways	208.5 lane·km	37.22[b]	4.41
Berkeley Hills tunnel	3.1 lanes	37.21	2.57[c]
Trans-Bay crossing	5 lanes	135.19	16
CBD parking structures	21 675 spaces	49.09	3.39[d]
Total		277.71	28.62

Notes: 1 PJ = 948 billion Btu; 1 km = 0.62 mile.
Unless otherwise noted, a conversion factor of 118.4 MJ (112 200 Btu) per constant 1963 dollar is used.

[a] Constant 1963 dollars.

[b] Costs (9, p. 28) converted to constant 1963 dollars of $544 130/lane·km ($875 694/lane mile) of urban highway and $178 432/lane·km ($287 159/lane mile) of urban-suburban highway.

[c] BART conversion factor of 81.9 MJ/dollar (77 605 Btu/dollar) (30).

[d] Facility construction factor of 69 MJ/dollar (65 400 Btu/dollar) (1, p. 670).

Table 7. Operating energy costs for BART and for highway alternative.

System Option	Operating Energy (kJ/passenger·km)				
	Construction of Vehicle[a]	Propulsion	Stations and Vehicle Maintenance	Total	Total Annual Operating Energy (PJ)
BART					
Current three routes with 723 495 000 passenger·km/year	43	1721	698	2462	1.78
Upper bound on four routes with 1 019 583 000 passenger·km/year	43	1488	511	2042	2.08
Lower bound on four routes with 1 019 583 000 passenger·km/year	43	1349	465	1857	1.89
Highway					
Average automobile and bus					
Automobile (6.1 km/L)	604	4685[b]	1071[c]	6360	
Bus (2.3 km/L)[d]	58	1532	564	2155	
Average[e]				4531	
723 495 000 passenger·km/year					3.28
1 019 583 000 passenger·km/year					4.62
Future automobile and bus					
Automobile (11.7 km/L)	335	2454	570[c]	3359	
Bus (2.3 km/L)	58	1532	564	2155	
Average[e]				2835	
723 495 000 passenger·km/year					2.05
1 019 583 000 passenger·km/year					2.89

Notes: 1 kJ/km = 1.53 Btu or 0.000 45 kW·h/mile; 1 PJ = 948 billion Btu or 277 million kW·h; 1 km = 0.62 mile; 1 km/L = 2.35 miles/gal.
Occupancies (passenger kilometers per vehicle kilometer) are 21.4 for BART, 1.3 for automobile, and 11.5 for bus.

[a] Data given by Fels (4, p. 300) converted by using 3.6 MJ/kw·h; conversion inefficiencies were already included.

[b] Including total refining costs in conversion of 37.3 MJ/L (133 800 Btu/gal) for gasoline and 41.2 MJ/L (147 800 Btu/gal) for diesel.

[c] Average conversion of 76.24 MJ/dollar (72 260 Btu/dollar) (7, p. 22) and $0.019/vehicle·km ($0.03/vehicle mile) (or 23 percent of propulsion cost) for automobile maintenance and tires and $0.087/vehicle·km ($0.014/vehicle mile) for bus.

[d] Diesel efficiency of Alameda-Contra Costa County Transit.

[e] 56.5 percent automobile, 43.5 percent bus.

Table 8. BART energy-payback periods versus automobile efficiencies.

Condition	Construction Energy Factor Used	Payback Period (in years) Versus	
		6.1-km/L Automobile	11.7-km/L Automobile
Current BART demand of 131 300 trips/d and operating energy of 2462 kJ/passenger·km (723 495 000 passenger·km/year)	Healy	36.5	—[a]
	Bezdek and Hannon	14.4	—[a]
Projected 1981 four-route BART service (185 000 trips/d and 1 019 583 000 passenger·km/year)			
2042-kJ/passenger·km operating energy	Healy	17.9	56.3
	Bezdek and Hannon	4.9	15.3
1857-kJ/passenger·km operating energy	Healy	16.7	45.6
	Bezdek and Hannon	4.6	12.4

Note: 1 kJ = 0.948 Btu; 1 km = 0.62 mile; 1 km/L = 2.35 miles/gal.

[a] Comparison with the 11.7-km/L (27.5-miles/gal) automobile is not appropriate because BART will be in four-route service with a minimum of 1 019 583 000 passenger·km/year (633 538 000 passenger-miles/year) by 1981. The on-the-road automobile is not likely to approach this average gasoline consumption until well after introduction of 11.7-km/L automobiles, in 1985 or later. Using the Healy factor gives 202.2 years and using the Bezdek and Hannon factor gives 79.7 years for these cases.

proportion of the longer trips would be associated with the automobile, which consumes more energy.

OPERATING ENERGY REQUIREMENTS OF BART AND ALTERNATIVE HIGHWAY-BASED MODES

The total operating energy requirement for BART and the portion of that requirement represented by traction energy are given in Table 7. This analysis uses a California Department of Transportation conversion ratio of 2.07 J of energy used per joule of electrical output (7095 Btu/kW•h) to reflect the efficiency of hydroelectric power sources in California. Lave's calculation compares the total energy use of BART, including maintenance and station energy use, with the traction energy requirements of other modes of transportation. Any comparison that ignores the energy required to operate and maintain highways, parking facilities, and garages and at the same time includes those energy costs for BART is biased against rail transit. This analysis makes some conservative assumptions—also given in Table 7—about the energy costs of these items.

Data in Table 8, which uses the construction energy factors of Healy (30) and Bezdek and Hannon (1), clearly show that BART energy construction costs will be paid back from operating energy savings within a period of a few years. Even the worst cases used for each assumption about automobile energy consumption show payback periods shorter than those estimated by Lave for the ideal transit situation.

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32. Parking in the City Center. Wilbur Smith and Associates, New Haven, Conn., May 1965.

Author's Closure

First, my paper was explicitly an energy analysis, nothing more. There are many possible reasons why some given city might want to build a rail transit system, and saving energy is only one of them. If a properly done benefit/cost analysis of these other factors shows that a rail system is justified, then the slightly adverse energy consequences may, of course, be ignored.

In the following comments, I take up the points of each discussant in order.

REPLY TO TENNYSON

Energy Conversion

Based on input-output analysis, I use a figure of 81.9 MJ/dollar (77 600 Btu/dollar) to calculate the amount of energy represented by a dollar of construction. Tennyson converts this into a gasoline equivalent by using the retail price of gasoline and the known energy per liter and concludes that my energy-per-dollar conversion factor is equivalent to $0.215 worth of gasoline for every dollar of construction and, therefore, my conversion factor must be wrong because $0.215 is too high a ratio.

But this is not the way that input-output analysis works. Those 81.9 MJ were put in at the source, not at the point of final consumption. Tennyson's calculation based on gasoline price is not relevant because the energy did not come from gasoline but from considerably cheaper energy sources at the origin of manufacture.

Diversion From Automobile Mode

Contrary to Tennyson's statement, I did not take my diversion figures exclusively from the trans-Bay link and ignore East Bay travel. The official BART impact report (3, p. 108) gives a detailed breakdown of prior mode for all three parts of the BART line. When these figures are weighted by the latest total patronage data (3, p. 71), they yield exactly the data in the BART line entry in Table 1. Furthermore, Tennyson's data and mine are in this case essentially identical.

Tennyson says that my 49 percent bus figure for Lindenwold actually represents the total of both former bus and former train passengers. This is true, but my only point was that the majority of the passengers were drawn from other public transit, which is still correct.

Peak-Hour Duration

My 4-h-peak figure comes from the official BART impact report (3, p. 86). Tennyson's 2-h figure comes, as he says, from "personal observation," as does his 9000-automobiles/h figure. In any event, I show below that his resultant lane-kilometer figure does not affect the outcome of my analysis.

Freeway Costs

Tennyson says that urban freeways cost $6.2 million/lane•km ($10 million/lane mile) to build but cites no evidence for this. I used $0.787 million/lane•km ($1.2 million/lane mile), which comes from a careful University of California, Berkeley, study of actual construction experience in California (9, p. 28). National figures from official publications of the Urban Mass Transportation Administration (33, p. IV-19) reveal a cost (in 1973 dollars) of $0.707 million/lane•km ($1.1 million/lane mile) for CBD construction in cities of 500 000 to 1 000 000 population.

Parking Structures

Tennyson requires parking structures for all automobiles diverted by BART. Surely there must be some surplus capacity in existing structures, and surely not all the excess people should be put into parking structures. After all, they were not all going to the high-density San Francisco CBD. Many could have been served by ordinary parking lots. Calculating the cost of such parking structures, however, does not affect my results.

The 1970 cost of a three-level parking structure was $1550/space (33, p. IV-24), which is $2260 in 1974 dollars (Engineering News Record construction index). This amounts to $42.7 million for Tennyson's 18 861 spaces. After this is converted into energy by using the very conservative highway coefficient, the amount of energy required to build parking structures turns out to be only 3 percent as large as the amount of energy necessary to build BART. Clearly 3 percent should not be a source of great concern, and in any event even this figure requires extreme assumptions about necessary parking-structure spaces.

Bus Capacity

I use 1200 buses/lane•h, the appropriate figure (4, p. 304) for a freeway, which is the kind of highway BART replaces. Tennyson uses 120 buses/lane•h, which is appropriate for constantly picking up and discharging passengers on a city street. As an alternative way of examining Tennyson's figure, the resultant passenger capacity would be 120 × 11.5 passengers/bus = 1380 passengers/lane•h compared to that for an all-automobile highway, which is 2000 cars × 1.6 passengers/automobile = 3200 passengers/lane•h. (Both the bus and automobile load factors are national averages.) That is, using Tennyson's suggested figures for bus capacity results in automobiles carrying more than twice as many people as buses on a lane of highway, which is clearly wrong.

Station Operating Energy

The difference here is that I included the energy used to heat, light, and air condition the BART stations and Tennyson wants to use traction energy only. Tennyson argues that the energy used for street lighting and traffic controls is the automobile analog of BART station energy and that, because I do not add the cost of lighting and signals to the operation of automobiles, I should not add the cost of stations to BART. There are three problems with this argument.

First, even if there were no automobiles at all, street lighting would still be needed for reasons of public safety (all of the new automobile-restricted zones still use such lighting). Traffic signals too would still be needed for public transit vehicles, police cars, and fire engines.

Second, Tennyson's argument does not distinguish between marginal effects and average effects. Energy used for street lighting and traffic signals cannot be counted against automobiles at the average rate because the marginal cost of accommodating additional vehicles is essentially zero. In more direct terms, what street lights and traffic signals should we turn off because BART has attracted some former automobile drivers?

Third, before a project is undertaken, all of its costs are marginal costs. The decision to build BART was a decision to incur large yearly energy costs to operate stations. A decision to terminate BART operations (which I am not advocating) would be a decision to save these station operating expenses. These energy costs are directly caused by BART and must be charged against it.

Future Energy Efficiency of BART

The most optimistic figures I have seen for possible improvement of BART energy efficiency show a possible future 25 percent energy-consumption improvement (3, p. 50). Meanwhile, Congress has mandated that automobile efficiency be increased by 100 percent by 1985, and the automobile companies are complying. In other words, BART may possibly improve by 25 percent, if it can double its present ridership, while automobiles will definitely improve by 100 percent. Future changes thus work in the direction of greatly decreasing the relative energy efficiency of BART.

Significance of Changes in Overall Results

Although I have shown that Tennyson's figures for extra lane kilometers of highway and for extra parking structures are not justifiable, if I accepted them and recalculated my results, would it matter? I have already shown that Tennyson's parking structures amount to only 3 percent of the energy cost of BART. As to the differences in highway figures, I calculated a BART-caused savings of 74.8 freeway lane•km (46.5 lane miles) and Tennyson calculated 99.3 lane•km (61.6 lane miles). Using his figure would raise my energy estimates by only one percentage point. That is, my original calculation showed that the kilometers of freeway construction replaced because of building BART amounted to an energy saving that was only 3 percent as large as the energy cost of building BART. Even if I use Tennyson's figures, this estimate would be raised to only 7 percent; thus, my overall conclusion would not be affected.

REPLY TO HOLDEN

Value of Time

The value-of-time concept, on which I did some of the pioneer work with regard to behavioral measures (34), does not seem to be operating in favor of BART. The reason BART attracts so few people out of automobiles is that it is not faster than automobiles for most trips. It is not even faster than express buses for most trips: Their patronage has been growing while BART patronage on parallel routes has been relatively stable. In addition, Holden does not indicate how this value of time is to be incorporated in my energy analysis.

Transit Operating Energy

First, it is irrelevant to compare the energy efficiency of the New York subway system with that of BART. All the literature in the field points out that the older subways operate in denser areas with higher load factors and lower vehicle acceleration and that they use much less energy on station amenities. Second, the BART energy figures are based on actual measured energy consumption over a long period of operation (3, p. 50; 35), and they are nearly identical to figures for the Lindenwold Line (2).

Construction Energy

Holden's position is the reverse of Tennyson's. Holden takes the construction/energy ratio, 81.9 MJ/dollar (22.7 kW•h/dollar), too literally, dividing \$1 by 81.9 MJ (22.7 kW•h) to compute that 1 MJ = \$0.012 (1 kW•h = \$0.04). He then concludes that the energy conversion concept must be erroneous. Because it is the concept that is the subject of disagreement, I will substitute a simpler example of the same concept, namely, the energy represented in a ton of steel. Holden's argument would then be as follows: Claimed energy necessary to make 1 Mg of steel × current home cost of delivered electrical power ≠ selling price of 1 Mg of steel. That is, because Holden observes that the two sides of the equation are not equal, the concept must be wrong. The problem with this analysis is that (a) energy is not the only input used to produce steel and the other inputs have prices too and (b) furthermore, the energy represented by the ton of steel was put in at low cost and high efficiency in the furnace where the steel originated.

REPLY TO LIST

Importance of Energy Considerations

List makes the point that my analysis assumes only energy considerations are important. First, my reply to Holden concerning the value of time is relevant here. Second, for the record, I agree that there are many things a transit system might be called on to do other than to save energy. My paper is explicitly an energy analysis.

BART Energy Investment Versus Marginal Freeway Energy Investment

The comparison I made between the full energy investment in BART and the marginal energy investment needed to handle BART passengers via freeway expansion is the correct one for an energy analysis. If you are trying to make a decision to build a new, heavy rail system, you should balance the cost of building the whole rail system against the cost of accommodating the same number of people on highways—that is, the marginal cost of adding a rail system versus the marginal cost of adding new highway capacity.

List's suggested method of doing the calculation does not give the appropriate numbers. He says (a) BART could carry 21 000 passengers/h, (b) it would take 14 highway lanes to carry this many people, (c) BART is 114 km (71 miles) long, and, therefore, (d) 14 × 114 = 1596 lane•km of freeway (994 lane miles) needed to replace BART. There are two serious problems with this calculation:

1. It assumes that 100 percent of BART passengers come from automobiles. We now know that more than half come from buses; therefore, the 14-lane requirement is far too large.
2. There is no need for 14 lanes of freeway over the entire 114-km BART length. Traffic builds up slowly and only reaches 21 000 passengers/h on one small stretch of BART.

Alternatively, the traffic on the 1596 km of freeway that List says are needed can be compared with the load carried by BART. According to Kabel of the California Department of Transportation, one freeway lane in an urban area can be expected to carry about 18 000 people/d. (This figure is much lower than its capacity—48 000 automobiles/d; it is an expected-use figure for a corridor with enough traffic to justify a rail system.) Using the average BART trip length of 21 km (13 miles) and List's figure of 1.6 passengers/automobile gives 2.2 million person trips/d as the expected use of List's BART-equivalent highway system. But, in fact, BART itself carries only 0.13 million person trips/d. Therefore, the supposedly minimum necessary amount of highway would be used for 17 times as many trips as BART carries.

As an alternative way of looking at this, List says that it would take a 14-lane freeway parallel to BART to serve the people that BART serves. But before BART was built, no place along the route had 14 lanes of freeway. How did those commuters manage to get to work before BART? Furthermore, once BART was opened and somehow diverted 14 lanes of traffic from the existing highway system, why did not someone notice and write about the newly empty freeway space?

List's calculations of required terminal space and freeway width are subject to the same problems mentioned above.

Use of Unique Parameters

It is true that I used the best single estimate I could find for each parameter. However, I performed a tough sensitivity analysis on the final results, which is an alternative procedure for accomplishing List's goal here.

Other Issues

List states that I ignore the cost of a bridge across the Bay. My reply to Usowicz and Hawley, which follows, is relevant here. List then makes a number of points that I do not have the space to deal with here. Even if I accept his points, however, it makes a difference of only three to six percentage points in the energy analysis.

List ends with the statement that other studies dispute my results, and he cites two of them, neither of which is an analysis of BART. These non-BART studies cannot be analyzed here. But, if the weighing of authorities is relevant, I must point out that the recently completed analyses by the Congressional Budget Office (36) make an even stronger case than I do in my paper against energy saving by modern rail transit systems.

REPLY TO USOWICZ AND HAWLEY

First, Usowicz and Hawley also cite two studies that are not analyses of BART to show that other analysts contradict my findings. I deal with this in my reply to List and in my comments elsewhere on this type of analysis (37).

Energy-Conversion Factor

Usowicz and Hawley point out that my energy conversion ratio (in joules per dollar) is based on 1963 data, but my construction costs are in 1974 dollars. They advocate deflating all costs back to 1963 dollars by using a construction-cost deflator. This procedure would only be valid if the energy intensity of construction processes had remained constant between 1963 and 1974; that is, they are assuming that the energy used per real unit of output was constant. In fact, this assumption is contradicted by most of what has happened since the industrial revolution. One of the main reasons that output per unit of manpower has risen is that capital and energy are always being substituted for labor and thus increasing the ratio of energy to output. That is, inflation is working one way, and the change in technology is working the other. But which is dominant?

In 1963, average highway construction consumed 117 MJ/dollar (32.4 kW•h/dollar) of construction cost, and by 1967 this had risen to 124 MJ/dollar (34.3 kW•h/dollar), in current dollars, according to a detailed input-output analysis done by the University of Illinois (38). In other words, despite inflation of 18.8 percent over those 4 years, the energy per current dollar had gone up, not down.

For this period, the only one that has been analyzed by input-output techniques, the Usowicz and Hawley procedure would have understated energy costs by 25.1 percent. Furthermore, not only is their suggested procedure contradicted by the evidence on the increased energy intensity of technology, but it is also inconsistently applied in their own paper. They use the largest deflator, 1.89 ($1705/$902), for BART costs and a much smaller deflator, 1.45 ($1296/$876), for urban freeway costs. [All of these figures are taken from English (32).] That is, by using an inconsistent deflator, they overstate the relative construction-cost ratio. Finally, even if their procedure is used, it still gives an energy payback time of about 240 years: Both transit and highway costs have to be deflated, and so the 30:1 cost ratio still dominates the outcome. As to the proper 1963 energy-per-dollar conversion to use, I used the estimate of Healy and Dick (6), the only one based on actual BART experience.

In summary, then, (a) the only available evidence indicates that the suggested deflator procedure is inappropriate; (b) when Usowicz and Hawley apply it in their own work, they do so inconsistently in a way that greatly favors BART; and (c) even if the procedure is used, it does not alter the conclusion of my analysis.

Highway Costs

Usowicz and Hawley cite English's estimate (32) for the cost of a BART-equivalent highway system. But the English estimate used average daily modal split for the United States rather than the peak-hour BART modal split and average bus load factors rather than peak-hour load factors. English ends up needing 914 lane·km (568 lane miles) of highway to replace the 114-km (71-mile) BART system. In fact the replacement highway system would carry about ten times as many people as does BART. (My calculations in reply to List on relative energy investment for BART and for highway apply here.)

In Table 6, Usowicz and Hawley calculate the incremental size of a highway system to replace BART. Their major costs are for a bridge crossing and a tunnel. Both figures are far too high. According to the official BART impact report (3, p. xv), BART has reduced the total daily traffic over the Bay Bridge by 6000 to 10 000 vehicles. We know that 59 percent of BART patronage occurs during the 4 peak h, which means that BART reduced peak-hour traffic by 885 to 1475 vehicles/h. BART's net effect, in other words, was to reduce bridge needs by less than one lane, but in Table 6 Usowicz and Hawley assume it will take a 3.5-lane bridge to replace BART. This is too much by a factor of about four. (I am, of course, assuming a reversible lane such as the one on the Golden Gate Bridge.) Nor is the cost of a bridge as large as Usowicz and Hawley say. The best source of alternative data here is the projected cost of the Southern Crossing of the San Francisco Bay: $144 million (January 1972 dollars) for an eight-lane bridge, which is only $18 million/lane.

Concerning the question of tunnel replacement, patronage through the entire tunnel line is only 29 percent as much as trans-Bay patronage, which indicates that (at most) BART replaced 250 to 430 vehicle trips/h through the tunnel during peak hours. This is, of course, much less than the capacity of a single highway lane, and yet Usowicz and Hawley base their calculations on using a 2.3-lane highway tunnel to replace BART.

They then take up the need for parking structures and considerably overstate the cost and need for these (I have dealt with this issue in my reply to Tennyson).

In summary, under the most extreme possible assumptions, if I change my analysis to accommodate Usowicz and Hawley, it would make a difference of only three to seven percentage points in my calculation.

BART Modal Split

Usowicz and Hawley based all of their calculations on the assumption that 56.5 percent of current BART passengers were derived from automobiles. They seem to have assumed that all nonbus people must have come from automobiles. The former mode of current BART passengers was 44.6 percent from buses, only 38.7 percent from automobiles, and 1.6 percent from other modes; 15.2 percent had never made the trip before (3, pp. 71, 108, 110, 136, 137). The consequence of their assumption is that Usowicz and Hawley considerably overstate the number of highway lane kilometers necessary to replace BART and considerably underestimate the fuel efficiency of alternative modes.

Energy Conversion Efficiency

In their section on operating energy requirements, Usowicz and Hawley use an energy conversion constant of 2.07 J/J (7095 Btu/kW·h). This is, in fact, the average conversion efficiency in California. About 29 percent of its electricity comes from hydroelectric sources. But there have been no new hydroelectric sources for some years. The marginal megajoules in California, the megajoules that BART consumes, come from fossil fuels with an overall efficiency of only 29.1 percent (site plus transmission loss), which yields a conversion of 3.5 J^2 (11 753 Btu/kW·h). That is, the appropriate constant is 65 percent higher than the one used by Usowicz and Hawley, and BART energy consumption is increased accordingly.

Nonpropulsion Energy

In footnote c of Table 7, Usowicz and Hawley cite Hirst's 23 percent figure (7, p. 22) and then go on to calculate the cost as $0.019/km ($0.03/mile) for automobiles. But, in fact, 23 percent of propulsion costs is only $0.0059/km {0.23 [$0.158/L ($0.042/gal) ÷ 6.11 km/L (14.35 miles/gal)] = $0.0059}. I think the use of these nonpropulsion energy costs for automobiles is questionable in the first place (see my reply to Tennyson regarding station operating energy). In addition, a mathematical mistake has caused the estimates to be three times too big.

Finally, if Usowicz and Hawley want to assess such a cost against automobiles and buses, then they must assess it against BART also. In a recent calculation of BART energy consumption done by the Stanford Research Institute (SRI) for the Energy Research and Development Administration (39), the energy content of current nonsystem operating costs is estimated as 4.01 MJ/passenger·km (6120 Btu/passenger-mile). This is four times larger than the corresponding consumption figure for automobiles given in Table 7 by Usowicz and Hawley; BART energy consumption is nine times greater than the corrected figure for automobiles in Table 7. Furthermore, the SRI calculation of system operating energy is 3.97 MJ/passenger·km (6060 Btu/passenger-mile), which is almost twice as large as the Usowicz and Hawley figure. An alternative estimate of this figure is provided by Sherret of the BART evaluation team (35). He shows that the actual, measured energy consumption of BART last year was 3.53 MJ/passenger·km (5387 Btu/passenger-mile), a figure that is almost as large as the SRI estimate and is considerably larger than the 2.46 MJ/passenger·km (3754 Btu/passenger-mile) that is the basis of the Usowicz and Hawley calculations.

TRIP-CREATION EFFECTS

In an effort to simplify the original analysis, I made a deliberate decision to work at a somewhat abstract level; for example, I did not do a specific analysis of exactly where the highways that would replace BART would have to be located or of the detailed costs of highway widening (which accounts for most of the criticism). To compensate for this deliberate lack of detail I did a conservative analysis that always used the assumptions most favorable to BART; for example, I assumed that no trip-creation effects were caused by BART. I also performed a tough sensitivity analysis at the end of the paper to demonstrate that my overall conclusions were valid no matter what was assumed about the future. A "perfect" analysis might well demonstrate that BART can repay its construction energy in, say, 205.7 years instead of 535, but the conclusion would still remain the same. Furthermore, a perfect analysis is much more likely to show an infinite payback period, which I demonstrate below.

One of my major conservative assumptions about

BART was that it had not created any new trips. Such an assumption defies logic. By making distant suburbs more easily and comfortably accessible, BART obviously encourages people to live farther from their jobs in the city. Such an assumption also defies the empirical evidence: The average BART trip is 40 percent longer than had been anticipated by its planners, and the largest growth of patronage has been at the most distant stations (20).

Assuming that BART has created no new trips also contradicts the results of on-board surveys done shortly after each BART route was opened, which show an overall trip-creation effect of 15.2 percent (Table 1). According to the on-board surveys, 15.2 percent of the passengers indicated that they had never made the trip before. In my paper I ignored these people. If they are to be counted in explicitly, the simplest way to do so is to make a 15.2 percent reduction in the BART load factor in Table 2, which increases energy intensity to 3.67 MJ/passenger•km (1.65 kW•h/passenger-mile). Making the conservative assumption that all of the 1.6 percent who formerly used other modes should be added to those who formerly used automobiles, I calculate that the diversion mode split would be 47.5 percent automobile/52.5 percent bus. Given the energy intensities in Table 2, it is easy to calculate that, on their former combination of modes, these people had an average energy use of 3.59 MJ/passenger•km (1.62 kW•h/passenger-mile). Thus, they use more energy now than they did before. It can be seen, therefore, that moving even this one assumption closer to reality would show that BART can never repay its invested energy. The same thing would happen if I were to use more realistic figures for gasoline consumption.

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Publication of this paper sponsored by Committee on Energy Conservation and Transportation Demand.

Energy-Crisis Travel Behavior and the Transportation Planning Process

Thomas M. Corsi, College of Business and Management, University of Maryland
Milton E. Harvey, Kent State University

This study investigated the adjustment strategies adopted by individual households in response to situations of real and potential fuel shortages and higher prices. It also determined the attitudes of individual households toward regional policies to deal with existing or prospective transportation facilities and costs. The study used a mail questionnaire distributed in November 1975 to a random sampling of households in southeastern Wisconsin. The results suggest that the transportation planning process needs substantial revision only under conditions of excessive fuel-price increases or restricted fuel availability. Moderate and gradual increases in fuel prices are unlikely to bring about significant modifications in the travel patterns of households.

During the post-World War II era, American cities physically expanded as the total population increased, and individual households, encouraged by the relatively inexpensive price of automobiles and fuel, began to locate in single-family homes in suburban areas. The availability of the automobile for the typical American family also enabled families to locate at greater distances from employment locations (5, 6). At the same time, federal, state, county, and local governments made massive financial commitments to the construction and maintenance of highway facilities. The post-World War II era has witnessed the near completion of a 68 383-km (42 500-mile) Interstate highway system as well as thousands of miles of urban expressways and suburban roads. The much improved highway network allowed trucking firms to become major transporters of manufactured goods and large factories to locate on the urban periphery to take advantage of lower land costs and larger available tracts of land (1, 2, 4).

The net result of these interacting factors is what is commonly referred to as urban sprawl. In many American cities, location is not dependent on distance from major activities but on total commuting time from place to place by the family automobile. This increasing reliance on the automobile has meant a commensurate increase in gasoline consumption for urban travel. Present estimates indicate that urban automobile travel consumes about 40 percent of the total energy used in the transportation sector or 10 percent of the nation's energy consumption.

The 1973 Arab embargo on shipments of crude oil to the United States was the first in a series of events that ended the cheap and abundant supply of gasoline to the American household. In 1973 the Organization of Petroleum Exporting Countries also substantially increased the price of crude oil. Although the embargo was subsequently lifted, the higher prices of gasoline remained. These events meant that many individual households had to develop strategies for coping with the situation. Such strategies may be designed to solve either specific transportation problems or a set of transportation problems. The aim of this study is to investigate three major aspects of such strategies devised by households during the period of the energy crisis: (a) the adjustment strategies adopted by individual households in response to situations of real and potential fuel shortages and higher fuel prices, (b) the attitudes of individual households toward regional policies that may be considered for dealing with existing or prospective transportation facilities and costs, and (c) the policy implications of the basic findings.

CONCEPT OF HOUSEHOLD ADJUSTMENT

Given the rigid budget constraint under which the average household operates and the fact that most of the entries in the monthly budget list are fixed, the period of the fuel crisis between 1973 and 1975 must have created situations of stress for many households. One such area of stress is the overcoming of the problem of distance to work, recreation, and shopping.

The literature on stress theory asserts that when stress results in a stress-strain conversion, a stress situation exists and the individual has to devise strategies either to remove the cause of stress or to reduce the situation to more manageable levels. Whatever their goals are, households select from a finite set of alternatives. This selection is largely influenced by the household's socioeconomic attributes and the nature and the intensity of the information available to that household. In this study, the types of alternatives available to households can be described as behavioral and distance-related strategies. These strategies can be categorized as follows (3):

Strategy	Type of Change	Activity	Change
a	Behavior	Journey to work	Change mode Purchase additional, smaller automobile Trade in larger for smaller automobile Sell automobile and do not replace it Postpone purchase of second automobile Purchase motorcycle
b	Behavior	Shopping	Combine shopping trips Combine shopping and other trips
c	Behavior	Recreation	Use public transportation for vacation and other recreation Car pool
d	Distance	Journey to work	Relocate residence Quit job
e	Distance	Shopping	Shop closer to home Move closer to shopping area Make fewer shopping trips
f	Distance	Recreation	Cancel long-distance vacation Take shorter distance vacation

In a set of households, individual households that experimented with combinations of these strategies could be identified. They ranged from households that adopted one strategy in either the distance or the behavior category to households that combined two or more strategies in one category or the other or both categories. The two remaining groups of sample households were those who selected all strategies and those who chose none.

One of the hypotheses proposed and tested in this paper is the null hypothesis (H_0) that there are no variations in the number and combination of strategies preferred by households for coping with the transportation effects of the energy crisis. The proposition that the types of strategies adopted are influenced by the socioeconomic attributes of households is also tested. The following appear to constitute a reasonable set of discriminating variables for the analysis: (a) income, (b) household size, (c) automobile ownership (size and number), (d) household employment characteristics, (e) distance to work, (f) household location, (g) age of household members, and (h) educational level of the household head. The particular strategy adopted by a household is a function of the complex interactions among these variables.

When a situation causes stress to a large part of the population, institutional attempts to reduce or remove the causes of stress become necessary. Such attempts are here called planning policies. In the formulation and selection of such policies, the attitudes of households to the policies must be known. That might lead to the selection of some policies, the rejection of some, and, in some cases, to the identification of a new set of potential policies. This paper attempts to determine household attitudes toward various planning policies for energy-crisis conditions.

STUDY QUESTIONNAIRE

Planners from the Southeastern Wisconsin Regional Planning Commission (SEWRPC) consulted and assisted in developing a questionnaire to determine how shortages and higher prices of gasoline have influenced the travel habits and patterns of households in the past and may influence them in the future. Some of the questions used in that survey are used to investigate the research questions posed here.

The questionnaire was mailed during November 1975 to a random sample of 9881 households in the southeastern Wisconsin region (which includes the counties of Washington, Ozaukee, Waukesha, Milwaukee, Walworth, Racine, and Kenosha), and 1461 usable returns (or 14.6 percent of the total) were received. The highest returns came from the predominately suburban counties of Ozaukee (20.7 percent) and Waukesha (20.9 percent), in which the majority of household heads were employed in professional occupations, were middle-aged, and owned two or more vehicles. These occupational, locational, and demographic biases in the survey are understandable because households with these attributes generally have extensive, diversified travel patterns that would be seriously affected by changes in gasoline price and availability.

PATTERNS AND DETERMINANTS OF HOUSEHOLD STRATEGIES

The questionnaire asked respondents to list the types of transportation strategies they used during the fuel crisis and what strategies they might use if there were a future fuel scarcity and if the price of gasoline were increased by \$0.05/L (\$0.20/gal). Table 1 gives the combinations of strategy selections that characterized the response groups in the sample.

Table 1. Response groups formulated by pattern of strategy selection.

Response Group[a]	Strategy Selection					
	a	b	c	d	e	f
1	No	No	No	No	No	No
2	No	Yes	No	No	No	No
3	Yes	No	No	No	No	No
4	Yes	Yes	No	No	No	No
5	No	No	Yes	No	No	No
6	No	Yes	Yes	No	No	No
7	Yes	No	Yes	No	No	No
8	Yes	Yes	Yes	No	No	No
9	No	No	No	No	Yes	No
10	No	Yes	No	No	Yes	No
11	Yes	No	No	No	Yes	No
12	Yes	Yes	No	No	Yes	No
13	No	No	Yes	No	Yes	No
14	No	Yes	Yes	No	Yes	No
15	Yes	No	Yes	No	Yes	No
16	Yes	Yes	Yes	No	Yes	No
17	Yes	Yes	No	Yes	Yes	No
18	No	Yes	No	No	No	Yes
19	Yes	Yes	No	No	No	Yes
20	Yes	Yes	Yes	No	No	Yes
21	No	No	No	No	No	Yes
22	No	No	No	No	Yes	Yes
23	Yes	No	No	No	No	Yes
24	No	Yes	No	No	Yes	Yes
25	Yes	No	No	No	Yes	Yes
26	Yes	Yes	No	No	Yes	Yes
27	No	Yes	Yes	No	Yes	Yes
28	Yes	No	Yes	No	Yes	Yes
29	Yes	Yes	Yes	No	Yes	Yes
30	Yes	Yes	No	Yes	Yes	Yes
31	Yes	Yes	Yes	Yes	Yes	Yes
32	Yes	Yes	Yes	Yes	Yes	No

[a] Response groups with less than 10 observations are not included in the table.

Table 2. Regional percentage distribution of response groups for actual and future energy-crisis conditions.

Response Group	Regional Percentage Distribution		
		Future Crisis Condition	
	1973 to 1975	Higher Fuel Prices	Restricted Fuel Availability
1	9.172	4.928	2.738
2	3.286	1.848	0.890
3	3.012	1.369	1.711
4	2.533	0.890	0.753
5	1.437	0.958	–
6	1.369	0.890	0.890
7	0.684	0.890	0.753
8	1.095	1.437	1.300
9	2.190	1.095	0.684
10	8.556	3.560	2.122
11	1.848	1.369	1.164
12	7.529	4.312	2.533
13	1.437	1.164	0.890
14	4.928	2.738	2.190
15	1.232	1.848	1.848
16	5.955	7.187	9.582
17	0.753	–	–
18	1.369	0.890	–
19	1.437	1.574	1.027
20	–	1.027	0.753
21	0.890	–	–
22	1.437	0.753	–
23	0.958	–	–
24	7.734	4.244	2.396
25	1.780	2.053	1.437
26	10.268	8.419	7.118
27	3.901	5.544	3.833
28	–	1.437	1.027
29	6.434	29.911	38.809
30	1.095	0.753	1.232
31	0.753	2.190	6.776
32	–	–	0.890
Groups with <10 observations	4.928	4.722	4.654
Total	100	100	100

1973-1975 Period

The basic pattern of behavior change during the energy-crisis period is summarized in the data given in Tables 2, 3, and 4. These data indicate certain basic tendencies.

1. Over 75 percent of the sampled households made multiple adjustments in travel behavior. The most common strategy involved some combination of distance-related and behavioral changes in travel. Some households combined changes in the journey to work with changes in recreation and shopping. Across all categories of households, however (Table 3), the most important method of coping with the crisis is always that involving both types of modifications.
2. Households preferred an adjustment strategy of careful retreat, making changes that caused the least disruption to their precrisis travel patterns and putting off hard decisions that would involve major changes. For example, approximately 70 percent made one or more of the following changes in shopping behavior: combined several shopping trips, combined shopping trips with other trips, made fewer shopping trips, and shopped at

Table 3. Regional percentage distribution of households by number and mix of strategies selected for actual and future energy-crisis conditions.

Number and Mix of Strategies Selected	Regional Percentage Distribution		
		Future Crisis Condition	
	1973 to 1975	Higher Fuel Prices	Restricted Fuel Availability
One			
a	3.012	1.369	1.711
b	3.286	1.848	0.890
c	1.437	0.958	–
d	–	–	–
e	2.190	1.095	0.684
f	0.890	–	–
Total	10.815	5.270	3.285
Two			
ab, ac, bc	4.586	2.670	2.396
de, df, ef	1.437	0.753	–
Both categories	14.168	6.983	4.176
Total	20.191	10.406	6.572
Three			
abc	1.095	1.437	1.300
def	–	–	–
Both categories	24.640	16.769	11.431
Total	25.735	18.206	12.731
Four	20.877	23.614	22.313
Five	7.529	30.664	40.931
All	0.753	2.190	6.776
None	9.172	4.928	2.738
Groups with <10 observations	4.928	4.772	4.654
Total sample	100	100	100

Table 4. Actual and intended behavior change of sample households by strategy category.

Strategy	Percentage Making at Least One Change		
		Future Crisis Condition	
	1973 to 1975	Higher Fuel Prices	Restricted Fuel Availability
a	49.56	68.65	80.29
b	71.87	79.81	85.01
c	32.58	60.03	72.01
d	5.40	5.41	10.75
e	71.04	81.04	86.72
f	41.34	62.22	67.76

Table 5. Actual and intended work-trip transportation mode of all wage earners in sample.

Transportation Mode	November 1975 (%)	Future Crisis Condition: Higher Fuel Prices (%)	Future Crisis Condition: Restricted Fuel Availability (%)
Automobile			
Driver	68.6	63.4	45.7
Passenger in family automobile	9.5	3.3	3.6
Automobile and bus	2.5	2.1	2.8
Car pool	7.2	13.2	17.7
Bus	5.0	6.1	10.1
Motorcycle	0.2	0.9	2.6
Bicycle	0.5	1.5	2.5
Walk	5.7	7.2	8.4
Other	0.7	2.2	6.7

stores closer to home. It should be noted that the first two strategies constitute behavior changes and the last two are distance changes.

3. Besides reducing the frequency of trips and changing the places visited, approximately 50 percent of the sample households made one or more of the following adjustments: purchased an additional automobile that was smaller than automobiles already owned, traded in a larger for a smaller automobile, sold one automobile and did not replace it, postponed purchase of a second automobile, purchased a motorcycle, and shifted mode for the journey to work. These adjustments are all behavioral journey-to-work changes. In approximately 20 percent of the households, at least one wage earner made a shift in the mode used for the journey to work.

4. Over 40 percent of the households made changes in recreation travel. Canceling plans for a long-distance vacation and taking vacations of shorter distances were more frequent adjustments than was using public transportation for vacations because such an adjustment involved a higher out-of-pocket cost, especially for households with children.

5. Residential relocation as a response to the fuel crisis was rare. Only 5 percent of the households moved closer to their place of employment.

6. Nine percent of the respondents are households who indicated no change in their travel behavior.

Future Crisis

Investigating what households did during the 1973-1975 period may give an indication of what they will do in future fuel-crisis situations, but it is not a sufficient basis for formulating policies for the future. Therefore, households were asked to suggest which strategies they might use in two future situations: (a) if the price of gasoline were increased by $0.05/L ($0.20/gal) but no limit were placed on its availability and (b) if gasoline per driver were restricted to 30 L/week (8 gal/week) but the price remained at current levels. These restrictions would last for at least 5 years. The basic findings for these future situations are also given in Tables 2, 3, and 4. In comparison with the 1973-1975 situation,

1. Households are more likely to adopt multiple adjustment strategies in the future. The economic and psychological effects suffered by many households during the energy crisis and the associated flood of information about fuel conservation may have contributed to the decision of many households to cope with such emergencies in the future by experimenting with several strategies.

2. In the two future conditions of higher prices and restricted fuel availability, more than three-fourths of the respondents would modify their shopping behavior by using both kinds of strategies.

3. Approximately 68 and 80 percent respectively said they would make one of the following adjustments under a situation of gasoline price increases or restricted fuel availability: purchase an additional, smaller automobile; trade in a larger for a smaller automobile; sell one automobile and not replace it; postpone purchase of a second automobile; purchase a motorcycle; and shift the mode for the journey to work.

4. According to the respondents, an increase in the price of gasoline of $0.05/L ($0.20/gal) would have a substantially less severe mode-shift impact on the journey to work than would gasoline rationing (Table 5). More households would tend to use car pools and public transportation for the journey to work under conditions of restricted fuel availability than under conditions of higher fuel prices.

5. Even in a future crisis, the sample households would be very reluctant to move closer to their jobs. Only 5.4 percent and 10.8 percent of households in the sample said they might relocate their residences in the two future crisis situations.

SOCIOECONOMIC AND LOCATIONAL FACTORS OF HOUSEHOLD ADJUSTMENT

1973-1975 Period

The following significant relations were found between household adjustment patterns and the attributes of households:

1. Households with younger heads were more likely than households with older heads to change their journey-to-work behavior, to make distance-related shopping changes, and to relocate closer to employment. In general, younger households are more flexible in their travel patterns and less likely to be tied to a particular residential location. They are usually renters and are more likely than homeowners to change residential location in response to higher fuel prices.

2. Behavioral shopping changes, distance-related recreation changes, car pooling, the purchase of a new small automobile, and the trade-in of a larger automobile for a smaller automobile were more common among middle-income households, possibly because of the less diverse travel patterns of low-income households. In contrast, higher income households (over $25 000/year) do not need to adjust because of higher gasoline prices.

3. Individuals with certain occupations had a tendency to respond in similar ways to the higher fuel prices that occurred between 1973 and 1975. Sales workers were more likely to make a change in their recreation behavior (involving the use of public transportation) than were craftsmen, foremen, and operatives. Behavioral recreation changes are generally less likely for a blue-collar homeowner with a large family than they are for a high-income sales worker who can afford the expense of a vacation on public transportation. Clerical workers were the group most likely to move closer to places of employment between 1973 and 1975. Many clerical household heads are nonhomeowners and thus better able to relocate in response to higher fuel prices than are professionals or managers, who are likely to be homeowners. Professionals, managers, and blue-collar workers who were most likely to work either in a central location or in establishments that have a large number of employees have the highest car-pooling rates. Sales persons were the group with the highest percentage of households purchasing a smaller automobile, which in-

dicates that sales persons tend to maintain precrisis travel patterns by purchasing a more fuel-efficient automobile.

4. Households with one or two children made more adjustments in shopping than childless households or households with more than two children, possibly because larger families may have made the necessary distance and behavior adjustments in shopping before the crisis occurred. Because many childless households often have two wage earners, the need for shopping adjustments may not be critical.

5. Geographic location influenced households' use of car pooling and other distance-related journey-to-work adjustments. Car pooling was highest among residents of Waukesha County and then among residents of the exurban counties of Walworth, Ozaukee, and Washington.

Future Crisis

The most important similarities and dissimilarities in the way in which household attributes may have affected adjustment patterns between 1973 and 1975 and the way they may affect them under future conditions of rising fuel cost and restricted quantity of fuel can be summarized as follows:

1. Younger households may again make more behavioral changes in recreation travel and more distance-related changes in the journey to work and in shopping than do older households.
2. In a future situation of restricted fuel availability, sales workers will be more likely to make behavioral recreation changes than will craftsmen and operatives. If the quantity of gasoline is restricted, clerical workers will be more likely to change their journey-to-work behavior than will professional and managerial groups.
3. In a future fuel crisis, families with one or two children are more likely to make changes in their shopping patterns than are childless families or those with more than two children. This was also true of the 1973-1975 period.

The basic patterns that emerged from an analysis of future household adjustments are similar to those that emerged from an analysis of behavioral change between 1973 and 1975. Although in certain cases the number of significant contributing variables was greater for the two future categories than it was for behavior between 1973 and 1975, in all cases actual behavioral changes contributed significantly to the explanation of intended behavioral changes in future crisis situations.

HOUSEHOLD ATTRIBUTES AND ATTITUDES TOWARD PUBLIC POLICY

The questionnaire also investigated the attitudes of the sample population toward certain potential public policies. The major policy areas examined were (a) gasoline price levels, (b) freeway construction, (c) bus transportation costs, (d) public subsidy for bus transportation, and (e) fuel conservation measures. An analysis of the responses to these five types of policies indicates that households prefer those policy alternatives that minimize costs or maximize benefits to themselves, that they seek to maintain current travel patterns at current prices, and that they are most willing to accept policy changes that will adversely affect groups other than themselves. Opposition is greatest to policy alternatives that increase costs or threaten to disrupt current travel patterns.

Gasoline Price Levels

Households were asked to determine a gasoline price threshold beyond which they would make significant changes in their travel patterns. Approximately 30 percent cited $0.21/L ($0.80/gal) or more. Only 9.9 percent of the households stated that a gasoline price level of $0.13 to $0.15/L ($0.50 to $0.59/gal)—the actual level of gasoline prices at the time of the survey—would bring about significant changes in travel patterns. The results suggest that high-income households or households with wage earners in certain occupation groups (sales workers, managers, officers, proprietors) have very high gasoline price thresholds. In contrast, low-income households or households in which wage earners are craftsmen, foremen, operatives, and workers and laborers employed in private homes have very low gasoline price thresholds.

Freeway Construction

Approximately 65 percent of the respondents felt either that the planned freeway system should be completed or that it should be completed and expanded. More than 27 percent believed that the construction of freeways should be stopped. Suburban households that rely heavily on the automobile and need to shorten lengthy work trips were more likely to support additional freeway construction than were low-income households or those in which heads of households were older.

Bus Transportation Costs

Approximately 70 percent of the respondents believed that public transportation costs should be shared between the rider and a combination of federal, state, and local support. About 25 percent believed that transportation costs should be assumed entirely by the rider. Households opposed to public financing of bus systems are more likely to be high-income, suburban households to whom bus service is not currently available. In spite of the fact that only a small percentage of households in the study region use the bus system on a day-to-day basis, substantial support exists for the maintenance of a bus system.

Local Sources of Public Subsidy for Bus Transportation

The questionnaire tested attitudes on the sources of local funds for a public transportation subsidy. The specific local sources considered were taxes on property, sales, income, and vehicles. Only 6.8 percent of the respondents believed that local subsidy funds should come from a local property tax. In contrast, 28.9 percent felt that a local sales tax should be used to collect the transportation subsidy and 18 percent preferred the local income tax. The highest percentage of households (31.3 percent) favored a local vehicle tax. Fifteen percent of the respondents did not favor any of the stated local sources. In fact, many households in this group were opposed to the use of any local funds for a public transportation subsidy.

A review of the attributes of particular household groups indicates that support for the use of a local income tax was highest among low-income groups (those least affected by increases) and lowest among high-income groups (those most affected by increases). Support for the use of a local vehicle tax was greatest among younger households and lowest among households in Waukesha County, the most automobile-dependent county in the region. In general, greater regional support was found for either a local sales tax or a local vehicle tax than for a local property tax or a local income tax.

Measures to Increase Fuel Conservation

Respondents were asked to list their first, second, third, and fourth choices among a series of policy suggestions designed to increase the conservation of gasoline. The four specific policy choices were (a) place a higher tax on a liter of gasoline, (b) place a higher registration fee on large than on small automobiles, (c) ration gasoline, and (d) offer free or reduced-fare bus transportation.

Among the 1445 respondents identified by geographic location, the policy indicated by the most respondents (approximately 36 percent) as first choice was a higher registration fee for larger automobiles. Logically, this policy represents the least threat to existing travel patterns and costs. Once the higher fee is assessed, the action in no way restricts the amount of driving an individual may do. The next most popular policy action—the first choice of 27 percent of the households—was free or reduced-fare bus transportation. Again, this type of action represents no basic threat to the current travel patterns of individual households. The two policy alternatives that pose a threat to either the cost of travel or the amount of driving done by households were least preferred: Only 17 percent gave gasoline rationing as their first choice, and 14 percent gave higher gasoline taxes.

The pattern of household attitudes toward the four policy alternatives is clear: Households give greater support to the policy alternatives that have the least adverse impact on them. They will support policy alternatives that do not interfere with current travel patterns or do not adversely affect them economically. Thus, gasoline rationing, for example, would be extremely unpopular. Low-income households would, however, prefer gasoline rationing to substantial increases in gasoline prices that would restrict their travel patterns but would not affect the travel patterns of high-income households.

POLICY IMPLICATIONS OF THE RESULTS

In 1972, SEWRPC conducted a home interview survey to provide the data base for a reevaluation of transportation and land-use plans that were first developed on the basis of 1963 data. The results of the energy-use survey are discussed below in relation to the procedures used in the SEWRPC plan reevaluation report (7) in developing transportation models for the future: trip generation, trip distribution, modal split, and traffic assignment.

Trip Generation

SEWRPC estimated both trip production and trip attraction in the region. Trip-production rates were analyzed and forecast by using the disaggregate technique of cross-classification analysis. Trip-generation rates were explained on the basis of the two independent variables—household size and automobile availability—that were best able to account for variations in trip-production rates. Trip attractions were analyzed and forecast by means of multiple regression based on land uses in the various zones of the region. Trip-generation rates were developed and projected for the following types of trips: home-based work, home-based shopping, home-based other (including personal business, medical-dental, social-eating, and recreation), and non-home-based trips. Trip-generation rates were calculated for four subregional units: the urban areas of Milwaukee, Racine, and Kenosha and all other areas in the region. According to the SEWRPC report (7),

> Separate models for each trip purpose were developed for these four areas because analysis of regional household trip-making as surveyed in 1963 and 1972 indicated substantial differences in trip frequency between urban and rural areas within the Region and between urban areas of different sizes within the Region.

The urban areas of the region had higher trip-generation rates than did the rural areas.

The significant findings of the energy-use survey in relation to trip generation are as follows:

1. The basic pattern of higher trip-generation rates in urban areas remains essentially unchanged in the two future fuel-crisis situations. The study showed that adjustments, especially in shopping and the journey to work, were fewer in Milwaukee County than in the exurban counties of Walworth, Washington, and Ozaukee.
2. The figures for the proportion of people working at home varied slightly from SEWRPC data for the two future alternatives. In general, individuals would continue to go to work, though possibly by a different mode. Under conditions of restricted fuel availability, however, a small percentage of wage earners said they might quit their jobs rather than continue the long commuting journey. Thus, overall trip-generation data for the home-based work trip analyzed for the region by SEWRPC would be affected only slightly by the future restricted availability of fuel.
3. The energy-use survey suggests substantial changes in shopping behavior under the suggested future crisis conditions. One of the major findings is that trip-generation rates may be reduced. Distance-related variations in shopping changes may be evident in future crises. A lower percentage of households in Milwaukee County said that they would change shopping behavior than did households in Racine, Kenosha, Waukesha, and the exurban counties of Washington, Walworth, and Ozaukee. Furthermore, shopping changes would increase as the number of automobiles in the household increased. Such a change would also be higher among households with one or two children than among childless households. In short, trip-generation rates for shopping may decline significantly in either of the alternative future situations. As a result, the data used in the SEWRPC trip-generation tables may need to be reevaluated.

Trip Distribution

The results of the energy-use survey indicate that significant changes may be made in the distribution of work and shopping trips. The basic findings include the following:

1. The energy crisis did not cause a significant amount of residential relocation as a way to reduce the journey to work. Even under future conditions of higher prices and restricted fuel availability, sample households indicated they were very reluctant to move their places of residence closer to their jobs. Thus, regional lines that connect trip ends and their associated trip-length distribution for the journey to work should remain essentially unchanged.
2. In future crises, shopping trips and patterns would be modified. Many households indicated that they would shop at stores closer to home, which implies that smaller neighborhood shopping areas may increase their traffic and therefore their customers at the expense of regional shopping malls. Thus, the 1963-1972 pattern of increase in the mean distance for shopping

trips, attributed by SEWRPC to the increased construction of regional shopping malls, may change during future fuel crises.

Mode Choice and Automobile Occupancy

The results of the energy-use survey also suggest that in future fuel crises changes can be expected in choice of mode for the work trip. An additional $0.05/L ($0.20/gal) increase in the price of gasoline, for example, would effect some mode change in the journey to work. But this effect is substantially less than what might occur under gasoline rationing.

In November 1975, approximately 68 percent of wage earners were automobile drivers. If fuel prices increased, over 63 percent would continue to be automobile drivers. The most important effect of higher fuel prices would be a decrease in the percentage of wage earners who are passengers in family automobiles—from 9.5 to 3.3 percent—and an increase in the percentage of wage earners who are car poolers—from 7.2 to 13.2 percent. In November 1975, 16.7 percent of wage earners were either passengers in family automobiles or car poolers. Higher prices would change this only slightly, to 16.5 percent. Increased car pooling in response to higher fuel prices might bring about greater automobile occupancy if wage earners who ordinarily ride as passengers in family automobiles obtained additional riders for the journey to work. Increased automobile occupancy, of course, would affect vehicle trips in the region (person trips divided by automobile occupancy) and thus possibly influence the traffic-assignment models.

Changes in the journey to work would be far more substantial if fuel availability were restricted. According to the energy survey, the percentage of wage earners who are automobile drivers would decline from the current level of 68.6 to about 45.7 percent. Car pooling would increase from the current 7.2 to 17.7 percent and bus ridership from 5 to 10.1 percent.

Traffic Assignment

Traffic assignment is the assignment of trips to an existing or proposed transportation network. The travel changes predicted in the energy-use survey are bound to reduce the number of trips (especially automobile trips) that can be assigned to the transportation network. Nevertheless, the assignment process would remain unchanged; nothing in the study suggested that the basic rationale for choosing a route between an origin and a destination (i.e., a minimum time path) would be changed. In view of the findings of the survey, however, planners now have the basis for testing the sensitivity of their traffic-assignment models. If fewer trips are loaded onto the system, certain proposed freeway links may no longer be needed. Test runs could determine the amount of trip reduction required to reduce the need to construct specific freeway links. In short, the energy-use survey provides a basis for checking the sensitivity of traffic-assignment results to various future conditions.

SUMMARY

The results of this study suggest that the transportation planning process needs substantial revision only under conditions of excessive fuel price increases or restricted fuel availability. Moderate and gradual increases in fuel prices are unlikely to cause significant modifications in household travel patterns.

ACKNOWLEDGMENTS

This paper was prepared with the assistance and cooperation of the Urban Research Center and the Center for Urban Transportation Studies of the University of Wisconsin—Madison and the Southeastern Wisconsin Regional Planning Commission. The results and views expressed are ours and are not necessarily concurred in by these agencies.

The authors also wish to express appreciation to H. M. Mayer, R. P. Schmitt, E. A. Beimborn, E. Schenker, and H. M. Rose.

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Publication of this paper sponsored by Committee on Energy Conservation and Transportation Demand.

Maximum Potential Energy Savings Resulting From a Cessation of Federal Aid to Urban Highway Construction

William B. Tye, Milene Henley, and Michael J. Kinnucan, Charles River Associates,
Cambridge, Massachusetts

Evidence indicates that a cessation of federal capital assistance to urban highway construction would not contribute significantly to the conservation of energy used for urban highway travel. The effect of such a policy would be weakened by four factors: (a) Additional facilities built with federal grants would not significantly affect highway capacity; (b) federal grants have not been as effective in stimulating urban highway construction as their matching requirements would suggest; (c) off-peak travel, which constitutes most of the total urban vehicle kilometers of travel, would not be significantly affected; and (d) increased congestion would reduce vehicle operating efficiency and thus increase energy consumption. Direct actions to reduce the demand for vehicle travel in metropolitan areas and to improve the fuel efficiency of automobiles will be much more effective than indirect programs such as attempts to restrict highway capacity.

Federal capital grants and other related policies have an effect on the size of the transportation sector and the allocation of demand among modes. Because the transportation sector is a major source of demand for energy, especially for petroleum products, considerations of energy conservation must enter into the determination of federal policies on capital grants to transportation and other related policies.

A recent analysis by Charles River Associates of the impact of federal capital-grant policies (1) concentrated on the energy consequences of federal programs that were judged to have the greatest potential for affecting energy consumption. This paper focuses on an analysis of federal aid to urban highway construction. Limitations of space preclude an analysis here of the other programs, but the Charles River Associates analysis produced results for other programs similar to those for the urban highway program.

The reduction in urban highway construction that would result from the elimination of future federal aid to highway construction has three potential effects on energy consumption:

1. Energy consumed in building highways would be reduced.
2. The resulting reduction in urban highway capacity, by decreasing the peak-period performance characteristics of highways, would lead to a reduction in demand and therefore in peak-period vehicle kilometers traveled. This reduction would lower total fuel consumption by automobiles if the demand were not merely diverted to the off-peak.
3. Increases in peak-period congestion brought about by the deterioration of the highway system would raise fuel consumption per vehicle kilometer driven.

This paper deals primarily with the change in automobile fuel consumption. The direction of the net overall change in fuel consumption in response to a reduction in highway capacity depends on the comparative percentage reduction in vehicle kilometers traveled and the percentage increase in fuel consumption per vehicle kilometer.

This paper uses a sensitivity analysis to evaluate public policy. Rather than producing a "best estimate" of energy savings, it makes simplifying assumptions favorable to energy savings. For example, the additional energy consumption caused by increased highway congestion is not considered. If the resulting energy savings under these assumptions are not appreciable, it is reasonable to assume that energy policy should concentrate on other options.

The maximum potential energy savings that would result from cessation of federal aid to urban highway construction were estimated by using upper bound assumptions on the reduction in urban highway peak-period travel caused by a given reduction in urban highway capacity. Even when these extreme assumptions are used, calculations show only a 1.3 percent nationwide reduction in 1989 urban automobile energy consumption in response to an elimination of the entire urban federal-aid highway program between 1974 and 1989. An analysis by Charles River Associates (1), which was expanded by Toder (4), made a best estimate of energy impact that considered the net effect of energy losses and savings. Reducing urban highway capacity, according to this analysis, would lead to a slight increase in automobile fuel consumption because the energy loss caused by increased congestion would more than offset the energy savings caused by reduced travel.

The findings imply that decisions on the magnitude of federal capital grants to highways should be based on considerations other than direct effects on fuel consumption. The problem of the high fuel consumption that results from automobile travel on congested highways can best be attacked by more direct measures, such as congestion tolls or other highway-entry controls, in selected urban areas that are characterized by the most severe congestion, and improved automobile fuel efficiency, if higher fuel prices are ruled out as a policy alternative.

REVIEW OF PAST RESEARCH ON EFFECTS OF FEDERAL AID ON HIGHWAY CONSTRUCTION

Sherman Model

Sherman (2), in a study sponsored by the U.S. Department of Transportation, studied the effects of federal highway grants on state highway expenditures based on data from each of the 48 contiguous states over a 14-year period from 1957 through 1970. Sherman conducted separate analyses for the three categories of federal-aid highway grants: Interstate, primary, and secondary.

Interstate System

Although the federal assistance program for the Interstate highway system caused a decrease in expenditures on non-Interstate highway systems, it apparently created an incentive for the states to increase their total highway expenditures. According to Sherman's estimates, long-run total state capital expenditures (including the federal portion) on the Interstate system increased by \$1.57 for each incremental dollar of federal aid for Interstate highway construction. To some extent, this increase was at the expense of other highway systems; capital expenditures for primary-system roads dropped by \$0.05 and those for secondary-system roads by \$0.03 for each dollar of federal aid. Capital expenditures on non-federal-aid roads increased by \$0.03, however, so that net state capital expenditures on all categories of roads increased by \$1.52 for every dollar of federal Interstate aid. Total highway expenditures including maintenance and other miscellaneous expenses increased somewhat more, by \$1.62 for every dollar of federal aid received.

Primary System

Primary-system grants were less successful than Interstate grants at stimulating highway investment. Although matching requirements call for states to put up a dollar of their own funds for each dollar of primary-system aid received, Sherman's model indicates that a \$1 increase in primary-system grants actually increased total state capital expenditures for the system (both federal and state shares) by only \$1.72. Moreover, primary-system grants had a depressing effect on all other categories of highway expenditures. The sum of the effects on all categories of expenditures indicates a negligible change in total highway expenditures. Investment in total highway infrastructure did increase but by only \$1.04 for every dollar of federal aid. The net impact of these grants thus appears to be to cause states to substitute funds within their highway programs—that is, increase primary-system investment at the expense of other highway programs and presumably use the federal funds to reduce state highway taxes.

Secondary System

The same general pattern of effects emerges for secondary-system grants as for primary-system grants except that this program, overall, stimulated the aided system in particular and total capital investment in general even less. The net impact of federal grants on total highway expenditures again appears to be negligible. Even within the aided category, a dollar increase in federal aid caused an increase in state capital expenditures of only \$1.04. The effect on capital expenditures for all categories of highways was even less: Each dollar of federal aid increased state expenditures by only \$0.63. Sherman's results indicate that states used secondary-system grants in the same way they used primary-system grants—primarily to reduce taxes earmarked for highway expenditures—and that the slight stimulation to secondary-system expenditures came at the expense of other highway expenditures.

Summary of Past Findings

Although the effect of each of the federal-aid grant programs during the study years was to increase state capital expenditures for the aided highway system in particular and for all highway systems in general, only the Interstate grants stimulated total highway expenditures. Because increases in capital expenditures on the non-Interstate systems reflected decreases in other, noncapital expenditures without substantially affecting states' total highway expenditures, these findings suggest that ending federal aid may cause both (a) a diversion of state funds away from construction to other highway expenditures and (b) an increase in total state commitments to highway expenditures that will make up for much of the lost federal aid.

EFFECTS ON STATE URBAN HIGHWAY CONSTRUCTION AND ENERGY CONSUMPTION OF ENDING FEDERAL AID

Estimating the effects of a cessation of federal aid to urban highway construction from 1974 to 1989 involves three steps:

1. Estimate the effects on state urban highway expenditures from 1974 to 1989,
2. Apply this estimate to reasonable assumptions about the mix and the capacity of highways to be built by 1989 and calculate the reduced highway capacity, and
3. Estimate the effect of that reduced capacity on urban highway travel and energy consumption.

Effect of Cessation of Federal Aid on Highway Expenditures

Sherman's findings may be used to determine the impact on capital expenditures for urban highways of ending federal aid. Under existing federal funding programs, state and local governments would be granted \$11.08 billion of federal aid for urban segments of the Interstate system from 1972 through 1979 (1, 3) and \$17.6 billion for other urban highways from 1974 to 1989. Sherman's results indicate that states would reduce their total capital expenditures (federal and state portions) for urban highways by \$0.87 (a weighted average of \$0.63 and \$1.04) for every dollar of primary- and secondary-system aid lost and by \$1.52 for every dollar of Interstate aid lost. These figures yield the following total reduction in capital expenditures over the 1974-1989 period (in constant 1973 dollars):

$$(\$11.08\text{ billion} \times \$1.52) + (\$17.6\text{ billion} \times \$0.87) = \$32.15\text{ billion} \quad (1)$$

Effect of Reduced Highway Expenditures on Highway Construction

The cost per kilometer of urban highway construction must be estimated if the dollar decrease in capital expenditures for urban highways is to be converted into an estimate of the resultant decrease in kilometers of urban highway construction. In 1973, the total expenditure by all levels of government for the construction of federally assisted urban highways was \$1.56 million/km (\$2.5 million/mile), including the cost of capital improvements to existing facilities as well as the costs of entirely new facilities (3, p. 259). If the mix of urban highways built or improved in the 1974-1989 period is assumed to be the same as that in 1973, then the failure to spend \$32.15 billion over that period represents at most (\$32.15 billion ÷ \$1.56 million/km) = 20 605 km (13 861 miles) of urban highways that will not be built by 1989 as a result of the elimination of federal aid to urban highway construction.

Table 1. Increase in peak-hour traffic flow on urban highways by 1989 as result of federal aid to urban highway construction.

Highway Type	Assumed Average Number of Lanes[a]	Capacity (vehicles per hour per lane)[b]	Additional Kilometers (new and improved)	Peak-Hour Travel on Additional Kilometers[c] (vehicle·km)
Divided				
Full access control	7	1700	5 979	71 150 100
Partial access control	6	1350	698	5 656 230
No access control	5.5	1000	2 817	15 495 700
Undivided				
Four or more lanes	5	850	3 076	13 074 700
Three lanes	3	850	404	1 029 945
Two lanes	2	850	7 718	13 121 280
Total			20 693	119 530 000

Note: 1 km = 0.62 mile.

[a] Selected to represent upper bound.

[b] Intermediate figures based on several surveys because of variance in capacity estimates for different types of highways.

[c] Average number of lanes x capacity x additional kilometers.

Effect of Reduced Highway Capacity on Urban Highway Travel

In attempting to predict the effect of reduced highway capacity on urban highway travel, the issue is how much new travel demand would be created by the new facilities that could be built with the highway aid. Consider two extreme examples of peak-hour demand response to new highways:

1. No new vehicle kilometers of travel may be generated by the new facilities. The only effect of improved highway services during peak hours is a narrowing of the peak as more people find that they can make their trips at the same time. In this extreme case, some off-peak travel shifts to the peak periods but there are no new trips. The result may be a net energy savings attributable to the new facilities if a reduction in peak-hour congestion occurs that is not offset by the increased congestion experienced by diverted traffic.
2. Increased service levels during peak periods may divert riders from transit and otherwise generate a significant number of new or longer trips rather than merely shift demand from the off-peak. In this case, the construction of new highways could be the more energy-saving option only if more energy is consumed without the new highways (because of congestion) than is consumed in the case of improved service levels (because of generated traffic).

If it is assumed that peak-hour levels of service are those primarily affected and that during the peak any new facilities are filled to capacity by new travel, an upper bound effect on urban highway travel of a cessation of federal aid to urban highway construction can be estimated. Specifically, the facilities that would be created by a continuation of federal grants are assumed to be used to capacity in one direction during the two morning and two evening peak hours of each workday, and all traffic served by the additional capacity is assumed to be new traffic generated by construction of these federally aided facilities. Because of the special assumptions of 2-h morning and evening peaks, complete capacity utilization on all new facilities, and entirely new traffic, this estimate should represent an extreme upper bound. Although some additional increased traffic may be expected because of improved off-peak service, it is not likely to be large relative to the generated peak demand.

Table 1 gives the estimated kilometers of various types of highways that would be built with federal aid during the 1974-1989 period as well as the average number of lanes assumed for each type of facility and the capacity of that facility. Capacity figures are instrumental in converting incremental kilometers of highway into incremental vehicle kilometers of travel. The Highway Capacity Manual defines capacity as "the maximum number of vehicles per unit of time that can be handled by a particular roadway component under the prevailing conditions" (5, p. 1). Maximum average speed and average density (vehicles per lane kilometer) on the highway depend on capacity and may be used to derive vehicle kilometers traveled per unit of time on a given facility; that is,

$$(km/h)\cdot(v/lkm) = [(vkm/lkm)/h] = (v/h)/l \qquad (2)$$

where

km = kilometers,
h = hours,
v = vehicles,
l = lanes,
lkm = lane kilometers, and
vkm = vehicle kilometers.

Additional kilometers of highway in Table 1 were derived by deducting the 4142 km (2574 miles) of urban Interstate highways to be built as of 1973 (4, p. 221) from the total 20 693 km (12 861 miles) of highways that would be built as a result of federal aid and assuming that the remaining 16 551 km (10 287 miles) would be divided among the various types of highways in the same proportion as are the existing kilometers of non-Interstate, federal-aid primary and urban systems (4, pp. 245-246). The 4142 km of Interstate highways were then similarly divided among highway categories according to existing highway kilometers (4, p. 264). Data by number of lanes and degree of access control are not available for kilometers of federal-aid secondary highways. Thus, the figures for additional kilometers may be concentrated too heavily in the high-performance highway categories, which may result in an overestimate of increased capacity.

The number of vehicle kilometers traveled in both directions on each type of highway given in Table 1, during each hour of complete capacity utilization, can be obtained by multiplying lane-capacity figures for each type of highway by the number of lane kilometers for each type. That is,

$$[(v/h)/l]\cdot l\cdot km = km/l \qquad (3)$$

The sum of vehicle kilometers traveled on each type of highway yields total vehicle kilometers traveled per hour of complete capacity utilization on all additional kilometers of highway.

If it is assumed that 20 percent of the additional kilometers of highway comprise entirely new facilities and the remaining 80 percent are capital improvements to old facilities that increase capacity by 20 percent (i.e., new vehicle kilometers of travel are 16 percent of total vehicle kilometers of travel after the improvement), then new peak-hour vehicle kilometers of travel would be 20 percent of the total traveled on all additional kilometers of highway plus 16 percent of the remaining 80 percent, or

$$\tfrac{1}{3} \times 119\,530\,000 \text{ km} = 39\,445\,000 \text{ km} \qquad (4)$$

Multiplying this total by two (4 peak hours per day with one-way full-capacity utilization) and by 250 for the number of workdays per year (260 weekdays minus 10 holidays) gives 19.7 billion km (12.4 billion miles), an annual total of new vehicle kilometers of travel attributable to the continuation of federal aid to urban highway construction by 1989. This figure represents 1.3 percent of the projected 1572.6 billion vehicle kilometers of travel on urbanized-area highways in 1989 (6, p. V-15). If the effects of increased congestion on automobile fuel efficiency are ignored, the effect on energy consumption can be assumed to be of a similar magnitude.

Sensitivity Tests

Estimated Effect on Highway Capacity of Cessation of Federal Aid

Because the sample period used by Sherman (2) ends in 1970, his results cannot be brought to bear directly on the numerous significant changes in the federal-aid highway program since that time. The upward revision of the primary- and secondary-system matching ratios in fiscal 1974, the creation of the urban system in 1970 and of three new general highway programs in 1973, and the availability beginning in 1974 of highway funds for mass transit improvements all represent structural changes in the program relative to the period Sherman analyzed. These and other considerations probably cause actual energy savings to be less than forecasts based on Sherman's analysis.

There is some question whether Sherman's findings on the effects of small increases in federal funding may be validly applied to a large decrease. The analysis assumed that the average and marginal effects are the same, i.e., that the relationship is linear so that the first and last federal dollars have the same impact. The actual impact on highway construction of such a large diminution of federal funds would likely be substantially less than the effects of the small changes used in Sherman's analysis. The cessation of federal aid would have to cause a substantial decline in the level of service of automobile travel if it were to appreciably affect travel demand. Such a decline in highway service levels would cause considerable pressure on state and local governments to make up for the loss of federal funding, especially if the federal gasoline tax were also reduced.

Sherman's model did not consider separately the effects of federal aid on urban and rural highways but assumed that urban and rural effects are the same and that the analysis results apply equally well to both urban and rural highways. The general deemphasis on rural and the increased emphasis on urban transportation reflected in the Federal-Aid Highway Act of 1973, however, may reflect changing priorities of state and local governments. If the reduction in urban highway capacity estimated here resulted in a large increase in peak-hour congestion, state and local governments might be pressured to make up for the loss of federal funding by shifting funds from rural to urban highway projects. On the other hand, increased resistance to new highway developments from urban environmentalists might more than compensate for the increased pressure from highway users. In both cases the estimated reduction in urban vehicle kilometers of travel would be too large, in the first case because the reduction in urban highway capacity resulting from an end of federal aid would not be as great as that assumed here and in the second case because the highways would not be built even if federal aid continued.

Since 1970 the federal-aid highway program has been relaxed considerably to permit restricted use of highway funds for mass transit improvements. For example, since fiscal 1974, under certain conditions states may exchange Highway Trust Fund money allocated for a nonessential segment of the Interstate system in an urbanized area of more than 50 000 population for an equal amount from general funds to be used for the construction or purchase of facilities for public transportation. Although the construction and operation of mass transportation facilities also consume energy, this mode is, under certain occupancy and operating conditions, more energy efficient than the private automobile. The extent to which these new provisions will be applied is difficult to predict. However, to the extent that they would be applied, the energy savings resulting from a cessation of federal aid to urban highways would be reduced.

Another consideration that may prevent the energy savings that would result from a cessation of federal aid from being as large as might otherwise be expected is the possibility that large maintenance expenses may consume an inordinately large portion of highway capital expenditures. If federal highway grants have in the past caused an overcapitalization of the highway system at the expense of noncapital needs such as maintenance, these delayed expenses may catch up and create severe pressures for eliminating the requirement that federal funds be used for construction. In the future, the stimulating effect of federal aid may be considerably reduced because the states can no longer neglect noncapital expenditures. Again, to the extent to which these expenditures represent money that would not be spent on new highway construction in any case, the estimates of the reduction in highway capacity and energy consumption are too high.

Some of the evidence cited by Sherman suggests that the federal-aid program had virtually no impact on states' decisions to invest in highways: Namely, states spent more than the minimum required to qualify for the maximum aid available. Matching requirements do not necessarily ensure that the recipients will spend more than they otherwise would have on the subsidized program because recipients can merely substitute federal funds for funds they would have spent anyway. For example, with a 50 percent matching ratio, the recipients' incremental investment per incremental dollar of federal aid should fall between zero and $2.00.

Because states are required to put up only $0.11 for every dollar of federal aid received under the Interstate program (specifically, $0.10 for every $0.90), the rational maximum by which states should increase Interstate capital expenditures in response to an additional dollar of federal aid is $1.11. Sherman estimated that the actual increase was $1.52. Sherman's finding that states actually provided more than the minimally required matching funds may contradict the conclusion that the program stimulated state investments because the cost of incremental highways could not have been affected by the grants.

One explanation is that federal highway grants do not cover all costs associated with building highways. This qualification would be particularly important for the limited-access Interstate system, for which a significant number of kilometers of feeder and access streets may be required to complement the main system. Because accounting procedures are not standardized, many states may include these expenses as well as others associated with capital maintenance activities in their cost figures for Interstate highway construction.

Providing further evidence for this hypothesis, Sherman estimated the responses to the level of federal funding of short-run, project-selection decisions within a fixed budget as well as long-run, expenditure-level decisions. He found that, in the short-run allocation process, states allocated exactly the requisite amount, or $1.11, to Interstate construction projects for every dollar of federal grant money received for Interstate construction. It seems possible that the greater state capital expenditures on the Interstate system in relation to the level of federal funding may in the long run be accounted for by state expenditures complementary to the federally assisted portion of Interstate system construction.

The paradox is that Sherman's empirical results indicate that states not only spent more than the minimum amount required to receive the federal aid (which implies that additional construction may not have been stimulated by the aid program because states paid the full cost of additional facilities) but also shifted funds to favor the aided program. One explanation for this economically irrational decision is the "bias effect": The mere offer of aid will cause more to be spent on the aided program than can be explained by the economic incentives of the grant alone.

Estimated Effect of Reduced Highway Capacity on Urban Highway Travel and Energy Consumption

Several factors may cause the actual energy savings resulting from a cessation of federal aid to be less than the upper bound estimate.

1. Many federal-aid highway expenditures, particularly those in smaller cities, would not appreciably affect urban highway congestion and travel demand both because some of the new facilities will not be used to capacity even in the peak hours and because some of the investments would not be for the high-volume facilities assumed in the calculations.
2. Many of the peak-hour trips served by the new facilities are likely to be diverted from the off-peak rather than to represent entirely new trips or trips diverted from mass transit. Scheduling a trip to avoid rush-hour traffic is probably more common than giving up the trip altogether. The likelihood that ending the federal program will cause trips to be diverted to transit is reduced by the fact that the level of bus service will also suffer during the peaks. According to preliminary figures of the American Public Transit Association (7, p. 16), buses carried approximately 71 percent of total transit passenger traffic in the United States in 1974 and 69.7 percent in 1973.
3. Conserving energy by restricting highway capacity and service levels involves an inherent contradiction: If the decline in highway performance is severe enough to discourage trip making, it will adversely affect the energy efficiency of automobiles by creating high congestion levels.
4. If the peak-hour automobile trips eliminated because of reduced federal aid were diverted to transit, the transit sector would use more energy.
5. Ending federal grants for urban highways would result in severe pressures for ending federal user taxes. States might in turn increase their taxes to keep total user charges constant.

On the other hand, certain assumptions in the analysis could be modified to produce somewhat higher energy savings.

1. Total energy savings might be slightly increased because of a saving of highway-construction energy (though the resources conserved may be diverted to other energy-intensive activities). Hirst (8) has estimated that highway construction accounts for 6.59 percent of all direct and indirect energy requirements for automobile use and about 11.11 percent of direct energy use (gasoline consumption by automobiles). If so, a 1.3 percent reduction in urban vehicle kilometers of travel as a result of fewer highways would approximately equal a 1.44 percent reduction in energy use ($1.3 + 1.3 \times 0.1111$) if operating fuel efficiency is unchanged and if resources not used in highway construction do not otherwise consume any energy.
2. More funds might be used for the construction of entirely new facilities than were assumed. However, the estimate of the reduction in vehicle kilometers of travel on urban highways is not highly sensitive to the assumption that only 20 percent of urban highway construction represents entirely new facilities. If as much as 50 percent of total urban highway construction represents new facilities, 58 percent of total vehicle kilometers of travel on all additional kilometers of highway would be new [$0.50 + (0.16 \times 0.50) = 0.58$], and the total expected reduction in urban vehicle kilometers of travel in 1989 would rise to 2.2 percent. The expected reduction becomes as great as 3.8 percent if all highway construction represents entirely new facilities.
3. Improved highway facilities could prompt urban location decisions that increase travel demand by encouraging urban decentralization. The effect of lengthening work trips is included in the analysis of induced peak-hour automobile demand. Although some off-peak, non-work-trip demand might be generated because of the effects of improved highways on residential location, initial, less than conclusive studies of the effect of automobile level of service on trip length (9; 10; 11; 12; 13; 14, p. 5) do not show a strong impact.

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Publication of this paper sponsored by Committee on Energy Conservation and Transportation Demand.

Policy Preferences for Conservation of Transportation Energy in Case of Fuel Shortage

Kenneth A. Brewer and Bernice H. Gray, Engineering Research Institute,
Iowa State University

The attitude and behavior of travelers during the oil embargo of the winter of 1973-1974 were analyzed. Immediately after the embargo period, questionnaires containing forced-choice pairs of combinations from a set of 10 possible transportation-related energy-conservation policy actions were mailed to 2323 households in regions of Iowa that did not contain a city of 50 000 or more population. Tabular analysis of the data indicated that respondents overwhelmingly favored policies of uniform speed regulation and voluntary participation and were strongly opposed to increased prices as a conservation policy. Analysis of the data by means of paired-comparison scales indicated that the aggregate sample was more concerned about the degree of constraint and its effect on life-styles than about the type of conservation policy (pricing versus rationing). Young adults favored severe rationing or severe price increases less than other groups. Persons earning high incomes favored voluntary participation more than speed-limit regulation, and low- and middle-income groups felt the opposite. Regions with few high-speed highways favored the 88.5-km/h (55-mph) speed limit significantly more than did other areas. Public acceptance of any future transportation-related energy policy appears to be strongly related to the perceived distribution of available transportation options.

The oil embargo imposed by the Middle Eastern petroleum-exporting nations from November 1973 through March 1974 created a situation in which transportation-related energy conservation policies could be evaluated. The embargo affected manufacturing processes that depended on relatively cheap fuels, agricultural fertilizer production, homes heated by oil, and those portions of the power industry that used oil-fired furnaces to generate electricity. But the impacts on automobile transportation were the most dramatic and pervasive. The general public, legislative and executive governmental processes, and the market economy were subjected to three conditions:

1. Gasoline shortage—Available gasoline supplies were significantly short of demand in some areas, which produced long lines at service stations;
2. Price rise—The pump price for gasoline approximately doubled in most areas during the embargo period; and
3. Conservation debate—A highly publicized debate developed about the various social and economic aspects of conservation policies.

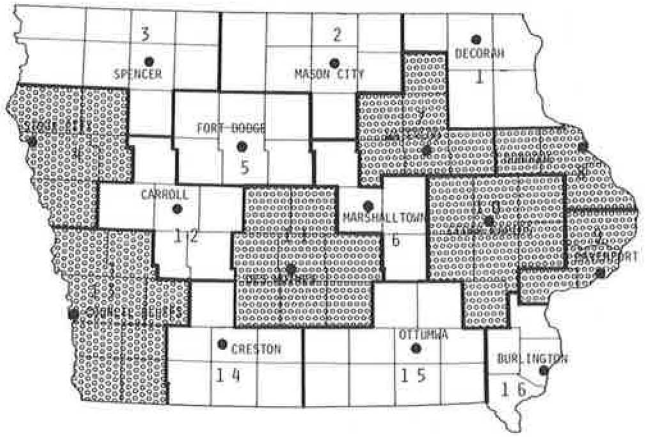
Several research activities resulted that were designed to examine fuel consumption levels and public perception of the long- and short-term impact of policy alternatives (1, 2, 3). The research reported here is one such study.

CONTEXT OF THE RESEARCH

The original research dealt with 59 Iowa counties in nine multicounty planning regions that do not contain cities of 50 000 or more population as regional centers (Figure 1). A random sample of 2323 households was selected from cities ranging in size from 32 366 (Burlington, 1970 census) to 599 (Titonka, 1970 census) to individual rural residences to represent the approximately 1 200 000 persons residing in the 59 counties.

A questionnaire designed to determine individual preferences for policy alternatives and other data to be correlated with the preferences was initially mailed to all sample households. The first mailing was followed up with a postcard—a combination reminder-thank you—7 d later. A second mailing to all nonresponding households about a month later and subsequent telephone contacts brought the total returns to 1837 questionnaires (83.7 percent of the original sample). A total of 1398 questionnaires were completed and analyzed. Deceased persons and untraceable bad addresses accounted for 127 questionnaires, and 3.8 percent of the households refused to participate in the survey. The response rate is attributed to the systematic approach to both the design of the questionnaire and to distribution procedures as well as extensive media efforts to keep the public in-

Figure 1. Nine multicounty Iowa study regions (unshaded areas).



formed of the survey content and the results. These details of the survey are reported elsewhere (4, 5, 6).

FORMAT OF SURVEY QUESTIONNAIRE

A trade-off strategy was used to estimate a preference for one fuel conservation policy over another by the forced-choice method of paired comparisons (7). It is difficult for persons or households to relate an existing value system to an unknown and untried transportation alternative. Questions that require direct valuation—such as, If a bus came to your door and was fare-free, would you ride it?—have in the past overestimated the willingness of people to ride a bus. People are prone to answer yes without comparing the trip advantages at the origin with a potentially more efficient means of reaching the destination. A forced-choice paired comparison always provides reference data for scaled ranking of preferences to avoid such respondent bias.

Several factors were considered significant in establishing the format of the questionnaire items:

1. If n alternatives are presented, (n/2) (n - 1) paired choices must be presented for a complete scale of n factors. Thus, the total number of unique alternatives had to be minimized to ensure a reasonable rate of cooperation on a mailed survey questionnaire.
2. Each alternative policy should be presented at several levels of conservation constraint. Some of the alternatives had to be presented at a severe enough level to involve sacrifice by all households and yet for all alternatives there had to be at least a remote possibility of implementation.
3. The range of alternatives should include price variations, constraints on fuel availability, tax incentives, intercity travel-speed constraints, and various incentives to individual participation. Such diverse alternatives would cover the public debate and experimentation encountered during the embargo period, which households were asked to use as a reference.

Transportation-related energy conservation policy alternatives were then formulated in the form of constraints and incentives, as follows (1 L = 0.26 gal, 1 km = 0.62 mile, and 1 km/L = 2.35 miles/gal):

Constraint	Policy
Gasoline price	
$0.26/L	D-1
$0.40/L	D-2
$0.80/L	D-3
Fuel supply	
75.7 L/week/household	E-3
37.8 L/week/household	E-4
18.9 L/week/household	E-5
Travel speed	
Rigidly enforced 88.5-km/h limit	F-3
72-km/h limit at present enforcement level	F-4
48-km/h limit at present enforcement level	F-5

Incentive	Policy
Individual participation	
Subsidies to bus systems to encourage increased ridership	G-1
Special incentives to car pooling	G-2
Voluntary reduction in household travel	G-3
Tax	
Automobiles with <8.5-km/L efficiency	H-1
Automobiles with < 10.6-km/L efficiency	H-2

These alternatives would have generated 91 separate pairs from which survey respondents would have had to make choices. Consultation with other researchers involved in this kind of research (the mail survey) led the staff to believe that people simply could not or would not complete such a long list of paired choices, especially when it was combined with other survey items. The length of the paired-choice list was therefore reduced by using only two gasoline-price constraints [$0.26 and $0.80/L ($1 and $3/gal)], two fuel-supply constraints [37.8 and 18.9 L/week (10 and 5 gal/week)], one tax incentive to automobile efficiency [<8.5 km/L (<20 miles/gal)], two intercity travel-speed constraints [rigid 88.5-km/h (55-mph) speed limit and 72-km/h (45-mph) speed limit], and all three incentives to individual participation.

Further reduction in the required number of pairs was achieved by assuming that most respondents would not be able to perceive a significant difference between the incentives to voluntary behavior and the other, more drastic alternatives. Thus, no pairs comparing voluntary travel reduction, bus subsidies, and car-pool incentives were presented. A further assumption was that all respondents sought to minimize personal costs and maximize personal options. Therefore, it was assumed that all persons preferred 37.7 L (10 gal) to 18.9 L (5 gal) of gasoline per week as a ration limit, preferred to pay $0.26/L ($1/gal) for gasoline rather than $0.80/L ($3/gal), and preferred a speed limit of 88.5 km/h (55 mph) rather than 72 km/h (45 mph). This reduced the set of paired choices to 39, and these were arranged in random order before the questionnaires were printed.

SURVEY FINDINGS

Compatibility With Socioeconomic Census Data

The table below compares the age, education, and household income of the sample respondents with 1970 U.S. Census data for the survey population (8):

Characteristic	Percentage of Population (1970 Census)	Percentage of Sample
Age		
14 to 18	13.3	0.2
19 to 24	7.8	7.4
25 to 64	58.5	69.6
65 and over	20.4	20.0
No response		2.8
Total	100	100

Characteristic	Percentage of Population (1970 Census)	Percentage of Sample
Education		
No school	0.5	0.1
Some grade school	7.8	1.6
Completed grade school	21.8	11.4
Some high school	14.2	11.9
Completed high school	38.2	35.1
Some college	10.6	19.6
Completed college	6.9	13.7
Trade school		0.4
No response		6.2
Total	100	100
Income		
< $3000	12.4	6.7
$3000 to $4999	12.8	7.8
$5000 to $6999	15.4	8.7
$7000 to $9999	23.6	16.1
$10 000 to $24 999	32.7	45.3
$25 000 and over	3.1	6.5
No response		8.9
Total	100	100

If persons 18 years old and younger are deleted from the total 1970 population distribution, it conforms closely to the indicated age profile of the respondents. It was assumed that in almost all households an adult would complete the questionnaire.

Respondents to mailed-questionnaire surveys tend to be better educated but, because a substantial proportion of the respondents to this survey had not completed high school or had only completed grade school, the education bias was considered minimal. Furthermore, because of a strong correlation between education and income, income was taken to be a better variable than education in explaining variation in preferences. Income levels tended to be higher in 1974 than the 1970 Census indicated they were for 1969. This is partly accounted for by the inflation that occurred between 1969 and 1974 and partly by the higher education levels within the sample.

Overall, the sample group was sufficiently compatible with 1970 U.S. Census information to be considered representative of the approximately 1 200 000 persons residing in the survey regions.

Aggregate Sample Preferences

The percentage rankings of the paired choices made on each pair of alternatives are given below, in descending order of preference. The table indicates average preference for each of the 10 policy alternatives over the other 9 possible choices (n = 1398):

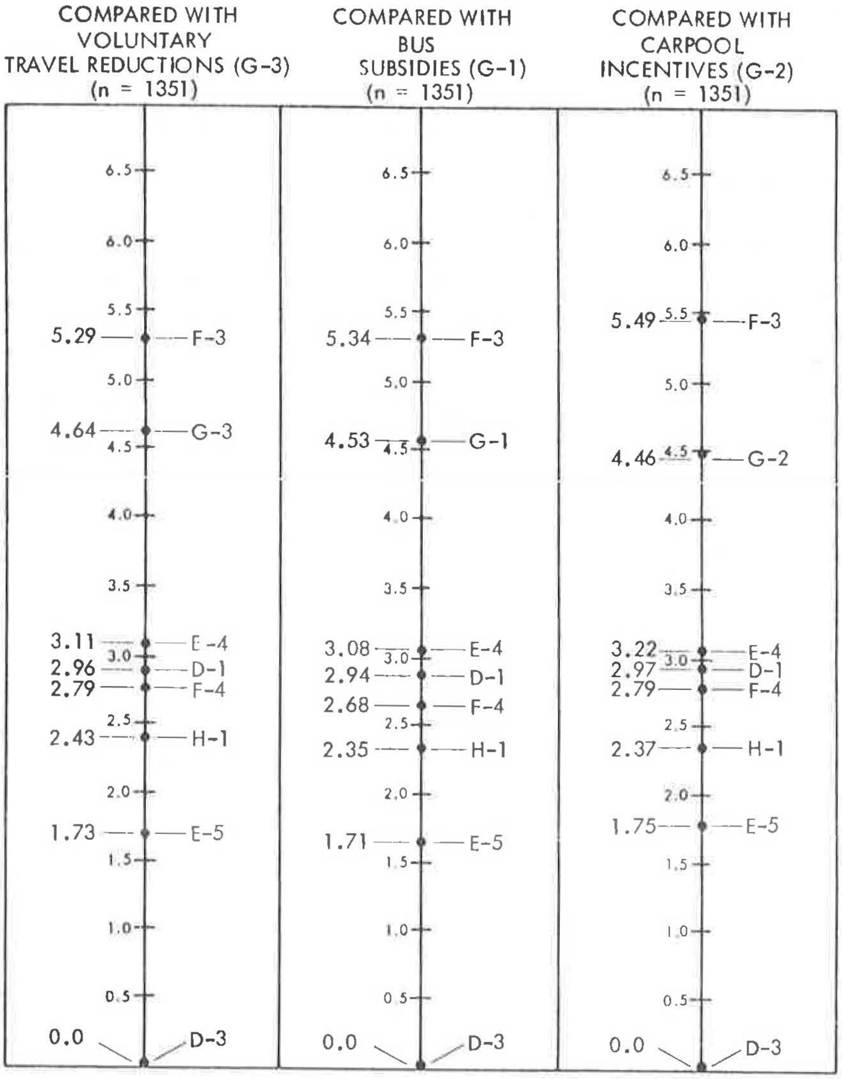


Figure 2. Preference scale for nonvoluntary versus voluntary measures.

Policy	Percentage of Sample Preferring Policy	Policy	Percentage of Sample Preferring Policy
F-3	85.2	E-4	40.7
G-3	75.3	H-1	40.3
G-1	73.9	E-5	22.7
G-2	67.9	D-1	17.4
F-4	55.1	D-3	3.9

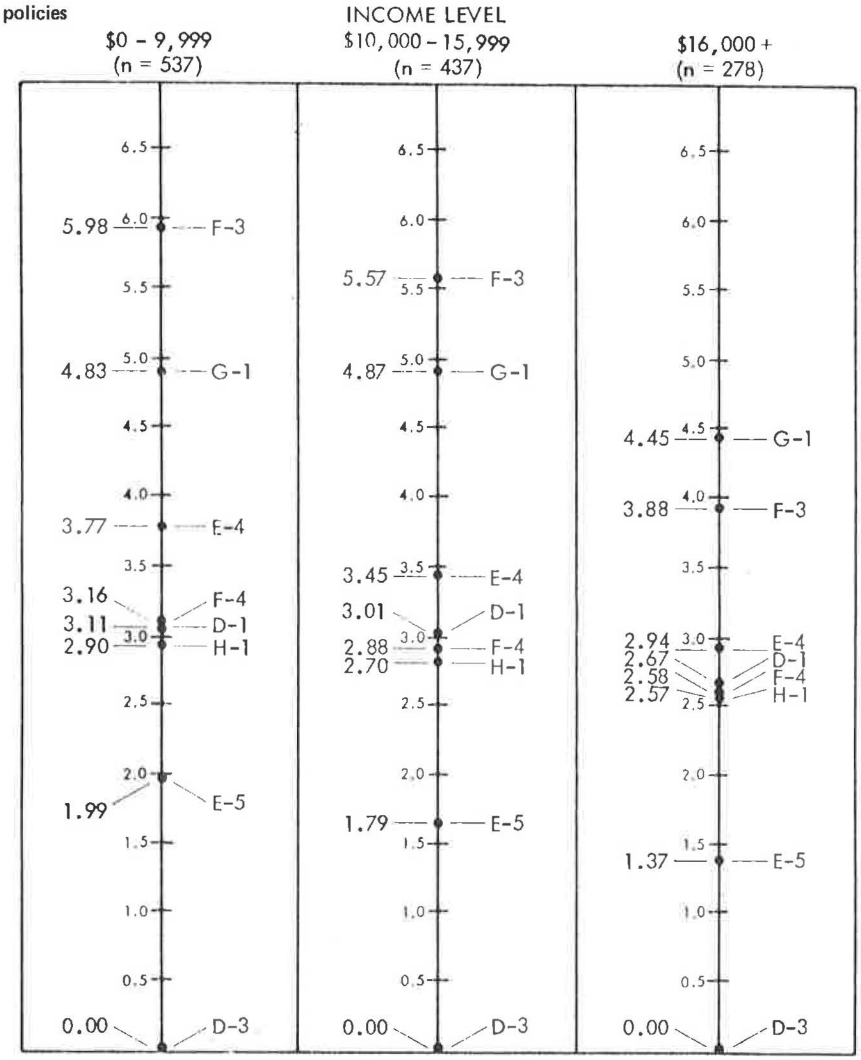
Note that no direct comparison is made among policies G-1, G-2, and G-3.

The respondents have in effect said that they most prefer the current major conservation effort: the 88.5-km/h (55-mph) speed limit. The next most preferred alternatives were those policies that involve incentives to individual behavior, which leave the individual free to participate or not depending on what best suits each person's needs, desires, and opportunities for participation—i.e., voluntary travel reduction, bus subsidies, and car-pool incentives. These are essentially "soft" policies in that none requires a radical restructuring of most life-style patterns. The remaining order and percentages of the preferences seem to indicate that the respondents emphatically preferred strong regulatory measures over greatly increased prices. (Data collected on energy-related policy alternatives have in the past most often been presented and analyzed in this form.)

An analysis of the preferences by use of a paired-comparison attitude scale reveals a somewhat different pattern for the "hard" policies. Figure 2 shows the separate scales constructed for each of the voluntary-behavior policies. The 88.5-km/h (55-mph) speed limit was still clearly the most preferred of the alternatives presented and voluntary travel restriction was the next most preferred alternative in each scale. (Note that the higher the scale value is, the more an alternative is preferred with respect to choices lower in value on the scale.)

D-3 was the least preferred alternative, which is consistent with the raw average preferences. However, E-4, D-1, and F-4 were all about equally preferred, F-4 being the least preferred of the three. This is a reversal of the average preferences given in the table above. Such a finding is particularly important because tabular analysis of the preferences would ordinarily have shown a strong tendency among respondents to indicate a potential willingness to adopt strict governmental conservation measures rather than market price constraints on consumption if large reductions in consumption were required. The relatively high ranking of policy D-1, with respect to all the alternatives presented to the respondents except F-3 and the voluntary-behavior alternatives, suggests that overall the survey respondents were no more strongly opposed to pricing than to other options as a means of curtailing energy consumption.

Figure 3. Preference scale by income level for policies including bus subsidies (G-1).



Policy Preference by Income Level

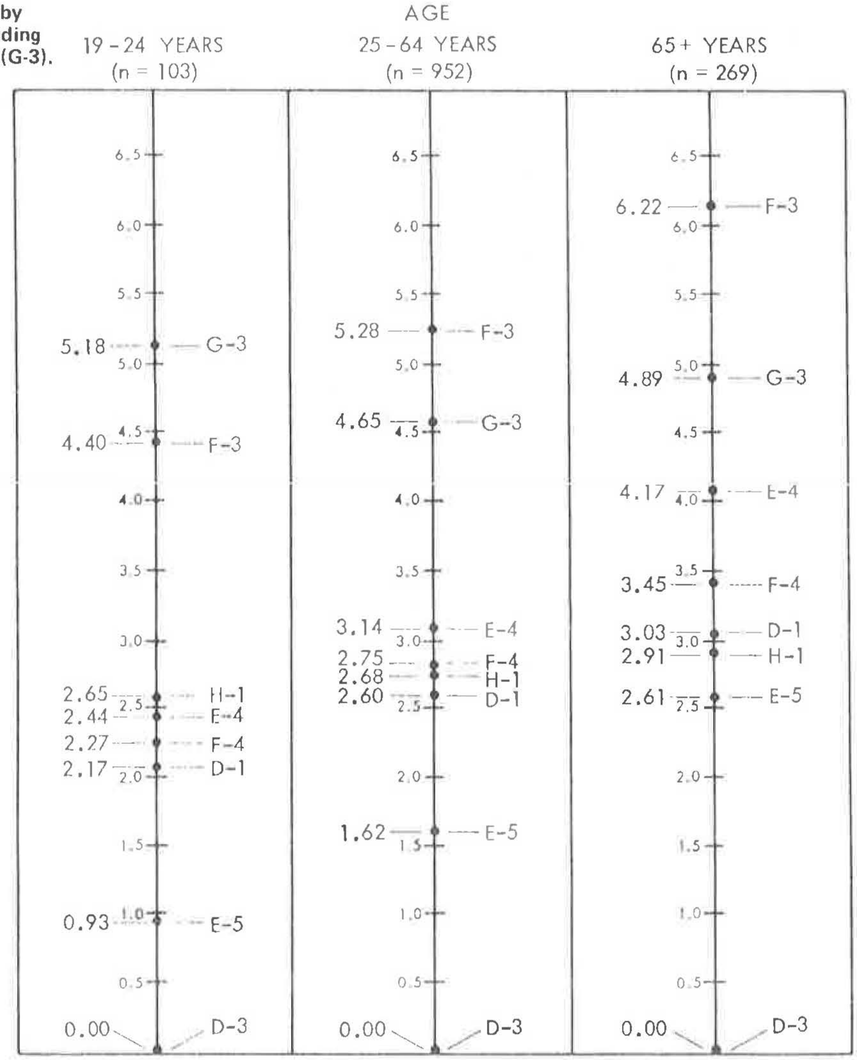
The respondents were subdivided into subsamples by income levels of <$10 000/year (household budgets with little economic flexibility), $10 000 to $16 000/year (households with the potential to have more than one automobile), and $16 000 or more/year (households with sufficient income to purchase alternative transportation in a crisis) to test the possible effect of income bias on the scaling of price-related policies. Figure 3 shows that, in contrast to the total sample pattern, E-4 is now preferred to D-1 by the low- and middle-income groups. These two groups represent about 80 percent of the total population. If one assumes nationwide average annual travel of about 16 000 km/year/automobile (10 000 miles/year/automobile) and current nationwide average automobile efficiencies, 37.7 L/week (10 gal/week) represents a driving allowance of about 10 800 km/year (6700 miles/year). A vehicle that averages more than 8 km/L (19 miles/gal) of gasoline could be driven approximately 16 000 km/year on 37.7 L/week. A gasoline price of $0.26/L ($1/gal) would have represented a doubled price at the time of the survey. The fact that a policy that would on the average tend to curtail travel by one-third is perceived by the vast majority of respondents as being more restrictive (but not greatly more so) than a doubling of fuel prices is interesting.

The high-income scale for all three policies that involve voluntary, individual participation showed an interesting and important shift in the ranking of alternatives. (Although Figure 3 shows only one of the three sets of scales, all three scales were similar.) First, the scales closed up significantly with respect to the zero-value alternative (D-3); extremely high-priced fuel was indicated as acceptable to such persons under certain conditions. Second, the nationwide 88.5-km/h (55-mph) speed limit was perceived as less desirable than the voluntary-behavior policies. Apparently persons with substantial incomes do not value the savings in energy and the greater safety associated with the lowered speed limit as much as they value their travel time for intercity trips. This implies that public acceptance of an energy policy is related to variations in income-related options within the population.

Policy Preference by Age Level

The total sample was factored by age to seek a measure of the age-related effect of life-style on policy preferences. The age groups chosen were those aged 19 to 24, to represent young households without an established community position or occupation; 25 to 64, to represent those in the primary employment years; and 65 and older, to represent the group withdrawing from active participation in the regular travel demands associated with employment. Figure 4 shows preference scales by

Figure 4. Preference scale by age group for policies including voluntary travel reduction (G-3).



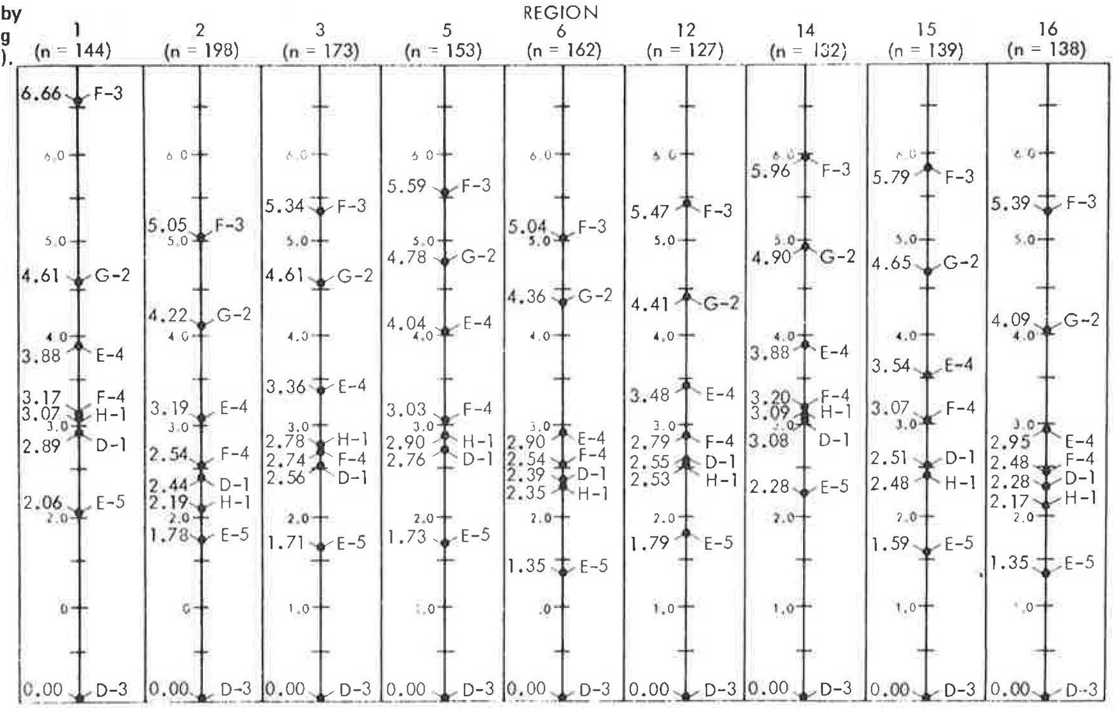


Figure 5. Preference scale by region for policies including car-pooling incentives (G-2).

age group for policy sets containing the car-pooling incentive. (A similar pattern existed for the other scale groups containing voluntary measures.) The 19-to-24 age group ranked the restrictive or hard policy alternatives lower than did the other age groups. Preferences of younger persons tended to be very similar to those of the high-income group; both groups showed no preference for any policy that represents a constraint on household mobility. Younger persons also considered an 18.9-L/week (5-gal/week) ration limit almost as restrictive as a gasoline price of $0.80/L ($3/gal).

The elderly indicated a preference pattern significantly different from that of the total sample. They strongly favored those policies that could be considered to have little or no effect on the life-style of retired persons, such as the 88.5-km/h speed limit and the policies involving voluntary participation. The indication that elderly persons do not favor policies that will constrain their life-style is significant for obtaining public support for conservation policies in states in which a large proportion of the population is over 65 (e.g., Iowa, Nebraska, and Florida).

Policy Preference by Region

The total sample was divided into subsamples by planning regions in which respondents resided. Preference scales by region for policy sets containing the car-pool incentive are shown in Figure 5. Region 1 consistently showed an unusually high preference for the 88.5-km/h (55-mph) speed limit. Region 1 is in the northwest part of Iowa where a large proportion of the highways are in sharp curves and high-speed vehicle operation is thus not safe or prudent. Residents in these regions thus indicated a preference for a policy from which they incur little or no penalty. Representatives of some western states have contended that the nationwide imposition of an 88.5-km/h speed limit is more of a penalty on their areas than it is on the eastern part of the nation. The variations in topography and highway networks found in this sample indicate that these representatives may be expressing the views of their constituents. The preference scales do indicate that any highly restrictive and rigidly enforced energy policy should consider regional variations if widespread public support is needed to ensure policy effectiveness.

IMPLICATIONS AND CONCLUSIONS

The preferences indicated in the total sample illustrated that, immediately after the fuel shortage associated with the 1973-1974 oil embargo, people desired the energy conservation policy that least affected their personal life-style or, as an option, allowed them to decide the conditions under which to participate. Thus, they were most disposed to accept the already existing 88.5-km/h speed limit or to be in favor of actions such as voluntary reduction of travel, car-pool incentives, and bus subsidies. Further stratification of the total sample indicated that young people were not at all in favor of severe ration limits, that high-income groups preferred policies that encouraged individual participation to the existing 88.5-km/h speed limit, that the elderly were strongly in favor of the 88.5-km/h speed limit over anything else, and that areas without high-speed highways preferred the 88.5-km/h speed limit. In other words, people preferred those policies that would least affect their life-style, and after that they preferred those policies that were comparatively less severe in nature. These findings suggest that, in making future policy choices between the hard options of rationing and pricing, the issue is not which of the two is a more acceptable philosophy to the public but whether the resulting distribution of supply is perceived as acceptable to the household life-style, regardless of the form the conservation policy takes.

ACKNOWLEDGMENT

The research on which this paper was based was supported by funds from the Office of University Research, U.S. Department of Transportation, and the Engineering Research Institute, Iowa State University. We gratefully acknowledge this support but also state that the

findings and conclusions are solely our responsibility. The manuscript was typed by Nante Brewer.

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Publication of this paper sponsored by Committee on Energy Conservation and Transportation Demand.

L_{eq} Traffic Noise Prediction Method

J. J. Hajek, Ontario Ministry of Transportation and Communications

The development, accuracy, reliability, and application of the L_{eq} highway noise prediction method developed in Ontario are outlined. This empirical method for predicting energy-equivalent sound levels is based on 182 sound measurements taken near rural and urban freeways, highways, and residential streets. The method is in the form of a nomograph and can be used to predict traffic noise on both highways and residential streets. The standard error of estimate for the L_{eq} method was about 2.24 dBA. Comparisons of measured and calculated L_{eq} levels indicated that this method is more accurate than the Revised Design Guide method of the National Cooperative Highway Research Program. The paper also outlines a simple method for direct prediction from annual average daily traffic volumes of day-night A-weighted equivalent sound levels (L_{dn}) caused by traffic noise.

The original 1974 Ontario highway noise prediction method predicts L_{10} and L_{50} sound levels (sound levels exceeded 10 and 50 percent of the time) for all typical highway situations (1). The accuracy of the L_{10} predictions provided by the method has been shown to be equal to or better than the accuracy of the predictions of some more complicated methods (2, 3). However, the original Ontario method does not enable the prediction of energy-equivalent sound level (L_{eq}), which is now coming into common use. For this reason, the method has been expanded to include a simple, reliable prediction of L_{eq}.

Some of the characteristic differences between the L_{eq} and L_{10} measures and the reasons for the growing use of L_{eq} are as follows:

1. A recent experimental study by Pearsons and others (4) concluded that L_{eq} correlates with annoyance and speech interference caused by traffic noise as well as or better than L_{10}. Although other studies (5, 6) have not reached exactly the same conclusion, they have not established a practical difference between L_{eq} and L_{10} in regard to the correlation with annoyance caused by traffic noise. This may be explained by a very high correlation between the L_{eq} and L_{10} levels themselves (2).

2. The adoption of a universal noise measure for the measurement and evaluation of all transportation noise sources is one of the basic requirements for transportation noise control (and noise-pollution control in general) and for consistent and integrated analyses of transportation systems. For example, a transportation planner should be able to compare directly the noise environment near an expressway with the noise environment near a railroad. This requirement cannot be met by using L_{10}.

3. Units of measurement for transportation noise should be understandable to planners, who in turn should be able to explain the results of noise studies to the public. L_{eq} does not appear to be more difficult to grasp than L_{10}. Both units generally use the A-weighting.

4. Because L_{eq} for any given period does not depend on the sequence in which noise events occur, a theoretical prediction of traffic noise that uses L_{eq} is less complicated than a prediction that uses L_{10}. This also applies to the prediction of noise from other sources, such as railway, construction, and industrial noise.

5. L_{eq} is potentially easier to measure than L_{10}; savings in instrumentation costs can be expected to result from the adoption of L_{eq} as a universal noise measurement. A relatively cheap instrument for direct L_{eq} measurement is becoming available.

6. The adoption of a widely recognized measurement unit makes the studies, research, and experience of other countries fully accessible. The trend in both the United States (7) and Europe (8) is definitely toward the use of L_{eq}.

7. Units of sound measurement should enable easy manipulation of measured or calculated quantities. L_{eq} levels emitted by different sources can be added, but adding L_{10} or similar statistical measures is rather complicated. (Direct addition of the L_{10} levels from two sources may not yield the L_{10} of the sources operating together.) These considerations are important in, for example, noise analyses of joint rail and highway corridors.

DATA BASE

The original Ontario highway noise prediction method (1) is an empirical method based on about 130 noise measurements taken in the field by the Ontario Ministry of Transportation and Communications (MTC), for various planning and design purposes, between 1970 and 1973. The description of these measurements (including variables of location, traffic volume and speed, and distance) is given by Hajek (9). The L_{eq} method used these measurements as well as an additional set of 55 measurements taken between 1973 and 1976. Most of the additional measurements were taken in the vicinity of nonexpressway facilities (two-lane highways and residential streets). The locations at which the L_{eq} measurements were taken and the number of observations made at each location are given below.

Facility	Observations
Urban freeways with six or more lanes	
Highway 401, Etobicoke	3
Don Valley Parkway, North York	4
Total	7
Four-lane rural or urban freeways	
Highway 401, Bay Ridges to Newcastle	53
Queen Elizabeth Way near Hamilton	12
Highway 401, Oshawa	19
Total	84
Four-lane highways	
Highway 17, S.S. Marie	1
Highway 27 near Rexdale Boulevard	1
Total	2
Two or three-lane highways	
Highway 17, Naughton-Whitefish	8
Highway 7, Georgetown	4
Highway 17 near S.S. Marie	16
Highway 11, South River	7
Highways 11, 17, 102, Thunder Bay area	9
Miscellaneous, Peterborough area	3
Miscellaneous, Caledonia	7
Total	54
Four or five-lane urban streets	
Woodbine Avenue, North York	19
Kennedy Road, Scarborough	5
E. C. Row Expressway, Windsor	6
Total	30
Two or three-lane urban streets	
Downsview	2
Caledonia	3
Total	5
All observations	182

All MTC observations that satisfied the basic data requirements of accuracy and completeness were included in the study, with the following two exceptions:

1. At several locations where a number of observations were made at the same point, those to be included in the study were selected randomly.
2. All observations made at traffic volumes of less than 100 vehicles/h were rejected because in such instances the background noise may dominate.

The equipment and procedures used in taking sound-level measurements are described by Harmelink and Hajek (10, p. 13). The microphone was located approximately 1.2 m (4 ft) above the ground. The following information was collected for all observations:

1. Traffic volumes—Highway vehicles were classified into four categories (passenger automobiles, light two-axle trucks and vans, heavy two- or three-axle trucks and buses, and combination-unit trucks with three or more axles), and the volumes in each category were recorded simultaneously with the sound measurements;
2. Speed—Speed of vehicular flow was either measured simultaneously with the sound measurements or estimated by using volume-speed relations given in the 1965 Highway Capacity Manual (11) and the posted speed limits;
3. Distance from the edge of the pavement of the first traffic lane;
4. Road and site geometry—The grade of the highway was below 3 percent at all locations; and
5. Weather—Weather conditions when measurements were taken ranged from cloudy winter weather to sunny summer weather, and ground-surface attenuation varied according to location and seasonal conditions.

Table 1 gives average values and ranges of the variables on which the L_{eq} model is based. For example, the distance between the edge of the pavement and the measurement location ranged from 3.3 to 450 m (10 to 1370 ft) and averaged 74 m (226 ft).

There was some disadvantage in using these data for research purposes because the observations were made under a variety of conditions and rigorous attention was not given to data accuracy. However, results based on such wide-ranging data should be applicable to a variety of commonly encountered situations.

L_{eq} MODEL

A number of mathematical models that empirically relate L_{eq} to independent variables such as distance and vehicle flow and speed were constructed and evaluated. The following model for the prediction of L_{eq} caused by highway traffic was chosen for its accuracy and relative simplicity:

$$L_{eq} = 49.5 + 10.2 \log_{10}(V_c + 6V_t) - 13.9 \log_{10} D + 0.21\ S \qquad (1)$$

where

L_{eq} = energy-equivalent sound level during 1 h (dBA),
V_c = total volume of automobiles (highway vehicles with four tires only) (vehicles/h),
V_t = total number of trucks (highway vehicles with six or more tires) (vehicles/h),
D = distance to the edge of the pavement of the first traffic lane (m), and
S = average speed of traffic flow during 1 h (km/h).

The nomograph shown in Figure 1 provides an example of the use of the model as represented in Equation 1.

Statistical Evaluation

The standard error of estimate for the L_{eq} model was 2.24 dBA. Assuming a Gaussian distribution of error, the 2.24-dBA error suggests that in about two out of three cases the predicted L_{eq} levels will be within ±2 dBA or that in 12 out of 13 cases the predicted values will be within ±4 dBA of the true measured values. This applies to L_{eq} predictions for a wide variety of roadway situations (both highways and residential streets) and traffic conditions.

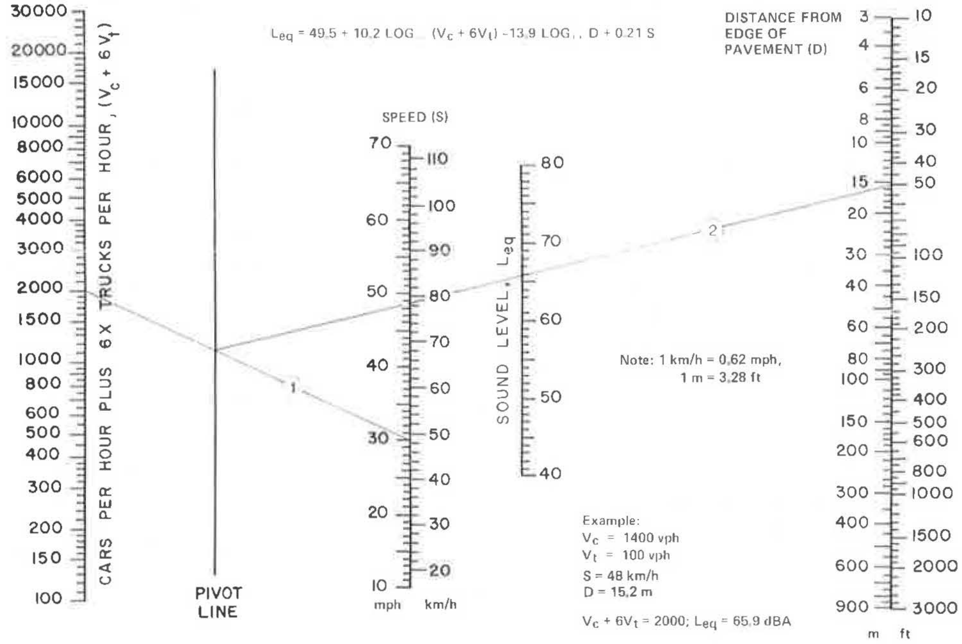
The multiple correlation coefficient of the model was 0.94, which indicates that about 89 percent of the total variance was explained by the model. All partial regression coefficients of the model were significant at the 0.1 percent probability level.

Table 1. Range of variables used in L_{eq} model.

Type of Observations	Variable Automobile Volume (vehicles/h) Max	Min	Avg	Truck Volume (vehicles/h) Max	Min	Avg	Trucks in Total Traffic Flow (%) Max	Min	Avg	Distance From Pavement Edge (m) Max	Min	Avg	Speed of Traffic Flow (km/h) Max	Min	Avg	Measured L_{eq} Sound Level (dBA) Max	Min	Avg
Expressway	7500	570	1636	1170	60	315	26.8	8.6	16.2	450	4	105	108	63	96	84.4	48.3	65.5
Nonexpressway	2356	86	773	368	12	105	43.9	2.3	12.0	230	3.3	41	106	24	70	73.6	49.1	62.6
All	7500	86	1214	1170	12	212	43.9	2.3	14.9	450	3.3	74	108	24	83	84.4	48.3	64.1

Note: 1 m = 3.3 ft; 1 km = 0.62 mile.

Figure 1. Nomograph for prediction of L_{eq}.



Rational Behavior of the Model

According to the model, the average rate of L_{eq} attenuation with distance was 13.9 log D or about 4.2 dBA per doubling of distance. This attenuation rate compares favorably with the rate of 4.5 dBA per doubling of distance obtained for L_{10} sound levels (1). The figure of 4.2 dBA applies to an average ground attenuation along roadways and an observer height 1.2 m (4 ft) above the ground. For higher observer heights, ground-attenuation corrections given by Hajek (1) can be used. However, it is difficult to classify ground conditions along roadways as sound absorbing or sound reflecting. Usually there is a mixture of sound-reflecting surfaces (e.g., the pavement itself, service roads, or driveways), sound-absorbing surfaces (e.g., soft, moist grassland), and "in-between" surfaces (e.g., unpaved shoulders or hard, dry grassland).

The traffic-volume multiplication coefficient of 6 used in the model suggests that the sound level of an average truck is about 8 dBA higher than the sound level of an average automobile. This result is compatible with data given by Foss (12). Note that, although the original traffic volumes were divided into four vehicle categories, these categories were not used in the model because specifically including them did not appreciably improve on the statistical parameters of the model. Automobiles and light two-axle trucks and vans (vehicles with four tires only) were grouped in the automobile category, and all other vehicles were grouped in the truck category.

The speeds of passenger automobiles and trucks are highly correlated. For this reason, only average traffic-flow speed—defined as the average speed of all highway vehicles over a given section of highway during 1 h—was used in the model. According to the model, the L_{eq} levels change with speed at the rate of 0.21 S. This corresponds to a 2.1-dBA increase in L_{eq} levels for each speed increase of 16 km/h (10 mph), all other variables being constant. This rate appears to be reasonable and within the expected range for automobiles and trucks considered separately.

Reliability

An important characteristic of the Ontario L_{eq} prediction method is its empiricism. Empirical models can offer several advantages over theoretical models:

1. Empirical models are based on a substantial number of field measurements that are normalized by the model and thus tend to reflect average conditions, i.e., conditions most likely to be encountered in practice.
2. Empirical models do not need calibration. Results of theoretical models have to be compared with measured results, and when adjustments or corrections are needed they may not be based on rigorous statistical analyses. Many of the principal components of noise prediction methods based on theoretical models (e.g., rate of attenuation with distance) are essentially empirical.
3. Empirical models are easy to understand and easy to use. Their accuracy is usually equal to or better than the accuracy of theoretical models (2, 3).

Table 2. Comparison of measured and predicted L_{eq} levels.

Site	Type of Road	Comments	Average Traffic Speed (km/h)	Traffic Volume (vehicles/h)		Distance From Pavement Edge (m)	L_{eq} (dBA)		
				Automobiles	Trucks		Measured	Calculated	Difference
1	Six-lane arterial	Free flowing	64	2325	90	13.4	68.9	70.3	-1.6
2	Six-lane arterial	Two far lanes closed	64	1068	132	15.2	67.2	67.6	-0.4
3	Four-lane arterial	Stop-and-go traffic	48	2248	84	13.4	69.0	68.0	1.0
4	Four-lane arterial	Stop-and-go traffic	40	3480	60	13.4	69.3	68.5	0.8
5	Eight-lane freeway	Mild upgrades near lanes	89	5210	312	27.1	71.5	73.2	-1.7
						42.4	69.1	70.5	-0.6
						72.8	66.6	67.3	-0.7
						133.8	62.5	63.6	-1.1
6	Eight-lane freeway	Microphone among trees	89	4785	–	15.2	73.2	75.0	-1.8
						28.7	69.9	71.2	-1.3
						59.1	66.9	66.8	0.1
						120.1	60.6	62.5	1.9

Notes: 1 km = 0.62 mile; 1 m = 3.3 ft.
Data for average traffic speed were obtained by the author; calculated L_{eq} data were obtained by the Ontario L_{eq} prediction model (Equation 1); all other data were obtained by Wyle Laboratories (17).

A distinct advantage of theoretical models is their structure, which enables one to analyze and quantify the effects of the various model variables, such as the theoretical effect on highway noise of changes in the noise emissions of different categories of vehicles. Thus, theoretical models are more suitable for analyzing various strategies of vehicle noise control. They may also be more accurate in predicting noise when the variables assume values well outside those in the data of empirical models. However, empirical models can be better for making simple, reliable predictions of traffic noise for day-to-day planning and design purposes, which may explain their popularity in Europe (13, 14, 19).

The standard error of 2.24 dBA obtained for the L_{eq} prediction model compares favorably with the standard deviation of differences between measured and predicted sound levels of 2.5 dBA reported by Kugler (15) or with standard deviations reported by Cohn (2) and Bradley (3) for similar comparisons. In fact, it is possible to hypothesize, on the basis of these data, that the standard deviation of differences between measured and predicted traffic noise levels of about 2.5 dBA or slightly less is a minimum error achievable by universal traffic noise prediction models that use only the basic variables of traffic-flow volume, speed, and distance. Greater accuracy would require the introduction of complex environmental, topographic, and traffic-flow variables.

The measured L_{eq} levels were also compared with L_{eq} levels calculated by using the Revised Design Guide (16), which resulted from a project of the National Cooperative Highway Research Program (NCHRP Project 3-7/3). The results of this comparison were similar to the results reported by Cohn (2) for L_{eq} measurements made by the New York State Department of Transportation: On the average, the L_{eq} levels were overpredicted by the Revised Design Guide by about 2.5 dBA.

As an independent check of the reliability of the Ontario L_{eq} prediction method, the method was used to calculate L_{eq} levels for a complete set of sound measurements taken by Wyle Laboratories on freeways and arterials in southern California (17, p. 25). A comparison of the measured Wyle L_{eq} levels and the L_{eq} levels predicted by the Ontario method is given in Table 2. The average difference between the measured and predicted levels was -0.75 dBA, and the corresponding standard deviation was 1.0 dBA.

APPLICATION OF ONTARIO L_{eq} PREDICTION METHOD

The Ontario method uses the basic relation between traffic-flow density, traffic-flow speed, distance, and the resulting L_{eq} levels established by the regression model. The relation is defined by Equation 1 and by the nomograph in Figure 1. Both the equation and the nomograph calculate L_{eq} levels 1.2 m (4 ft) above the ground for a simple case of traffic flow on an infinitely long, straight, level roadway where there are no intervening structures between the source and the observer. If the problem at hand involves more variables than those included in the nomograph (such as highway grade or intervening structures), adjustments are made in a way similar to that used in the NCHRP Design Guide (18). The step-by-step procedure for application of the Ontario method given by Hajek (9) has recently been modified to permit use of a separate nomograph for noise-barrier attenuation (16).

The Ontario L_{eq} prediction model was also modified to enable prediction of day-night A-weighted equivalent sound levels (L_{dn}) by direct use of annual average daily traffic volumes. The modified model has the following form:

$$L_{dn} = 38.2 + 10.2 \log_{10} [\text{AADT} + (\text{T\%}\ \text{AADT}/20)] - 13.9 \log_{10} D + 0.21\ S \qquad (2)$$

where

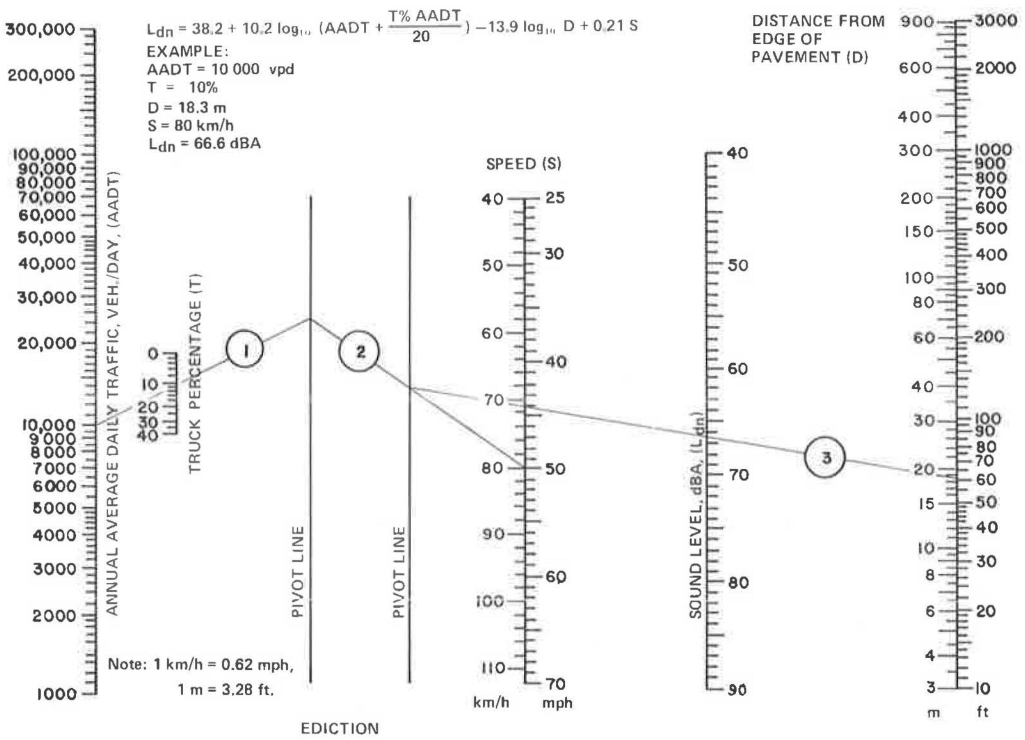
L_{dn} = equivalent A-weighted sound level during 24-h time period with a 10-dBA weighting applied to the equivalent sound level from 10 p.m. to 7 a.m. (dBA),
AADT = annual average daily traffic (vehicles/d),
T% = average percentage of trucks during a typical day,
D = distance from the edge of the pavement (m), and
S = average traffic speed during a typical day (km/h).

(Highway networks are usually divided into highway sections. AADT and other traffic data are available for each section and are updated annually.)

The L_{dn} prediction model is based on the following assumptions:

1. Nighttime traffic (from 10 p.m. to 7 a.m.) represents about 10 percent of the total traffic volume. This assumption is correct on a majority of highway sections.
2. Speed of traffic flow is fairly uniform during the 24-h period. This assumption is incorrect on highway sections that experience periodic traffic congestion.

Figure 2. Nomograph for prediction of L_{dn}.



Note that if the above assumptions are satisfied the following relations apply:

$$L_{dn} = L_d + 1.2 = L_n + 8.6 = L_{eq}(24) + 2.8 \qquad (3)$$

where

L_d = daytime L_{eq} (from 7:00 a.m. to 10:00 p.m.) (dBA),
L_n = nighttime L_{eq} (from 10:00 p.m. to 7:00 a.m.) (dBA), and
$L_{eq}(24)$ = 24-h L_{eq} (dBA).

Equation 2 calculates L_{dn} levels 1.2 m (4 ft) above the ground by assuming a simple case of traffic flow on an infinitely long, straight, level roadway with no intervening structures. Again, by using appropriate corrections, it is possible to expand the L_{dn} model (Equation 2) to include other variables such as barriers and pavement-surface type. The use of the L_{dn} model is illustrated by the nomograph shown in Figure 2.

CONCLUSIONS

1. The Ontario L_{eq} prediction method, based on an empirical model, provides reliable estimates of traffic noise on both highways and residential streets.
2. The standard error of estimate of 2.24 dBA suggests that in two out of three cases the L_{eq} levels predicted by the Ontario method will be within ±2 dBA of the true measured values. This applies to a wide variety of roadway situations and traffic conditions.
3. The standard deviation of differences between measured and predicted traffic-related noise levels of about 2.5 dBA or slightly less appears to be a minimum error achievable by universal traffic noise prediction models that use only simple, conventional variables of traffic-flow volume, speed, and distance. Greater accuracy would require introduction of complex environmental, topographic, and traffic-flow variables.

ACKNOWLEDGMENTS

I am grateful to D. N. May for the review of the manuscript and to the MTC personnel who conducted the field noise measurements on which this report is based.

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Publication of this paper sponsored by Committee on Transportation-Related Noise.

Comparative Analysis of HIWAY, California, and CALINE2 Line Source Dispersion Models

Kenneth E. Noll, Department of Environmental Engineering, Illinois Institute of Technology
Terry L. Miller and Michael Claggett, Enviro-Measure, Inc., Knoxville, Tennessee

This paper provides a comparison of three different, idealized line source dispersion models—HIWAY, California Line Source, and CALINE2—that predict carbon monoxide concentrations near highways. All are based on the Gaussian dispersion equations and are compared by means of sensitivity analysis and model validation. The sensitivity analysis analyzes the dependence of normalized pollutant concentration on variations in several independent input parameters such as stability class, wind angle with respect to the highway, and receptor distance from the highway. The models are validated by comparing carbon monoxide concentrations measured near a highway with concentrations predicted by the models.

Determining the changes in air quality near proposed highway projects often involves the use of mathematical diffusion models (1, 2, 3). These models provide theoretical estimates of air pollution levels and their temporal and spatial variation for present and proposed conditions. The model estimates are a function of meteorology, highway geometry, and downwind receptor location. The sensitivity of model predictions to changes in these input parameter values can be used to evaluate the performance of the diffusion models for a variety of conditions.

The objective of this paper is to provide a comparison of three different line source dispersion models by means of sensitivity analysis and model validation. The sensitivity analysis was performed for specific sets of conditions for the three models. Field measurements of traffic, meteorological conditions, and carbon monoxide (CO) concentrations were used in the model validation.

DESCRIPTION OF MODELS

In the HIWAY model of the U.S. Environmental Protection Agency (EPA), concentrations are calculated by the approximation of a line source by a finite number of evenly spaced, continuous point sources of strength equal to the total line source strength divided by the number of sources used to simulate the line. The California Line Source model calculates concentrations of pollutants within a turbulent mixing cell above the highway as well as at receptor points downwind. Dispersion downwind is dependent on atmospheric stability class. In the case of parallel winds, the California Line Source model accumulates pollutants within the mixing cell to account for downwind buildup. Pollutants are then dispersed laterally at a rate dominated by stability class.

CALINE2, a revised version of the California Line Source model, maintains the mechanical mixing-cell concept of the original California model. In the case of a "pure" crosswind (a wind angle of 90° with respect to the roadway), the mathematical model is based on the Gaussian infinite line source diffusion equation. In the case of a pure parallel wind (a wind angle of 0° with respect to the highway), the highway length is divided into a number of area sources. Each area source is transformed into a virtual point source, and these sources are summed at the downwind receptor. For wind angles other than pure crosswind or pure parallel wind, CALINE2 assumes the wind angle has a crosswind and a parallel wind component. The concentration downwind is calculated from a weighted average of the pure crosswind and the pure parallel wind.

Major Differences

The major differences in the models are as follows:

1. The California Line Source model uses a Gaussian line source equation, and the EPA model uses an integrated point source equation. Under crosswind and parallel wind conditions, the California model requires separate equations for prediction; the EPA model needs only one equation. CALINE2 uses the Gaussian line source equation for the pure crosswind and an integrated point source equation for the pure parallel wind.
2. The EPA model requires separate traffic and emission data for each lane of highway. Both California models use the combined total traffic volume and emission rate for all lanes, assuming that all emissions are initially dispersed from a uniform mixing cell that extends from shoulder to shoulder of the road [medians of <9 m (<30 ft)].
3. The EPA model uses a virtual source correction that provides an initial vertical dispersion parameter of $\sigma_z = 1.5$ m (5 ft). The California models assume a mixing cell with an initial $\sigma_z = 4$ m (13 ft).
4. The EPA model uses dispersion coefficients that differ from the coefficients used by the California models (1, 2, 3).

Assumptions

The following basic assumptions are common to all three models:

1. The mass of pollutants is conserved throughout the downwind length of the plume. No material is lost by reaction or by sedimentation.
2. The ground surface, when it is encountered, is a perfect plume reflector.
3. There exists no wind shear in the vertical direction. The wind velocity used should be representative of the average wind velocity between $\pm\sigma_z$ from the plume centerline in the vertical sense.
4. Dispersion occurs only by turbulent diffusion, which varies according to the atmospheric stability categories developed by Pasquill.
5. Atmospheric stability is constant within the mixing layer that contains both sources and receptor.
6. There is no mixing of material in the x-axis (i.e., longitudinal mixing).
7. Emissions are from continuous sources.
8. The dispersion parameters (σ_y) and (σ_z) are useful for modeling atmospheric dispersion over flat, grassy terrain with no significant aerodynamic roughness or any artificial vertical instability induced by heat-island effects associated with urban areas.

Input Parameters

The input parameters required for the models are

1. Geometry of the highway, that is, road angle with respect to north and road elevation (at grade, elevated, or depressed);
2. Receptor location in both the horizontal and vertical directions with respect to the road;
3. Meteorology including wind speed, wind direction with respect to the road, and Pasquill atmospheric stability class; and
4. Pollutant emission rate from vehicles based on traffic volume and speed, vehicle mix by age, and mix of heavy-duty vehicles.

Model Operations

HIWAY

HIWAY simulates a highway with a finite number of point sources, and the total contribution of all points is calculated by a numerical integration of the Gaussian point source equation over a finite length. The concentration (χ) from the line source of length (L), incremental length ($d\ell$), and incremental emission rate ($q\ell$) is given by

$$\chi = (q\ell/n) \int_0^L F\, d\ell \tag{1}$$

where the function (F), for stable conditions or conditions in which the mixing height is greater than or equal to 5000 m (16 500 ft), can be calculated as follows:

$$F = (1/2\pi\sigma_y\sigma_z)\exp[-\tfrac{1}{2}(y/\sigma_y)^2](\exp\{-\tfrac{1}{2}[(z-H)/\sigma_z]^2\} + \exp\{-\tfrac{1}{2}[(z+H)/\sigma_z]^2\}) \tag{2}$$

where

σ_y = horizontal dispersion parameter (m),
σ_z = vertical dispersion parameter (m),
z = height of receptor above ground level (m), and
H = height of road above ground level (m).

The value of the integral in Equation 1 is approximated by use of the trapezodial rule. Let $\Delta\ell = L/N$. Then the trapezodial approximation gives

$$\chi = q\Delta\ell/u\left[\tfrac{1}{2}(f_o + f_N) + \sum_{i=1}^{N-1} f_i\right] \tag{3}$$

where f_i is evaluated from Equation 2 for $\ell + \Delta\ell$.

California Line Source Model

In the California Line Source model, the crosswind equation generally takes the form of the Gaussian line source equation:

$$C = (4.24Q/2K\sigma_z\bar{U}\sin\phi)\{\exp - \tfrac{1}{2}[(z+H)/\sigma_z\}^2 + \exp - \tfrac{1}{2}[(z-H)/\sigma_z]^2\} \tag{4}$$

where

C = concentration of pollutant (g/m^3),
Q = source emissions ($g/s \cdot m$),
$\underline{K}$ = empirical coefficient = 4.24,
$\bar{U}$ = wind speed (m/s), and
ϕ = angle of wind with respect to highway alignment.

For parallel winds, the estimated concentrations within the mechanical mixing cell, where the ratio of 30.5/W is ≤1, can be determined from the following equation:

$$\{ppm\}_{mc} = A(Q/\bar{U})\,(1/K)\,(30.5/W) \qquad (5)$$

where

$\{ppm\}_{mc}$ = concentration of pollutant within the mechanical mixing cell (g/m^3),
A = downwind concentration ratio for parallel winds (accumulation term), defined as ($C\bar{U}K/Q$) ($W/30.5$) (2, Vol. 5, Figures 70 to 85),
30.5 = initial highway width used for the finite element of area in developing the model for parallel winds (m), and
W = width of roadway from edge of shoulder to edge of shoulder (m).

For parallel winds, the source emission strength (Q) is calculated by using the following equation:

$$Q = \text{emission factor} \times \text{vehicles per hour} \times 5.26 \times 10^{-6} \qquad (6)$$

where the numerical constant is a factor used to convert units of the product of vehicles per hour times the emission factor to grams per second for 30.5 m (100 ft) of highway.

To estimate ground-level pollution concentrations away from the highway (when the wind is parallel to the alignment), the following equation is used:

$$C = \{ppm\}_{mc}[\exp - \tfrac{1}{2}(Y/\sigma_y)^2] \times \tfrac{1}{2}\{\exp - \tfrac{1}{2}[(z+H)/\sigma_z]^2 + \exp - \tfrac{1}{2}[(z-H)/\sigma_z]^2\} \qquad (7)$$

where Y is the normal distance from the receptor to the near edge of the highway shoulder in meters.

CALINE2

In the CALINE2 model, the mathematical equation for pure crosswinds takes the form of the Gaussian line source equation:

$$C_{xwind} = (Q/\sqrt{2\pi}\sigma_z\bar{U})\{\exp - \tfrac{1}{2}[(z+H)/\sigma_z]^2 + \exp - \tfrac{1}{2}[(z-H)/\sigma_z]^2\} \qquad (8)$$

where C_{xwind} represents the concentration of the pure crosswind component in grams per cubic meter.

For pure parallel winds, the mathematical model uses the Gaussian point source equation:

$$C_p = (Q/2\sigma_y\sigma_z\bar{U})[\exp - \tfrac{1}{2}(y/\sigma_y)^2]\{\exp - \tfrac{1}{2}[(z-H)/\sigma_z^2]^2 + \exp - \tfrac{1}{2}[(z+H)/\sigma_z^2]\} \qquad (9)$$

where C_p represents the concentration of the pure parallel wind component in grams per cubic meter.

The highway length, which is assumed to be 0.8 km (0.5 mile), is divided into a series of square area sources (WXW, where W is the highway width). Each area source is transformed into a virtual point source by Equation 9, and these are summed at the receptor for a cumulative concentration. A scaling factor is then used to increase concentrations to those for a line source 8 km (5 miles) in length by stability classification (3), as given below.

Stability Class	Scaling Factor	Stability Class	Scaling Factor
A	1.00	D	1.37
B	1.06	E	1.64
C	1.16	F	2.08

The resulting concentration for pure parallel winds can be represented by the following formula:

$$C_{PARWIND} = sf\left(\sum_{n=1}^{NSEG} C_p\right) \qquad (10)$$

where

$C_{PARWIND}$ = resulting concentration of the pure parallel wind component (g/m^3),
sf = scaling factor, and
NSEG = number of area sources in a highway length of 0.8 km (0.5 mile).

For oblique winds, concentrations at receptor points are calculated from a weighted average of the terms for pure crosswind and parallel wind. The weighted average is represented by the following equation:

$$C = \sin^2\phi \times C_{xwind} + \cos^2\phi \times C_{PARWIND} \qquad (11)$$

where

C = concentration at the receptor point (mg/m^3) and
ϕ = wind angle with respect to the roadway (rad).

SENSITIVITY ANALYSIS

Method

The sensitivity of model predictions to changes in input parameter values was analyzed by comparing normalized pollutant concentration versus normal distance to the highway edge for crosswind, parallel wind, and oblique wind conditions. The model predictions are made for Pasquill stability classes B and E. Stability classes A and F were omitted because they represent extreme stability conditions.

Normalized pollutant concentration is defined for this analysis as Cu/Q (m^{-1}), where C is the resultant downwind concentration in micrograms per cubic meter, u is the mean wind speed in meters per second, and Q is the source strength in micrograms per second. Specific wind-angle values were chosen to represent the three wind-angle categories: $\phi = 90°$ for crosswinds, 0° for parallel winds, and 45° for oblique winds.

The highway configuration was an at-grade, two-lane highway with a total width of 7.3 m (24 ft) and with equal emissions from each lane. The highway length was assumed to be 2000 m (6600 ft). The receptor height above the ground was taken as 1.5 m (5 ft), and the effective vertical mixing height (EPA model input) was set at 1000 m (3300 ft).

Discussion of Results

Figure 1 shows variation in normalized pollutant concentration with downwind distance under crosswind conditions for all three models. The California Line Source model and CALINE2 perform similarly, the only difference being that CALINE2 predicts 20 percent less pollutant concentration for all downwind distances. [When CALINE2 was developed, a factor of $2/\sqrt{2\pi}$ ($\cong$0.8) was incorporated into the crosswind equation.] Generally, HIWAY predicts higher pollutant concentrations than the two California models for the crosswind case.

Initial concentrations (at x = 0 m) predicted by the California models are not sensitive to stability classification, whereas HIWAY predicts initial concentrations as a function of stability class. The rate of dispersion for the California models is greater than that of HIWAY within 20 m (66 ft) of the highway. Beyond 20 m, HIWAY has a greater rate of dispersion. Figure 2 shows normalized pollutant concentration as it varies with downwind distance for parallel winds. HIWAY and CALINE2 perform similarly for this case except that, although both models predict initial pollutant concentrations as a function of stability class, HIWAY predicts an initial concentration that is approximately two times that predicted by CALINE2. The California Line Source model generally predicts higher pollutant concentrations for the parallel wind case than those predicted by HIWAY and CALINE2.

Figure 3 shows normalized pollutant concentration versus normal distance from the highway for oblique wind conditions. The EPA model generally predicts higher pollutant concentrations than the California models for this case, with two exceptions: (a) For stability class E and x < 30 m (98 ft), CALINE2 predicts higher concentrations; and (b) for stability class B and x > 70 m (230 ft), the California Line Source model predicts higher pollutant concentrations. HIWAY and CALINE2 predict initial pollutant concentration as a function of stability class; the original California model does not.

MODEL VALIDATION

Experimental Procedure

Air pollution, meteorological, and traffic measurements were made near a major arterial in Nashville, Tennessee, over a 5-d period in July and an 8-d period in August of 1973. The site was at grade; a 76-m (250-ft), flat, grass-covered area extended north from the road. A small hill 21 m (70 ft) high with a gradual slope was located 670 m (2200 ft) to the southwest.

Wind speed and direction were measured continuously during the field investigation. During the first monitoring period, a single MRI wind instrument was mounted 3.7 m (12 ft) above the ground and 9.1 m (30 ft) from the road edge. During the second monitoring period, an additional wind instrument was mounted at a height of 9.1 m.

CO concentrations were measured at various distances north of the highway by using a sampling array of five probes along a horizontal profile perpendicular to the highway. Each of the probes was at a height of 1.5 m (5 ft) above the ground. Air samples were pumped continuously through tubing to a sampling manifold located at a mobile air-monitoring trailer and were analyzed by using a nondispersive infrared (NDIR) CO analyzer.

During the second field monitoring period, large variations in wind direction occurred. Because of this, CO concentrations were measured on both sides of the highway. A bag sampling network was used on the south side of the road (9).

Figure 1. Normalized pollutant concentration versus normal receptor distance from road edge for perpendicular wind conditions.

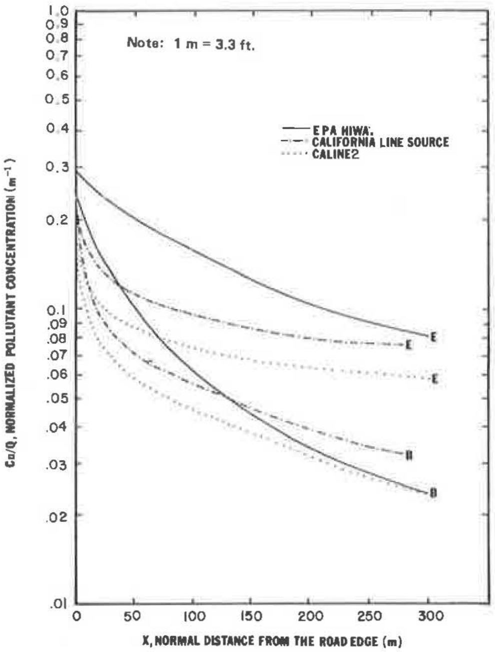


Figure 2. Normalized pollutant concentration versus normal receptor distance from road edge for parallel wind conditions.

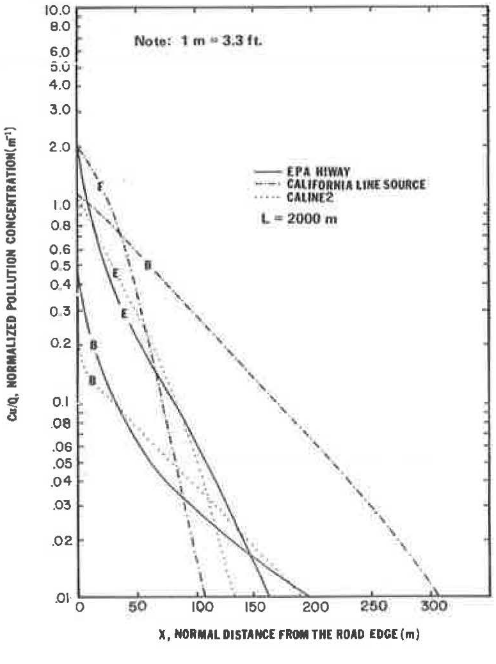
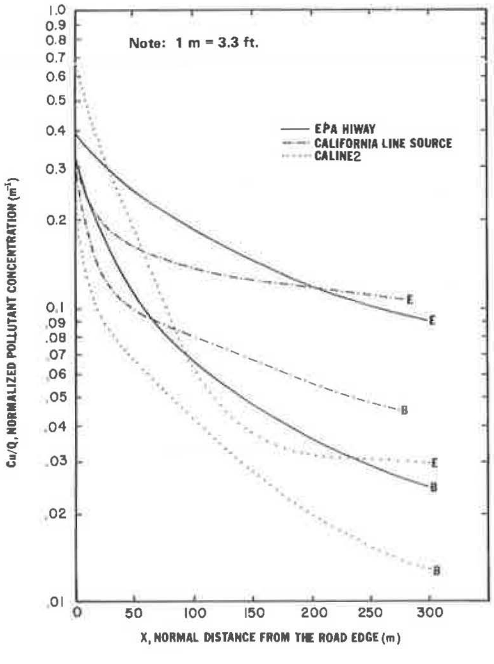


Figure 3. Normalized pollutant concentration versus normal receptor distance from road edge for oblique wind conditions.



Accuracy in pollutant concentration measurements was ensured by calibrating the analyzers before and after each peak-traffic sampling period. A two-point calibration procedure was employed that used a zero and a span gas. Before field use, linearity of the instruments was checked in the laboratory by using span gases of different concentrations (10). Two different procedures of calibration—for sampling lines and instruments—were performed in the field.

Fifteen-minute traffic counts were made by pneumatic counter-recorders. A separate counter was used for inbound and outbound traffic volumes. Average vehicle speed was measured by timing vehicles over a known distance. The time-averaging method uses an observer who times a randomly chosen vehicle between two easily recognizable end points. Adequate course length [>152 m (>500 ft)] and a stopwatch provide the necessary accuracy of measurement. The heavy-duty vehicle mix was obtained by manual count.

Table 1. Results of regression analysis comparing measured CO concentrations and concentrations predicted by California Line Source model.

Data Set	N	Mean	CV (¢)	r	M	b	k
0-0-0	568	1.6	70	0.51	0.38	1.10	0.84
11-0-0	44	1.8	55	0.83	0.35	0.11	2.70
12-0-0	226	1.5	64	0.65	0.69	0.62	0.84
13-0-0	298	1.7	52	0.74	1.46	0.35	0.55
11-0-1	14	3.4	24	0.92	0.35	0.96	2.06
11-0-2	30	1.1	68	0.70	0.22	0.20	3.65
12-0-1	75	2.4	48	0.64	0.60	1.15	0.84
12-0-2	151	1.0	73	0.38	0.46	0.64	0.84
13-0-1	109	2.6	43	0.68	1.33	0.65	0.57
13-0-2	189	1.2	61	0.48	1.28	0.39	0.53
0-1-0	6	1.6	29	0.96	1.25	-0.33	0.97
0-2-0	223	1.5	61	0.59	1.26	0.45	0.56
0-3-0	281	1.6	72	0.51	0.43	1.05	0.85
0-4-0	26	1.9	45	0.74	0.38	1.04	1.20
0-5-0	26	2.2	66	0.70	0.31	0.74	2.10
0-6-0	6	0.3	20	0.96	0.89	-0.34	2.54

Note: Measured background subtracted.

Table 2. Results of regression analysis comparing measured CO concentrations and concentrations predicted by HIWAY model.

Data Set	N	Mean	CV (¢)	r	M	b	k
0-0-0	538	1.6	73	0.49	0.33	1.13	0.89
11-0-0	19	2.2	55	0.85	0.24	0.59	3.11
12-0-0	224	1.4	65	0.67	0.76	0.44	0.91
13-0-0	295	1.7	58	0.67	1.33	0.15	0.69
11-0-1	5	5.2	28	0.61	0.10	3.61	2.98
11-0-2	14	1.1	60	0.81	0.19	0.40	3.35
12-0-1	69	2.4	35	0.83	0.96	0.71	0.73
12-0-2	155	1.0	73	0.44	0.39	0.58	1.10
13-0-1	103	2.7	42	0.67	1.34	0.67	0.56
13-0-2	192	1.2	61	0.52	0.80	0.38	0.84
0-1-0	6	1.6	29	0.95	2.03	-0.45	0.64
0-2-0	207	1.6	51	0.73	1.90	-0.12	0.57
0-3-0	273	1.6	65	0.67	0.80	0.49	0.87
0-4-0	20	1.6	31	0.87	1.76	-1.40	1.16
0-5-0	26	2.2	64	0.72	0.21	0.96	2.66
0-6-0	6	0.3	29	0.91	2.63	-2.56	4.00

Note: Measured background subtracted.

Table 3. Results of regression analysis comparing measured CO concentrations and concentrations predicted by CALINE2 model.

Data Set	N	Mean	CV (¢)	r	M	b	k
0-0-0	568	1.6	70	0.53	0.49	1.05	0.72
11-0-0	44	1.8	62	0.78	0.41	0.57	1.66
12-0-0	226	1.5	69	0.58	0.54	0.86	0.77
13-0-0	298	1.7	60	0.63	1.46	0.38	0.53
11-0-1	14	3.4	34	0.83	0.39	1.49	1.46
11-0-2	30	1.1	77	0.58	0.26	0.54	1.96
12-0-1	75	2.4	49	0.63	0.56	1.42	0.71
12-0-2	151	1.0	73	0.37	0.30	0.78	0.84
13-0-1	109	2.6	46	0.62	1.43	0.83	0.48
13-0-2	189	1.2	65	0.37	0.74	0.66	0.60
0-1-0	6	1.6	34	0.94	2.42	0.14	0.38
0-2-0	223	1.5	55	0.69	2.11	0.08	0.45
0-3-0	281	1.6	61	0.70	1.15	0.44	0.64
0-4-0	26	1.9	38	0.82	0.66	0.46	1.16
0-5-0	26	2.2	41	0.90	0.50	-0.49	2.45
0-6-0	6	0.3	46	0.75	0.39	-0.41	6.53

Note: Measured background subtracted.

Atmospheric stability measurements were based on surface wind speed, insolation (strong, moderate, or slight), percentage of cloud cover, and time of day (angle of the sun). A hygrothermograph was used in the field to determine temperature changes. Field estimates were made of insolation and percentage of cloud cover. Stabilities were classified in one of the six Pasquill stability classes—A, B, C, D, E, or F—which range from extremely unstable to extremely stable (11).

Data Presentation

Tables 1, 2, and 3 present the results of the correlation and regression analysis that compared measured ambient CO concentrations to concentrations predicted by the HIWAY, California Line Source, and CALINE2 models. The raw data used for statistical analysis consisted of 568 data sets of CO concentrations measured downwind of the highway, background concentrations measured upwind of the highway, and the concentration predicted by the models. Measured versus predicted concentrations have been evaluated according to wind angle, receptor distance, and stability by using the following criteria (12).

1. Wind angles with respect to the road alignment were separated into three categories: parallel (0° to 13°), oblique (13° to 60°), and perpendicular (60° to 90°).
2. The distance from the sampling probe to the center of the road is the receptor distance. The data were separated only according to those receptors at the edge of the road shoulder or mixing cell (roadside receptor) and those located at distances farther downwind.
3. Pasquill's six stability categories were used to separate data subsets.

Tables 1, 2, and 3 use the following code: (a) a three-digit coded description of the data set in which the digits indicate wind angle [11 = parallel winds, 12 = oblique winds, and 13 = perpendicular winds (with reference to the road)], stability category (1 = A, 2 = B, 3 = C, 4 = D, 5 = E, 6 = F), and receptor distance [1 = roadside, 2 = downwind, to 91.4 m (300 ft) from center of road] and 0 means all data in the category; (b) N, the number of data points in the data set; (c) mean, the mean measured CO concentration; (d) CV(¢), the coefficient of variation, equal to the ratio of the standard error of y from the regression line divided by the mean measured concentration; (e) r, the correlation coefficient; (f) M, the slope of the calculated least squares regression line; (g) b, the intercept of the regression line; and (h) k, the ratio of the mean predicted concentration divided by the mean measured concentration.

Discussion of Results

The output of the regression analysis can be used to indicate the precision and the accuracy of mathematical model predictions when they are compared with measured pollutant concentrations. The method of analysis uses the correlation coefficient (r) as an index of the precision of the association between predicted and measured concentrations. Whenever the correlation coefficient is high, the model performs well under the conditions included in the data set.

A second parameter (k), equal to the ratio of the average predicted pollutant concentration divided by the average measured concentration, is used as an indication of the relative accuracy of the model. Values of k greater than one indicate that, on the average, the model tends to overpredict the measured concentration; k-values less than one indicate underprediction. The size of the data set (n) is also important and must be considered when the significance of the values of r and k is evaluated. It is also important to note that model accuracy is dependent on precision to the extent that k-values tend to be meaningless when correlation coefficients are quite low.

Experimental Error

Variability in the comparison of measured and predicted concentrations results from two sources: (a) inadequacies of the model to predict accurately under the range of conditions contained in a data set and (b) experimental error. An estimate of experimental error can be made by comparing the expected accuracy of CO measurements to the concentrations typically observed in the field. The sensitivity of CO analyzers, as reported by the manufacturers, is 0.6 mg/m^3 (0.5 ppm). More than half of the field measurements of CO were less than 2.3 mg/m^3 (2.0 ppm). Therefore, errors of a magnitude equal to $(0.5/2.0) \times 100$ percent = 25 percent or greater probably occur frequently in the data. Background concentrations averaged less than 1.1 mg/m^3 (1 ppm); therefore, errors of 50 percent and greater probably occur in these data because of analyzer sensitivity. Additional errors can be attributed to the use of different analyzers.

Model Performance

The overall precision of the EPA model is reflected in the correlation coefficient, $r = 0.49$, which is significantly improved when the data are separated by wind angle (where $r = 0.85$ for parallel winds and $r = 0.67$ for perpendicular and oblique winds). HIWAY tends to overestimate for parallel winds and underestimate for crosswind conditions. The parallel case overpredicts by ≅3. The average accuracy of perpendicular and oblique wind predictions ranges from 44 percent underprediction to 10 percent overprediction. Model precision tends to be better for roadside receptors, but accuracy is better for downwind receptors. The relative accuracy of downwind receptor predictions compared to roadside-edge receptor predictions is approximately 40 percent for perpendicular and oblique wind conditions.

HIWAY also tends to overestimate for stable atmospheric conditions and to underestimate for unstable conditions. The error ranges from 43 percent underprediction for class B to 166 percent overprediction for class E.

The California Line Source model performs similarly. The overall correlation coefficient, $r = 0.51$, is improved when the data are separated by wind angle (where $r = 0.83$ for parallel, 0.65 for oblique, and 0.74 for crosswind conditions). The model tends to overpredict for parallel winds by a factor of from 2 to 3.6 and to underpredict for oblique wind and crosswind conditions by 16 and 45 percent respectively. Although the California model is generally less precise than the EPA model, the accuracy of its roadside receptor prediction is comparable to downwind receptor predictions for both crosswind and oblique wind, which indicates that the California Line Source model tends to predict the rate of downwind dispersion rather well.

The overall precision of CALINE2 is slightly greater than that of HIWAY and the California Line Source model, as reflected in the correlation coefficient, $r = 0.53$. This precision is improved when the data are separated by wind angle (where $r = 0.780$ for parallel, 0.579 for oblique, and 0.632 for perpendicular winds), but it is generally less than that exhibited by the other models for the same categories. CALINE2 tends to overpredict for parallel winds and underpredict for oblique and perpendicular winds. The model overestimates by 66 percent for parallel winds, which is significantly less than the overestimates observed for the EPA model (211 percent) and the California Line Source model (170 percent) for the same case. The model underpredicts by 23 percent for oblique winds and 47 percent for perpendicular winds. In the category of atmospheric stability, CALINE2 tends to overestimate for stable conditions and underestimate for unstable conditions. The CALINE2 estimates range from a 56 percent underprediction for the B stability class to a 145 percent overprediction for the E stability class.

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Publication of this paper sponsored by Committee on Transportation and Air Quality.

Philadelphia Air Quality Control Region: Need and Recommendations for Revision of Transportation Control Plan

C. Abdul Latif and Rasin K. Mufti, Delaware Valley Regional Planning Commission

The Philadelphia transportation control plan, its status and evaluation process, and the technical background on which it was based are evaluated. A summary of transportation control plan strategies is presented as well as a review of their status and the major implementation problems of the plan. Legal, administrative, and technical problems are found to exist. A review and an analysis of the latest available air quality data for the Philadelphia central business district are presented. Air quality standards were found to be based on limited studies and did not take into account time of day, frequency, or duration of high concentrations of pollutants. The power of the U.S. Environmental Protection Agency to regulate the states or to require them to enforce a regulation has been questioned. A need for revising the Philadelphia plan is established, and it is recommended that the metropolitan planning organization be involved in the revision process. Possible strategies that could be considered in revising the plan and the place of such a plan in the transportation planning process are discussed.

Under the Clean Air Act of 1970, all states were required to submit plans for meeting the national ambient air quality standards set by the U.S. Environmental Protection Agency (EPA) in 1971. Transportation control measures were mandated for the air quality control regions (AQCRs), areas in which controls on stationary sources—such as power plants and other industries—combined with federal emission standards for new automobiles were considered inadequate to ensure attainment or maintenance of the ambient air quality standards.

The Philadelphia AQCR fell into this category. The state of Pennsylvania submitted and later revised a state implementation plan (SIP) that was found to be unsatisfactory by EPA. EPA then supplemented the state-prepared plan, producing the transportation control plan (TCP) currently in effect for the Philadelphia region. The TCP was published in November 1973 (4). At the time of its promulgation it was expected to have a profound effect on travel patterns and, thus, on the quality of the environment and on the economic well-being of the region.

This paper discusses the following major issues concerning the Philadelphia TCP, which has now been in existence for over 3 years:

1. Where does the plan stand today?
2. Which strategies in the plan have been implemented and to what extent have they succeeded in achieving their purpose?
3. What types of problems have been encountered, what are their sources and degree of complexity, and how are potential solutions to be evaluated?
4. Is the TCP a practicable plan? Should it continue or should it be made more realistic through revision?

SUMMARY OF TRANSPORTATION CONTROL STRATEGIES

The primary goal of the SIP and the TCP was to achieve within the Philadelphia region by May 31, 1976, the primary and secondary standards for ambient air quality for several pollutants including carbon monoxide (CO). A reduction of 55.5 percent in CO emissions over the 1971 level was estimated to be necessary. A concurrent result of the successful implementation of the TCP would have been a reduction of about 36.3 percent in the level of hydrocarbons (HC) over the level of the base year, which would go a long way toward achieving a targeted HC reduction of 54.7 percent.

Detailed strategies were promulgated by EPA in the following broad categories:

1. Measures to reduce the emission rates of individual vehicles (automobiles and trucks) and thereby reduce the rate and the quantity of emissions, and
2. Measures to reduce vehicle kilometers of travel, particularly by low-occupancy vehicles (automobiles), to reduce the level of emissions.

Measures to Reduce Emission Rates

Federal Motor Vehicle Control Program

The single most important measure in the emission-reduction category is the federal motor vehicle control program (FMVCP) for vehicles produced in model year 1968 and after. Although the program is not technically a part of the TCP, the resulting reduction of pollution is a necessary input to the TCP.

This program, in its original form, envisaged the introduction of technological changes in the design of automobile engines that would, by the year 1975, reduce the level of CO and unburnt HC emissions from automobile exhaust by more than 90 percent from the pre-1968 level. This measure was expected to contribute to about 44 percent of the CO reduction and 22.7 percent of the HC reduction prescribed by the TCP. For a number of reasons, the major automobile manufacturers have not adhered to this time schedule, and the final compliance date is now likely to be extended to 1981 or later.

The result of this postponement is that the emission reductions called for in this program cannot be accomplished by 1977 or even by 1980. Although interim emission standards are still in effect for vehicles manufactured after 1968, they have not had considerable impact on ambient air quality. In addition, the recent years of economic recession in the United States have resulted in somewhat restricted production and distribution of new automobiles. This factor may also have affected the impact of the lower interim emission rates of newer model automobiles: Many users have retained the older models beyond their customary service life for economic reasons.

Vehicle Inspection and Maintenance Program

A program of strict vehicle inspection was introduced that was designed to induce compliance with the requirements of corrective maintenance and thus to reduce the rate of CO and HC emissions. The reductions attributable to this program were estimated to be on the order of 4.2 and 1.9 percent for CO and HC respectively.

The Pennsylvania Department of Transportation has recently published proposed voluntary regulations for vehicle inspection and maintenance. These regulations are awaiting fiscal and legislative approval, which is not expected for some time.

Retrofit Devices on Pre-1968 Vehicle Models

Pre-1968 vehicle models that had no antipollution devices were required to be fitted with appropriate devices (called air-bleed to intake manifold) to bring down their emission rates. This step was estimated to account for a 4.8 percent reduction in CO and a nominal 0.7 percent reduction in HC. Again, this strategy has not been put into practice.

Although the installation of such devices was originally considered administratively feasible, many problems were encountered in its implementation. Some of the reasons for nonimplementation are (a) a lack of proven effectiveness for any particular device, (b) problems of manpower training and workshop resources for the installation and upkeep of the devices, (c) the number of devices that would have to be procured for the older fleet of automobiles involved, (d) the purchasing cost involved, and (e) the equity of requiring such devices.

Older model automobiles are owned by those who can least afford a newer model; the retrofit device is therefore a highly regressive requirement. EPA has not insisted on the implementation of this measure anywhere in the country. The effect of nonimplementation is of course significant because an expected 4.8 percent reduction in CO emissions is unrealized.

Measures to Reduce Vehicle Kilometers of Travel

Strategies addressed to reducing vehicle kilometers of travel in the Philadelphia AQCR are the core of the Philadelphia TCP. Although the number of strategies and the range of possibilities in this category are large, the actual reduction attributable to these measures is relatively insignificant (EPA estimated that these strategies would contribute to reductions of 2.9 and 0.2 percent in CO and HC emissions respectively). The following measures designed to reduce vehicle kilometers of travel were included in the TCP:

1. Management of parking by subjecting all new parking facilities for more than 50 automobiles to the requirement of written approval by EPA (the lower limit has been raised to 250 spaces);
2. Limitation of public parking on streets and highways, particularly those where exclusive bus lanes or trolley lanes are established;
3. Introduction and encouragement of computer-matched car-pool systems for all establishments with more than 100 employees;
4. Formation and maintenance of exclusive bus and trolley lanes on certain routes in Philadelphia such as CBD-Ben Franklin Bridge and Roosevelt Boulevard between Grant Avenue and the Huntingdon Park exit as well as on specified CBD streets (with accompanying parking restrictions) and outside the CBD (during morning and evening peaks);
5. Creation of exclusive bus lanes on West Chester Pike, I-95, and the Schuylkill Expressway;
6. Establishment of at least 40 km (25 miles) of bikeways in the CBD; and
7. Introduction of transit-use incentives by employers who provide more than 700 parking spaces, such as restrictions on the number of parking spaces, increased parking fees for automobile users who drive alone, and encouragement of the use of spaces by car poolers and van poolers.

These strategies were expected to shift transportation mode choice in favor of mass transit. The increased mass transit ridership would in turn further improve the quality of service (by reducing headways) and increase the transit share of trips. The reduction of vehicle kilometers of travel, with the associated reduction in highway speeds, would improve air quality as well as reduce energy consumption.

Implementation of strategies in the categories of reduction of vehicle kilometers of travel and traffic-flow improvements has been partly successful. In general, progress was made in implementing those strategies that were the responsibility of the state or the local authorities in the Philadelphia AQCR. These include the establishment of (a) bikeways, (b) a car-pool computer matching system, (c) busways between the Ben Franklin Bridge and the Philadelphia CBD, (d) CBD bus and trolley lanes, and (e) limited public parking on streets where bus or trolley lanes have been established. In addition to these measures, the city of Philadelphia has successfully implemented the Chestnut Street Mall, which provides for an automobile-free zone on Chestnut Street between 6th and 18th streets.

The measures that remain to be implemented are under the jurisdiction of either EPA (management of parking supply) or private employers in the region (mass transit incentives). Measures that require exclusive bus lanes were found to be infeasible (1). Major obstacles in the implementation of these projects include the resistance of citizens to any measure that seeks to limit travel choices without providing equally attractive alternatives.

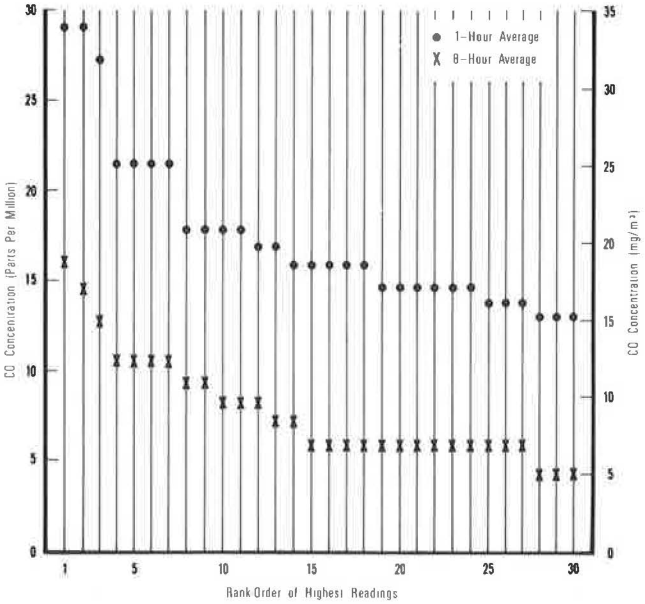
TCP Impact on Air Quality Data

In spite of the partial implementation of the strategies that form the core of the Philadelphia TCP, the real impact of these measures on the level or the density of emissions is very small. Even a complete implementation of all the measures would not have affected ambient air quality to any noticeable extent in the absence of successful measures to reduce emission rates. The total proportion of CO reduction attributable to these measures is only 2.9 percent.

In an assessment of the real impact of partial implementation of the TCP, 1971 to 1976 hourly air quality data from two air-monitoring stations—the Continuous Air Monitoring Project (CAMP) and the Air Management Service (AMS)—were reviewed. Continuous graphs of 8-h average CO concentrations were plotted and violation periods were summarized. The number of violations and their intensities are given below (1 mg/m^3 = 0.87 ppm):

	Number of Violations		Highest Concentration		
Year	CAMP	AMS	Amount (mg/m^3)	Duration (h)	Time of Occurrence of Highs
1971	13	2	23.0	11	12:00 m.n.
1972	12	4	16.8	9	4 a.m.
1973	14	12	20.2	14	2 a.m.
1974	6	3	21.3	14	2 a.m.
1975	2	3	16.8	10	3 a.m.
1976 (to November)	–	1	24.2	13	4 a.m.

Figure 1. Thirty highest average 1-h and 8-h CO readings at CAMP monitoring station in 1974.



Thus, from 1973 to 1976, when some limited elements of the TCP were in effect for over 3 years, the air quality was in violation of the 8-h standards [8-h average CO concentrations not to exceed 10.3 mg/m^3 (9 ppm) more than once a year]. The situation as observed over these years does not seem to be improving; the level and duration of the highest average concentrations remain high.

PROBLEMS WITH EXISTING TCP

Efficacy of TCP Elements

A review of the status of the various elements of the TCP shows that only a few of the elements of the plan have been implemented and that these elements have a limited chance of having a positive impact on the air quality of the region. As discussed earlier, all of the measures meant to reduce vehicle kilometers of travel taken together were expected to reduce CO emissions by only 2.9 percent.

Other elements of the TCP that did have promise of reducing total emissions were those that would reduce the emission rates of vehicles without reducing the level of travel. These elements of the TCP, which are within the jurisdiction of state and local authorities, encompassed the most unpopular—or unrealizable—elements. Even if the FMVCP is eliminated, the expected emissions reduction attributed to vehicle inspection and maintenance and retrofit devices on older automobile models—a significant 9 percent reduction in CO—remains unrealized because of technological, economic, and administrative factors.

Attitudinal, Institutional, and Legal Problems

The attitudinal problems of the Philadelphia plan were the result of apparent philosophical gaps between EPA staff and the staffs of other transportation agencies that stemmed from an attitude of distrust between environmentalists on one side and transportation planners and engineers on the other. The institutional problems grew out of the absence within EPA of the framework and the expertise to deal with transportation plans and strategies. The situation in these two areas, however, has greatly improved since the inception of the TCP.

Legally, EPA had no authoritative position from which to deal with local governments. Its authority stems from the 1970 Clean Air Amendments, which entitled the agency to deal only with state governments, using the federal interstate commerce power (on the assumption that air pollution fell under interstate commerce). This limited EPA's direct (legal or regulatory) involvement with communities and political jurisdictions affected by the TCP.

A more complex legal problem arises from court decisions in several cases involving EPA and transportation control plans. Common to all these cases is a challenge to the power of EPA to force the states to enact and enforce specific transportation controls. Although the decisions in these cases vary considerably, they have hindered EPA's ability to implement the TCP, particularly in Maryland and California.

Technical Problems

The four major types of technical problems are those pertaining to ambient air quality standards, air pollution monitoring, implementation of the FMVCP, and various elements of the TCP.

Ambient Air Quality Standards

In the 1970 Clean Air Act, Congress called for the establishment of performance standards governing ambient air quality. EPA was assigned this task, which means that the agency was left to quantify the relationship between ambient air quality and the state of the public health and welfare. Based on a study undertaken by the U.S. Department of Health, Education and Welfare (2), EPA fixed the following standards for CO: 1-h concentration not to exceed 40.3 mg/m^3 (35 ppm) more than once a year and 8-h average concentration not to exceed 10.3 mg/m^3 (9 ppm) more than once a year.

The establishment of these standards has given rise to considerable controversy, and the debate still continues. Some believe the standards to be very stringent; others consider them adequate. Nevertheless, the standards appear to be oversimplified, supported by only limited theoretical and experimental data.

Figure 1 shows the 30 highest 1-h and 8-h average CO concentrations at the Philadelphia CAMP station during 1974. The figure suggests that a curve representing CO concentrations in descending order resembles a decaying exponential distribution. The density in such distribution tends to decline very sharply at the beginning and then levels off. Everyone is aware of the serious nature of air pollution, but the safety margin in the concentration standards, the infrequency of and the long periods between high pollutant concentrations, and the human ability to compensate during nonexposure time indicate that a more relaxed stance on the number of permissible violations of standards should be investigated.

Air Pollution Monitoring

Air pollution data collected by monitoring stations are inadequate for several reasons:

1. There are a limited number of monitoring stations, and the number varies depending on the pollutant being monitored. Until 1974 there were only three stations monitoring CO in the Philadelphia area, one of which is in the CBD (CAMP).

2. Although the stations monitor continuously, all of them experience some gaps in data, and significant portions of the data provided are ruled invalid.
3. No clear standards exist in relation to height, distance from the roadway, and general location of the equipment (measurements are extremely sensitive to these factors).
4. Partly as a result of the lack of clear standards, it is not uncommon to find CO concentrations reading higher in the outlying section of the city than in the CBD because, although the traffic may be of decidedly lower density, the monitoring equipment is more sensitive to location factors.
5. A major problem seems to exist with the technique by which 8-h average concentrations are calculated, especially the number and the duration of each violation of the standards and the highest numerical value assignable to each violation. EPA must prescribe the averaging method in clear, specific, and well-documented terms.

Federal Motor Vehicle Control Program

Another problem that has legal as well as technical aspects involves the FMVCP. The unresolved points are intermediate motor vehicle emission standards and the final date established for attainment of the mandated 90 percent reduction of emissions from pre-1968 vehicles. Several versions of an amendment to the Clean Air Act are circulating in Congress, and they all include a deferral of the established date from its latest revised date of 1977 to 1981 or later.

The FMVCP is the most important strategy for reducing emissions. It was expected to contribute over 40 percent of the 55 percent required CO reduction in the Philadelphia SIP. However, there are major problems associated with this program in that the vehicles already in use are emitting more pollution than the respective model-year emissions mandated for them. Lack of adequate maintenance is among the reasons for these excessive emissions.

Inadequacies of Plan

Several problems and inadequacies exist with the transportation control plan in general and with specific strategies in particular, at least partly because of the extremely short statutory deadlines imposed on EPA by the Clean Air Act of 1970. These inadequacies include the following:

1. No evaluation was made of the social and economic costs of implementing the TCP, nor was the plan evaluated for its effect on areas beyond the immediate vicinity of the facilities included in the plan.
2. The strategies seem to have been selected randomly without any regard to their regional applicability. An example is the selection of exclusive bus lanes parallel to commuter rail routes (the Philadelphia-Paoli corridor). Another example is the application of the transit-use incentive to employers who provide more than 700 parking spaces: No employer in the Philadelphia CBD is in this category.
3. The compliance schedule for most of the strategies concentrates on implementation without time for feasibility analysis or study of alternatives.

ALTERNATIVE TCP

From the list of problems summarized above it can be concluded that the Philadelphia TCP requires a major overhaul. The need is serious enough to suggest the development of a totally new plan, built on current experience but based on a more refined process. The refinements, although primarily technical, require more than technical changes. They are very much related to the attitudinal, institutional, legal, organizational, and other types of problems outlined earlier.

In the attitudinal and institutional areas, EPA has taken many forward steps. Its relationship with other agencies, particularly those in the transportation field, has markedly improved. Through better staffing and internal reorganization, EPA has begun to deal with transportation questions more effectively. Its regional staff has recognized many of the local problems inherent in the TCP and has transmitted these problems to policy makers in Washington.

In the legal area, amendment of the Clean Air Act is required to clarify the intent of Congress in granting EPA its regulatory power as well as the extent to which EPA or the federal government as a whole can sanction the action (or inaction) of a state or local government with respect to pollution control.

Involvement of Metropolitan Planning Organizations

Amendments to the Clean Air Act are needed to ensure that transportation control strategies are developed and adopted by local, regional, and state governments rather than promulgated by EPA. This, among other things, would reduce the likelihood that legally controversial strategies would be adopted.

The thinking of lawmakers is already moving along these lines. A 1976 Senate version of the Clean Air Amendments (8) requires the metropolitan planning organizations (MPOs) to carry out the task of defining transportation controls in conjunction with the overall planning process. Both this Senate version and a House version of the measure (H.R. 10498) provide the state with a 2-year period from the date of the amendment to complete and adopt a new TCP.

The thinking of the U.S. Department of Transportation and others is also on these lines. In a 1975 position paper issued by the Intermodal Planning Group for Federal Highway Administration Region 3, it has been rather strongly suggested that the planning of control measures should be done by the MPO because any transportation measures developed outside the 3-C planning process are not likely to have the technical and community support needed to ensure implementation. The position paper recommends that (a) when revising the state implementation plan, the responsible state air pollution control agencies should delegate to the MPO the responsibility and financial support to plan the transportation controls necessary to attain national ambient air quality standards; and (b) no measures should be included in the TCP unless they are also included in the transportation system management elements (TSME). In addition, a stronger emphasis is being placed on short-range planning in transportation, through TSME (7). Under TSME, short-range needs are to be filled by making more efficient use of existing transportation resources without making major changes in the facilities or adding new facilities. The applicable federal regulation requires that the transportation plans of the MPO be consistent with environmental and energy objectives and that these plans be coordinated with air quality planning.

TCP and the Transportation Planning Process

A much more important need for revision in the TCP process is in the area of planning. The region can no longer afford to keep different plan elements separate from each other. Transportation control strategies must be made an integral part of the regional plans and the planning process and not merely a remedial measure. Environmental considerations should be as much a part of the plan and the planning process as are other selected concerns and goals. The TCP as currently understood may in this context be only an interim measure to be replaced by a transportation plan prepared with all objectives, including environmental objectives, in mind.

The Delaware Valley Regional Planning Commission (DVRPC) has already included environmental concerns in the planning process for the year 2000 plan (9). In fact, environmental objectives are being addressed even at the sketch-planning level. By including environmental concerns in the planning process, the 3-C process is not only being extended but is also being made more responsive.

An implementable and politically and socially workable transportation control plan is necessary for reasons other than air quality concerns. Involving the local constituencies of DVRPC and interested citizens in the preparation of the TCP is therefore very important. A successful TCP process may be instrumental in bringing to the attention of the public the necessity of modifying its automobile travel habits. The TCP will also help to promote energy efficiency as well as to maintain air quality once the standards have been met.

Technical Changes Required

Several technical changes, reevaluations, or refinements in the TCP are necessary, including those discussed below.

Reevaluation of Ambient Air Quality Standards

In view of the difficulty of determining compliance or defining strategies based on a single value, an alternative standard is required that takes into account frequency, duration, and time of day of high pollutant concentrations and that admits the probability of the occurrence of more than one value above the stated concentration. In such a standard, a statistical relation accounting for the relevant parameter (frequency, duration, time) of the measured concentration above the permissible level would replace the single permissible exceedence. The 8-h CO standards could conceivably be lowered below 10.3 mg/m^3 (9 ppm) and the manner in which the standard could be exceeded could be stipulated.

Establishment of Monitoring Criteria and Program

The city of Philadelphia and the state of Pennsylvania have taken steps toward establishing detailed monitoring criteria and a broadly based monitoring program for both air pollution and such transportation characteristics as vehicle kilometers of travel and speed. The number of continuous monitoring stations in the city increased from 3 in 1971 to 11 in 1974; 3 more were added in the suburbs of the region in late 1975. What remains to be achieved is proper maintenance and calibration of the equipment and accurate and consistent data interpretation.

Revisions of Basic TCP Assumptions

An important basis for revisions in the TCP is changes in the state of knowledge about certain basic but key factors and, to some extent, changes in the state of the art. Examples of the first kind include revisions in the basic emissions factors for automobiles and trucks. When the original TCP was prepared, these factors depended only on the model year of the vehicle; a speed adjustment curve was used for different types of vehicles. Later investigations have made it necessary to include the effects of cold starts and ambient temperatures in the calculation of emissions factors (5). The effect of this change is most likely to be evident in the CBD at the p.m. peak because of the relatively high percentage of travel that could qualify as cold starts. Different emissions factors may have to be used for other areas depending on the nature and volume of traffic.

Additional changes are necessary so that the plan will reflect the level of travel in various parts of the region instead of only travel in the CBD. Thus, it may no longer be valid to speak of a given percentage reduction in vehicle kilometers of travel or emissions except in terms of regional totals. It may be much more meaningful to attempt to specify the maximum daily vehicle kilometers of travel and the corresponding level of emissions (yearly or daily) that are consistent with the standards if the worst meterological conditions occur simultaneously. In addition, the actual or forecast amount of travel and emissions (as well as expected ambient concentrations) should also be calculated so that remedial measures can be initiated under emergency conditions (3).

URBAN GOALS AND CANDIDATE STRATEGIES FOR A REVISED TCP

Urban Goals

A large number of strategies responsive to selected planning goals and objectives have recently been compiled under the joint sponsorship of EPA, the Federal Energy Administration, and the Urban Mass Transportation Administration (6). That study presents three major sets of urban goals and systematically presents various strategies that could be used to achieve those goals. Of course, not all of these strategies can be uniformly applicable to all urban areas and not all of them would qualify to be labeled as TCP. Some of the strategies have far-reaching social and economic consequences on the national or even the global level, for example, design of the nonpolluting engine and introduction of non-petroleum-fueled engines. (Action is already being taken in both categories.)

Many of the other strategies discussed here may be unpopular because they would tend to restrict the mobility and the mode choice that people have been accustomed to getting from the automobile. These strategies are directed toward reducing vehicle kilometers of travel and restricting automobile access. A great deal of effort will have to be expended on educating the public before these strategies can be effective. Whatever strategies and measures are selected, successful implementation would need positive commitment from all levels of government in the Philadelphia region, from the federal to the local level.

Various urban goals and broad action categories that should be fully analyzed with respect to their social and economic implications before they are selected for inclusion in a revised TCP are examined below. The three major goals are improvement of urban mobility, reduction in the rate of exhaust emissions, and conservation of energy. The various actions for mobility improvement and energy conservation complement the major goal of improving air quality by helping to reduce the amount of exhaust emissions.

Improvement in Urban Mobility

Historically, improvements in urban mobility have been caused by the introduction of faster means of transportation and an extensive network of highways and other travel modes. Of course, the ever-increasing use of the automobile and low automobile occupancy have ultimately resulted in a waste of energy and increases in pollution, congestion, delays (particularly during peak hours), and accidents.

Major strategies for improving urban mobility should be directed toward providing a reasonable balance between the use of the automobile and public transportation. These strategies must therefore aim at reducing the demand for highway-related automobile use as well as increasing transit supply and demand.

Reduction in Rate of Exhaust Emissions

Besides measures for reducing the use of the automobile and thus vehicle kilometers of travel, measures will be needed to reduce the level of automobile emissions. Such measures do not lie within the scope of the MPO; they must originate in the federal government, which can legislate in this sphere as well as provide the appropriations and the leadership for research and development of new technology.

Although new-automobile strategies and measures belong outside the TCP, they are an essential component of any effort to conform to federal air quality standards. The only jurisdictions outside the federal government that can play a useful role in reducing automobile emissions are the state governments, which can institute more responsible inspection and maintenance policies for vehicles already on the roads so that those vehicles continue to perform as close to the federal standards as possible. MPOs must be kept up to date on the state's progress in implementation of inspection and maintenance programs and control of stationary sources of pollution.

Conservation of Energy Resources

Urban transportation is perhaps the greatest consumer of energy. Not only are huge quantities of gasoline consumed by automobiles, affecting the economy's ability to keep pace with the rising demand for this fuel, but also the fuel after combustion is discharged into the atmosphere in the form of pollutants. Any reduction in gasoline use would favorably affect air quality.

In addition to more efficient engines, the conservation of gasoline can be effected in two ways: (a) by reducing kilometers of travel by automobile and (b) by concomitantly increasing the use of transit, which is usually understood to be a more energy-efficient mode. Rigorous studies of the effect of a more widespread use of transit may, however, be necessary to assess the effect of a change to alternate fuels. For example, more diesel buses on the street may raise other problems, e.g., smoke particles. The use of high-speed transit, such as commuter rail and light rail, will not only change the type of fuel used but will also cause fuel to be burned at fixed points where energy conversion would take place. Effects of increased emissions at those locations will, therefore, also need to be studied.

Measures for realizing the energy objective no doubt belong to various levels of government acting, when appropriate, through the MPO. The federal and state government roles lie in legislating smaller vehicle size, weight, and power, providing research and development assistance for new propulsion technology, and providing leadership in the development of clean energy sources and in inspection and maintenance.

Candidate Strategies for Revised TCP

Possible strategies that should be discussed and analyzed further and incorporated in the revised TCP are presented below. Strategies must be implementable, and their social and economic implications should be analyzed before they are included in a revised TCP. Although this group of strategies includes certain measures that are part of the existing Philadelphia TCP, such as car pools, bus lanes, and parking restrictions, the difference may lie in the specific application of the measures—in how, where, and how much. Locating an exclusive bus lane parallel to a high-speed rail corridor may be an obviously inconsistent or ineffective measure, but it may be quite effective in some situations. Workable elements of the existing TCP should be included in the revised TCP and as part of the region's TSME. The real point in revising the TCP should not be to replace entirely the existing strategies but to make the planning process more responsive and effective.

Automobile Travel

Possible strategies for improving automobile alternatives are as follows:

1. Improve transit service by increasing its frequency, quality, safety, and security;
2. Revamp the transit fare structure and include the possibility of multizone fares and fare-free service on CBD loops;
3. Encourage the use of bicycles and walking by providing safer roads and streets, in terms of traffic engineering for the safety of both people and property; and
4. Extend transit service to the areas not currently served, i.e., areas with latent demand but relatively low patronage.

Vehicle Movement on Highways

Strategies for improving vehicle movement on highways are as follows:

1. Improve the conditions of highway and street networks;
2. Improve traffic control measures, including installation of volume-responsive signaling, provision of appropriate turn restrictions, and use of one-way streets where such use is indicated;
3. Prohibit or at least strictly control on-street parking, particularly in the CBD and on other streets where transit routes are located;
4. Monitor instantaneous conditions of traffic congestion during peak hours and in situations that involve delay caused by traffic accidents and introduce ramp metering and the posting of alternate routes for highway uses;
5. Where possible, and where so indicated, introduce special bus lanes that may also be used by car poolers (bus-activated signals may be installed); and
6. Introduce more and new transit service in heavily traveled corridors and other areas of service (CBD loops, shuttles, airport service).

Reduction of Automobile Use

Strategies designed to reduce the use of automobiles are as follows:

1. Introduce and encourage car, van, and bus pools and other shared-ride programs;
2. Revamp working hours (staggered work hours, staggered workdays, flextime);
3. Rationalize parking policy in congested areas by such actions as providing parking facilities at the fringes of critical areas where they interface with public transportation and manipulating parking fees;
4. Introduce incentives to the use of public transportation (by such measures as reimbursement of transit costs and free or subsidized travel) for use by employers located in critical areas; and
5. Examine and recommend entry and exit points in heavily traveled areas such as the CBD by designating one-way streets and specified points of entry and exit, more turning restrictions, and more automobile-free streets such as the Chestnut Street Mall.

Vehicle Inspection and Maintenance Programs

Periodic checkup and repair of antipollution devices, in accordance with model-year specifications, should be required.

Energy Efficiency of Vehicles

Strategies for improving the energy efficiency of vehicles are as follows:

1. Introduce more efficient passenger pickup and drop-off by public transportation vehicles by introducing appropriately spaced stops and
2. Introduce one-way collection of tolls on toll bridges to expedite the processing of vehicles, improve speed, reduce emissions, and save energy.

CONCLUSIONS

The Clean Air Act, the creation of the U.S. Environmental Protection Agency, and subsequent EPA regulations for clean air are long-overdue responses to the concerns of various segments of society. Like many other responses to public pressure, the act, the agency, and the regulations were all formulated with a certain degree of expediency, which gave rise to many legal, administrative, and technical problems. The legal problems involve a challenge to EPA's regulatory powers, the administrative problems are manifested by the lack of a clear definition of EPA's powers and responsibilities, and the technical problems are inherent in the rather hastily generated regulations. Lack of public acceptance further aggravated the problem.

The need for a revision of the TCP is the most obvious conclusion of this paper. However, that revision perhaps should be extended beyond the TCP to the SIP and possibly to the air quality standards and the Clean Air Act. The Clean Air Act is currently being amended. It is hoped that the amendment will clarify some of the otherwise ambiguous provisions. The national ambient air quality standards are the subject of much debate, and the need still exists for more comprehensive standards that include a multiplicity of pollution factors (level, duration, time of day) and better technical justification. Revision or reformulation of a new TCP must begin with the basic premise that it should evolve through the regional comprehensive planning process with the full participation of local governments and concerned citizen groups.

In formulating the TCP, the MPOs must ensure not only the total cohesiveness of the plan but also its homogeneity with the short- and long-range elements of the regional transportation plan. In particular, the integration of the TCP into TSME is essential to the conduct of the regional planning process.

ACKNOWLEDGMENTS

This paper was financed in part by the Federal Highway Administration and the Urban Mass Transportation Administration of the U.S. Department of Transportation and by the Pennsylvania Department of Transportation. The contents reflect our views and do not necessarily reflect the official views or policies of the funding agencies.

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Publication of this paper sponsored by Committee on Transportation and Air Quality.

Development of Criteria for Reserving Exclusive Bus Lanes

C. C. Miesse, U.S. Environmental Protection Agency,
Philadelphia

The reservation of an existing traffic lane for the exclusive use of buses and car pools results in increased congestion and slower speeds on the remaining lanes until a sufficient number of automobile drivers have been diverted to buses. Equations are developed to determine the variation of the resultant emissions with the percentage of diversion for various values of initial speed, number of lanes, and directional split (for counterflow lanes). Results of the analysis indicate that minimum diversion percentages exist below which carbon monoxide emission rates and total hydrocarbon emissions are greater with than without the exclusive bus lanes for both in-lane and counterflow configurations.

The reservation of existing traffic lanes for the exclusive use of express buses and car pools has been proposed and promulgated as a technique for encouraging the use of public transit on the assumption that air quality will be improved by a decrease in the number of private automobiles. Various transportation agencies have noted that implementation of this measure along specific corridors would impede traffic to the extent that pollutant concentrations may even increase; the following analysis was therefore undertaken to quantify the anticipated results, based on empirical relations between traffic flow, average speed, and pollutant emission rates.

The analysis is based on the following assumptions:

1. Variation of traffic flow with operating speed, for both the peak-flow (inbound) and counterflow (outbound) directions is determined by the volume-speed curves given in the Highway Capacity Manual (1).
2. Variation of pollutant emission rates with average speed is determined by equations developed by the U.S. Environmental Protection Agency (EPA) (2).
3. Automobile drivers who have not been diverted to buses will be evenly distributed over the remaining lanes in such a way that the resulting total traffic density is maintained.
4. Free-flow conditions are assumed to be such that level of service F (1) is not considered except where it occurs because of resulting congestion in the remaining traffic lanes.
5. Additional emissions caused by buses or car pools that are permitted to use the exclusive lanes are disregarded as negligible.
6. For the counterflow bus-lane configuration, flow in the outbound (less congested) lanes will remain constant during the peak period.

NOMENCLATURE

The following terms are used in the analysis (for those terms in the equations that are formulated in customary units, no SI equivalents are given):

D = number of automobile drivers per mile diverted to buses,
E = emission rate for carbon monoxide (CO) (g/mile·h),
e = composite CO emission factor (g/mile),
F = lane volume (traffic flow) (vehicles/h),
$f = f(V)$ = speed factor for CO emissions,
$g = g(V)$ = speed factor for hydrocarbon (HC) emissions,
H = total HC emissions (g),
h = composite HC emission factor (g/mile),
$k = (N_o - D)/N_o$ = fraction of automobile drivers not diverted to buses,
L = average trip length (miles),
M = number of inbound lanes,
$N(M)$ = total traffic density for M lanes (automobiles/mile),
P = number of peak-period automobiles,
$q = (100 - y)/y$ = ratio of outbound to inbound traffic flow,
T = length of peak period (h),
V = average traffic speed during peak period (mph),
y = percentage of total traffic flow on inbound lanes,
$\phi = M/(M - 1)$ = ratio of number of traffic lanes before and after reservation of bus lane,
o = before reservation of exclusive lane,
1 = after reservation of exclusive lane,
$\bar{\ }$ = inbound lanes after reservation of counterflow bus lane, and
$'$ = outbound lanes in counterflow configuration.

ANALYSIS

The effect of reserving one lane of a four-, six-, or eight-lane highway for the exclusive use of express buses is analyzed by using relations between traffic volume and operating speed observed on limited-access highways across the country and reported in the Highway Capacity Manual (1). The typical variation of traffic volume with operating speed, which is used as a basis for the following equations, is shown in Figure 1. Figure 1 shows that the traffic flow (F), lane volume in vehicles per hour, for a design speed of 112 km/h (70 mph) can be approximated by

$$F = 1.633V(V_d - V) \tag{1}$$

where V_d is the design speed for the highway (112 km/h or 70 mph in Figure 1).

Because traffic flow equals the product of speed (V) and traffic density (N) in automobiles per mile, traffic density for a single lane can obviously be represented by

$$N(1) = 1.633(V_d - V) \tag{2}$$

For M lanes, the total traffic density is thus represented by

$$N(M) = N_x = 1.633M(V_d - V) \tag{2a}$$

In the analyses that follow, it is assumed that the original N automobiles per mile will reduce to N - D automobiles per mile (evenly distributed over the remaining inbound lanes), where D is the number of automobile drivers per mile diverted to buses. In Figure 2, a schematic diagram of the assumed in-lane traffic density before and after reservation of the exclusive

Figure 1. Variation of traffic volume per lane with expressway operating speed.

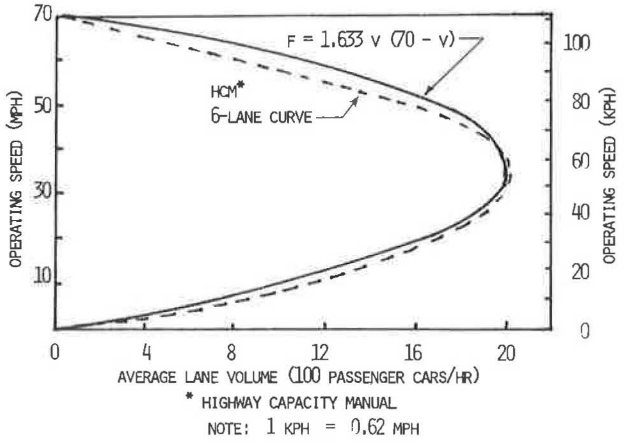
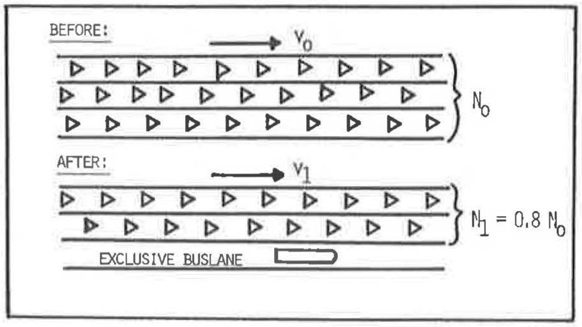


Figure 2. In-lane configuration: 20 percent diversion from automobiles to buses.



lane indicates an assumed 20 percent diversion for three lanes (M = 3) in the peak-flow direction.

Emissions

Because the air quality impact of CO emissions is local and dependent on the instantaneous emission rate, the appropriate equation for M lanes can be written as follows:

$$E = F \times M \times e \times f(V)$$
$$= N(M) \times V \times e \times f(V)$$
$$= 1.633MV(V_d - V)e[f(V)] \quad (3)$$

in grams per mile per hour where e is the base emission factor and V is assumed to remain constant through the peak period. The impact of HC emissions, however, is regionwide and is dependent on the total emissions during the morning peak period. The critical measure of HC emissions is thus expressed by

$$H = F \times M \times T \times L \times h \times g(V)$$
$$= 1.633MV(V_d - V)T \times L \times h \times g(V)$$
$$= P \times L \times h \times g(V) \quad (4)$$

in grams, where T is the time required to discharge the reservoir of P peak-period automobiles.

In-Lane Exclusive Bus Lanes

The initial traffic density is represented by

$$N_o = 1.633M(70 - V_o) \quad (5)$$

If $k = (N_o - D)/N_o$ represents the fraction of automobile drivers who are not diverted to the express buses, then the traffic density on the (M - 1) lanes remaining is represented by

$$N_1 = kN_o$$
$$= 1.633(M - 1)(70 - V_1) \quad (6)$$

where k is the decimal fraction of automobiles remaining in the traffic lanes. Simultaneous consideration of Equations 5 and 6 reveals that

$$V_1 = 70 - k\phi(70 - V_o) \quad (7)$$

where

$$\phi = M/(M - 1) \quad (8)$$

Corresponding values of the CO emission rates before and after implementation of the exclusive bus lane are determined from Equations 3, 5, and 6, as follows:

$$E_o = 1.633MV_o(70 - V_o)e[f(V_o)] \quad (9)$$

and

$$E_1 = N_1 \times V_1 \times e \times f(V_1)$$
$$= k \times N_o \times V_1 \times e \times f_1$$
$$= (k \times E_o \times V_1 \times f_1)/V_o f_o \quad (10)$$

where the subscripts o and 1 represent conditions before and after implementation and f_o and f_1 represent $f(V_o)$ and $f(V_1)$ respectively. Thus, the effectiveness of the exclusive bus lanes with respect to CO emissions is determined by the ratio

$$E_1/E_o = kV_1f_1/V_of_o \quad (11)$$

Table 1 gives the pertinent input variables and the resulting emission ratios for the following factors: V_o = 64 km/h (40 mph), M = 3, $\phi = M/(M - 1) = 1.5$, $N_o = 1.633\ M\ (70 - V_o) = 147$, $f_o = f(V_o) = 0.461$, and $g_o = g(V_o) = 0.617$. The table indicates that the emission ratios are always greater than k and exceed unity for k > 0.96 (CO) and k > 0.86 (HC). The additional emissions resulting from express buses operating in the exclusive lanes were found to be less than 2 percent of the automobile emissions and were omitted from further consideration.

The resulting variation of the minimum percentage diversion with the number of inbound lanes for reduction of CO emissions (emission-reducing effectiveness equals unity) is shown in Figure 3. The figure shows that, for an average pre-bus-lane speed of 56 km/h (35 mph), the installation of an exclusive bus lane will result in increased CO emissions unless 8 to 10 percent of the automobile drivers change to the transit mode.

Equations for total HC emissions, before and after reservation of a single lane for express buses, are derived from Equations 4, 5, and 6:

$$H_o = N_o \times V_o \times T_o \times L \times h \times g(V_o)$$
$$= P_o \times L \times h \times g_o \quad (12)$$

and

$$H_1 = N_1 \times V_1 \times T_1 \times L \times h \times g(V_1)$$
$$= P_1 \times L \times h \times g_1 \quad (13)$$

Table 1. Input variables and emission ratios for in-lane exclusive bus lane.

k	$V_1 = 70 - k\phi(70 - V_o)$	$f_1 = f(V_1)$	kV_1f_1	kV_1f_1/V_of_o	kg_1	kg_1/g_o
1.0	25.00	0.773	19.33	1.048	0.825	1.316
0.95	27.25	0.711	18.24	0.990	0.787	1.276
0.90	29.50	0.630	17.01	0.924	0.678	1.099
0.85	31.75	0.586	15.94	0.866	0.609	0.992
0.80	34.00	0.547	14.88	0.810	0.548	0.894
0.75	36.25	0.514	13.88	0.756	0.494	0.808
0.70	38.50	0.485	12.90	0.704	0.445	0.730
0.65	40.75	0.461	11.99	0.655	0.401	0.660

Figure 3. Minimum percentage diversion versus number of inbound lanes for in-lane CO emissions.

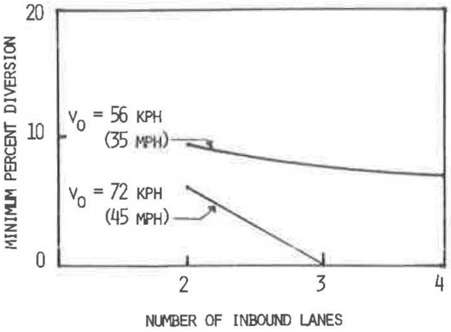
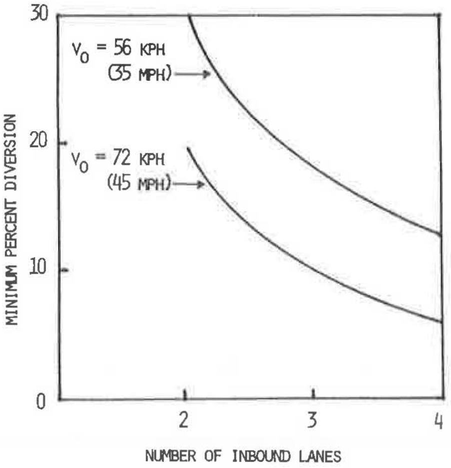


Figure 4. Minimum percentage diversion versus number of inbound lanes for in-lane HC emissions.



Under the assumption of steady-state traffic densities during the peak period, it is apparent that the traffic densities (N) are proportional to the total numbers of peak-period automobiles (P). Thus, $P_1/P_o = N_1/N_o = k$, and Equation 13 can be expressed by

$$H_l = k \times P_o \times L \times h \times g_l \tag{13a}$$

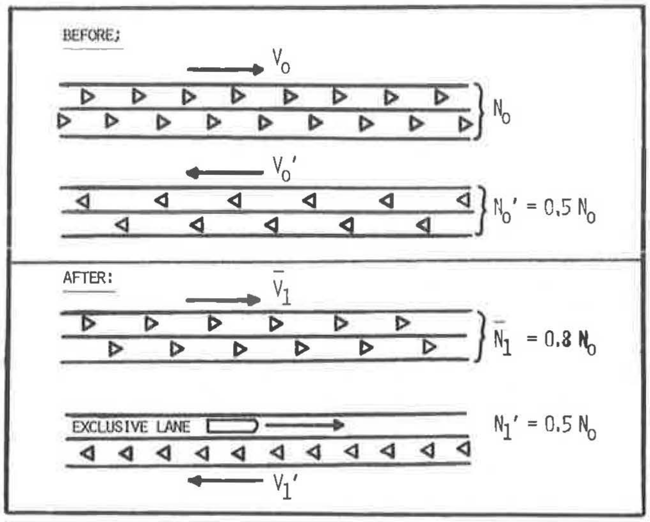
The emission-reducing effectiveness for HC of the in-lane exclusive bus lane is thus determined by

$$H_l/H_o = kg_l/g_o \tag{14}$$

The pertinent variables and the resulting ratios for V_o = 64 km/h (40 mph) and M = 3 are given in Table 1.

Figure 4 shows the variation of minimum percentage diversion with the number of inbound lanes (M) for reduction in HC emissions. The figure shows that reduction of HC emissions requires a diversion of 14 to 30 percent of automobile drivers on a highway where the normal peak-period speed is 56 km/h (35 mph).

Figure 5. Counterflow configuration: 20 percent diversion from automobiles to buses and 60-40 directional split.



Counterflow Exclusive Bus Lanes

Basic relations for the peak-flow direction in the counterflow configuration (Figure 5) are equivalent or similar to Equations 5 and 6 for the in-lane exclusive bus lanes:

$$\bar{N}_l = kN_o = 1.633M(70 - \bar{V}_1) \tag{15}$$

where it is noted that, because the bus lane is now assigned to the less congested, outbound portion of the highway, the number of inbound lanes (M) remains the same after implementation of the exclusive lane. Simultaneous consideration of Equations 5 and 15 results, therefore, in the following equation for $\bar{V}_1$:

$$\bar{V}_l = 70 - k(70 - V_o) \tag{16}$$

The relation of the initial outbound speed (V_o') to V_o is established by the directional split [y : (100 - y)]:

$$q = (100 - y)/y \tag{17}$$

where y is the percentage of total traffic flow ($MF_o + M'F_o'$) in the inbound (peak-flow) lanes and M′ is the number of outbound lanes. Therefore,

$$M'F_o' = qMF_o \tag{18}$$

and

$$M'V_o'(70 - V_o') = qMV_o(70 - V_o) \tag{19}$$

For M′ = M (which is assumed throughout the following analysis),

$$V'_o = 35\{1 + \sqrt{1 - [4qV_o(70 - V_o)/4900]}\} \tag{20}$$

Because it is assumed that neither the total number nor the total density of outbound automobiles is altered by the diversion of inbound automobile drivers to buses,

$$N'_I = N'_o$$

$$(M - 1)(70 - V'_I) = M(70 - V'_o) \tag{21}$$

from which

$$V'_I = 70 - \phi(70 - V'_o) \tag{22}$$

In Figure 5, a schematic diagram of the assumed traffic density before and after reservation of an exclusive counterflow bus lane indicates an assumed 20 percent diversion for a four-lane highway with a normal directional split of 60-40. Figure 5 shows that the reservation of one of the two outbound lanes as an exclusive bus lane results in a doubling of the lane density on the remaining outbound lane.

Appropriate values for CO emission rates, before and after implementation of the exclusive counterflow bus lanes, are determined from Equations 3, 9, 15, 19, and 21, as follows:

$$\begin{aligned}\bar{E}_I &= \bar{N}_I \times \bar{V}_I \times e \times \bar{f}_I\\ &= k \times N_o \times \bar{V}_I \times e \times \bar{f}_I\\ &= (k \times E_o \times \bar{V}_I \times \bar{f}_I)/V_o f_o \end{aligned} \tag{23}$$

$$\begin{aligned}E'_o &= N'_o \times V'_o \times e \times f'_o\\ &= q \times N_o \times V_o \times e \times f'_o\\ &= (q \times E_o \times f'_o)/f_o \end{aligned} \tag{24}$$

and

$$\begin{aligned}E'_I &= N'_I \times V'_I \times e \times f'_I\\ &= N'_o \times V'_I \times e \times f'_I\\ &= (q \times E_o \times V'_I \times f'_I)/V'_o f_o \end{aligned} \tag{25}$$

Thus, the effectiveness of counterflow exclusive bus lanes in reducing CO emissions is determined by the following ratio:

$$(\bar{E}_I + E'_I)/(E_o + E'_o) = [(k\bar{V}_I\bar{f}_I/V_o) + (qV'_I f'_I/V'_o)]/(f_o + qf'_o) \tag{26}$$

Equations for total HC emissions, before and after reservation of the exclusive counterflow bus lane, are derived from Equations 4, 12, 15, and 21 on the continuing assumption that the reservoirs of peak-period inbound automobiles (P_o, $\bar{P}_I$) are proportional to the corresponding densities,

$$\bar{P}_I/P_o = \bar{N}_I/N_o = k \tag{27}$$

and the straightforward assumption that the ratio of the total number of outbound automobiles to the initial number of inbound automobiles is equivalent to the ratio of the corresponding initial flows,

$$P'_o/P_o = F'_o/F_o = q \tag{28}$$

Therefore,

$$\begin{aligned}\bar{H}_I &= \bar{P}_I \times L \times h \times \bar{g}_I\\ &= k \times P_o \times L \times h \times \bar{g}_I\\ &= kH_o\bar{g}_I/g_o \end{aligned} \tag{29}$$

$$\begin{aligned}H'_o &= P'_o \times L \times h \times g'_o\\ &= q \times P_o \times L \times h \times g'_o\\ &= qH_o g'_o/g_o \end{aligned} \tag{30}$$

and

$$\begin{aligned}H'_I &= P'_I \times L \times h \times g'_I\\ &= q \times P_o \times L \times h \times g'_I\\ &= qH_o g'_I/g_o \end{aligned} \tag{31}$$

Emission-reducing effectiveness for HC is subsequently determined by the ratio

$$(\bar{H}_I + H'_I)/(H_o + H'_o) = (k\bar{g}_I + qg'_I)/(g_o + qg'_o) \tag{32}$$

Figure 6 shows the variation of the minimum percentage diversion with the number of inbound lanes for reduction of HC emissions for a counterflow configuration in which the normal directional split is 55-45. The figure shows that a reduction in HC emissions requires a minimum diversion of 15 percent for a four-lane highway with a pre-bus-lane speed of 56 km/h (35 mph) and diversions of 4 and 2 percent respectively for six- and eight-lane highways.

Figure 6. Minimum percentage diversion versus number of inbound lanes for counterflow HC emissions.

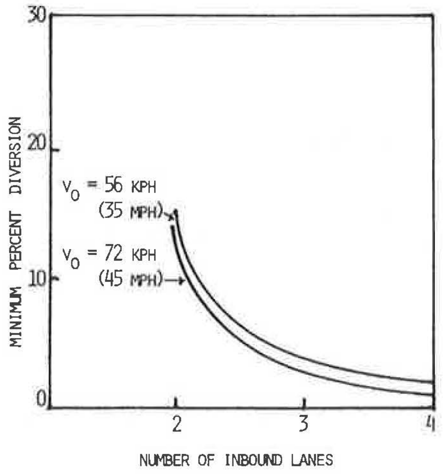


Table 2. Percentage diversion required to effect emissions reduction for in-lane exclusive bus lanes.

	Required Diversion (%)					
	CO			HC		
V_o (km/h)	Two Lanes	Three Lanes	Four Lanes	Two Lanes	Three Lanes	Four Lanes
56	10	9	8	30	18	13
64	8	4	2	27	15	10
72	5	0	0	21	11	8
80	0	0	0	15	6	4

Note: 1 km = 0.62 mile.

RESULTS

In-Lane Configuration

The percentage of diversion from automobiles to transit required to effect a reduction in pollutant emissions for in-lane exclusive bus lanes, as determined by Equations 7, 11, and 14, is given in Table 2 for various initial-

Table 3. Percentage diversion required to effect emissions reduction for counterflow exclusive bus lanes.

		Required Diversion (%)					
		CO			HC		
Directional Split	V_s (km/h)	Two Lanes	Three Lanes	Four Lanes	Two Lanes	Three Lanes	Four Lanes
50-50	56	5	5	4	>35	>35	22
	64	20	4	2	>35	35	18
	72	4	0	0	>35	18	10
	80	0	0	0	34	9	5
55-45	56	0	0	0	15	4	2
	64	0	0	0	18	4	3
	72	0	0	0	14	4	0
	80	0	0	0	9	0	0
60-40	56	0	0	0	3	2	0
	64	0	0	0	3	0	0
	72	0	0	0	3	0	0
	80	0	0	0	2	0	0

Note: 1 km = 0.62 mile.

Table 4. Minimum percentage diversion required to achieve significant reductions of CO and HC emissions.

	Required Diversion (%)											
	In-Lane			50-50 Counterflow			55-45 Counterflow			60-40 Counterflow		
Volume/Capacity Ratio	Two Lanes	Three Lanes	Four Lanes	Two Lanes	Three Lanes	Four Lanes	Two Lanes	Three Lanes	Four Lanes	Two Lanes	Three Lanes	Four Lanes
Carbon monoxide												
1.00	22	20	14	40	40	40	0	0	0	0	0	0
0.98	9	7	5	40	40	40	0	0	0	0	0	0
0.90	9	0	1	40	40	40	0	0	0	0	0	0
0.80			0			40			0			0
0.75		0			40			0			0	
0.70	0			40			0			0		
Hydrocarbons												
1.00	40	24	18	—[a]	—[a]	—[a]	—[a]	10	5	6	2	0
0.98	34	20	14	—[a]	—[a]	—[a]	—[a]	20	7	7	0	0
0.90	25	16	11	—[a]	—[a]	—[a]	—[a]	10	0	10	0	0
0.80			6			40			0			0
0.75		10			40			10			0	
0.70	20			—[a]			40			10		

[a] Impossible to achieve significant emission reductions at less than 50 percent diversion from automobiles.

speed values. The data show that, for highways with an average initial speed ≥56 km/h, HC reductions require diversions that vary from 15 to 30 percent for two inbound lanes and from 4 to 13 percent for four inbound lanes. CO reductions can be achieved for highways in which the average initial speeds exceed 72 km/h (45 mph) for two inbound lanes or 64 km/h (40 mph) for three or more inbound lanes.

Counterflow Lane Configuration

The percentage diversion required to effect a reduction in pollutant emissions for counterflow exclusive bus lanes, as determined by Equations 16, 20, 22, 26, and 32, is given in Table 3 for various values of average initial speed and directional split. The data show the following:

1. For highways with a 50-50 directional split, reductions in hydrocarbon emissions require a diversion from the automobile mode greater than 33 percent for half of the cases examined and an average diversion of 10 percent for the remaining cases.
2. For a highway with a directional split of 55-45, reductions in CO emissions will occur for all cases. HC reductions require diversions of 4 to 18 percent on four- or six-lane highways where the speed before the exclusive bus lane is less than 80 km/h (50 mph).
3. For a highway with a directional split of 60-40, emission reductions will occur for all cases except for four-lane highways, where reductions in HC emissions require a modest diversion from automobiles to transit.

Table 4 gives the minimum diversion percentages required, for various configurations and directional splits, if CO and HC emissions are to be significantly reduced (by more than half the diversion percentage).

CONCLUSIONS

Reductions in CO emissions can be achieved by means of in-lane exclusive bus lanes where average traffic speeds exceed 72 km/h (45 mph) and by means of counterflow lanes where directional splits equal or exceed 55-45. Reductions in HC emissions can be achieved by means of counterflow lanes if the directional split exceeds 55-45 and the percentage of people diverted from automobiles exceeds 5 percent.

ACKNOWLEDGMENTS

I thank Nancy Goldman of the University of Pennsylvania, a work-study student in the EPA regional office, and Steven Powers of EPA for their assistance in performing the calculations and preparing the figures for this report. The views expressed in this paper are mine and are not necessarily endorsed by the U.S. Environmental Protection Agency.

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Publication of this paper sponsored by Committee on Transportation and Air Quality.

Abridgment

Line Source Emissions Modeling

Lonnie E. Haefner, D. E. Lang, R. W. Meyer, J. L. Hutchins, and
Bigan Yarjani, Civil Engineering Department, Washington University

The objective of this paper is to describe the development of the line source sorting model NETSEN II and its use in conjunction with the automobile exhaust emissions modal analysis model of the U.S. Environmental Protection Agency (EPA) (1). Speed-profile analogies from the Regional Air Pollution Study of the St. Louis air quality control region (AQCR), developed for use in the modal emissions model, are used.

MODAL EMISSIONS MODEL

The automobile exhaust emissions modal analysis model developed by the Calspan Corporation for EPA was designed to calculate the amounts of hydrocarbons (HC), carbon monoxide (CO), and oxides of nitrogen (NO_x) emitted by individual automobiles or groups of automobiles stratified by age and geographic location (1). Emission rates were deduced from surveillance tests performed on a test fleet of 170 automobiles in six American cities at varying altitudes. Emissions were output for any given second-by-second driving sequence within a speed range of 0 and 96.8 km/h (0 and 60 mph). The model developers recognized that the emissions response of an automobile depends on the speed profile experienced by its occupants as they travel from origin to destination. The developers also recognized that different light-duty vehicles have separate emissions responses for the same speed, acceleration, and deceleration profiles. The model does not treat meteorological or transport processes. It specifically details the distribution of emissions along a user-defined highway link and computes the total CO, HC, and NO_x contributions to the atmosphere from the highway source.

The inputs into the EPA modal emissions model include both traffic and emissions data. The traffic inputs are representative second-by-second speed profiles on the defined line sources, the number of automobiles assignable to the particular speed profiles on the defined line sources, their age distribution by model year, and the relative altitude at which they are operated. The emission parameters include emission-rate coefficients that are specific to speed profiles and are either user supplied or produced by default in the computer program itself. Because of cost and time, unless the user has a vehicle fleet and dynamometer testing equipment, the default emission-rate coefficients should be used. The emission-rate coefficients supplied by the model do not include the effects of cold starts, which generate a sizable portion of automobile emissions. No deterioration factors are applied, but they are indirectly incorporated in that the vehicle fleet used in the surveillance program reflected age and maintenance effects.

The modal emissions model estimates actual CO and HC emissions within 13 percent but only predicts NO_x within 80 percent. Because the model was developed for a single vehicle fleet, its ability to reproduce emissions from additional vehicle fleets was also tested. The model replicated performance to within 30 percent. Although this error seems significant, the input data from the model's own original vehicle fleet could not be replicated any better a second time. Both microscale and mesoscale emission-analysis methods have this drawback.

The modal emissions model is capable of operating at a truly microscale level. It allows for highly specific analysis of the emissions effects of traffic congestion. In using the model for this purpose, however, the user must define the established regional highway network—a major undertaking for a region the size of St. Louis. In addition, second-by-second speed-profile data and localized data on the emission response of vehicles must be collected either in the field or by development of a systematic scheme of speed-profile analogies for line sources.

DESCRIPTION OF NETSEN II MODEL

The network sensitivity model NETSEN II is an updated version of NETSEN, which was designed in an EPA study (2). The updated version has additional variables and subroutines and the ability to test for the following roadway characteristics in defining a line source: average daily traffic, five types of special topography, four types of capacity alterations, eight types of sensitive land uses, five types of activity centers, five types of progressive movement, channelization, functional classification, link distance, peak speed differences, truck and bus volumes, and volume/capacity (V/C) ratio.

Definition of a Line Source

The definition of a line source hinges on the capability of analyzing the highway network and its traffic and design attributes at varying levels of detail, and that capability depends on the availability of data and the level of spatial refinement sought by the user for input into pollution models such as the modal emissions model. Thus, if adequate data are available, the user has a range of capabilities, from developing a very refined set of descriptors—termed ultimate line sources—to developing a very unrefined set of descriptors—termed gross line sources. The following basic definition of a line source was used in the development of the NETSEN II program: "A line source is the smallest segment of inventoried roadway depictable with a given specific set of attributes for the roadway" (2).

NETSEN II was designed to allow the user to select those links that have relevant characteristics at a level of refinement determined by the user.

Logic

The model begins by reading control cards that define the attributes for which the model is to test the line sources. Next, a line source from the roadway inventory link file is input into the model. The model then begins a series of sequential tests of the line source for the attributes previously defined in the control card. If the line source passes all the tests, it is output for further computation of its emissions and another line source is read in. If the line source fails an attribute test, testing of that line source ceases and the program goes back and inputs a new line source. When all of the line sources from the roadway inventory link file are tested, the set of line sources that passes the tests is ready for use in the modal emissions model.

Two specific points about NETSEN II are of major importance:

1. The network can be tested at any relevant level of data attributes. These levels can run from very gross descriptions (testing for all freeway links) to a very refined set of descriptors [testing for links that have a freeway classification with, for example, average daily traffic (ADT) of 40 000 to 45 000 vehicles/d and rolling topography].
2. The level of attribute refinement the user chooses to test may vary with the detail of the data available. The level of refinement of the data may also vary according to what the user determines is necessary for the study of emissions. Thus, there is complete flexibility in the behavioral aspects of the network with respect to the estimation of emissions.

SPEED-PROFILE ANALOGIES

A critical element in this research has been the development of a methodology for constructing speed-profile analogies for roadway segments for which no speed-profile data have been collected. Development of such analogies is necessary if the modal emissions model is to compute emissions for the entire AQCR network.

Speed-Profile Data

A basic item of data for this research was a study of speed characteristics for the St. Louis region conducted by the East-West Gateway Coordinating Council under contract to the Federal Highway Administration and EPA. The study provided second-by-second speed data over a variety of roadways on 16 different circuitous routes in the St. Louis region. Each roadway segment was run a total of 12 times. Speed-profile data existed for approximately 70 to 80 percent of the total kilometers of freeway in the St. Louis AQCR, but there were adequate speed-profile data for only about 50 percent of the arterial roadways.

Development of Methodology

Two basic approaches to analogy development were explored. The first was to attempt to construct second-by-second speed profiles for roadway segments for which data had not been collected by locating a segment of roadway that has traffic-flow parameter values similar to those of the segment in question. The traffic-flow parameters most indicative of emissions behavior are hourly volume, V/C ratio, average speed, and acceleration noise (defined as the standard deviation of velocity about the mean). Because a speed profile has an associated average speed and acceleration noise, it would be possible to physically construct a second-by-second speed profile of the appropriate length for the roadway segment without speed-profile data. But there are two basic problems with this approach. First, the data on which the analogy is based are not uniformly available and, if they were available, would probably not be applicable to peak-hour, worst case conditions. Second, the analogy between the segment with speed-profile data and the segment without speed-profile data is made on the basis of parameters such as peak-hour average speed and V/C ratio, but a single speed profile is only a single sample from some supposedly stable distribution of possible profiles on a segment. There does not appear to be any direct means of aggregating numerous speed-profile samples over the same segment. When this problem is combined with the problem of specifying what constitutes a peak-hour average speed or V/C ratio, the technique loses much of its desirability.

The second technique explored, and the one ultimately used for arriving at analogies, begins by cross classifying every line source segment in the entire network by three relevant and available indicators of traffic-flow quality: ADT, V/C ratio, and functional class of roadway. These three parameters imply much of the operational nature of a particular roadway segment. For purposes of this research, four appropriate ADT ranges were selected for each of three functional classes. In addition, four ranges of V/C ratio were selected that yielded 48 discrete roadway classifications; coupling these classifications with the use of peak and off-peak descriptors increased the number of possible classes of roadway operation to 96. For each of the 48 possible roadway classifications, a segment was sought for which plausible speed-profile data existed. In actuality, only 29 of the 48 classes currently exist in the St. Louis AQCR network. Two speed profiles were selected for each of these 29 base segments—one that represented off-peak operating conditions and one that represented peak-hour operating conditions.

Peak and off-peak speed profiles for each segment were run through the modal emissions model with a reasonable vehicle mix to arrive at unadjusted emission rates for each of the two profiles and for each of the 29 roadway classes. These rates were then adjusted for an ambient temperature of 29°C (85°F) and 10 percent cold operation by using EPA adjustment factors (3). In the emissions computation software, a set of line sources that pass the parameter tests of NETSEN II are checked to see which of the possible roadway classes they are contained in, and the appropriate emission rate is applied for the hour of interest.

This second methodology allows the use of appropriate traffic-engineering and emissions inputs to the emissions computation process but makes full use of available data. Based on the number of desired categories for each of the parameters, the classification scheme can be as refined as the user desires and the data will allow.

EMISSIONS SOFTWARE SYSTEM AND EXAMPLE OUTPUT

The software system designed to compute emissions for line sources consists of three basic programs. The first is the network sorting model, NETSEN II, the inputs to which consist of appropriate user control cards for selection of line sources and the network roadway inventory. The output of NETSEN II is a set of line sources that meet specified characteristics. These line sources are then passed to the ECOMP program, which computes the line source emissions by using these outputted line sources as the first input.

The second input to the ECOMP program is the emission rates computed by the modal emissions model. The modal emissions program uses the emission coefficients supplied by the model and the peak and off-peak profiles from each of the 29 roadway segments identified as representative of each of the analogy classes. The results of the modal emissions program are adjusted for 20 percent cold operation and an ambient temperature of 25°C (75°F) and are used as input in the ECOMP program for light-duty vehicles. The ECOMP program uses different modal emission rates for peak and off-peak operations.

The third set of inputs to the ECOMP program is the emission factors for trucks, which are computed from EPA publication AP-42 (3). For light-duty trucks, heavy-duty gasoline-powered vehicles, and heavy-duty diesel-powered vehicles, separate emission factors were determined for calendar year 1975 (3) by using an average speed of 48 km/h (30 mph), an ambient temperature of 25°C, and, for light-duty trucks, 10 percent cold operation. These emission rates were applied to hourly volumes for these three classes of trucks based on an assumed distribution among all vehicles of 5 percent light-duty, 4 percent heavy-duty diesel-powered, and 1 percent heavy-duty gasoline-powered trucks.

The fourth input to the ECOMP program is a control card to determine the total percentage of all trucks, the hours of the day for which emissions data are desired, and whether or not emissions are to be added to the grid totals or stored separately as hourly totals. Emissions of SO_2 and particulates were computed by ECOMP based on emission rates for each of the four types of vehicles for the appropriate hourly volumes under consideration. These SO_2 and particulate rates were taken from EPA publication AP-42 (3).

The outputs from the ECOMP program consist of three possible types. First, the program outputs on the printer an hourly summary for each line source that consists of geographic information, roadway volumes, functional roadway class, and emissions totals for the five types of pollutant. The second type of output is similar to the first except that it is stored on tape for later use. The third type of output is the totaling of all line source emissions for each grid. The last two outputs are optional and may be specified by the user.

In a freeway example that used NETSEN II, the line sources located by the program were freeways with ADTs in the range of 60 000 to 80 000 and V/C ratios in the range of 0.60 to 0.90. Fifty-seven line sources representing 49.2 km (30.5 miles) of roadway and 3.5 million vehicle•km (2.2 million vehicle miles) of travel fit this description. The ECOMP program computed total emissions for this set of line sources for the hours of 4:00 to 6:00 p.m., which resulted in 271.8 kg of HC, 4397.1 kg of CO, 367.9 kg of NO_x, 14.8 kg of SO_2, and 36 kg of particulates.

Another example consisted of all line sources that were principal arterials with ADTs in the range of 10 000 to 20 000 and with V/C ratios in the range of 0.30 to 0.60. These specifications resulted in 114 line sources representing 81.9 km (50.8 miles) of roadway and 1.04 million vehicle•km (0.6 million vehicle miles) of travel. The emissions for this set of line sources were computed for the 8:00 to 9:00 a.m. period and resulted in 97 kg of HC, 1334.1 kg of CO, 247.3 kg of NO_x, 2.6 kg of SO_2, and 6.4 kg of particulates.

CONCLUSIONS AND RECOMMENDATIONS

The data analysis and modeling efforts of the project yielded several tangible outputs:

1. The updated and refined version of the NETSEN model, NETSEN II, which is capable of defining line sources at any level of data refinement and inputting such line sources to a variety of emissions models, in this particular case of integrating with the modal emissions model by using the speed profile as the key linking variable;
2. Development of a truly microscale emissions estimation model, which allows emissions to be analyzed as a function of highly localized traffic operating conditions and roadway descriptions, through integration of NETSEN II and the modal emissions model;
3. The ability to develop accurate analogies of speed-profile and emission characteristics for links that do not possess speed-profile field data (these analogies are built by appropriate analysis of cross-classified links possessing speed-profile data, over a range of ADT, V/C ratio, and functional class); and thus
4. An exhaustive and accurate statement of emissions obtained from line sources in the St. Louis AQCR [encompassing sources, descriptions, attributes, and total emissions for CO, HC, NO_x, SO_2, and particulates from 2209 km (1370 miles) of roadway].

The following areas require further research:

1. Very refined measurement of second-by-second speed profiles for an exhaustive set of geometric design-traffic operations combinations, such as one-way streets, progressive signalization systems, links crossing intersections with channelized or signalized turn lanes (i.e., development of a "case book" of speed-profile typology, possibly for cities of varying size and urban characteristics, much as the Highway Capacity Manual classifies conditions for design and capacity analysis); and
2. The potential capability for studying speed-profile and emission characteristics by using speed and delay-related traffic-flow theories such as those for acceleration noise, freeway shock-wave phenomena, and queuing.

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Publication of this paper sponsored by Committee on Transportation and Air Quality.

Abridgment

Use of Traffic Simulation in Analysis of Carbon Monoxide Pollution

Stephen L. Cohen, Office of Research, Federal Highway Administration

One of the serious problems facing traffic engineers, from an operations and planning standpoint, is the requirement that certain standards for carbon monoxide (CO) concentrations be met. The problem of predicting traffic-generated CO concentrations near streets and highways is particularly important for meeting these standards. From the planning viewpoint, the question is what the effect will be on air quality if land use near a traffic facility is changed in such a way as to increase the traffic burden on the facility. From the operations viewpoint, the question is what the effect will be on air quality if changes are made in a traffic facility (e.g., more lanes or a computer-controlled signal system).

The standard approach is to consider the traffic facility, in the case of an arterial or a freeway, as a line source of pollution or, in the case of urban networks, as a set of line sources. A dispersion model is then applied to predict CO concentrations at various distances downwind from the line source. An example of such a model is the HIWAY model of the U.S. Environmental Protection Agency (1), which is based on the principle of Gaussian dispersion. But the HIWAY model has a serious shortcoming: It assumes that the strength of the emissions from the line source is constant along its length. This assumption means that the line source has a constant emission profile. Although this is a fairly good assumption for uninterrupted flow conditions, it is totally inadequate in interrupted flow conditions such as those caused by traffic signalization.

In a number of papers, Patterson (2, 3) has investigated the use of traffic queuing models at signalized intersections in an attempt to estimate the nonconstant emission profiles caused by stop-and-go traffic at the stop line. Although subject to the limitations described below, Patterson's work indicates that the queuing process is a copious source of CO near the stop line. As the author points out, the reason is not that CO emissions are high during low speed and idling—they are in fact about the same as during higher speed operations (4)—but that the amount of time spent near the stop line is much greater than the amount of time spent near midblock. Thus, most CO will be emitted near the stop line while automobiles are stopped for a red light, and the result is that the emissions profile will be sharply peaked at the stop line and fall off rapidly toward midblock, leading, under most wind conditions, to a similar nonuniformity in pollution levels between stop line and midblock.

There are, however, some limitations in Patterson's approach. The queuing models considered assume either constant or uniformly distributed arrivals to and departures from the queue. These assumptions are often violated in the field. Examples include right turn on red, unprotected left turns, pedestrian blockages of left- or right-turning traffic, buses dwelling at nearside stops, and platooned arrivals. The inclusion of such effects requires a much more comprehensive model.

UTCS-1 NETWORK SIMULATION MODEL

The UTCS-1 model (5) is a microscopic traffic-simulation model that was developed for the purpose of comparing traffic-control strategies in a laboratory, or controlled, environment. The term microscopic means that vehicles move individually through a network according to the laws of "car-following," responding to signal indications. The model is a time-scan simulation with a time step of 1 s. Three types of vehicles are included: a composite automobile, a heavy intracity truck, and a transit bus. Because vehicles are moved through the network individually, their speeds and accelerations are known and are stored in internal arrays at the end of each time scan. Thus, measures of effectiveness (MOEs) such as fuel consumption and emissions, which are dependent to a great extent on speed and acceleration, could be computed if this dependence were known. These MOEs have recently been added to the model (6) by including a set of fuel-consumption and emissions tables to be accessed by the mean speed and acceleration couplet available at the end of each time scan. Hergenrother of the Transportation Systems Center, Cambridge, Massachusetts, generated the fuel-consumption tables for the Federal Highway Administration by using a vehicle simulation model he developed (7). The emissions tables for HC, CO, and NO_x were generated by Cohen by using the EPA modal emissions model (8). Brief descriptions of these models are given elsewhere (4).

During simulation, speed trajectory information for each vehicle is written on a disk file, each record of which consists of the speed, acceleration, link, link location to the nearest 1.5 m (5 ft), and vehicle type (automobile, truck, or bus) at the end of every time scan. This trajectory file is then read at the end of a subinterval or a simulation run by a special program module that calculates fuel and emissions for each link and for the entire network. This is done so that vehicle types with different fuel-consumption and emissions tables could be simulated without running the simulation program again. For example, one could change the composite automobile by including different model years or different percentages of automobile types or both, inserting a new set of tables for fuel consumption and emissions, and computing a new set of fuel-consumption and emissions MOEs by using a trajectory file generated by a previous simulation run.

GENERATION OF EMISSION PROFILE

The emission profile for an arterial can easily be calculated if a few changes are made to the UTCS-1 fuel module. An x-y coordinate system is set up in which the arterial runs along the y axis. Then the y position of each stop line on every link is determined. Since the location of each vehicle on a link is known to the nearest 1.5 m (5 ft) with respect to the link stop line, the y location of the vehicle is known. The arterial is divided into 3.0-m (10-ft) "bins" that represent the resolution of vehicle positions. One can calculate the amount of CO emitted in each such bin during each time scan by locating the position of each vehicle, computing its CO emissions during the time step by accessing the CO table with its speed-acceleration couplet, and accumulating an appropriate counter corresponding to the bin occupied by the vehicle. The resulting emission profile is then written on a disk file (or tape) for later processing by a dispersion model.

The network shown in Figure 1—the link-node representation of Wisconsin Avenue in Washington, D. C., between N and Porter streets—has been chosen as a demonstration. The numbers along the diagram indicate the longitudinal positions of the stop lines. Volumes and turning movements for the a.m. peak for another study that involved comparison of different signal settings along Wisconsin Avenue were made available by the District of Columbia Department of Highways and Traffic.

Fifteen minutes of simulated time was run. Figure 2 is a plot of the emission profile on link 33-34. Here, the emission rate in grams per second per meter is plotted against longitudinal position in meters. Two things should be pointed out. The first is that the profile is greatly peaked at the stop line but falls off rapidly

Figure 1. Wisconsin Avenue arterial network.

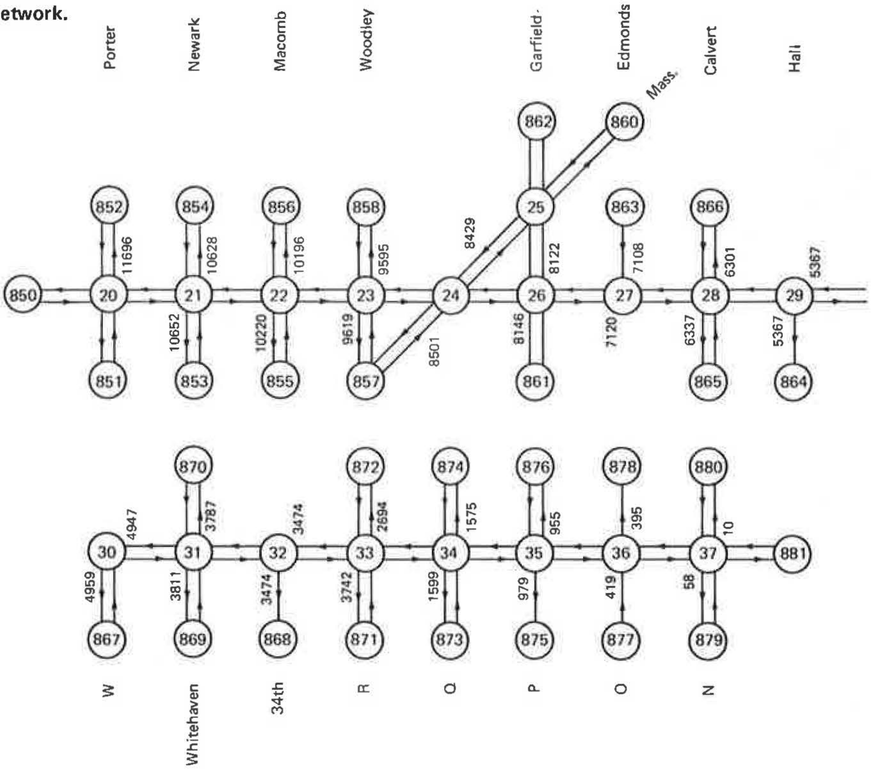
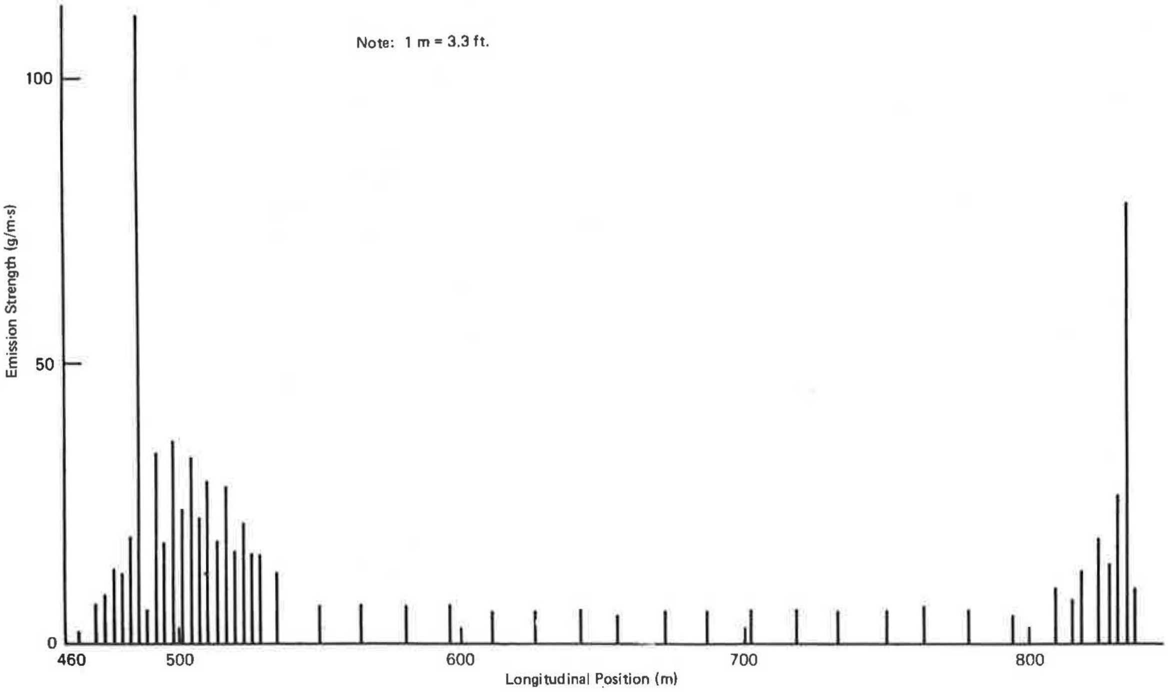
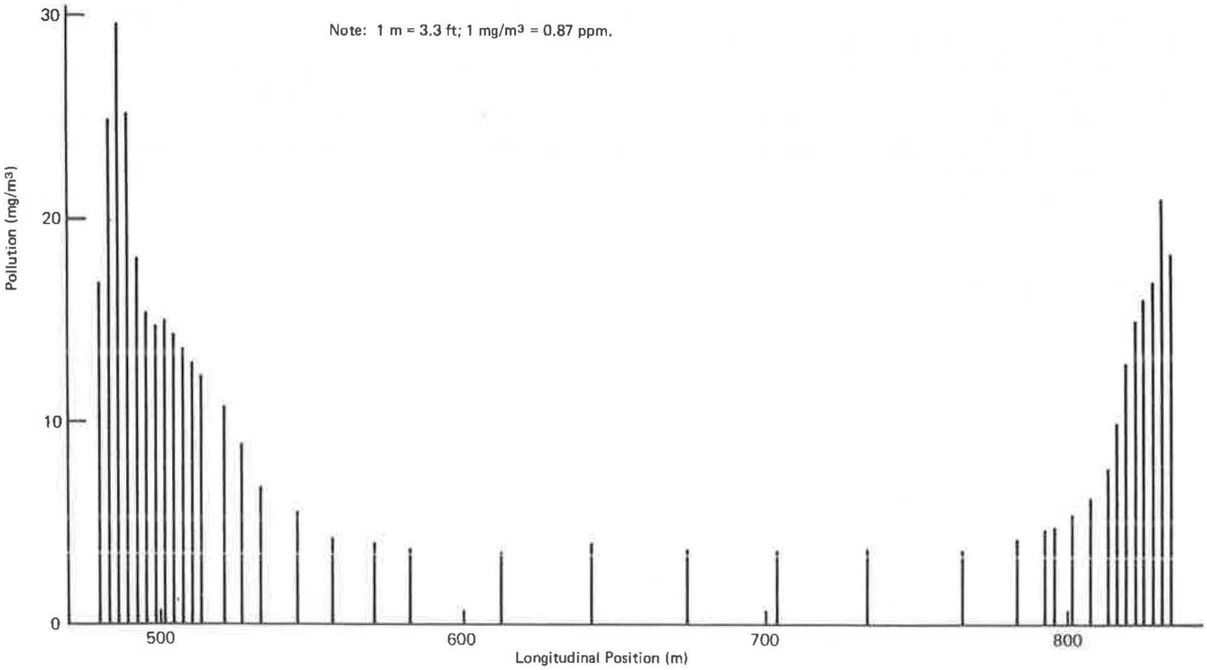


Figure 2. Emission profile on link 33-34, R to Q streets.



Note: 1 m = 3.3 ft.

Figure 3. Pollution levels along Wisconsin Avenue between R and Q streets.



as one approaches midblock. This was, of course, as expected. The second point is the strange oscillating behavior in the profile as one moves away from the stop line. This condition is due to the fact that the vehicles in the model occupy 6.1 m (20 ft) in the stopped queue but the bins into which the links are divided are 3.0 m (10 ft) long. Thus, in the standing queue, every other bin receives no emissions. Both of these factors demonstrate the dominating effect of idling on CO emissions and point up the inadequacy of using a constant emission profile in computing pollution levels in an urban environment.

CALCULATION OF POLLUTION LEVELS

The HIWAY model had to be modified to make use of the UTCS-1 computed emission profiles. The HIWAY model computes the pollution generated by a line source and measured at a receptor by integrating over the length of the line source, assuming the emission profile to be constant so that it may be removed from under the integral sign. Thus, pollution levels, aside from a constant value, are completely determined by meterological effects. The obvious change is thus merely to place emission strength back under the integral sign and appropriately modify the numerical integration in the model.

The modified HIWAY model was then used with an emission profile generated as described in the previous section. One run was made with receptors downwind, 3.0 m (10 ft) from the curb and at a height above the ground of 0.5 m (1.6 ft). Wind speed was taken to be 1 m/s (3.3 ft/s) and wind angle to be 265° (blowing from the north). Receptors were placed along links 33-34 and 34-33 with 1.5-m (5-ft) spacing near the stop lines and 6.1-m (20-ft) spacing at midblock locations. The results are shown in Figure 3, in which pollution levels are plotted against longitudinal position.

The major feature of interest is that the pollution levels behave similarly to the emission levels in that they are much higher at the stop line. Note, however, that the oscillating behavior is not present in the pollution levels, which indicates that the HIWAY model is insensitive to the choice of 3.0-m (10-ft) bins.

CONCLUSIONS

This work demonstrates that the emission profile is necessary for the prediction of pollution levels in urban areas and that the UTCS-1 model is a useful tool for generating such profiles under a wide variety of conditions.

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Publication of this paper sponsored by Committee on Transportation and Air Quality.